ON-BOARD AUTOMATIC AID AND ADVISORY FOR PILOTS OF CONTROL-IMPAIRED AIRCRAFT

by

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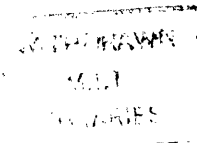Charles Stark Draper Laboratory, Inc.

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ABSTRACT

This thesis represents the consideration of the problem of aircraft control failures from a broader viewpoint than the usual control loop reconfiguration or redesign. The additional considerations involved in making full recoveries from control failures are categorized, and because it can be expected that pilots, if unaided, may continue often to be unable to recover aircraft, these considerations have been cast in the form of knowledge and capabilities that an automatic aid and pilot advisory system should have. Each major element of the categorization is supported with information from actual aircraft accident cases and from simulations of post-failure flight of a C-130 aircraft. Because automatic emergency control is seen to be a very significant part of the proposed system, a rule-based system to find a successful control strategy is developed for elevator failures on the C-130 aircraft. The advisory function of the recovery-aiding system is described for various post-failure flight phases. The issues of pilot interface are discussed, and there is a treatment of the problem of deciding what to calculate to support the advisory. There is a discussion of post-failure explicit retrimming and some demonstrations of the real impact of this. The problem of evaluating and conveying precise post-failure control capabilities so that the information is accessible to pilots has been addressed.

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Our whole life is startlingly moral. There is never an instant's truce between virtue and vice....The impure can neither stand nor sit with purity....From exertion come wisdom and purity; from sloth ignorance and sensuality. In the student, sensuality is a sluggish habit of mind....If you would avoid uncleanness, and all the sins, work earnestly, though it be at cleaning a stable.

Thoreau, Walden, "Higher Laws"

"And will a man do better working at many trades, or keeping to one only?"
"Keeping to one."

Plato, The Republic

To Billye Ruth

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List of Symbols and Abbreviations

α	Angle of Attack
θ	Pitch Angle
Beta	Sideslip Angle
CWS	Control Wheel Steering Autopilot
da	Collective Aileron Deflection
da_r	Right Aileron Deflection
da_l	Left Aileron Deflection
de	Elevator Deflection
detab	Elevator Tab Deflection
df	Flap Deflection
df_r	Right Flap Deflection
df_l	Left Flap Deflection
dr	Rudder Deflection
h	Altitude
hdot	Altitude Rate
KTAS	Knots True Airspeed
KIAS	Knots Indicated Airspeed
Pdeg	Roll Rate, Degrees/ Second
Phideg	Roll Angle, Degrees
Psideg	Yaw Angle, Degrees
q	Pitch Rate
Qdeg	Pitch Rate, Degrees/ Second
Rdeg	Yaw Rate, Degrees/ Second
SAS	Stability Augmentation System
Thedeg	Pitch Angle, Degrees
tlev	Thrust Lever Setting
V	Velocity
VAI	Indicated Airspeed

Chapter 1

Introduction
Perspective on the Problem of Aircraft Control Failures

1.1. Introduction

This chapter presents general motivation for treating the problem of control failures on aircraft, as the needs and capabilities for doing so are growing. Both airworthiness regulations regarding control failures and pilot training are insufficient to stop control failures from occurring and pilots from failing to respond properly even when the aircraft could have been recovered and lives saved. Support for automatic response in the initial post-failure period will be established by indicating that a few seconds of time could be available for many types of failures between time of failure identification and time of required control response. The current trends in research in failure-accommodating control will be identified. The main thrust of this work is presented as the need to augment control reconfiguration with a system to utilize all potential emergency control resources and with pilot-oriented advisory concerning how to fly the control-impaired aircraft to a full recovery.

1.2 Motivation for Treating the Problem

1.2.1. Accident Cases Involving Control Failures

Table 1.1 summarizes 27 civil aircraft accident cases, all involving control failures. These cases came primarily from a survey of recent NTSB and ICAO civil aircraft accident reports. Only two of the many accidents associated with engine failures found in the survey are included in this table; the rest involved failures of aerodynamic surfaces. Failure causes included mistrimming, control rods disengaging, foreign bodies and other mechanical restrictions of surface movement, as well as hydraulic and electrical system failures in the actuation system. On the military side, of course, battle damage is a very significant cause of control failures [1]. In 22 of the cases in Table 1.1, the malfunctions led to the deaths of most if not all on board the aircraft yet *at least* 12 of these could have ended safely if the pilot had acted in a correct and timely manner.

Control failures simply are not that *un*common. Among those interviewed during this research, every pilot as well as most others who were closely associated with aircraft flight had second-hand knowledge of incidents involving failures of controls other than engines.

Table 1.1: Civil Aircraft Accident Cases Involving Control Failures

Case	Date	Aircraft	Description of Failure and Outcome
1	March 1962	McDonnell-Douglas DC-7 (Caledonian Airways)	Elevator tab jammed nose down on takeoff, obliging extremely high pull forces to get aircraft off ground. Aircraft lifted off but could not climb out. It hit trees, crashed; fire on impact. [2]
2	Sept. 1970	McDonnell-Douglas DC-8 (Trans-International Airlines)	Right elevator jammed trailing edge up on takeoff due to rock lodged between elevator and stabilizer. Extreme aircraft pitch up at 300-500'. Roll to near vertical, then pitch down. Aircraft fell to ground. Not recoverable. [3].
3	March 1971	Boeing 720 (Western Airlines)	Hydraulic failure of rudder (to floating rudder) during practice three-engine approach. Aircraft yaw and roll to right, nose to near vertical down. Aircraft fell to ground. Recovery would have been possible only if pilot had symmetrized thrust within 4-5 sec. after failure (spoilers and ailerons alone not sufficient lateral control). [4]
4	Oct. 1971	Vickers Vanguard (British Emerald Airlines)	From cruise at 19,000', aircraft dived into ground. Escaping pressurized cabin air inflated tailcone and caused separation of tailplanes and elevators (initially, structural failure of bulkhead). Presumably unrecoverable. [2]
5	June 1972	McDonnell-Douglas DC-10 (American Airlines)	Sudden depressurization on climb-out at 12,000' when rear cargo door burst open (door latch failure). Cabin floor was disrupted and flight and engine controls seriously damaged. Result was shut-down failure of center engine, rudder jammed in deflected position, spurious stabilizer jam, and heavy but full-range elevator functioning. Aircraft was first stabilized in airspeed and then a long, slow final was flown to a nearby airport, using engines to aid in pitch-up control and with essentially full left aileron to counteract the failure-induced roll. Steering damage and rudder deflection necessitated staggered thrust on runway (idle on right and reverse thrust on left) to keep aircraft on pavement. [5]
6	March 1974	McDonnell-Douglas DC-10 (Turkish Airlines)	Same basic failure scenario as above but more damage to controls. Aircraft was not recovered. [2]

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Table 1.1, Continued

Case	Date	Aircraft	Description of Failure and Outcome
7	June 1974	Gulfstream G-1159 (IBM)	Jammed extension of left ground spoiler in flight after electrical failure caused deployment of ground and flight spoilers (at 10,000-18,000'). Lateral control of aircraft lost. There were several 360° rolls to the right and the aircraft dived to the ground. Recovery prospects uncertain. [6]
8	Nov. 1974	Boeing 747 (Lufthansa)	Leading edge slats not extended on takeoff. Loss of aircraft altitude and final ground impact. Fire on impact. If engine power had been increased to maximum sufficiently soon and pitch angle had been reduced, aircraft could have climbed out safely. 2 kts of airspeed would have made all the difference between being able to climb away and this gradual increase in drag and eventual loss of altitude and impact. (There had been at least nine B-747 incidents prior to this involving attempts to take off or land with some if not all of the leading edge slats retracted.) [2]
9	June 1976	Lockheed L-188 (Air Manila)	Engine failure. Flaps retracted too soon, below airspeed for maximum lift-to-drag ratio for flaps-up configuration. Loss of aircraft climb capability and aircraft hit rising terrain. Recoverable. [7]
10	April 1977	Lockheed L-1011 (Delta Airlines)	Flight 1080. Left elevator jammed pitch up from time of takeoff. Initial stall threat and problems with aircraft roll control. Skillful use of thrust by captain to provide countering pitch-down moment. Used standard procedures in optimum retraction of flaps on climb-out. Incremental approach to initial satisfactory stabilized climb then incremental movement through subsequent required flight configurations. Pilot recognized failure-induced restriction of controllable airspeed range and flew accordingly. Successful recovery to landing. Pilot never determined what had failed. [8]
11	May 1977	Boeing 707 (Dan Airlines, Zambia)	On approach. Structural failure and separation of entire right stabilizer and elevator (fatigue fracture). Aircraft dived to ground. Presumably unrecoverable. [2]

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Table 1.1, continued

Case	Date	Aircraft	Description of Failure and Outcome
12	Dec. 1977	Douglas DC-3 (National Jet Services)	Rudder and right aileron gust locks not removed before flight. Lateral aircraft control difficulties encountered. Pilot got behind power curve and could not recover. Possibly recoverable. [9]
13	Feb. 1978	Beechcraft 99 (Columbia Pacific Airlines)	Mistrimmed horizontal stabilizer on takeoff due to malfunctioning trim warning system. Aircraft climbed to 400' then stalled and crashed. Recovery possible if elevator used to prevent rapid pitch up within 5-6 sec. Sufficient elevator authority available for this. Pilot attempted to correct the setting of the trim (a slowly deploying surface) instead of pushing the control wheel forward. [10]
14	Sept. 1978	DeHavilland Twin Otter (Air West, Canada)	At 175' above surface on approach, left flap retracted due to failure of flap control rod while right flap jammed in extended position. Aircraft yawed and rolled left and plunged to the surface. Aircraft was laterally uncontrollable with this large flap asymmetry. [11]
15	Aug. 1978	Piper PA-31 Navajo (Las Vegas Airlines)	Elevator down-stop bolt backed out on takeoff, limiting downward elevator travel. Aircraft stall and final ground impact. Aircraft not controllable with this failure. [12]
16	April 1979	Boeing 727 (Trans-World Airlines)	At 39,000', one of the aircraft's several right wing leading edge slats jammed in extended position due to misalignment (leading edge surfaces had been extended to get additional performance). Aircraft descended 34,000' in 63 sec. before the slat broke away (hopeless situation otherwise) and the crew regained control to climb and stabilize at 13,000' then made a successful emergency no-slat, no-flap landing. In later simulations, right roll could be stopped and wings levelled if moment was opposed before the aircraft reached 117° of right bank (16 sec. available for this). Afterwards, increases in angle of attack and Mach number led to uncontrollable rolling moment imbalance. Pilot seemed to have levelled wings once but allowed roll again, past critical value; situation was worsened by allowing the aircraft to sideslip near critical configuration through application of full left aileron and rudder. Pilot never determined what had failed. [13]

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Table 1.1, continued

Case	Date	Aircraft	Description of Failure and Outcome
17	May 1979	McDonnell-Douglas DC-10 (American Airlines)	The well-known incident at Chicago O'Hare airport. Left engine and pylon fell away about a second before liftoff. Slat near wing station of this engine retracted. Pilot continued to follow flight director to deep asymmetrical wing stall (stall warning system lost in the failure). Ensuing roll and pitch down and impact. In later simulations, pilots aware of stall were able to recover and land by keeping airspeed up. [14]
18	July 1980	Cessna 404 (Scenic Airlines)	Engine power loss on takeoff. Pilot failed to correct non-minimum drag configuration (sideslip not 0; gear, flaps not up; aircraft not flying at best single-engine rate-of-climb airspeed). Aircraft stalled and crashed. Recoverable situation. [15]
19	Sept. 1981	Lockheed L-1011 (Eastern Airlines)	Engine failure sequence on climb-out at 10,000' resulted in rudder jam in neutral position. Emergency landing at nearby airport conducted successfully, using elevators, ailerons, and differential power for aircraft control. [16]
20	Jan. 1982	Piper PA-31 Navajo (Empire Airlines)	Split flap condition of 34° developed on approach due to electrical failure. Marginal control authority used successfully until at low altitude. Then aircraft left wing dropped to near vertical, aircraft pitched down. Aircraft uncontrollable at low altitudes with flap asymmetry of this magnitude. [17]
21	Jan. 1983	McDonnell-Douglas DC-8 (United Airlines)	Mistrimmed elevator on takeoff. Excessive pitch-up followed by stall and aircraft roll to the right. Uncontrollable descent. Recovery improbable if trim not corrected at rotation. [18]
22	Feb. 1983	DeHavilland Otter (Sierra Pacific Airlines)	Elevator rod disconnected when aircraft was near destination. Elevator no longer trimmed when power was reduced on approach. Pilot had started to apply power for pitch-up when aircraft crash-landed; survival of some passengers attributed to this action. Pilot could have brought about a recovery if maximum power had been applied within 25 sec. of initial power reduction to trim the aircraft to an airspeed somewhat above flap-retracted stall. [19]

Table 1.1, continued

Case	Date	Aircraft	Description of failure and outcome
23	Aug. 1985	Boeing 747 (Japan Air Lines)	Explosion in rear of aircraft badly damaged controls when aircraft was flying at 24,000'. Significant change in horizontal stabilizer trim, rudders totally inoperative, then ailerons and elevators inoperative. Significant dutch roll and phugoid oscillation began. Pilots' efforts to control these motions largely ineffective at best. Pilots attempted lateral/directional/longitudinal control via engine settings. Thrust changes, later flap extension, landing gear extension, and sideslip usually either interacted badly with phugoid oscillations or caused unnecessary altitude losses. Aircraft crashed in mountains. Recovery prospects extremely dim. [20]
24	Dec. 1985	Embraer Bandeirante (Provincetown-Boston Airlines)	Jamming of elevator or uncontrollable operation of pitch trim on departure. Crew's attempt to correct the pitch problem overstressed left elevator control rod, which led to asymmetrical elevator deflection and overstress failure of the horizontal stabilizer attachment structure; aircraft stabilizer detached. Aircraft reached altitude of 600' before striking the ground in steep, inverted descent. Presumably unrecoverable. [21]
25	Nov. 1986	Airbus A-300 (Thai Airways)	Explosion in rear of aircraft badly damaged hydraulic controls when aircraft was flying at approximately 30,000'. Steep, rolling descent of aircraft followed, 18,000' lost within minutes. Pilot righted the aircraft and landed safely. [22]
26	May 1987	Ilyushin 62M LOT, Poland	Aircraft developed difficulties with one or two of four engines soon after takeoff. Instead of diverting to one of two closer airports, pilot decided to turn back toward originating airport, which he was unable to reach. On the way, aircraft gradually lost power, and descended to ground. Fire on impact. Apparently recoverable. [23]
27	Aug. 1987	McDonnell-Douglas MD-80 (Northwest Airlines)	Flaps apparently not extended on takeoff. Apparent stall and crash. No-flap takeoff is possible with this aircraft given sufficient runway and environment allowing slower climb-out. [24]

The following [25] summarizes generic control system failure modes and ways in which the effector itself could fail.

--sensor failures
--computer system failures
--utility (hydraulic/ electric) system failures
--actuator/ surface failures
     -surface floating
     -surface partially/ entirely missing
     -surface centered/ jammed
     -reduced rate capability
     -effective gain alteration

For many years now both military and commercial aircraft have had extensive surface actuation redundancy. This typically takes the form of replication of entire actuation channels or actuators designed to accommodate passively most single-point failures. Many techniques have been developed to ensure that a large degree of actuator failure accommodation already takes place on a local level, before the control surface has actually been moved. The inability to get the required response from control surfaces is, then, an unusual occurrence. The problem of recovery and control reconfiguration after actuation failures remains an important one, and it is gaining increasing high-level attention [26].

1.2.2. Relevant Airworthiness Regulations and Flight Manual Information

Considerable knowledge on control failures has been gained over the years, through successful recoveries and *post mortem* simulations. For certain types of failures, nothing has resulted from this accumulation of knowledge beyond implicit recognition that better pilot training would be helpful. For certain circumstances and certain less unlikely failure modes, this information has resulted in regulations regarding aircraft functional capability. It should be understood that some control failures will inevitably lead to loss of lives, no matter what other control resources are available, because certain failure circumstances simply preclude saving the aircraft. It should also be stated clearly that the current regulations regarding these matters really reflect knowledge gained through many individual incidents, and are in no way the specific conclusions obtained from general, more theoretical considerations of control redundancy and flight safety. Information on recovery has found its way into flight manuals in the form of specified post-failure procedures, but usually only a few, very general ones.

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The following is typical and constitutes the relevant emergency procedures in the flight manual of the T-37, the primary USAF military training aircraft [27]:

[T]hree basic rules are established which apply to most emergencies occurring while airborne.

1. MAINTAIN AIRCRAFT CONTROL.
2. Analyze the situation and take proper action.
3. Land as soon as conditions permit.

Normally, ejection is the best course of action in the event both engines flame out...or positive control of the aircraft cannot be maintained.

If structural damage occurs in flight, the pilot must decide whether to leave the aircraft or attempt a landing. If aircraft is controllable, proceed as follows:

WARNING

• In no case allow airspeed to decrease below 90 KIAS.
• Do not reset wing flaps if significant structural damage is located in the wings.

[1. Communicate intentions to the ground.]
2. Climb to 10,000 feet above terrain (if practical) at a controllable airspeed.
3. Simulate a landing approach and determine airspeed at which aircraft becomes difficult to control (minimum controllable airspeed).

Note

If aircraft becomes difficult to control or approaches a stall, lower the nose and increase power for recovery.
4. If aircraft becomes difficult to control above 105 KIAS (full flap), fly a no flap landing approach. Abandon the aircraft if it becomes difficult to control above 130 KIAS (no flaps).
5. Maintain 20 KIAS above minimum controllable airspeed or 110 KIAS, whichever is higher, during descent and landing approach.
6. Fly a flat power-on, straight-in approach requiring minimum flare and plan to touch down at no less than minimum controllable airspeed. Do not begin to reduce final approach speed until the aircraft has crossed the runway threshold and is very close to the runway. Maximum recommended airspeed for touchdown is 105 KIAS (full flaps), 130 KIAS (no flaps).

This advice comprises the important admonition to try strenuously to maintain aircraft control and a description of how a check at altitude for controllability on landing should proceed. This check is to allow a determination of whether the minimum airspeed at which the aircraft is controllable is low enough to allow the aircraft to be landed. The recommended conservative landing procedure is also described. Use of most of this information, however, presupposes that the aircraft has been brought under control, arguably the most difficult part of any recovery.

This very limited procedural information undoubtedly reflects the wide variety of possible failure situations and the fact that control failures are unusual. Appendix 1 shows

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the most complete emergency flight manual procedures regarding control failures found during this study. The source was the flight manual for the C-5A aircraft, a major national resource, a relatively benign aircraft from a stability viewpoint, and an aircraft, incidentally, for which ailerons and spoilers can be rigged for collective deployment. In addition to guidelines similar to those of the T-37 manual, the emergency information provided to the C-5 pilot includes lists of alternate controls to substitute for primary control, some instructions for flying to minimize oscillations of the aircraft when the automatic flight control is degraded, and other control systems-related instructions. This information could be of considerable help in aiding failure recovery, but only after aircraft control is substantially regained so that alternate controls can be applied cautiously and on a trial basis.

Pilots are generally required to be knowledgeable about their aircraft's *systems*. This can be expected to help somewhat in recovery when a failure occurs. The reality, as has been established in many cases, is that only a few seconds of hesitation will allow a theoretically recoverable failure scenario to degenerate into one that is hopeless. Considering the complexity of current aircraft and the level of crew stress during these incidents, it is understandable that the solution will often not be found in time.

It might be useful at this point to discuss very briefly how the civil airworthiness regulations [28] address the possibility of aircraft control system failures. There are numerous regulations designed to prevent controls from failing in the first place. As instances of this, there are guidelines requiring good general control system design and construction (there must be reliable stops restricting ultimate control surface range of motion and flaps must be interconnected, for example) and requiring good cockpit layout, this being an integral part of the attempt to prevent pilot-induced problems. There are regulations regarding structural integrity of the controls under specified expected loading conditions. Overall, the design of the flight control system is to be guided by a "rational conservative" approach. Certain post-failure recovery capabilities must be demonstrated in the course of the aircraft certification process, however. The condition of flight after failure of the critical engine(s) comes in for particularly detailed consideration. Safe takeoff and climb capability must be established under this condition, in turbulence, with unfavorable weight and balance, all with generally *reasonable*--not *exceptional*--piloting technique, in terms of skill, awareness, and strength. What follow in the regulations are requirements concerning power-off controllability and trim, and, for multi-engine airplanes, obliging limited, specified symmetric maneuverability and trim in general departure and approach configurations. Good stall recovery capability with the critical engine(s) failed is also obligatory. As for the aerodynamic controls, there is a requirement (for smaller aircraft) that the trimming surfaces themselves allow safe flight and landing in the event of disconnection of the primary

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longitudinal or directional control surfaces. In addition, it must be possible for certain larger-category aircraft ultimately to land safely after any "probable" trim tab runaway, with reasonable pilot response. For the largest, transport-category airplanes, the requirements for accommodation of control system failures are quite specific:

FAR 25.671

> (c) The airplane must be shown by analysis, test, or both, to be capable of continued safe flight and landing after any of the following or jamming in the flight control system and surfaces (including trim, lift, drag, and feel systems) within the normal flight envelope, without requiring exceptional piloting skill or strength. Probable malfunctions must have only minor effects on control system operation and must be capable of being readily counteracted by the pilot.
>> (1) Any single failure, excluding jamming (for example, disconnection or failure of mechanical elements, or structural failure of hydraulic components, such as actuators, control spool housing, and valves).
>> (2) Any combination of failures not shown to be extremely improbable, excluding jamming (for example, dual electrical or hydraulic system failures, or any single failure in combination with any probable hydraulic or electrical failure).
>> (3) Any jam in a control position normally encountered during takeoff, climb, cruise, normal turns, descent, and landing unless the jam is shown to be extremely improbable, or can be alleviated. A runaway of a flight control to an adverse position and jam must be accounted for if such runaway and subsequent jamming is not extremely improbable.
> (d) The airplane must be designed so that it is controllable if all engines fail.

An automatic takeoff warning system must also be provided in transport aircraft, to provide an aural indication during initial takeoff roll whenever the configuration would not allow safe takeoff (i.e., flaps, slats, or spoilers not within approved range). There are requirements, too, concerning automatic control systems, that protect against the effects of single failures. One pilot must be able to overpower the autopilot or disengage it as needed, letting him control the aircraft, and autopilots cannot produce hazardous flight or loads in any appropriate use condition or in event of a malfunction corrected in a reasonable period of time. Finally, regulations require that flight manual information be provided for recovery from engine failures only.

Although the desired end of meeting the regulations can be seen to be generally the same, regulations regarding control failures in the airworthiness regulations for military aircraft depend upon a more quantitative assessment of the remaining capabilities [29]. The fundamental concept of quantitative flying quality "levels" is employed in anticipation, really, that the aircraft may be required to operate with handicaps. The regulations specify that *all* failure states for the aircraft be enumerated, and that, for *all but the most remotely improbable* of these states, post-failure flight characteristics be analyzed in terms of flying quality levels. There are specified allowable probabilities per flight of the flying quality level degrading due

to any failure, each specific failure assumed to be present at the most critical point in the flight envelope, with the aircraft in the most critical configuration, and with the effects of turbulence included. In the case of all but remotely improbable failures, the flying qualities and the control authority must remain such that the flight can at least be terminated safely with reasonable pilot corrective action. Evaluating flying qualities involves determining whether stability and performance--modal time constants and damping, roll rate and vertical acceleration capability, lateral/ directional coupling, and capability on takeoff and landing in crosswinds, as well as general pedal and stick forces--meet specified regulatory levels. Airplane motions due to failures shall not exceed specified limits for a few seconds after the failure, allowing some time for diagnosis and correction by the pilot. Again, the effects of engine and trim surface failures and of failures in the automatic flight control system come in for specific consideration in the regulations.

1.2.3. Control Redundancy in Current and Planned Aircraft

The flight control task after failure may be described as the utilization of whatever control resources remain to regain control of the aircraft, to avoid dangerous flight regimes, to prevent further damage by excessive airloads, and to provide some time for better assessment of the situation. The ability to perform this task, in most cases, depends critically on inherent control redundancy. There is already some very significant control redundancy in even the most traditional aircraft configurations, as will be seen. It is reasonable to say, however, that, with few exceptions, aircraft control surfaces have *not* been designed on the basis of explicit need for control redundancy. Aerodynamic controls are designed primarily for trim, maneuvering, enhancing flying qualities, or for other special purposes such as rotation at takeoff or spin recovery. New performance requirements are yielding even greater control redundancy in the form of additional surfaces, including needs for unusual system control modes, including decoupled-axis flight, which *explicitly* requires redundant control surfaces, and the host of needs that has yielded active control technology on so-called "control-configured" aircraft, with their flight-critical stabilizing and maneuver load-controlling surfaces. Adaptive structures, such as variable-camber wings, are being flight-tested and may be considered as potential (low-authority) control degrees-of-freedom, along with the potentially very important effects of thrust and thrust vectoring. Figure 1.1 is very illustrative of the degree of control redundancy in the control-bound high-performance military aircraft being studied. Simply "splitting" more conventional surfaces--making them capable of independent actuation (at required bandwidth)--has been shown to provide considerable additional flexibility and redundancy, and thus it is considered probable that

Figure 1.1: Research Fighter Configuration [25]

Controls Include:

All-Flying Canard
All-Flying Vertical Tail
Multi-Segmented Flaperon
Multi-Segmented Leading Edge Flap
Dual Elevator
Three Spoilers
Two Engines with Vectoring and Reversal
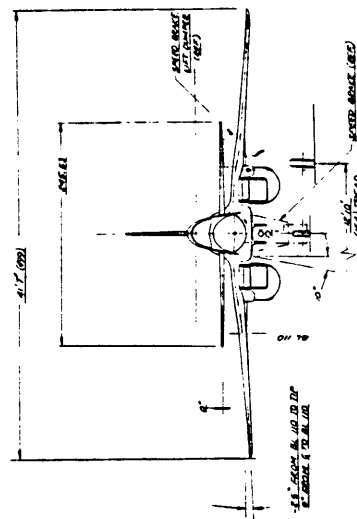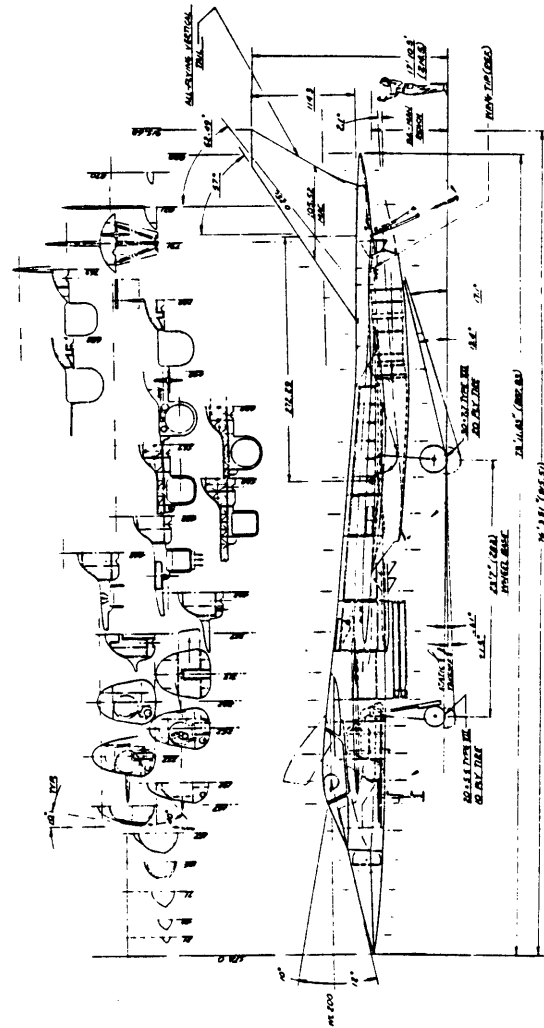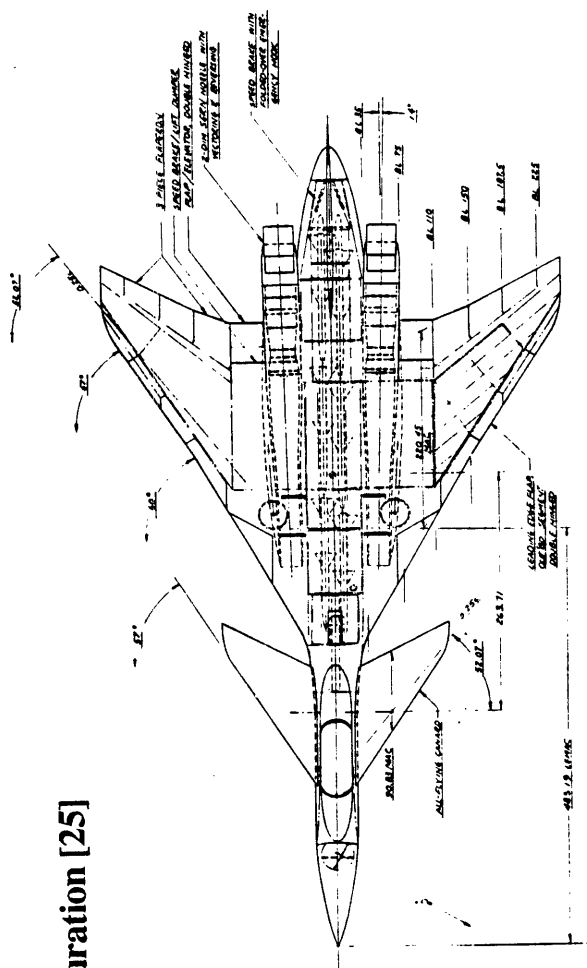
many traditionally configured aircraft could be flown directly with alternate existing controls in the event of significant failures [30]. Table 1.2 lists the primary and secondary effects of some types of aircraft controls, suggesting functional redundancy. The flexibility afforded by fly-by-wire control is, of course, a significant element in making post-control-failure flight feasible. It is crucial that the computational capabilities needed to utilize the additional control redundancy are also maturing.

Along with the additional potential, however, comes the *need* to consider utilizing the control redundancy more fully. The proliferation of surfaces is not without penalty in basic reliability. Although, in some aircraft, considerable segments of the flight control system are replicated whole several times to provide the desired degree of reliability, integrating all of this redundancy has made control actuation cumbersome, heavy, complex, and *costly* in many cases. At present, however, most of the potential flexibility in using *functionally* redundant different controls has not been exploited on any aircraft. Increasing the need to consider better utilization of control redundancy is the fact that, for the most advanced "control-configured" aircraft, with their reduced inherent stability and flight-critical control functions, it is all the more likely that a failure will lead to a complex if not catastrophic situation if not carefully accommodated. Moreover, future aircraft with highly sophisticated controls are likely to have multiple interdependent failure modes which will be difficult for the pilot to recognize. Such failures may lead to unanticipated sequences of events from which the pilot cannot intuitively recover and for which manual control blending without automated assistance to achieve effective reconfiguration does not appear feasible. In addition to reducing maintenance and other life-cycle costs, it is expected that exploiting functional control redundancy will allow completion of more flights, including more missions for the military. The aim of the USAF Reliability and Maintainability Initiative [31] is eventual failure-tolerant aircraft *design*, with no single critical surface, and with performance that is only marginally degraded by efficiently using the remaining surfaces in the event of an isolated failure. By exploiting failure tolerance, the Air Force expects to reduce significantly the flight control system life cycle cost for the Next Generation Fighter. An important additional aspect of the Air Force initiative is work toward "positive pilot alert," where there is sufficient indication of the ramifications of the failure to allow full post-failure range of action.

This thesis is concerned with the aspects of failure-tolerant control that will lead to utilization of inherent control redundancy among different controls. It should be clear that this would only be a part of improving capabilities of preventing and accommodating aircraft control failures. Failure tolerance of sensors and computing will also play a role, and there is also some current work on improving surface actuators themselves. Study has shown,

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<div align="center">

Table 1.2: Effects of Aircraft Controls * [26]

</div>

Control	Primary Function	Secondary Function
Traditional		
Elevator	Pitching moment	Z-force
Aileron	Rolling moment	
Rudder	Yawing moment	Y-force
More Recent		
Differential elevator	Rolling moment	
Collective aileron	Z-force	Pitching moment
Split rudder, speed brakes	X-force	
Leading edge slats, flaps	Z-force	Pitching moment
	Pitching moment	Z-force
Trailing edge slats, flaps	Z-force	Pitching moment
	Pitching moment	Z-force
Servo throttle (integrated thrust control)	X-force (Z-force)	Pitching moment
Differential throttle	Yawing moment	
Spoilers	Rolling moment	
	X-force	Z-force
		Pitching moment
Canard surfaces		
Horizontal	Pitching moment	Z-force
	Rolling moment	
	Z-force	Pitching moment
Vertical	Yawing moment	Y-force
	Y-force	Pitching moment
Direct lift flaps	Z-force	
Most Recent		
Thrust vectoring	Pitching, yawing moments	X-, Y-, Z-forces
Inlet changes	Yawing moment	

* Any listing of controls and their functions such as the above can only be a partial listing. The newest fighter aircraft designs, for example, have included such unusual controls as chin fins, strake panels, and variable incidence wings or outer wing panels [32].

however, that utilizing functional redundancy of controls offers the greatest potential of all of these techniques for improving aircraft survivability [30].

1.3 Automatic and Piloted Recoveries in Perspective

1.3.1. When is an Automatic Response to a Control Failure Needed?

The accidents summarized in Table 1.1 all involved commercial aircraft with relatively unsophisticated control systems. Thus one would expect that control failures could be fairly readily diagnosed and appropriate action taken. As has been seen, this does not necessarily hold.

All of the pilots interviewed for this thesis stated outright that *the most important problem of control failure recovery* is to obtain the very quick and correct response to failures indicated in precarious situations like high-speed or ground-proximity operations. Uncontrolled ground impact with or without the usual fire is an obvious catastrophe, although several control failures have resulted in catastrophic structural failure of the aircraft before it reached the ground due ultimately to overspeeding. All of the pilots were agreeable to—in fact, they *wanted*—full-authority automatic response in precarious-failure situations.

Simulator studies have produced some data on pilot reaction times to failures [33]. In one such study, the time required for pilots (simply) to initiate power reduction after experiencing malfunction of the elevator on rotation was about 3 sec. Given the special conditions pertaining in a simulator exercise, these estimates are undoubtedly near the low end. Among the unrecovered but potentially recoverable cases, the time frame for required pilot response was on the order of 4 to 5 sec., although up to about 25 sec. were available for some. Although it is difficult to be certain, it would seem that even more familiar types of failures were not even identified by the pilot in most cases. The cases speak for themselves concerning the need for some sort of automatic pilot-augmenting response, even for these relatively low-performance aircraft. To insist that the problem can be solved by better pilot training alone is somewhat naive. It will be difficult for the pilot to learn and retain sufficiently for guaranteed faultless application of recovery control in a wide range of emergencies. At the far end of the performance spectrum, it has been estimated that, in certain situations, the X-29 could tolerate only approximately 0.2 sec. lapse in active flight control before catastrophic loss of the aircraft.

There is every suggestive evidence that a quick opposition to the primary disturbance induced by the failure is the best initial recovery strategy. No case was found in which prolonged acquiescence was necessary for recovery of the aircraft.

In talking about a quick automatic response to failures, one becomes concerned with failure detection and isolation (FDI) capabilities.

1.3.2. Concerning Detection and Isolation of Control Failures

Failure detection and isolation (FDI) research addresses the problem of *detecting* deviations from normal behavior among certain components and *isolating* which component has failed. Explicit accommodation of actuator failures and surface damage depends critically on FDI. Ideally, an FDI system must be general enough to respond accurately to failures of many different types *yet* avoid giving false alarms. This will be of utmost importance for the application of interest here.

Numerous techniques for failure detection and isolation have been developed, and FDI is a fast-developing research area. In current schemes, FDI may employ the idea of looking for control surface failure signature in the whole-system dynamics (ultimately the most important level), and there has been some work on more local schemes for control surface FDI. There has also been a recent wave of work on "expert-system" FDI, which aims at combining analytical redundancy with more qualitative causal reasoning.

It might be useful at this point to comment briefly on the time that might be required for FDI to isolate control failures. There have been few numerical demonstrations of the capabilities of the various FDI schemes in identifying aircraft control surface failures. Exceptions found are in references [34, 30, 35]. Work in the first two references employed more traditional system-level FDI, and in the third, an FDI scheme involving use of transducers mounted on surface actuators and hinges was used. In the first study, bias failures of approximately .2° of all primary surfaces were *detected* in roughly 0.5 to 2 sec. (with no modeling errors involved), but considerable additional time--perhaps 10 sec. after detection--was considered to be required to *isolate* flap or aileron failures. In the second study, the system isolated neutral failures within about 1.2 sec. with the aircraft attempting a variety of maneuvers and in the presence of turbulence. A "decentralized" FDI approach was used in the last study. Individual redundancy relationships of different types were exploited to give successful isolation of elevator failures leading to 50% loss of effectiveness in about a quarter of a second.

As has been seen, only a very short time is available before beginning a recovery in precarious situations. It will continue to be a matter of some debate whether control failures can be assumed uniformly to be fully identifiable before recovery efforts must begin. It is probably to be expected that control failures cannot all be assumed to be fully and quickly identified--some perhaps not even identifiable at all, and that reasonable ways of acting with

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uncertainty must be part of any good recovery-aiding system. The assumption is made in this thesis, however, that the failure has been identified before recovery action is taken. This assumption has allowed the first steps toward looking at facilitating end-to-end recoveries to be taken. Relaxing this assumption will not change the types of capabilities needed for full recoveries, but then subsequently exercising those capabilities must take uncertainty into account.

On-board parameter identification would require much more time and computational capability than identifying which control has failed. Although parameter identification would be very useful, inasmuch as it is recognized that certain control failures could be expected to change the aircraft dynamics in more than relatively simple ways, full real-time parameter identification can only be considered a far-off goal.

1.3.3 Concerning the State of Research in Failure-Accommodating Control

What does the loss of a control mean?

--Force and moment generation capability is lost.

--Some aircraft modes may become less controllable, or become unstable, and disturbances to the system cannot be rejected as well.

--For more off-nominal failures, the failure can contribute so much adverse input that the aircraft cannot be equilibrated easily or at all.

Generally, when researchers refer to the issue of recovery from control failures, they refer to basic failure-robustness of the *automatic* control--of which most aircraft have some-- or to reconfiguration or redesign of that control. The vast majority of research on the general problem of dealing with control failures has been done in the area of control loop robustness and redesign. Motivating this work have been the considerations that--in order to have any possibility for recovery from failures--the aircraft must be dynamically stable or stabilized, and that it is most desirable that the remaining capabilities of the aircraft be recovered as much as possible for potential utilization. It is to be understood that research has only begun to address the basic problems of post-failure accommodation in the automatic control.

The importance of changing the automatic control law after a control failure cannot be overemphasized, particularly for higher-performance aircraft. But automatic control can also be considered to be limited in an important way. Automatic control should be distinguished from the *pilot's* controlling activities. There may be no automatic control or several nested loops of it. The pilot, however, can be considered to be the outermost, highest-authority

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control loop. The authority regarding important aspects of the aircraft's flight will be reserved to the pilot, and his perception of the remaining capabilities of the control-handicapped aircraft can be a crucial factor in determining whether the flight will end safely. This will be examined further, and is a fundamental consideration behind the research undertaken here.

1.3.4. Introduction to an Extended Conception of Recovery from Control Failures-- The Flight 1080 Case

As a first step toward extending the notion of failure recovery from (just) automatic control robustness and restructuring--difficult as these things may be--a motivating example is presented. This is case 10 in Table 1.1, involving a left elevator jammed pitch-up on takeoff on an L-1011 aircraft. This is one of the few failure cases in which the initial post-failure period was gotten through safely and the flight continued on to a landing. This example should help to indicate the many difficulties involved in making a long recovery. Although this was a successful recovery, it points up several things that, in more extreme manifestations, that is, in other accident cases, would have called for assistance. Thus it will help motivate the elements of the recovery aid and advisory system that are the subject of this thesis.

The following is a description of events as reported by the captain, Jack McMahan [8]. In reading this, it should be kept in mind that the failure was not identified by the pilot until after safe conclusion of the flight.

The flight took place in April 1977. The L-1011 departed at night and in instrument flight conditions. Little elevator input was required to rotate and there was an abrupt aircraft pitch-up excursion. This was controllable during the very early climb-out, although the pilot was pushing the column full forward. When the aircraft had climbed a few hundred feet, the airspeed had increased and the pitch angle started to become uncontrollably high. Both pilots were exerting full forward force on the column. Elevator trim was checked and reset, as were all other switches associated with trim. Hydraulic indicators and circuit breakers were checked. By the time the aircraft had reached an altitude of 3000', all emergency procedures had been exhausted and had given no improvement in controllability of the aircraft. The situation was confounding to the pilot:

> "The huge flying tail of the L-1011 has a tremendous amount of authority in pitch; the aircraft is trimmed full nose down--why no response? Do we have a spoiler problem causing the roll? Is the problem hydraulic?"

As the pitch angle continued to increase, airspeed decreased. There was also a slight roll problem during right turns in the departure. The captain observed the pitch exceeding 22° and airspeed decaying below 138 KIAS. At about the time that the aircraft had climbed to about 5000', the captain had

> "the horrifying realization that loss of the aircraft was imminent....It appeared certain that the aircraft would enter a stall, and, having no control over pitch to effect recovery, crash into the ocean."

The captain reported thinking at this time that

> "thrust is affecting pitch. Drag is affecting airspeed. If I can reduce pitch, if I can regain airspeed, we might have a chance to recover some degree of controllability."

The pilot abruptly reduced thrust on all three engines and obtained a modest change in control "feel." He then advanced the center engine throttle full forward, almost simultaneously increasing thrust (to a lesser extent) on the two wing engines to prevent further loss of airspeed. The pitch soon corrected downwards a few degrees and airspeed slowly increased. The captain further increased thrust on the left engine to oppose a left roll tendency. As soon as sufficient airspeed was attained, the flaps were mostly retracted, and the airspeed started to increase at a better rate. With full pitch-down control, the pitch attitude remained high but steady.

At 9000', the aircraft broke out of the clouds to welcome visual flight conditions. The airspeed had increased sufficiently that all remaining flaps could be retracted. The aircraft was still climbing steeply and uncontrollably—there was no margin of control over pitch. The aircraft passed the assigned altitude of 10,000'. The captain reported thinking,

> "if I don't do something rather quickly, this aircraft is going to climb to some unknown altitude, 25,000 or even 30,000 feet, then run out of airspeed and controllability and descend as steeply as it went up."

Approaching 14,000', the pilot "had no alternative" but to retard thrust on both wing engines. The aircraft slowly responded with a slight pitch change, and the pilot attempted to descend back to 10,000 feet. With constant thrust adjustments, he was able to stop the descent at 9500'. After several altitude excursions of a few hundred feet, the aircraft was stabilized at 10,000', with a high nose-up pitch and a high thrust level like that associated with nominal *climb*. The throttles were staggered again (thrust reduced on center and left engines) to maintain control over pitch and roll. The captain concluded that airspeed would have to be kept below 200 KIAS to keep the aircraft from climbing.

"It appeared that we were working within a narrow airspeed envelope--too fast and control over pitch and altitude was impossible, too slow and a stall would occur."

All emergency procedures were double-checked at this time in an unsuccessful attempt to identify the nature of the problem. There were no additional known procedures relating to the malfunction.

With the aircraft stabilized at 10,000', "plenty of altitude to work with in the event we had further difficulties," the question of destination was raised. Time (fuel) remaining, terrain, turbulence and other weather conditions, and runway orientation at nearby airports were all factors that were considered at this stage. The captain decided to divert to a nearby airport. The next question was how a landing could be accomplished with so little pitch control. The captain felt that a normal low airspeed, high flare landing with flaps much extended (thus in a high-lift configuration) would be infeasible because of the minimal pitch capability:

"When the aircraft entered ground effect I would not be able to force it on the runway, or worse, when we set up the landing flare the aircraft might pitch up to an altitude of 200 or 300 feet, stall and crash. And we would be helpless to prevent it."

Another consideration in planning the landing was the power available/ power required situation on approach.

"If we got behind the power curve, would there be enough thrust to overcome drag and still be able to control the aircraft?"

An over-water approach to the airport was selected to avoid endangering lives and property on the ground. Beginning the descent, then, according to Capt. McMahan,

"I decided that we would try one step at a time, using incremental flaps, verifying pitch control with each increment and attempting to establish a configuration of 22° flaps and an airspeed of 165 KIAS for the approach and landing. At 4° flaps the aircraft pitched down slightly and I was able to recover about one-half inch of control column movement from the full forward limit. At 10° flaps the additional pitch down gave me another half inch of control response. The aircraft was stabilized at 180 KIAS, 10° flaps, 12° pitch, and one inch of control movement was available."

It was planned that deployment of flaps to 22° would be delayed until closer to time of landing. The landing gear was extended at 2500', causing the aircraft to pitch up uncontrollably; the airspeed then began to decrease again. The pilot considered retracting the gear to regain control and ditch the aircraft in the ocean:

> "I felt that it would be impossible to control a missed approach or a go-around and that this was a 'one-shot' attempt."

The captain once again increased thrust on the center engine and reduced thrust on the outboard ones. The landing gear was left extended, however. The aircraft responded slowly and was maneuvered back to the glide slope. 18° flaps were selected. At 700', the pilot decided to leave the flaps unchanged and not to attempt a flare.

> "Things were going so well....Don't change a thing--just get it on the ground. The aircraft was flown onto the runway. Up-pitching reverse thrust on the center engine was avoided, and auto-ground spoilers were disabled for similar reasons."

This flight lasted 55 minutes. Capt. McMahan received FAA's Distinguished Service Award four months later for saving the aircraft and passengers on this flight.

This case rather vividly illustrates the usefulness of timely opposition of the failure-induced disturbance with alternate control (the center tail-mounted engine here), and the fact that the pilot was obliged to fly the aircraft at an operating point different from the nominal. The pilot was able to remain mindful of and to use flaps optimally and retain the capability to climb out early in the flight. He was able to determine later in the flight that he was constrained considerably in airspeeds that would allow control over aircraft pitching. He had essentially no certain knowledge about the aircraft's remaining capabilities--even whether the aircraft could be landed safely. Each change in configuration, from climb to landing, was effected very tentatively, and new goals in the flight were set conservatively and approached sequentially. Capt. McMahan demonstrated the effectiveness of reshifting the control burden associated with pitch compensation to free up control for maneuvering during descent and landing. He was able to evaluate accurately the use of all secondary controls on landing from the standpoint of their effect on pitch.

1.4. Thesis: More than Control Loop Reconfiguration is Required for Recovery

It is the major contention of this thesis that depending solely on what is commonly considered to constitute failure-tolerant control, namely, robust or restructured control in the

sense of Section 1.2.3, will generally be not be sufficient to allow a control-impaired aircraft to be recovered. The following are several reasons for this.

--Neither the pilot nor the automatic control, even if redesigned, will probably take into account all of the alternate control capabilities of the vehicle. Use-- or misuse--of the landing gear, spoilers, leading edge slats, flaps, and even of reverse thrust when on the ground can all impact the recovery in significant ways.

--Failures often induce significant constraints (beyond the usual ones) on the controllable operation of the aircraft and on the performance that it can achieve. Traditional types of automatic control, and especially where the post-failure automatic control is not precisely tuned, will not "know" about these constraints. It would be far better to take them into account explicitly.

--The failure may easily be such that the aircraft can only safely (or otherwise reasonably) fly at quite different operating points than prior to the failure. In an immediate post-failure situation, provided there *is* automatic control, the post-failure automatic control alone may or may not achieve such a point. Specifying the new feasible point explicitly may make a tremendous difference in achieving safety. Achieving a necessary degree of efficiency could also depend on unusual adjustment of the impaired aircraft's configuration.

--There will always be some number of miscellaneous guidelines that would be very important in recovering from a failure.

--Given that some of the responsibility for post-failure actions can be expected to continue to reside with the pilot, information about specific types of residual control capability as well as other advice and warnings could be helpful and should be provided to the pilot during post-failure flight.

1.5. Focus and Overview of the Thesis

This thesis work began with a survey of the results in failure-tolerant control research and evolved from dissatisfaction with their narrowness and the naivete of proposing them as the full solution to the problem of aircraft control failures. The first focus of this thesis is, in short, the *other* considerations involved. The second focus was on finding a format for facilitating emergency control in which all control resources could be brought to bear on the problem of initial stabilization of the aircraft after the failure. The third focus was on integrating these two elements in an automated aid and advisory system that could be implemented on board an aircraft and would have acceptable type and degree of pilot interface.

Sources of information and organization for the recovery aid and advisory system included 1) discussions with pilots; 2) reported failure cases; 3) simple reasoning about

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aircraft dynamics and performance; 4) flight manuals; and 5) manual failure recoveries using the C-130 simulation. The ideas contained in this thesis, with noted few exceptions, are expected to be applicable for all types of aircraft, from low- to high-performance.

Chapter 2 of this thesis presents a categorization of the new constraints and other types of information about the control-impaired aircraft that could be needed to effect full recoveries. Motivating examples from the accident cases of Table 1.1 as well as from C-130 aircraft flight simulations are included. An important part of the automatic aid envisioned is emergency control in the initial post-failure period, and Chapter 3 presents a rule-based expert system developed to guide iterative pre-simulation to find successful emergency control. Chapter 4 gives a preliminary integrated description of a full recovery aid and advisory system. In the same chapter, there is an examination of what advisory information should be made available on board the aircraft and of pilot/ system interaction issues. Chapter 5 summarizes the thesis and the contributions. Appendix I gives an example of flight manual information regarding control failures and Appendix II describes an aircraft simulation used extensively in this research. A reconfiguration developed in early thesis research on failure recoveries is described in Appendix III. Appendix IV gives some theoretical results concerning properties of constant-rate surfaces for nonlinear dynamics, such as those governing aircraft motion. Finally, Appendix V contains the program for the rule-based system.

Chapter 2

Concerning New Constraints and Explicit Retrim
of the Control-Impaired Aircraft

2.1. Introduction

Even pilots who are intimately familiar with the nominal capabilities of their aircraft can become very bewildered when the aircraft has some non-functioning control. In this situation, pilots resort to guesswork to a large extent in attempting to fly the aircraft. For control-impaired aircraft in many situations, however, safe recovery could require explicit knowledge of new feasible or desirable operating points and of new constraints, particularly as they directly invalidate nominal piloting.

Certain types of new constraints on operating state and performance important in flying a control-impaired aircraft are introduced in this chapter. The question of the need for explicit determination of valid operating points for the impaired aircraft is discussed. Examples from the accident cases and from work with the C-130 aircraft are used throughout to motivate the ideas.

2.2. Post-Failure Operating Constraints

An aircraft with control failures can be expected to have operating limitations beyond the normal ones to which the pilot would be accustomed. These new constraints may be significantly or insignificantly different from the old ones. But for certain failures, if, for example, new limitations on airspeed or bank angle or sideslip that the pilot is not aware of are exceeded for some reason, then the aircraft can achieve a state from which recovery will be very difficult or even impossible. In discussing these new post-failure operating limitations, the intent is to reinforce the point that these constraints are real, and to make clear what *sorts* of limitations pilots might prefer to work with. The following constitutes some breakdown of various types of control failure-induced operating constraints. Each has figured in a control failure case.

2.2.1. Controllability Airspeed-Type Limitations

The term "controllable airspeed" is already a familiar one in aircraft operations as it is used in connection with asymmetric engine failures to indicate the minimum indicated

airspeed at which the rudder can neutralize the failure-induced yaw. Figure 2.1 illustrates this idea. This terminology will be used here in a more general way to refer to airspeed-related limitations of the functioning controls in counterbalancing the effects of *any* type of control failure and thus re-equilibrating or maneuvering the aircraft after the failure. Examples of situations from Table 1.1 in which knowledge of the failure-controllable indicated airspeed (thus, to a lesser degree, altitude as well) would have been important in recovery include the following.

> Case 22. DeHavilland Otter with disconnected elevator. There was enough elevator trim control to trim the aircraft to an airspeed above the flap-retracted stall speed. A pilot apprised of this could have attempted to trim and, afterwards, completed a successful landing.

> Case 10. Flight 1080, right elevator jam in highly deflected position, pitch up. The pilot discovered during the recovery that there was an airspeed cap on stabilized flight. The pitching moment due to the failed elevator could not have been counteracted by the left elevator and variations in thrust at high airspeed. There was a similar lower limit on cruise airspeed in that trying to cruise at a slower airspeed would have involved flight at higher angle of attack (and pitch angle), adding drag to what was already a high-drag configuration. Increasing thrust to compensate, presumably obliging change to the center engine setting, would have provided unwanted extra pitch-down moment.

> Case 7. Gulfsteam G-1159 with jammed spoilers. Although the aircraft was possibly unrecoverable here, this case points up the possibility of operating at airspeeds that would blow down the spoilers sufficiently to allow level flight or even certain maneuvering. Under certain circumstances and with sufficient control resources, information about blow-down speeds could have been a useful part of a recovery.

Breaching the controllable airspeed constraints could cause only significant complications and delays in stabilizing the aircraft (as in the Flight 1080 case). Breaching the constraint under other circumstances--especially without knowing about the existence of the restriction--might have been disastrous.

An example of controllability airspeed constraints for a fairly common control failure mode, jammed asymmetric flap failure, will support this idea. The following Figure 2.2 shows a matrix of airspeeds and flap asymmetries for the C-130 aircraft. Trim points for equilibrium flight with the failure were sought using a nonlinear trim algorithm at 1000' and for zero sideslip, with the results indicated. As the figure shows, for a given asymmetry, there may be both floor and ceiling airspeed restrictions on controllability with flap asymmetries. The low-speed limitation is associated with the limited ability of the ailerons to control the failure-induced rolling tendency at low airspeeds, the high-speed limitation with limited thrust available to counteract the drag induced by the flaps. Being able to carry some

**Figure 2.1: Directional Control Airspeed Required to Oppose Effects
of Asymmetric Engine Failures
(independent of weight and altitude)**

Yawing Moment Coefficient
from Asymmetric Thrust

Minimum Directional Control Speed

Yawing Moment Coefficient from
Maximum Usable Rudder Deflection and Opposite Bank

Yawing Moment Coefficient

Indicated Airspeed

Right flap failed position, percent (Left flap failed at 0%--unextended)
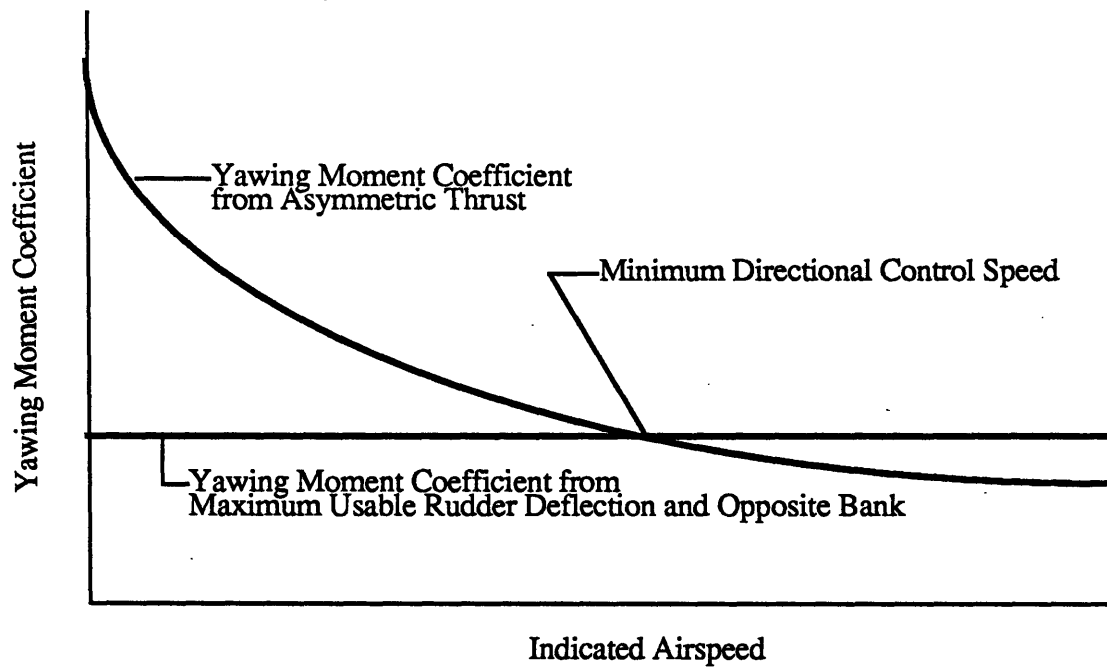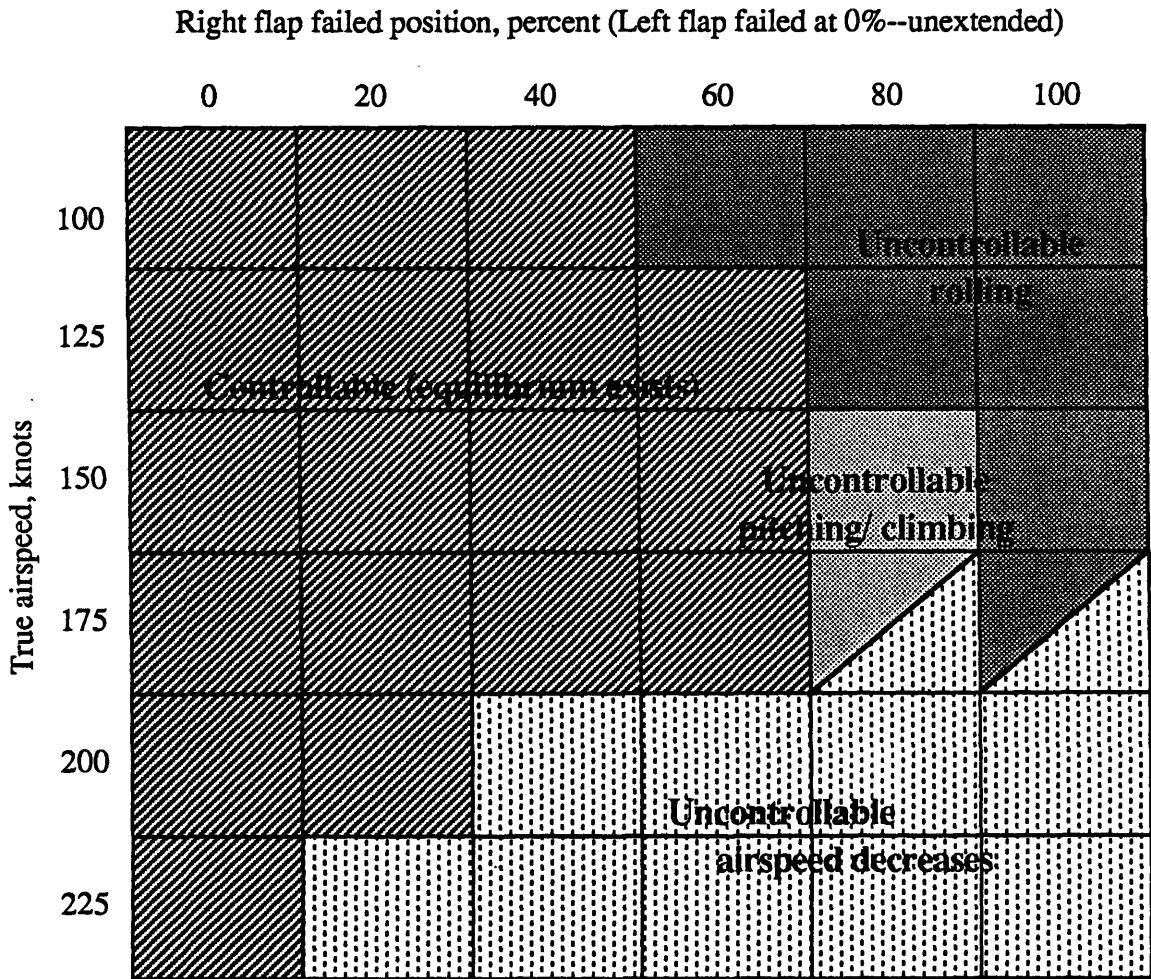
Figure 2.2: Effects of Asymmetric Flap Failures on
the C-130 Aircraft
(Looking for trim points at 1000')

sideslip to induce some failure-countering roll through dihedral--a well-established general means of help in this type of circumstance--would have increased the roll-controllable region in this figure, but the basic problem would still remain.

One might expect that the possibility of counteracting a failure of an aerodynamic control with another aerodynamic control would be basically independent of indicated airspeed, given that the desired stabilization could be achieved at *some* value. Unfortunately, certain effects induced by the failure cannot be counted upon to be quadratic in indicated airspeed (linear in dynamic pressure). Jammed extension of a surface may cause effects that will vary quite differently with indicated airspeed than the effects of the potentially counterbalancing surfaces (as happened with the leading edge slat failure in case 16), and there will be other types of failures for which the "artifact" associated with using a failure-compensating control will similarly constrain the airspeeds for which a failure is controllable.

2.2.2. Changes in Stall Airspeed

Stall airspeed can change significantly as a result of a control failure. Case 16 (Table 1.1) shows the flow disruption due to a single leading edge slat that failed extended, and which could have caused stall problems on landing had it not broken off at altitude and the more critical induced-roll eliminated. Case 17, the Chicago DC-10 case, shows more dramatically the dangers involved in not taking the stall airspeed changes into account when lift-augmenting controls fail retracted on departure. It can similarly be expected that the buffet boundary (the airspeeds at which high speed flow separation occurs) can also change with control failures.

2.2.3. Changes in Control Reversal Airspeed

Failures of aerodynamic surfaces can also lead, either directly or indirectly in their counterbalancing, to changes in control reversal airspeed, that is, the airspeed associated with minimum power- or thrust-required. This is a very important and fundamental piece of information implicitly involved in normal landing of the aircraft. One could expect an *increase* in its value with certain types of control failures, thus making landing at normal speeds quite dangerous. Even if the control-reversal airspeed does *not* change with a failure, however, the nominal value may be of explicit importance during a recovery. Consider case 12, a DC-3 incident in which primary aerodynamic lateral and directional control was lost. Very careful use of thrust to provide some lateral and directional control would have been needed in recovery. Any attempt to control the aircraft with thrust in this type of eventuality

would decrease total available power for changing airspeed on approach, making the control-reversal airspeed a harder barrier than usual.

Another case in which control-reversal airspeed limitations played a role, although presumably *not* an unfamiliar role for the pilot, was case 8, in which the leading edge slats failed to extend on takeoff, and the aircraft was soon below the maximum lift-to-drag airspeed. In this case, two knots of airspeed would have made the difference between the aircraft being able to climb away and the gradual increase in drag, eventual loss of height, and the ground impact (and fire) that actually occurred. Case 27 resulted in a similar scenario.

2.2.4. Other Types of Post-Failure Restrictions on Aircraft Operating State

Figure 2.3 comes directly from the accident report for case 16. It shows the variation with angle of attack and Mach number of the rolling moment (coefficient) induced by the failed-extended leading edge slat and that available with the remaining lateral control resources. In the accident report, this figure supported the finding that the aircraft was unrecoverable once it was allowed to reach a certain bank angle. Not only allowable airspeed (Mach number) but also angle of attack were both (independently) restricted by the failure.

Potentially, any dependencies (in the functional sense) of a now-critical dynamic coefficient can be restricted by a failure, although airspeed tends to be a particularly important dependency because force and moment coefficients have a second-order dependence on it. Note that operating limitations may be expressed in terms other than the primary dependencies, rather, in terms of "derived" dependencies, like bank angle in this case. Constraints on operating states is an area awaiting elucidation through study of additional cases.

2.3. Post-Failure Performance Constraints

2.3.1. Changes in the Power Required/ Power Available Situation and the Ramifications

The hard operating limitations that can arise in control-failure situations have been introduced, and the *performance* aspects of post-failure flight will be considered now. Here, the term *performance* refers to capabilities in relatively steady flight as opposed to maneuver capabilities.

Aircraft performance can suffer greatly when an aircraft has had a control failure. In particular, the high drag that is often associated with highly deflected jammed surfaces or,
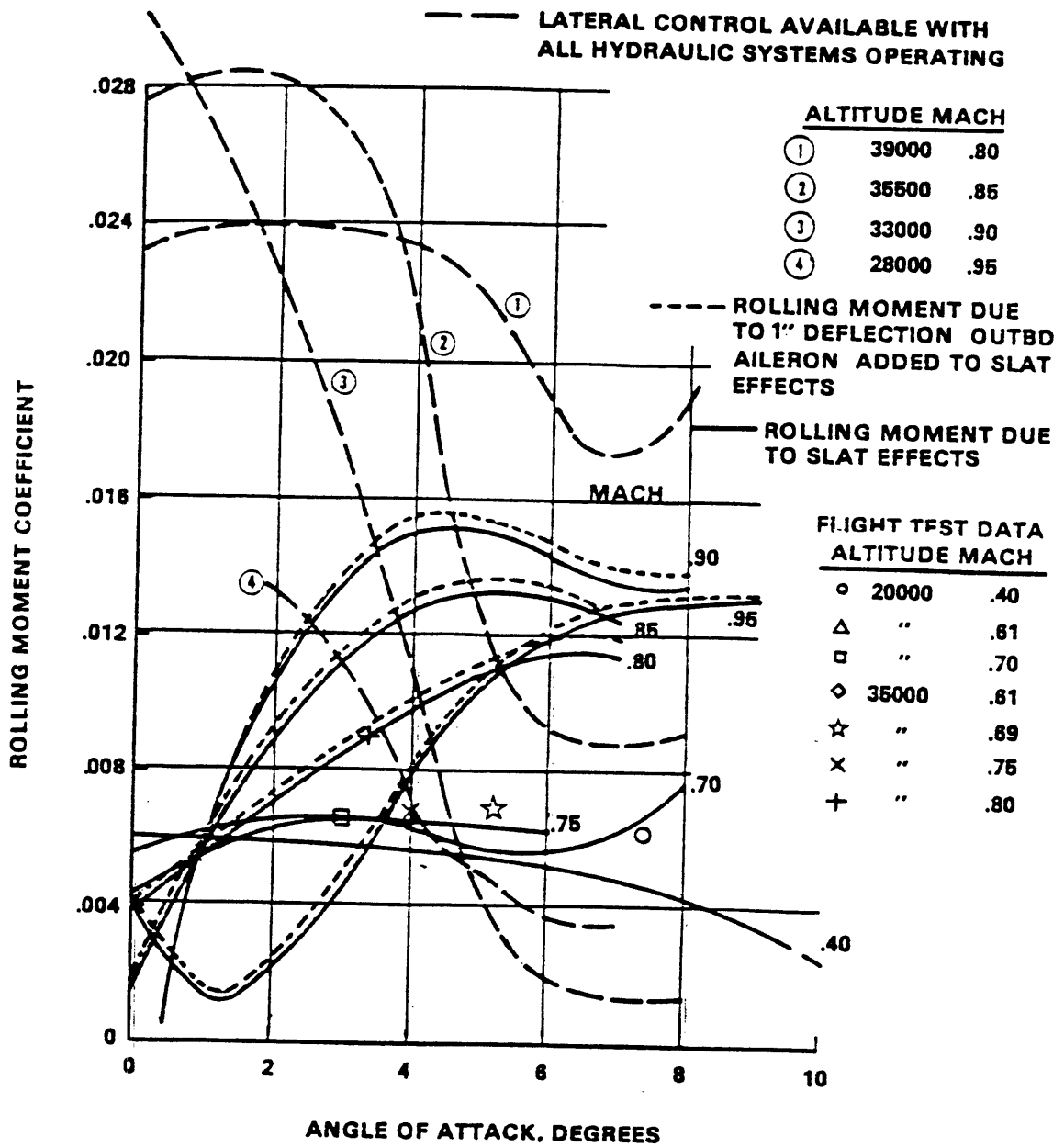
Figure 2.3: Rolling Moments from Extended No. 7 Leading Edge Slat on
B-727 Aircraft [13]
(Showing restriction on angle of attack and Mach number
for controllable flight)

secondarily, with the counterbalancing controls, can bring about significant degradation of such basic types of performance as

--Climb capability, both rate of climb and climb angle

--Aircraft range

--Flight endurance

--Maximum airspeed

--Maximum altitude

Failure of a wing surface such as a slat or a spoiler, by changing the basic aerodynamics of the aircraft, can also lead to significant changes in power required for flight. Engine failures alone will, of course, bring about degradation of all of these aspects of performance since they result in direct degradation in the power available. Not only can these types of performance be changed with a failure but so can be the configuration at which good performance is obtained, i.e., values of the airspeed and angle-of-attack at which maximum performance of a certain type is achieved.

Information on all of these performance measures can be obtained from power required/ power available curves for the aircraft., and it should be understood that much of the discrete flight information in pilot manuals directly reflects information of this type. Figure 2.4 shows examples of power available/ power required curves for the "power-producing"-type aircraft, such as the turboprop-driven C-130 aircraft. Power-required/ power-available curves can give immediate information on performance of the aircraft at the altitude for which the curves were computed and can give the airspeeds at which certain types of performance are maximized, as Figure 2.4 shows. The intersection of power-required and power-available curves give maximum and minimum achievable airspeeds for level flight at that altitude. Maximum endurance for aircraft with power-producing propulsion is associated with flight at minimum power required. For propeller aircraft and especially for jet aircraft, taking propulsion efficiency into account may drastically affect altitude and airspeed for maximum range or endurance.

2.3.2. Example from Work with C-130 Elevator Failures

An example will be used in order to help make clear what performance constraints induced by a failure can be very significant, even if the failure seems "small." The example that will be used is derived from a C-130 failure case involving an elevator jammed originally 5° off-nominal pitch down (jammed at 8.05°). The aircraft was flown to 10,000', after which

Figure 2.4: Power Available/ Power Required Curves Showing Performance Airspeeds [36] (Generic power-producing aircraft)
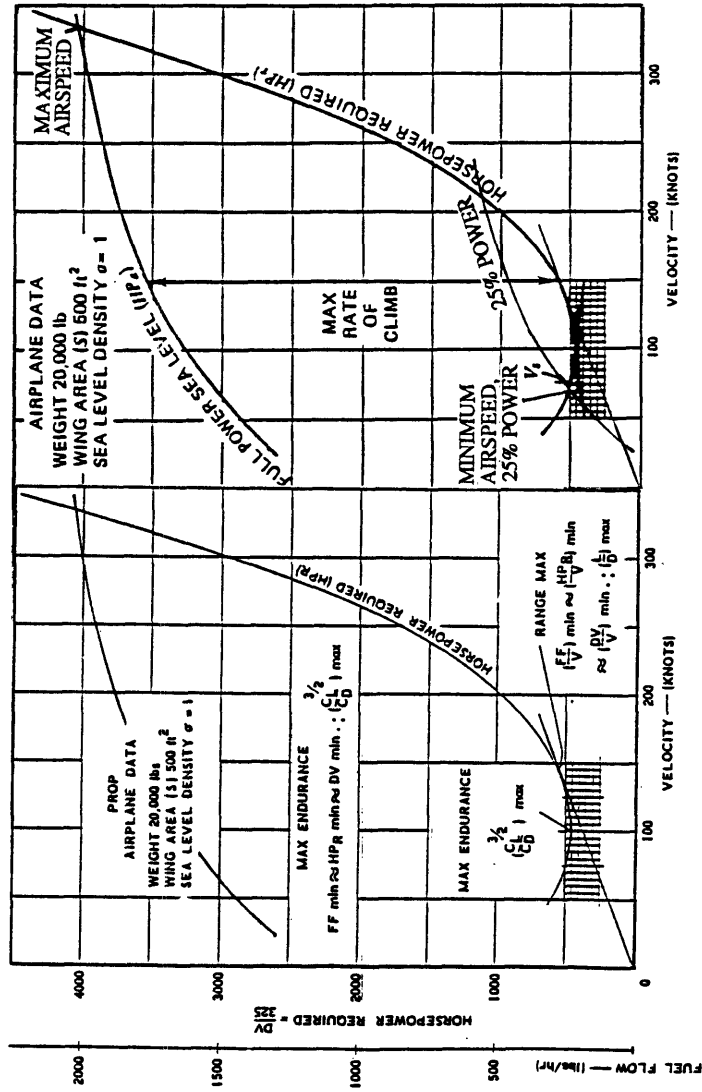
Under small angle of attack assumption:

Steady rate of climb

$$= \frac{P_{Avail.} - P_{Req'd}}{Wt}$$

Steady angle of climb

$$= \frac{P_{Avail.} - P_{Req'd}}{V * Wt}$$

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the power available/ power required curve for level flight at altitude of the post-failure aircraft was computed. This was compared with that for the nominal aircraft at the same weight and altitude, the nominal in clean cruise configuration (no flaps, no landing gear). Figure 2.5 displays the power required curves for nominal and handicapped aircraft and power available with two to four engines.

With this pitch-down failure, just keeping the failed aircraft flying level obliged the deployment of full pitch-up collective aileron, some elevator tab, and, especially, considerable flap extension. These surfaces, particularly the flaps, resulted in considerable drag, and the power-required curve for the handicapped aircraft--and this is the *minimum power required* curve (see Section 2.4.2)--is considerably changed from the nominal.

From Fig. 2.5, maximum-endurance steady level flight for the *nominal* aircraft at 10,000 feet would be at about 120 KTAS. Maximum range is achieved at the airspeed associated with maximum lift-to-drag, 165 KTAS approximately. The airspeed range available for steady level flight is 105 KTAS to 235 KTAS. Under the assumption of small angle of attack in the climb, maximum rate of climb is achieved at the airspeed at which there is maximum excess power available beyond the needs of power required, near 137 KTAS.

Consider the performance degradation induced by this elevator failure, as indicated by this new power-required curve[1]. Hash marks indicate the end of the equilibrium airspeed range, so the minimum and maximum achievable airspeeds are now approximately 140 KTAS and 180 KTAS, respectively. The steady maximum rate of climb and maximum climb angle at this altitude have been considerably reduced. The maximum endurance airspeed is now 30 KTAS higher, although the maximum range airspeed has decreased by about 10 KTAS. It can easily be imagined that knowing the new achievable levels of performance can be *very* important post-failure, and the airspeeds associated with best performance have changed considerably. Losing even one of the four engines now can restrict cruise operations very much, as the three-engine power-available curve of the Figure shows, and

---

[1] These points on the new power-required curve were obtained using quadratic programming, with successive linearizations of the dynamics at each major iteration. It should be noted here that the state and control settings for the cruise equilibria converged fairly slowly to their final values, *and a change in getting the state rates from 10^{-3} down to 10^{-6} or 10^{-8} could often mean considerable changes in the solved-for state and control settings.* This means that a not-fully-converged solution could lead one to believe in the existence of considerably more post-failure performance capability than is actually available. Linear models based arbitrarily on 5% perturbation in the total range in feasible values of the states and controls were used in the optimization. However, sometimes linear model-based retrim could not give a certain known minimum-power equilibrium point starting from certain other equilibria, even close ones. Nonlinear-type retrim would be preferable--perhaps using one of the newer algorithms in which the choice of perturbation used in calculating the gradients is part of the solution algorithm.
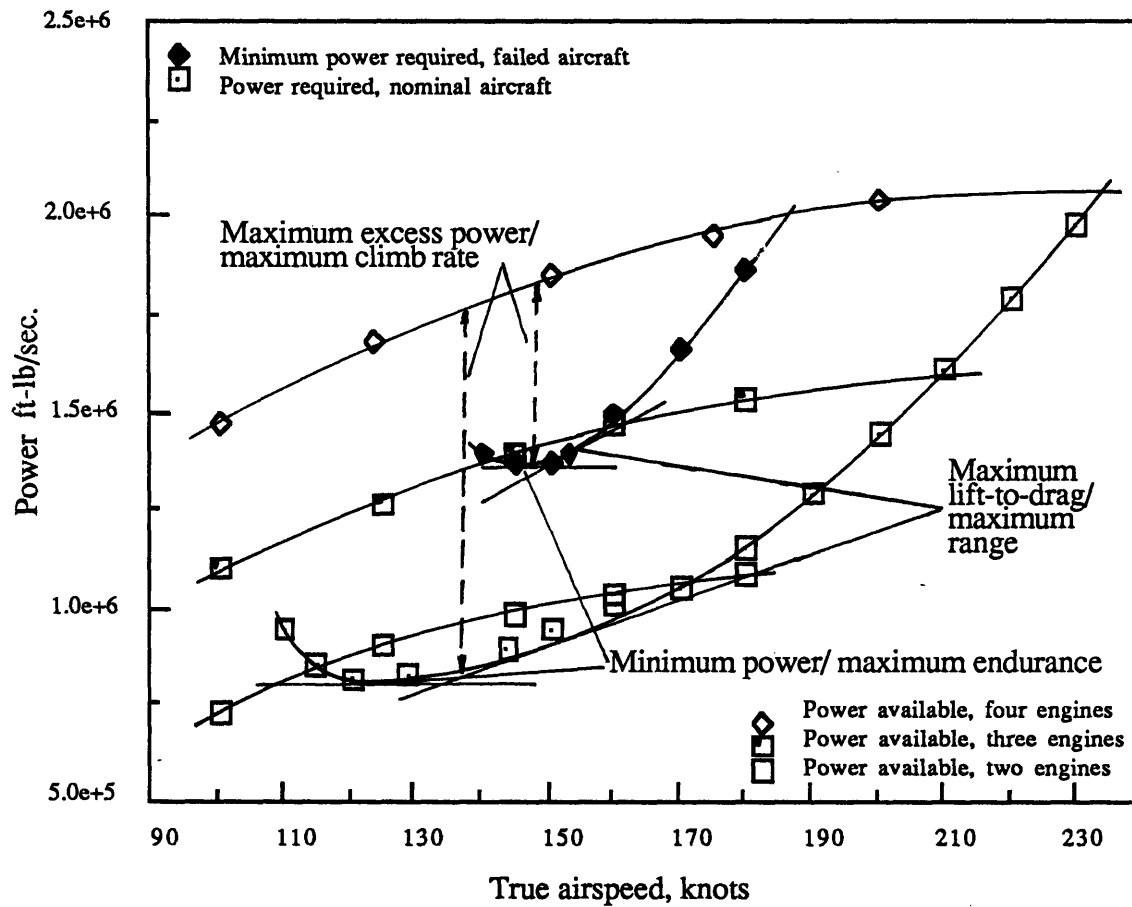
**Figure 2.5: Power Available/ Power Required Curves,
C-130 with Elevator Jammed at 8.05°,
Steady Straight and Level Flight at 10,000 ft.--
Shows new performance airspeeds**

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this could be a very important consideration in deciding whether the flight should be continued when a climb over an obstacle ahead is required.

It is clear that the use of flaps in compensating for this failure incurred most of the decreased performance. Consider again, however, the description of the Flight 1080 case presented in Chapter 1. The large elevator was jammed so highly deflected that much higher thrust levels than usual were required for stabilized flight even with the flaps not part of the compensation. The failed control itself contributed a very significant increase in drag.

2.3.3. Performance Changes in the Long Term

As has been discussed, one of the foreseeable consequences of control failures is reduced performance of the aircraft. Case 26 illustrates how misjudging aircraft performance after engine failures can lead to disastrous errors in deciding whether a desirable destination can be reached. The above post-failure power-required curves for the pitch-down elevator failure case suggest that this can also occur with failures of aerodynamic surfaces.

Although much of aircraft performance is determined by power required/ power available curves, this only gives local performance. Maximum performance and how it can be obtained will change, of course, with the progress of the flight. Figure 2.6 shows these variations with weight, configuration, and altitude for the generic power-producing aircraft. In the most strenuous cases, these variations must be accounted for.

2.4. Post-Failure Equilibria and Other Retrim Information

2.4.1. Introduction: Context for Needs for Explicit In-Flight Retrim Post-Failure

In the absence of a better term, "retrim" has been adopted here to indicate calculating and achieving new feasible or desirable operating points for the handicapped aircraft. Little research has mentioned the possibility that a control failure might oblige flight at significantly different operating points; [37] represents a notable exception.

A real question easily arises in dealing with control-impaired aircraft as to whether explicit retrim has a role in *immediate* post-failure flight. Suppose that, prior to the failure, the aircraft is flying at state x_0 and with control setting u_0 prior to failure and with state rates $dx/dt = f(x_0, u_0)$ and that control i jams Δn off-nominal. Explicit retrim immediately after the
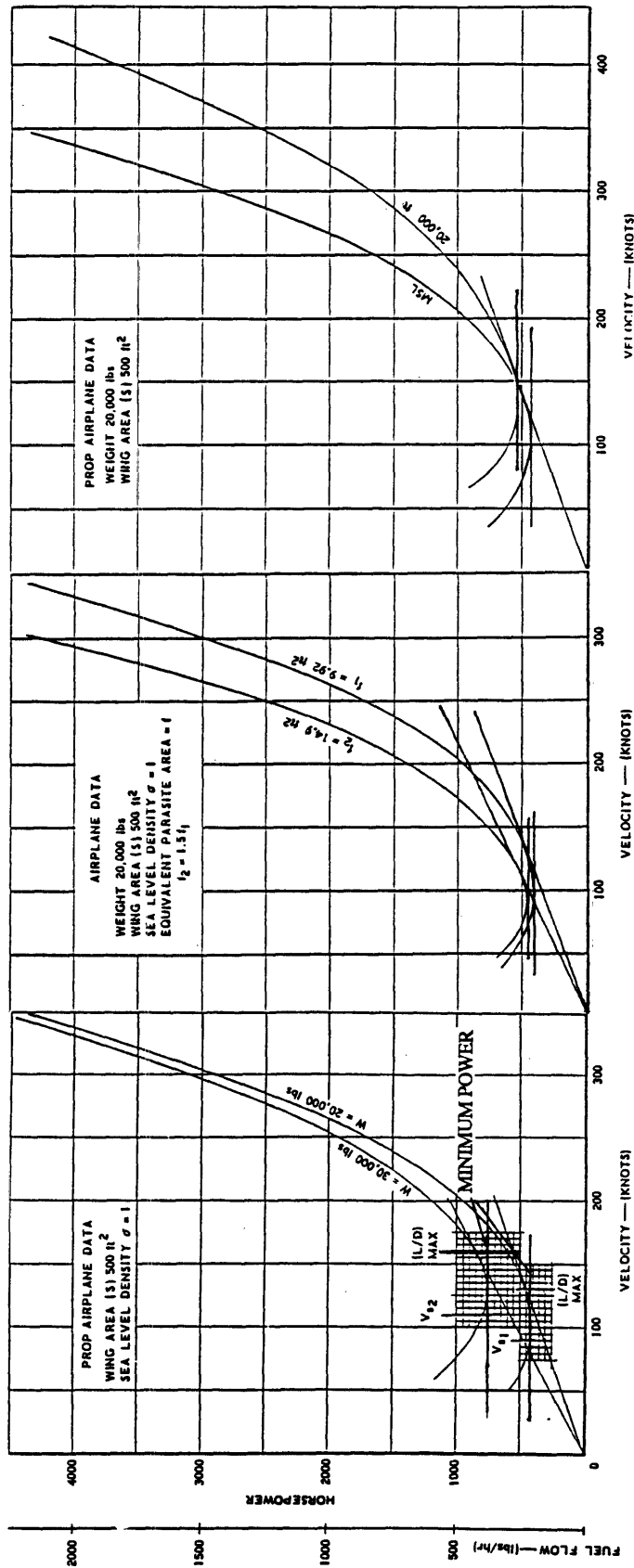
Figure 2.6: Power Available/ Power Required Curves Showing Variation in Performance Airspeeds with Weight, Configuration, and Altitude [36] (Generic power-producing aircraft)

failure would involve looking for a new operating point $x_0 + \Delta x$ with the unfailed controls at $u_{f0} + \Delta u_f$ such that Δx and Δu_f satisfy

$$A \, \Delta x + B_f \, \Delta u_f = -b_i \, \Delta n$$

(assuming linearity WLOG), thus maintaining (regaining) the pre-failure trajectory. Note that the idea of controllable airspeed could be involved in being able to find a solution to this.

There is, of course, the variant of this in which one speaks of retrim to a new trajectory where $dx/dt = f(x_0, u_0) + \Delta r$, through trying to solve

$$A \, \Delta x + B_f \, \Delta u_f = -b_i \, \Delta n + \Delta r$$

Since equilibration is not always the best course in some post-failure situations, one may prefer to climb up and away after the failure or make decreasing angle of attack the highest priority. Perhaps certain rates--and thus certain performance measures--can be allowed to sag in favor of securing others.

This researcher's experience with recovering aircraft with (single) failed controls has indicated that explicit retrim alone is not a very useful idea in the early periods of post-failure flight just after the failure has manifested itself. In the first place, *opposing the disturbance--* typically a large one--is a much more powerful general simplifying idea. Secondly, just having a single retrim point--which a single solution to these linear equations yields--says nothing about its basic reachability, nor, if guaranteed reachable, *how* to reach it, not to mention other possible solutions. Forcing the aircraft to try to fly to a given state and at a given control deployment may be too demanding. However, there have been cases where the retrim-related idea of control effectiveness has been crucial. This will be seen especially clearly in the asymmetric flap failure case to be discussed in Chapter 3, in the notion of controllability airspeed, which played an essential role in the recovery. Knowing about a retrim region, then, can play an important augmenting role. One can anticipate that, in recoveries after multiple failures, there will be a more pronounced role for explicit information about operating regions in which stabilization is possible relative to the role of disturbance-opposition. One can also imagine (probably rare) scenarios in which the failure is "small," so that the aircraft is diverging slowly from the nominal trajectory, and small explicit changes in trim could be made outright and perhaps should be suggested explicitly to the automatic control. Explicit information about retrim, however, would undoubtedly be most useful in periods of relatively quiescent flight, and it could be very useful and important there as will be seen. The following example suggests a good role for explicit retrim in later, more quiescent periods of post-failure flight.

2.4.2. Examples of the Need for Explicit Retrim (from C-130 Elevator Failure Cases)

The following example is from a case in which the elevator initially jammed pitch up, at -9°. An ascent to 10,000' was flown after initial post-failure pitch-stabilization of the aircraft. Considerable opposing control had been brought to bear in the initial stabilization, and pitch moment commands intended for the elevator were remapped to the functioning controls during the ascent. An approximate equilibrium was established at altitude. After the flight, this operating point was fine-tuned using a least-squares linear trim algorithm to get a true equilibrium, at the following point:

Velocity V = 120 KTAS
Angle of attack α = 15.2°
Pitch rate q = 0.
Pitch angle θ = 15.2°
Altitude h = 10,000'
Elevator de = -9.°
Aileron da_r = da_l = -20°
Flap df = 0.%
Thrust lever tlev = 62.0%
Elevator tab detab = 30.%

The least-squares trim algorithm was then used to find (locally) the equilibrium operating point associated with minimum-thrust flight at this same airspeed, that is, the local minimum-power operating point. The point converged to from the above point was

V = 120 KTAS
α = 12.4°
q = 0.
θ = 12.4°
h = 10,000'
de = -9.°
da_r = da_l = +20°
df = 0.%
tlev = 52.6%
detab = 37.9%

There is a considerable difference (52% versus 62%) in the thrust required at these two equilibria. The conclusion is that there was "force-fighting" amongst the equilibrating controls in the first point: the ailerons and elevator tab were providing more than enough pitching moment to counterbalance the jammed elevator's effects, obliging some pitch up input from the engines and thus relatively high thrust. This force-fighting was neutralized in the second point. Both points have the serious drawback of requiring hardover deflection of ailerons, albeit in different directions (deployment limits in Appendix II), obviating much turn capability, although it is to be expected that there would be equilibria with intermediate

use of ailerons and intermediate use of thrust. One is clearly faced with the prospect of very possibly wanting to transfer from the first configuration to the second in order to increase endurance.

For the case where the elevator has jammed at 8.05°, as introduced previously, a few additional operating points for steady straight and level flight at 10,000' have been superimposed as new higher-power-required points on Figure 2.5, as shown in the following Figure 2.7. Two separate equilibria were established for the failed aircraft at 150 KTAS, one with 62% flaps, $\alpha = -17°$, and one with 51% flaps, $\alpha = -2.25°$. The different flap settings meant very different required power settings (x vs y). Even though the difference in required thrust lever setting between these two points is only about 8%, achieving the minimum power operating point moves the aircraft into the realm of possible three-engine operation, if needed, as well as moving away from a larger flap deployment, which was, by the way, up against the structurally-limited value.

The *new* post-failure power-required curve is not unique because additional control degrees of freedom beyond those of the nominal aircraft have been introduced in enhancing the basic control redundancy of the aircraft. To see this, consider the linearized longitudinal equations of motion. To have a new cruise point at the same airspeed and altitude, one must have the change in state and control setting ($\Delta\underline{x},\Delta\underline{uf}$) satisfy

$$A \ \Delta\underline{x} + B \ \Delta\underline{uf} = \underline{0}$$

This is a system of five longitudinal equations of motion in five unknowns, namely $\Delta\alpha$, Δda, Δdf, $\Delta tlev$, and $\Delta detab$ (since $\Delta V = \Delta q = \Delta h = \Delta de = 0$ and $\Delta\theta = \Delta\alpha$). For the nominal aircraft, there would have been five equations in four unknowns ($\Delta\alpha$, Δde, Δda, $\Delta tlev$), so, in general, there could be no more than the one cruise point at each given airspeed and altitude. Figure 2.7 suggests some extent of the power required *band* for flight at 10,000' with the control failure.

There have been very few cases where the flight got past the opposition phase to show whether explicit retrimming is needed. Retrimming may be needed during any phase of post-failure flight, shifting control burden away from controls needed for maneuvering, say, or, for example, reaching better-performance cruise. The need to transition between equilibria could be expected to be even more needful with larger failures. Obviously, the general sort of transitioning indicated is, in some sense, a feature of nominal flight, but the use of unconventional controls and the possible considerable performance degradation after a failure can mean that *prompted* transitioning could be a desirable feature of pilot advisory. One cannot necessarily know how difficult or how dangerous any given post-failure
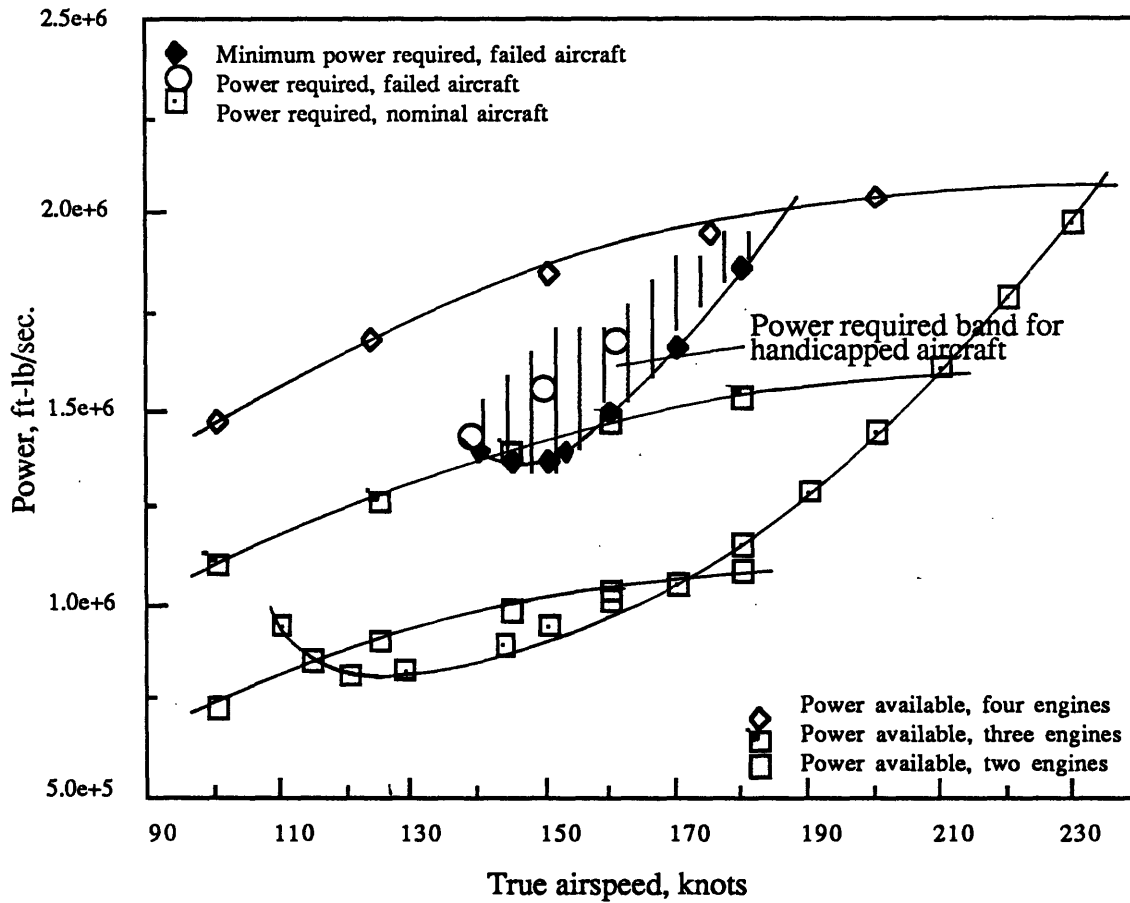
**Figure 2.7: Power Available/ Power Required Curves,
C-130 with Elevator Jammed at 8.05°,
Steady Straight and Level Flight at 10,000 ft.--
Shows power required band**

transition would be between two operating points, even where retrim has identified new points as being in themselves good operating points. Simply deciding to some degree what looks like a feasible, safe transition on the basis of qualitative reasoning will be possible in some cases. Providing the pilot with rudimentary instructions on phasing changes in deployment of the controls might be adjudged necessary in other cases. Reachability of the new point may involve some at least temporary losses in desirable operating quantities, however. Consider a transition to the maximum range operating point in Figure 2.7 from another, lower-airspeed cruise point. Airspeed could only be gained through effecting a decrease in pitch. Decreasing thrust would be able to bring this about, but altitude would be lost in the transition, altitude which might be especially difficult to regain afterwards.

2.4.3. Introduction to Constant-Rate State/ Control Input Regions for Aircraft Dynamics

The constrained quadratic programming method in [37] was used to find trim points for the C-130. Different scaling in the cost could give widely different equilibria, and it was clear that many equilibria could be found for the post-failure aircraft. However, this linear-model based trim could not find some of the equilibria refined from near-equilibrium points actually flown to. This led to some insecurity about this approach to retrim, with the result that questions about the properties and extent of constant-rate regions of aircraft nonlinear dynamics began to suggest themselves. Appendix III discusses the issue of constant-rate regions for the aircraft in a more general context, and presents some information about a few accessible properties originating from use of the implicit function theorem.

2.5. Summary

This chapter has demonstrated that control failures result in operating and performance constraints on the aircraft. Certain categories of these constraints have been presented. The idea of explicit retrim of the impaired aircraft to improve performance or maneuverability has also been introduced.

Chapter 3

A Rule-Based Expert System for Discovering Successful Emergency Post-Failure Control

3.1. Introduction

This chapter is a long introduction to and demonstration of the idea of emergency control in the immediate post-failure period, when the pilot is confronted for the first time with a significant disturbance. The failure-induced disturbance may arise from a significant off-nominal failure of the control or loss of part of a control surface, or, alternately, when the aircraft has moved into a new state for which the failed control is no longer nominal (for example, a detached elevator trimmed in the post-power reduction position induces a disturbance after the pilot has reduced thrust to begin a descent). It is clear that there will always be a need and a possibility of manual-type deployment of alternate controls with certain types of aircraft.

Essentially all of the recoverable cases in Table 1.1 are vivid demonstrations of the need for emergency control. Most of these flights never got past the initial period of flight to stabilization. Without having worked with the specific aircraft on these specific cases, it is not possible to draw strong conclusions regarding the success of a strategy of simple pilot prompting to at least try a suspected functioning disturbance-opposing control. This is an issue for more study. From this researcher's experience with a medium-performance aircraft, finding a fully successful emergency control was usually not immediate, and more was usually involved than simply knowing which controls could be used to oppose a failure-related disturbance. Finding a workable essentially manual recovery strategy for certain failures of the C-130 aircraft often involved several iterations of piloted simulation. However, it soon became clear that finding a successful strategy was not all that difficult, given the possibility of making a few attempts. The reasoning involved in compounding strategies is not deep. Sometimes, however, the strategy that was finally successful involved use of controls not to oppose the effects of the failure but enhance them, at least temporarily (there will be some examples of this later).

Basic general information on the qualitative effects of use of various controls for a given aircraft is immediate and would be similar to that in Appendix I. This information is

the first basis for compounding a strategy. It is desirable to go beyond pilot prompting with only this level of information to help in recoveries where, for example,

--Multiple controls must be used *simultaneously* and deployed *immediately* if recovery is to be possible at all.

--"Artifact" from usage of alternate controls could be devastating under the circumstances, so deployment must be gingerly done.

--Controls must be used somewhat counterintuitively .

It is to be expected that the pilot simply would need better support in certain and probably most failure situations.

Obviously the best way to be certain of the effects of alternate control strategies in a failure situation is to pre-simulate the application of the alternate controls with a high-fidelity model, although this is computationally intensive, of course. Knowing what the failure is can make pre-simulation accurate and extremely useful.

Why pre-simulate a recovery strategy?

--In the most strenuous failure cases especially, even a few degrees of control usage available or not could make all the difference.

--With the dynamic system so sensitive to changes in controls, it is worth close investigation of all possibilities to get a recovering control. Hard work is rewarded.

--"A miss is as good as a mile."

It soon became clear in working with the C-130 aircraft that a rule-based expert system could be written to automate the process of directed iterated simulation to find successful post-control failure recovering control. This chapter presents a preliminary look at such a system. As will be discussed later, although in-flight use of a system of this type may be feasible, it may be preferably used for pre-simulating recoveries from wide ranges of failures before the aircraft is flown. In the author's view, establishing this type of system is the *best compromise* between two ultimately unacceptable options: 1) an on-line system that would be expected to work with limited time and probably with a limited system model to find a successful strategy in real time, and thus probably denying the possibility of finding a difficult strategy--one that would require several iterations of simulation to compound, and 2) more qualitative prompting that might be possible without extensive pre-simulation of emergency post-failure control strategies.

3.2. Introduction to Knowledge-Based Systems [38]

An **expert system** is a computer program performing within a specified task domain at the level of a human expert within that domain. When knowledge is represented in discrete identifiable parts of the system rather than being dispersed throughout, the implementation is a **knowledge-based system**. Expert systems, because they can be considered generally to be knowledge-based in this sense, have typically been written as computational production systems. Computations in production system are quite different in style from those performed by programs written in procedural languages (like FORTRAN), commonly used in engineering work. Production systems use data-sensitive unordered rules as the basic unit of computation, rather than sequenced instructions. A production system is appropriate when domain knowledge naturally occurs in rule-type ("IF"-"THEN") form, where program control is complex, or where the program is expected to be significantly modified over time. These considerations, as will be seen, all hold for the system developed here. Many of the applications systems created with the production system model have in fact been expert systems, since the chunks of knowledge encoded in production systems (that is, rules) seem to be just the right size for capturing the steps that people employ when they attack nontrivial problems. There have been numerous expert systems developed, but none of them solves a problem much related to those of the research here.

Production system architecture typically includes three major components:

--a global (generally) database of symbols representing facts about the problem and the problem-solving goals--the *working memory*

--the constituent unordered rules, each with a condition ("IF"-type) part and an action ("THEN") part

--the inference engine, which must determine which rules are relevant given the current data configuration and choose the one to apply next.

The program control scheme, including the style of conflict resolution, depends on the variant of the production system model being used, typically a given production system *language*. In a rule-based system, control is based on frequent re-evaluation of the data states, not on any static control structure. Thus, one says that computation in a production-system model is data-driven, not instruction-driven as in a procedural computation model.

A variety of problem-solving paradigms can be built into the inference engine of a production system. Two fundamental categories here are forward- and backward-chaining. Forward chaining is progression from given information to a goal, as it is found to be attainable, and backward chaining starts from the overall goal and breaks it down into simpler subgoals, and so on, until the result is (hopefully) a collection of immediately attainable small

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goals. Explicit backward chaining figures in such activities as diagnosis, so it would certainly appear in expert-type FDI systems. Forward-chaining, on the other hand, is most appropriate when the situation is reversed and there are many acceptable goal states and a single initial state. Forward-chaining can often be thought of as being guided by means-end analysis, where successive actions are selected as determined by some measure to be closer to the ultimate goal. Piloting is, on the whole, mostly "forward" problem-solving. And because emulating pilots and keying the system to pilot usage is being sought, forward chaining should predominate in an expert system written to find a recovery control strategy.

3.3. System Developed for Thesis

3.3.1. Introduction

The system developed for this thesis was restricted to finding emergency control after jam failures of the elevator on the C-130 aircraft. Although less-than-hardover elevator jams are very uncommon in aircraft, they do in fact occur ([39] is one additional example). The results would be similar, however, when used with the less uncommon runaway or other pitch trim failures or with other more general damage to the elevator. The elevator of the C-130 was the target of choice for anti-aircraft artillery batteries in Viet Nam. The elevator on this aircraft is not normally split into separate right and left parts, and thus the simulations could be restricted to longitudinal motion only. The elevator on this aircraft is a large, highly effective surface, and thus even relatively "small" (2°-3° off-nominal) failures can lead to quite large disturbances to the aircraft. This control surface has a 55° total deployment range. Recovering the aircraft after various elevator failures was expected to require a wide range of types of recovery strategies. The C-130 was used because it has a traditional degree of control redundancy and is a medium-performance aircraft.

3.3.2. C-130 Elevator Failure Case Studies

The starting point for the development of the rule-based system to guide in discovering recovery strategies was making manual recoveries from elevator failures under various conditions. In first considering the possibility of automating the process of finding alternate emergency control, it was daunting to believe that solutions to the wide range of possible failure situations could be found only by dealing in abstract--and thus complex-- terms about the control problem (e.g., all the knowledge provided to the expert system being a formulation of controls as abstract "operators" acting on the system and with given

preconditions for their use). It was soon clear, however, that this sort of complicated treatment would not be necessary. It is likely that a system that is practical and that could give workable recoveries *for almost any type of aircraft* could be obtained by working on a much more concrete level.

The C-130, the aircraft used in this work, has some underdamped longitudinal poles, so some reconfiguration of the pitch damping loop after significant elevator failure would definitely be recommended. This will be clear from looking at the response in the simulations presented later. Although it would be desirable to reconfigure the pitch loop for the C-130, it will become clear from example failure cases that the aircraft has enough open-loop longitudinal stability to stabilize without reconfiguration and, more strongly still, without requiring much change of the controls after initial state "capture" in a fairly large state region. The easiest assumption will be made, namely, that *the failure has been fully identified*, although, as discussed later, this type of system may also be very effectively used when the failure is unknown. To allow for some nominal amount of time for FDI, emergency control was imposed in all cases only after a three-second post-failure delay.

Four groups of elevator failure cases were developed. For each set of cases, the aircraft was in steady flight at the time of failure. The initial states were

1. Steady straight and level flight at 120 KIAS, at 7000'
2. Steady straight and level flight at 147 KIAS, at 1000', with 50% (full leading edge) flaps
3. Full-power climb at 173 KIAS, through 7000' (climb as recommended by the flight manual for the standard C-130)
4. "Maximum penetration descent" at 145 KIAS, through 4000', with 50% flaps and landing gear extended

Flight at relatively low altitudes was represented here, and these are realistic examples. For each of these initial states, the elevator was failed in 1° increments through its entire recoverable range. The high-fidelity nonlinear aircraft simulation used in this research was flown using computer terminal output and simulation interrupts, as described in Appendix 2. Because the control inputs did not involve very sensitive flying--inputs were generally hardover--the simulations and the results that follow from this study should be considered very realistic.

The underlying heuristic behind the intended output of the expert system being considered here is that

> In the very *initial* stages of a post-failure emergency control, control changes to known values may be considered "optimally" achieved as quickly as deployment rates allow, and such changes in more than one control are "optimally" simultaneous.

The type of optimality being used here encompasses simplicity, although, with the generally very large disturbance to oppose, it is clear that resources must be brought to bear as quickly and definitely as possible. The form that the output will take most often is, then, which controls should be deployed--simultaneously--and settings to be commanded for these in the initial part of the recovery. As will be seen in example cases to follow, it was obligatory in certain recoveries that control deployments be reversed later in the recovery sequence--but never more than once--and the controls could always be commanded hardover to a new setting.

The criteria for success of an emergency control strategy were designed in this study to be fairly non-strenuous, although it is easy to believe that the criteria could be made very stringent and still this type of expert system framework would be eminently usable.

> Criteria used to establish success of a recovery control:
>
> --The aircraft is "stabilizing"--settling into stable oscillations in all of its longitudinal states.
>
> --The aircraft is recovering to a climb.

A climb was established for several reasons. Not the least of these reasons is that pilots might need some inactive time to mentally re-adjust after an unusual and confusing aircraft excursion. But it would also take some time for the aircraft oscillations to damp and more controlled descent made. It may be preferable in many cases to divert to another airfield to make an emergency landing or to abort if the failure occurs on approach. There could be simple objective tests for both parts of the criteria for success. *All* aircraft states must be stabilizing--an absence of oscillations in pitch angle alone, for example, would mean that the aircraft was diverging in its response.

3.3.3. Determining Effectiveness of Alternate Emergency Controls

The four possible longitudinal controls on this aircraft--collective ailerons, symmetric flaps and thrust, and elevator tab--were *all* used for at least some cases in making recoveries from the wide range of elevator failures considered, as were certain deployments of the landing gear. It was hard to avoid the simplification of a strict hierarchy of control usage in the recoveries. There were several issues to consider in establishing this hierarchy:

Structural limitations on use of a control. Since deployment limitations on aerodynamic controls are expressed in terms of maximum indicated airspeed, this is an aspect of use that is rather easily accounted for.

"Artifact" of the control usage. A control may have considerable beneficial impact on the quantities of most interest but at the expense of other quantities, for example, wing flaps may contribute considerable pitching moment but to the considerable detriment of airspeed. This undesirable artifact may build slowly, which is a consideration also associated with the next issue.

Short- versus long-term effectiveness of the control *relative to other controls.* As will be seen in the C-130 test cases, sometimes a relatively less effective or perhaps more artifact-laden control must be used as a temporary stopgap before a more potent but more slowly deploying control can be brought in.

Ultimate effectiveness of the control toward restabilizing the aircraft. In addition to the relative effectiveness issue is that of absolute long-term effectiveness of a given control in dealing with the effects of a failure. The available range of travel of a control and/ or its incremental effect on the dynamics may be such that this control alone cannot counterbalance the effects of the disturbance or cannot counterbalance before "reasonable" constraints on aircraft state are broached. In that case, additional control resources must be brought to bear.

Reversibility of usage, that is, how much time is required for *un*deployment. One of the pitfalls of trial deployment of a control to oppose a failure-associated disturbance, particularly a secondary-type control, is that its deployment may be slow to reverse. Flap and thrust changes are generally slow to be reversed.

It should be mentioned that determining basic incremental effectiveness of a control should not, in general, be done simply by looking at the associated column of the B-matrix. For most aircraft, for example, the B-matrix effect of thrust changes is to increase airspeed, but, acting through induced pitch up, thrust increases alone result in airspeed decrease. Nor should one look at the perhaps hopelessly distant steady-state response of the linear state transfer function to the control input.

Using these criteria, elevator tab alone was deployed first, because it can be highly effective in providing pitching moment, especially if there is considerable deployment range in the direction of interest, and elevator tab usage has little "artifact" effects on longitudinal-axis motion--here, little effect on anything but pitch moment. Collective ailerons were then tried along with the elevator tab, if the latter alone gave insufficient disturbance opposition. Flaps were added next in pitch-down failure cases. Flaps unextended at the time of failure have no potential for opposition to a pitch-up failure, but where deployed previous to the time of failure could be retracted after the failure to provide some helpful pitch down. Flaps, within reason, keep airspeed reasonable, enhance stall margin, and their deployment early may help avoid uncertainties about their deployment later, as landing is being considered. Thrust changes were the last resort. This choice was predicated mostly on the consideration that the throttle should be kept as independent as possible from pitch compensation, and reserved for usage in which it is more directly effective than in pitch moment, like changes in climb rate and airspeed. Moreover, thrust changes represent plenty of long-term "artifactual" changes in the system. Thrust changes in and of themselves were generally not that effective in pitch for this aircraft, although thrust changes did directly enable recovery in several cases, as will be seen.

There was an inviting simplification made early in the work on recovery from elevator failures. The intuitive thing to do--and this was carried over to the expert system--was to try first hardover deflection of successively more controls (added in the order above) and examine the response. The practical effect of this was that the ultimately recovering control could be bracketed with few simulations between too-little and too-much.

One of the important expected features of recovering control was confirmed through making these recoveries. Using the scheme of applying separate controls in order, the recovering control for a given failure fell along a *discrete spectrum of strategies*, basically according to the amount of off-nominal deflection. Figures 3.1-3.4 illustrate the recovery spectra for the four groups of cases. In general, recovery from the pitch-down failures was much more difficult than from the pitch-up failures. The successful recovery strategy varied in these cases from no explicit compensation to hardover or partial deployment of any or all of the four available longitudinal controls. For some cases, deployment and later reversal of the original deployments were required. The limited pitch-up range of the elevator tab is probably the cause. Not every type of recovery was needed for every initial condition. But the resolution was coarse (1.°). The expert system developed for this thesis is expected to be able to find a successful recovery strategy for every fractional off-nominal deployment. Note that the small regions of applicability for a given type of recovery strategy in these spectra
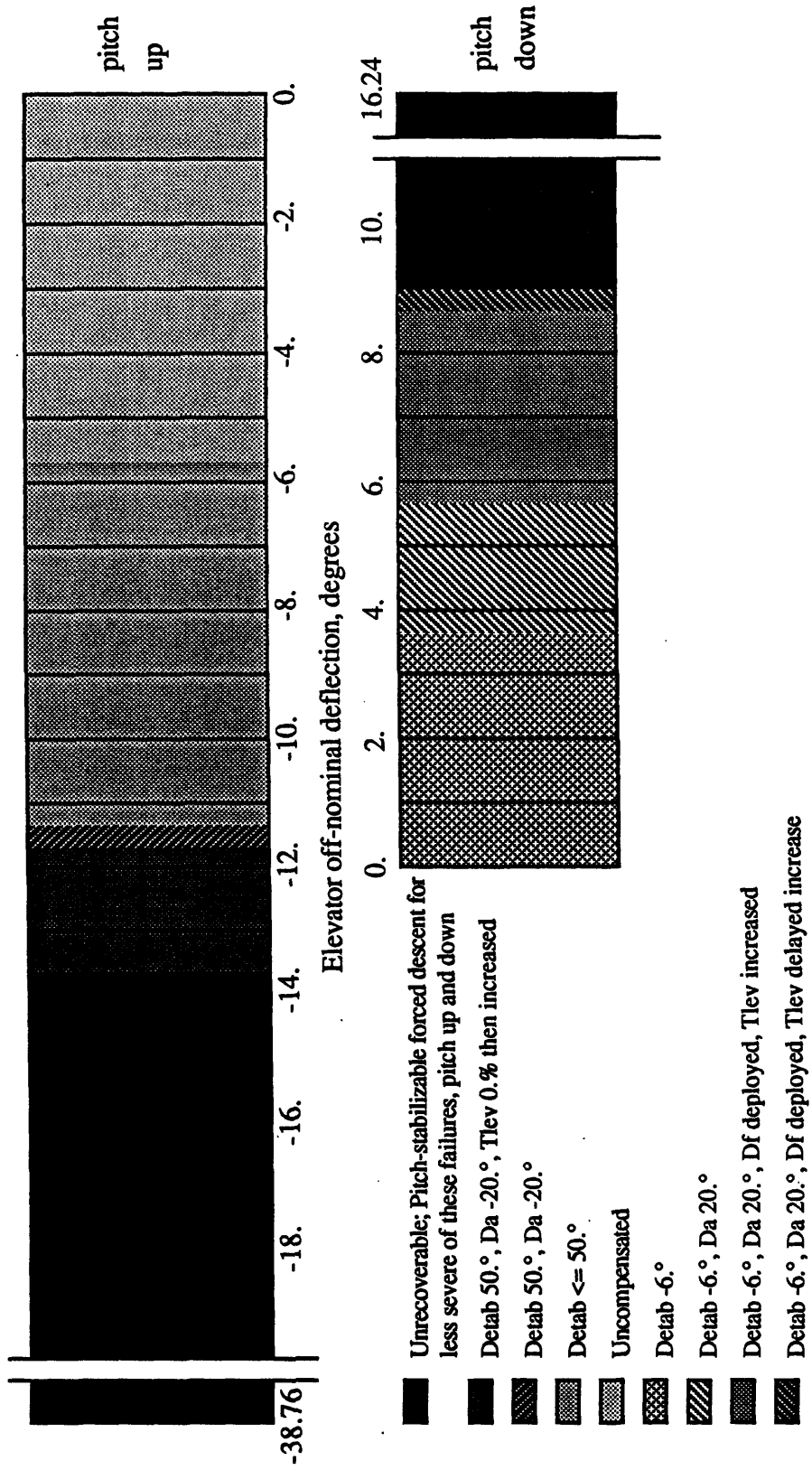
Figure 3.1: Recovery Spectrum--C-130 Elevator Jam Failures During Cruise at 120 KIAS, 7000'

pitch up

pitch down

Elevator off-nominal deflection, degrees

Unrecoverable; Pitch-stabilizable forced descent for less severe of these failures, pitch up and down

Detab 50.°, Da -20.°, Tlev 0.% then increased

Detab 50.°, Da -20.°

Detab <= 50.°

Uncompensated

Detab -6.°

Detab -6.°, Da 20.°

Detab -6.°, Da 20.°, Df deployed, Tlev increased

Detab -6.°, Da 20.°, Df deployed, Tlev delayed increase

Elevator off-nominal deflection, degrees

pitch up

pitch down

■ Unrecoverable; Pitch-stabilizable forced descent for less severe of these failures, pitch up and down

■ Detab 50.°, Da -20.°, Df reduced then restored for less severe cases

▥ Detab 50.°, Da -20.° then both deployments reduced

▨ Detab 50.° then reduced

▒ Detab <= 50.°

▓ Uncompensated

▓ Detab -6.°

▓ Detab -6.°, Da 20.°

▥ Detab -6.°, Da 20.°, Tlev reduced then increased

Figure 3.2: Recovery Spectrum--C-130 Elevator Jam Failures During Cruise at 147 KIAS, 1000'
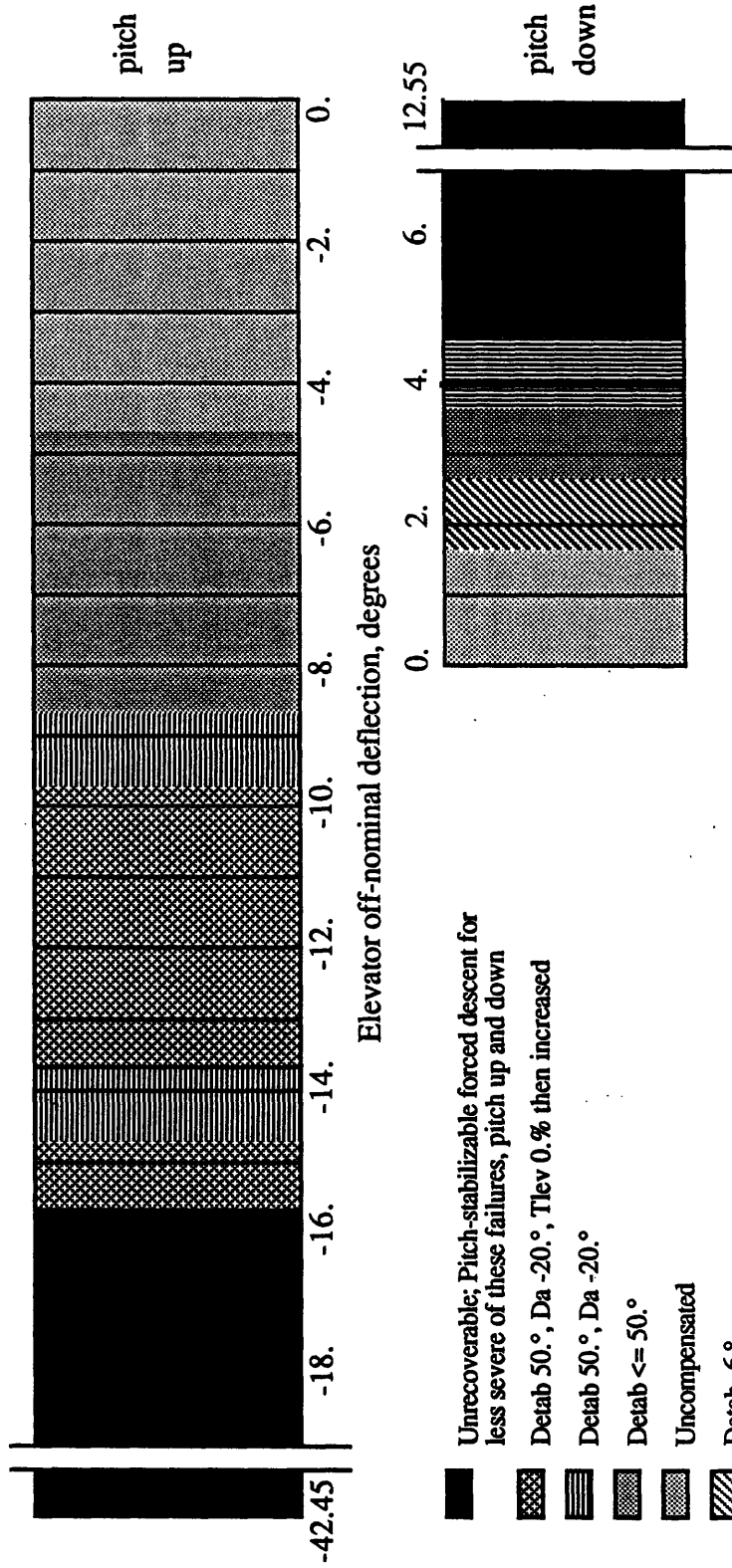
Figure 3.3: Recovery Spectrum--C-130 Elevator Jam Failures During Ascent, 173 KIAS, 7000'
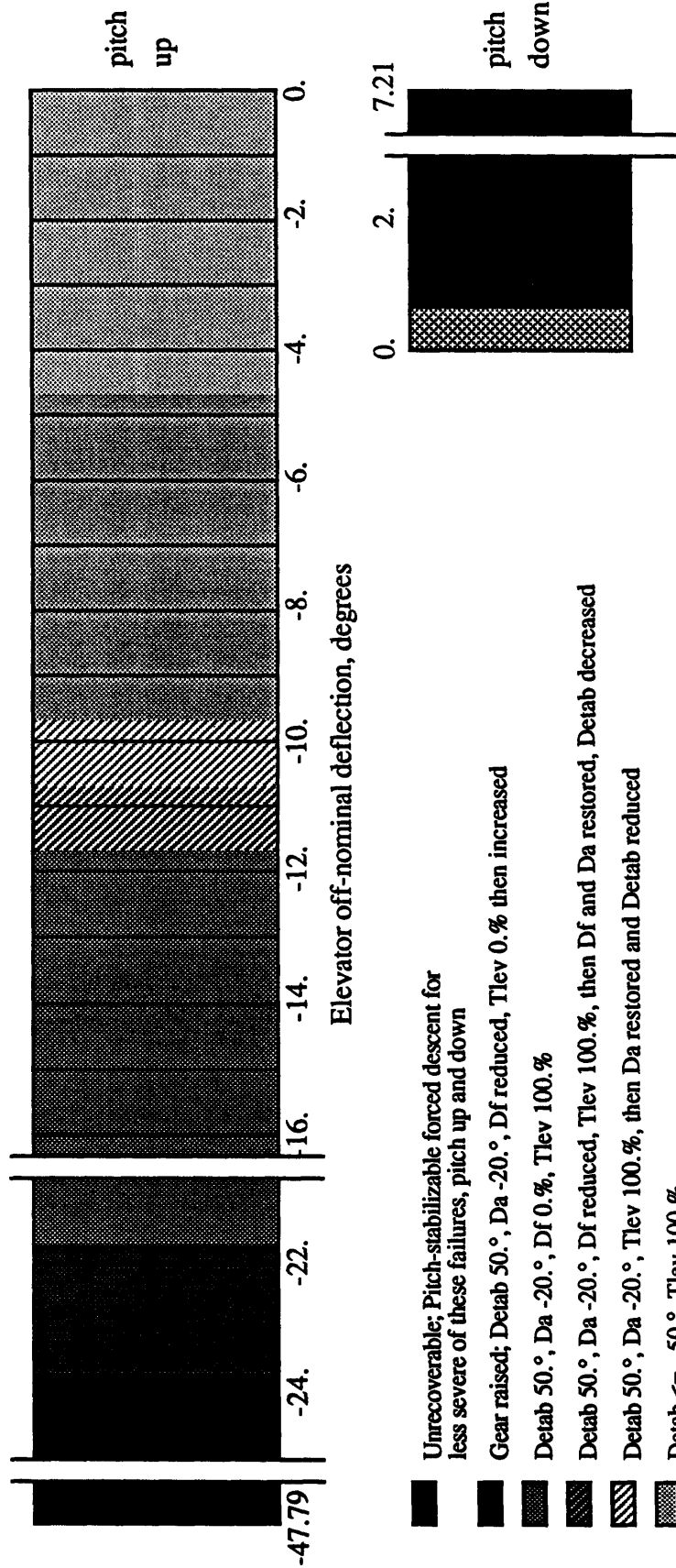
Elevator off-nominal deflection, degrees

Legend:
- Unrecoverable; Pitch-stabilizable forced descent for less severe of these failures, pitch up and down
- Detab 50.°, Da -20.°, Tlev 0.% then increased
- Detab 50.°, Da -20.°
- Detab <= 50.°
- Uncompensated
- Detab -6.°
- Detab -6.°, Da 20.°
- Detab -6.°, Da 20.°, Df deployed, Tlev 0.% then increased

Elevator off-nominal deflection, degrees

pitch up

pitch down

-47.79   -24.   -22.   -16.   -14.   -12.   -10.   -8.   -6.   -4.   -2.   0.

0.   2.   7.21

Unrecoverable; Pitch-stabilizable forced descent for less severe of these failures, pitch up and down

Gear raised; Detab 50.°, Da -20.°, Df reduced, Tlev 0.% then increased

Detab 50.°, Da -20.°, Df 0.%, Tlev 100.%

Detab 50.°, Da -20.°, Df reduced, Tlev 100.%, then Df and Da restored, Detab decreased

Detab 50.°, Da -20.°, Tlev 100.%, then Da restored and Detab reduced

Detab <= 50.°, Tlev 100.%

Tlev 100.%

Landing gear left down, Detab -6.°, Da 20.°, Df increased, Tlev increased; gear then raised

Figure 3.4: Recovery Spectrum--C-130 Elevator Jam Failures During Descent, 145 KIAS, 4000'

suggests strongly the sensitivity of the dynamics of this aircraft to changes in the control strategy.

3.3.4. Discussion of the Implementation

The rules to be used in the recovery strategy-finding expert system were written in a very commonly used rule-based system language, OPS5 [38]. OPS5 is a high-level expert system "shell," grounded in Lisp. It is one of a small number of general-purpose production system languages available--general-purpose as opposed to those languages more immediately suited for specific types of reasoning, like classification, diagnosis or learning, none of which seeming better suited for the problem at hand here. OPS5 is a mature language and is efficient (it has the admirable efficient Rete rule-matching algorithm in the inference engine). Because of its easy and widespread availability, it has been used to implement many expert systems, some moderately large. OPS5 has a flexible control system that allows immediate forward-chaining inference, but for which other types of problem-solving, namely backward-chaining, have to be explicitly programmed when desired. As the expert system here was written, however, there was no need for backward-chaining. Through the experience gained in manual recoveries of the aircraft, the system is all forward. The implementation was an OPS5 version for personal computer [40], with some programming in the supporting Lisp language [41].

The following is the briefest of tutorials in OPS5. Suppose that one wants to include the following rule in the rule-based system:

IF
the elevator failure is a pitch-down failure, and
the emergency strategy simulated does not include elevator tab usage, and
the simulation showed that the failure-induced pitching is not compensated for

THEN
try hardover elevator tab deflection to -6° [its maximum pitch-up setting].

Expressing this in OPS5, the core of a rule to effect this change in control in the expert system that was developed was written

```
(p Pitch-down::Uncompensated:too-much-pitch-down
 (Elevator-off-nominal-deflection ^ value {<v> > 0.})
 (Recovery-control ^ elevtab nil)
 (Sim-results ^ pitch-compensated no)
 -->
 (modify 2 ^ elevtab -6.))
```

The first line here gives the rule name ("p" indicates via a Lisp macro that this is a rule, or "production"), and the next three lines are condition statements to be matched against working memory. The clearly right-hand-side "modify" statement directs an (implementation-dependent) change in working memory, to wit, that the control strategy, the second working memory element matched on the left-hand-side of the rule, is now (hardover) elevator tab deflection to -6.°

To use this rule, one must first have declared the working memory objects permitted in the system, as in the following OPS5 "literalize" statements:

(literalize Elevator-off-nominal-deflection value)
(literalize Recovery-control aileron flap tlever elevtab)
(literalize Sim-results pitch-compensated aircraft-stabilized pitch-overcompensated...)

The working memory element headed "Recovery-control," for example, will have "attributes" or slots named "aileron", "flap", "tlever", and "elevtab." In general, attributes can be assigned values that are numbers or character strings.

In the rule given above, the symbol <v> indicates a temporary binding of a local variable (in the Lisp sense) to the value of the "value" attribute of the working memory object "Elevator-off-nominal-deflection." There is also a test that this number be positive, indicating that the failure must be a pitch-down failure.

The rule above would be "instantiated"--matched--by the system if working memory contained, for example, the following facts:

(Elevator-off-nominal-deflection ^ value 5.)
(Recovery-control ^ elevtab nil)
(Sim-results ^ pitch-compensated no)

The carat leads the attribute whose value follows the attribute name. The first of these facts could have been created in working memory by the command

(make Elevator-off-nominal-deflection ^ value 5.)

and the others similarly. This fact could similarly be deleted from working memory with the OPS5 "remove" command. Whether the rule above would actually fire once instantiated would depend, of course, on what other rules were also instantiated by working memory, and the production system's control strategy.

OPS5 code is quite readable and fairly easily written, and the brief treatment just given should suffice for reading the code for the system developed in this thesis, included in Appendix V. The rules that constitute this expert system are quickly compiled with the personal computer. One could dramatically reduce the actual number of rules via high-level

Lisp programming in the system, but this system runs fairly quickly as is. Using the rule format for certain processing steps, as in the rule just discussed, was not necessary, although it was natural enough to use throughout. Coding the basic inferences would have required only a small fraction of this number of rules. With this personal computer implementation, there is at most a couple of seconds of delay between user response to system queries about the results of the simulation and the next question or next suggested strategy. The OPS5-based system to guide discovery of successful initial post-failure control is practical and easy to use. It should be noted that, in general, production systems can be used for modular-type preliminary development of systems in which strong sequencing eventually develops, and thus for which an alternate type of programming is used for final implementation.

3.3.5. Overview of Rules in the Expert System

The expert system was written such that the process of finding a recovery started from scratch for each case. This was easy enough compared with interpolating or extrapolating from a data base of recoveries for other cases. The initial input consisted of the settings of the functioning controls at the time of failure and whether the failure was a pitch-up or pitch-down jam.

All of the termination guidelines of the system and all of the queries about the response (which assumed termination according to the guidelines) were designed to be automated. No imprecise "judgment" is required about the response. This was done in furtherance of the idea of a system that could automatically sweep a wide range of failure cases, and via this broad survey make generalizations about successful recovery strategies. With this one comes to the idea of a "simulation-demon," which could automatically terminate the simulation when the aircraft response looks "bad" according to empirical guidelines. An example for use with this particular system would be a test on whether the pitch was exceeding 111° with a pitch-up failure. These guidelines could become much more elaborate, though, if speed were of the essence.

The heart of this system is formed by the network of rules making inferences on the basis of the response of the aircraft to the trial control strategy. Ultimately the system decides between three options: the aircraft stabilized successfully, or the failure-induced disturbance was initially under-opposed or over-opposed. The following system rule is illustrative:

**IF failure was pitch down and pitch rate crosses zero but
later decreases below its first minimum
THEN the failure was under-compensated**

One of the interesting things about the expert system as it finally developed was that the same types of expert system criteria were applicable in determining under- or over-compensation regardless of which controls had already been deployed. The system was concerned with the potential pitch-moment resources of the controls and could ignore, in large measure, their artifact. When the system was "undercompensated," the next pitch-moment-producing control in the hierarchy was applied.

It was found through this study that it is important, given the sensitivity of this system, to try every possible means of saving the aircraft, but it was not ultimately difficult to decide when a failure situation was truly hopeless. The system developed for this thesis does give up at times, with an explanation.

There is plenty of heuristic reasoning embedded in these rules, although it became more implicit in the final system because of the initial work with manual recoveries. For the same reason, there was no need for explicit meta-level mediating among system rules. The expert system was built up incrementally as each manual recovery was made. System changes were made as cases were encountered for which the system could not find the successful recovery.

There can be no question that this expert system has been extensively tailored for the C-130 aircraft. This tailoring has allowed various important simplifications of the problems involved in finding emergency post-failure control. There was the choice of hierarchy in which controls would be tried (i.e., elevator tab alone before collective aileron would be added, and so on), and consideration of what was primary under- or overcompensation could be simplified by looking at rather simple types of features in the response. The expert system also takes advantage of the highly oscillatory uncompensated longitudinal response of this aircraft--the rules ask simply about zero-*crossings* of various aircraft states in the response to the trial control strategy, for example.

One of the appealing things about this system, as written, is that it is insensitive to specifics about initial condition or FDI delay. If there were an autopilot loop still engaged, it could also work independent of what the autopilot was doing during the recovery. It works off the response only.

It should be clear that, without thrust increases, the airspeed at which the aircraft stabilizes in a recovery may be fairly low in some cases, depending, of course, on the initial condition of flight and the severity of the failure. This airspeed could be below "maneuvering" airspeed, or below optimal climb airspeed, or perhaps not far from stall airspeed, in which case a small increase in pitch later (perhaps introduced by a pilot

confronted with an obstacle ahead) might lead to severe problems. There are a couple of reasons why low airspeed during the initial period of stabilization could be unavoidable:

--Thrust usage--including throttling back completely--can be very important in the primary pitch recovery of the aircraft, as will be seen.

--The need to *minimize altitude loss during a recovery* may be expected often to eclipse completely any concerns about recovering airspeed.

But it is clear that, once a recovery strategy that gives pitch stabilization with acceptably low altitude loss is established, there will come a point at which thrust increase or other adjustments are appropriate. It was elected to let later airspeed adjustments beyond achieving an airspeed above stall be beyond the time horizon of interest. At some point in post-failure flight, the authority for flying the aircraft would be returned to the pilot. At that point (judging from work with the C-130, about a minute after the failure, and the time at which stabilization was certain), the thrust increases for increasing airspeed would be appropriate. Then the pilot, preferably in combination with reconfigured automatic control because one may lose pitch stabilization with the thrust changes, could make them. One minute seems quite a bit of time for reconfiguring the automatic control.

The system rules are most easily introduced through failure case examples, as follow.

3.3.6. Examples of Usage of the Rule-Based System

In formulating the knowledge required to find recovery control in *rules*, it is inherent that the processing paths not be explicitly established before the data is given. Given the number of rules in the system developed for this thesis, there are numerous possible combinations of fired rules. Only a few will be represented in the example cases here. The following examples illustrate successively more involved recovery strategies, obliged by generally more strenuous failures. The totality of rules established for the thesis, and as listed in Appendix V, gives solutions to all degrees of elevator failure to a uniform level, even though not all different types of cases that the system can find a control for will be illustrated. The rules themselves were given very descriptive names in order to invite readers to evaluate the capabilities of the total system by looking at the OPS5 code. The core rules will be introduced and discussed in the context of applicable examples below.

The interface between this system and the user might go as indicated in the following output. In all cases, this output has come directly from actual system usage. The user-supplied answers to questions asked by the expert system are shown in italics. It should be kept in mind that answering any of the questions required no imprecise judgment, and that

the successful strategies could now be found by the expert system interacting directly with the simulation, sim-demon, and looking for objective features of the aircraft response to a given trial control strategy.

3.3.6.1. -4° Off-Nominal Elevator Jam (Pitch Up) During Ascent, at 7000'

Compensation: None necessary

With elevator jams not far off-nominal, the aircraft can recover to stabilized flight without control changes. Figure 3.5 shows the expert system output evaluating the uncompensated response of the C-130 to a -4° off-nominal jam during ascent. The response is shown in Figure 3.6. In the figures showing the aircraft response, the longitudinal control inputs are shown on the left, and, on the right, the longitudinal states--indicated airspeed, angle of attack, pitch rate and pitch angle, and altitude and altitude rate. In Figure 3.6, the aircraft was clearly pitch-stabilizing in a climb. Inquiring about this response, the first question asked by the expert system (highlighted in Figure 3.5) reflects the widest test for under-compensating initial emergency control--whether pitch rate is ever reversed and crosses zero. If it does not, then one has a looping aircraft. Once it has been established that pitch rate was brought to zero, the system asks whether the aircraft has stabilized and in non-descent. In this case, the uncompensated response was acceptable.

This aircraft's inherent lightly damped longitudinal response is clear here, and the response would not be comfortable for the aircraft crew. As seen in the spectra, Figures 3.1-3.4, 4° off-nominal pitch-up is approximately the largest failure that could be recovered from for any of the initial conditions considered without explicit compensation

```
;
;The aduisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft----------------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.------------------------------------
;End -- no production true
;
;(63 productions (533 // 1360 nodes))
;(6 firings (21 RHS actions))
;(9. Mean working memory size (9 maximum))
;(1. mean conflict set size (2 maximum))
;(26. mean token memory size (37 maximum))
;(26. "mean token memory size" (37 "maximum"))
```

Figure 3.5: Interaction with Expert System, -4° Off-Nominal Elevator Jam, on Ascent, 173 KIAS

(Trial 1: Figure 3.6)

Figure 3.6

71
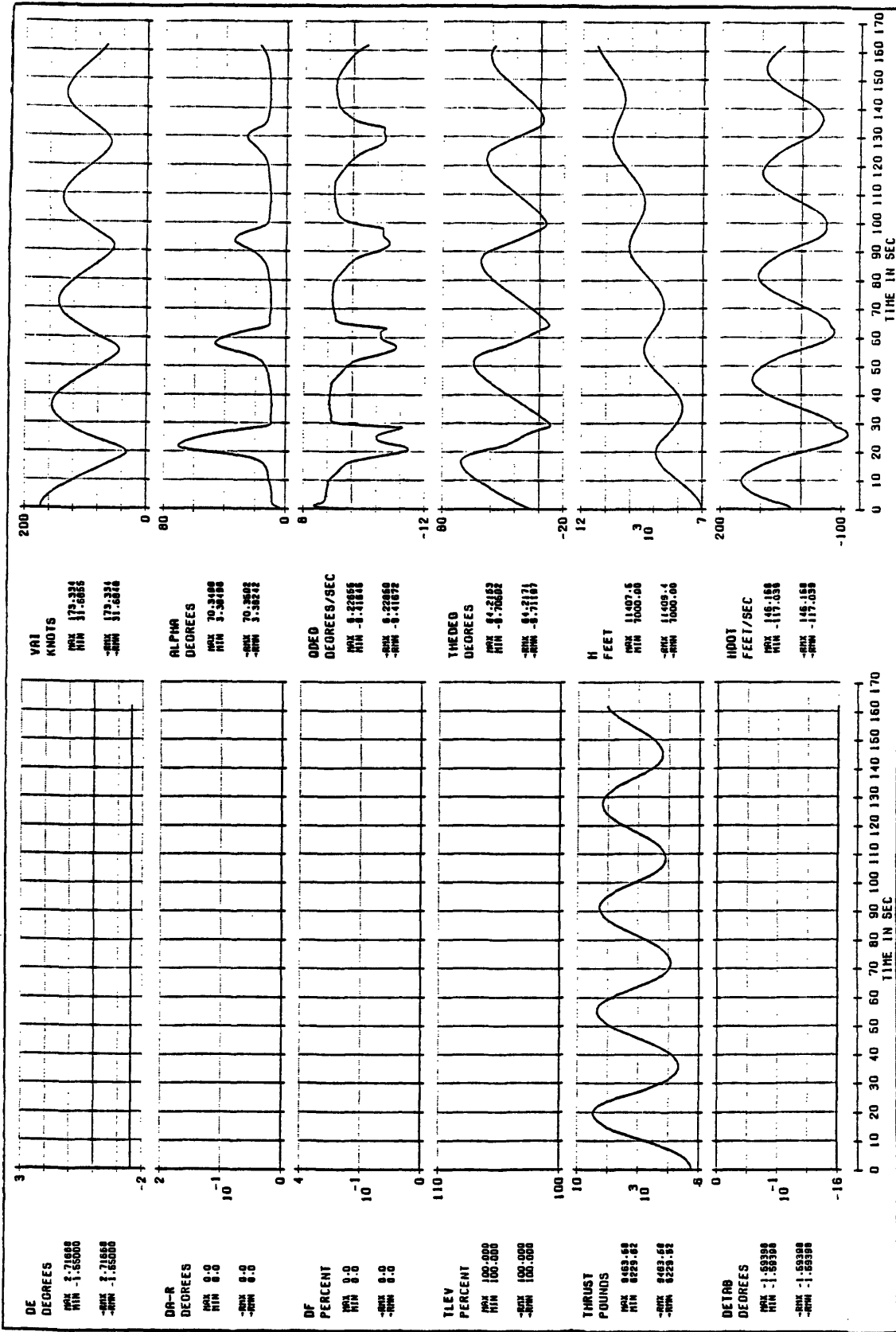
3.3.6.2. -9° Off-Nominal Elevator Jam (Pitch Up) During Ascent, at 7000'

Compensation: Hardover pitch down elevator tab and collective aileron deployment

Figure 3.7 is the output from expert system interaction guiding the emergency control strategy through three attempts to get to successful hardover pitch-down deployment of the first two controls in the hierarchy. When the failure goes unopposed in this case (Figure 3.8a shows the response), the pitch rate is never neutralized. Hardover pitch-down elevator tab deployment is then suggested (aircraft response to this control is shown in Figure 3.8b). Another general test for undercompensation comes into play when this response was evaluated. The test highlighted in the output reflects the observation that no case for which pitch angle exceeded 111.° (aircraft well looped) was ever found to be recoverable. The simulation was terminated after the aircraft exceeded this value. The expert system concludes that more pitch down control must be brought to bear, and hardover collective aileron deployment was added. Figure 3.8c shows that this gives a successful recovery. Use of collective ailerons on this aircraft *can* provide significant help in an emergency. Since even hardover collective ailerons cannot provide very much pitch moment, however, their usefulness when deployed with elevator tab almost certainly indicates their use is in a stopgap role, while the trim surface slowly deploys. The elevator tab deploys only 2 deg./sec., so full deployment can take on the order of almost half a minute from typical initial deployment.

```
;
;The advisory is beginning.
;The simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft-----------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?                                   (Trial 1: Figure 3.8a)
no
;
;Try the addition of immediate hardover elevator tab---------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?                                   (Trial 2: Figure 3.8b)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Add immediate hardover collective aileron deflection-------------------------------
;to -20. deg.
;Did pitch rate ever cross zero?                                   (Trial 3: Figure 3.8c)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.-------------------------------------
;End -- no production true
;
;(63  productions (533 // 1360  nodes))
;(14 firings (45 RHS actions))
;(9. Mean working memory size (9  maximum))
;(1. mean conflict set size (2 maximum))
;(29. mean token memory size (41 maximum))
;(29. "mean token memory size" (41 "maximum"))
```

Figure 3.7: Interaction with Expert Eystem, -9° Off-Nominal Elevator Jam, on Ascent, 173 KIAS

Figure 3.8a

74

Figure 3.8b

75

Figure 3.8c

76
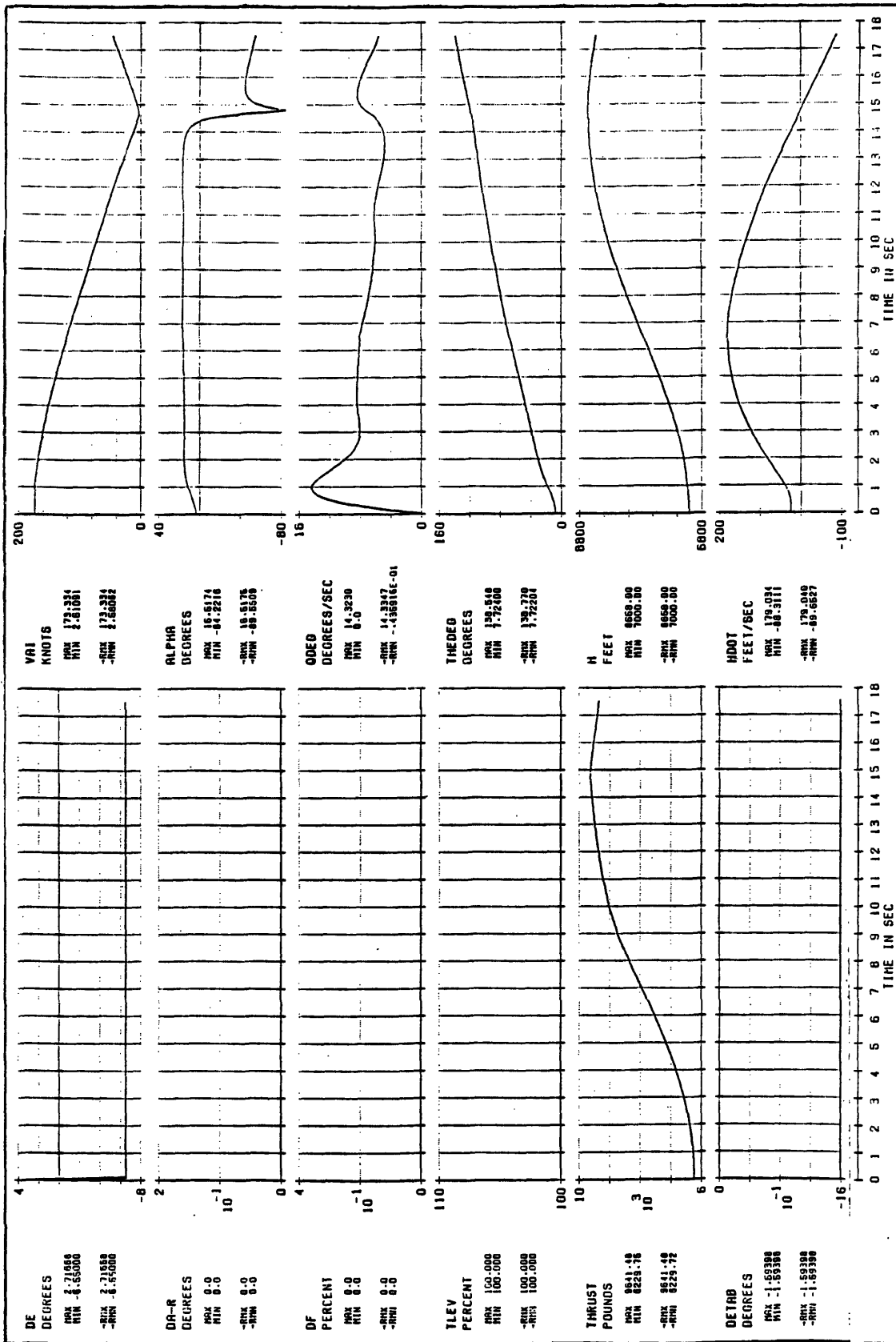
3.3.6.3. Concerning Stall Recovery During Recovery from Pitch-up Elevator Jam Failures

Determining whether a pitch-up failure is under- or over-compensated involves, for all but the least strenuous failures, seeing whether the precondition of adequate recovery from stall has been fulfilled. Figure 3.8c, from the last example case, illustrates a good stall recovery, induced in that case by the use of hardover elevator tab and collective aileron. There are several distinct features in this response that were common in all cases in which there was ultimately successful recovery from a large pitch-up failure.

Good stall recovery required pitch down to reduce angle of attack below approximately 25°. At about the point this level is crossed, pitch rate reached a minimum and began to increase rapidly. For the C-130, this pitch rate "break" occurs without any change from pitch down to pitch up control being required. In order that the aircraft be fully recovered from the pitch down associated with initial stall recovery, after this pitch rate minimization the aircraft pitch rate must reverse significantly--pitch rate must become positive, and such that the aircraft attains a non-descent state--that is, positive flight path angle.

Across all of the cases considered in this study, pitch down compensation was adequate for ultimate recovery when

--angle of attack remained below or decreased through 25.°

--pitch rate minimized within five seconds after angle of attack decreased through this level

Initial pitch down compensation could always be judged *excessive* when pitch rate did not re-cross zero after this minimization. Failure of flight path angle to regain a positive value after pitch rate broke to become positive could in all cases be taken to indicate a need for delayed control switching to reduce the pitch down control from its initial deployment. This switch could always successfully be made at the time at which pitch rate minimized. The expert system directly incorporates tests and recommendations based on these observations, as will be seen in the following cases.

3.3.6.4: -8° Off-Nominal Elevator Jam (Pitch Up) During Ascent, at 7000'

Compensation: Less than hardover pitch down elevator tab deployment

The rule-based system developed for this thesis has the capability of interpolating in initial deployments of a given control after it has bracketed between too little and too much deployment. In this example case, the aircraft looped when no failure compensation was applied. Hardover pitch-down elevator tab deployment represented too much pitch down control, however. Figure 3.9 indicates that the expert system concludes pitch-overcompensation on the basis of non-recovery of pitch rate, after undercompensation has been ruled out. The questions of interest here--all concerning stall recovery--are highlighted in the output; the answers are based on the response in Figure 3.10a. The expert system then proposed half as much initial deflection of the elevator tab. Figure 3.10b shows that the aircraft looped with this strategy, always a sign of under-compensation. Three-quarters of the hardover deployment was then suggested, and this strategy led to a successful recovery, as Figure 3.10c illustrates.

Whenever the system interpolates, it has already determined an interval in which the last control in the hierarchy can be expected to be set in order to have a successful strategy. In the absence of better (wiser) sensitivity information, interpolation was done on the basis of successive halving of the interval.

;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft----------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?   (Trial 1)
no

;
;Try the addition of immediate hardover elevator tab---------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?   (Trial 2: Figure 3.10a)
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes

;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes

;
;Did angle of attack remain below 25. deg.-or-
;if angle of attack ever exceeded this level did
;pitch rate reach a minimum before the end of the
;simulation and within 5. seconds after angle of
;attack last decreased through 25. deg.?
yes

;
;Did pitch rate cross back from negative to positive
;if angle-of-attack remained below 25. deg. or after
;angle-of-attack last decreased through 25. deg.?
no

;
;Try immediate hardover elevator tab deflection to---------------------------------
;24.203 deg.
;Did pitch rate ever cross zero?   (Trial 3: Figure 3.10b)
yes

Figure 3.9: Interaction with Expert System, -8° Off-Nominal Elevator Jam, on Ascent, 173 KIAS

```
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Try hardover elevator tab deflection to 37.1015  deg.--------------------------------
;Did pitch rate ever cross zero?
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.------------------------------------
;End -- no production true
;
;(63  productions (535  // 1388  nodes))
;(60  firings (205  RHS  actions))
;(9.  Mean working memory size (9  maximum))
;(1.  mean conflict set size (2  maximum))
;(28.  mean token memory size (43  maximum))
;(28.  "mean token memory size" (43  "maximum"))
```
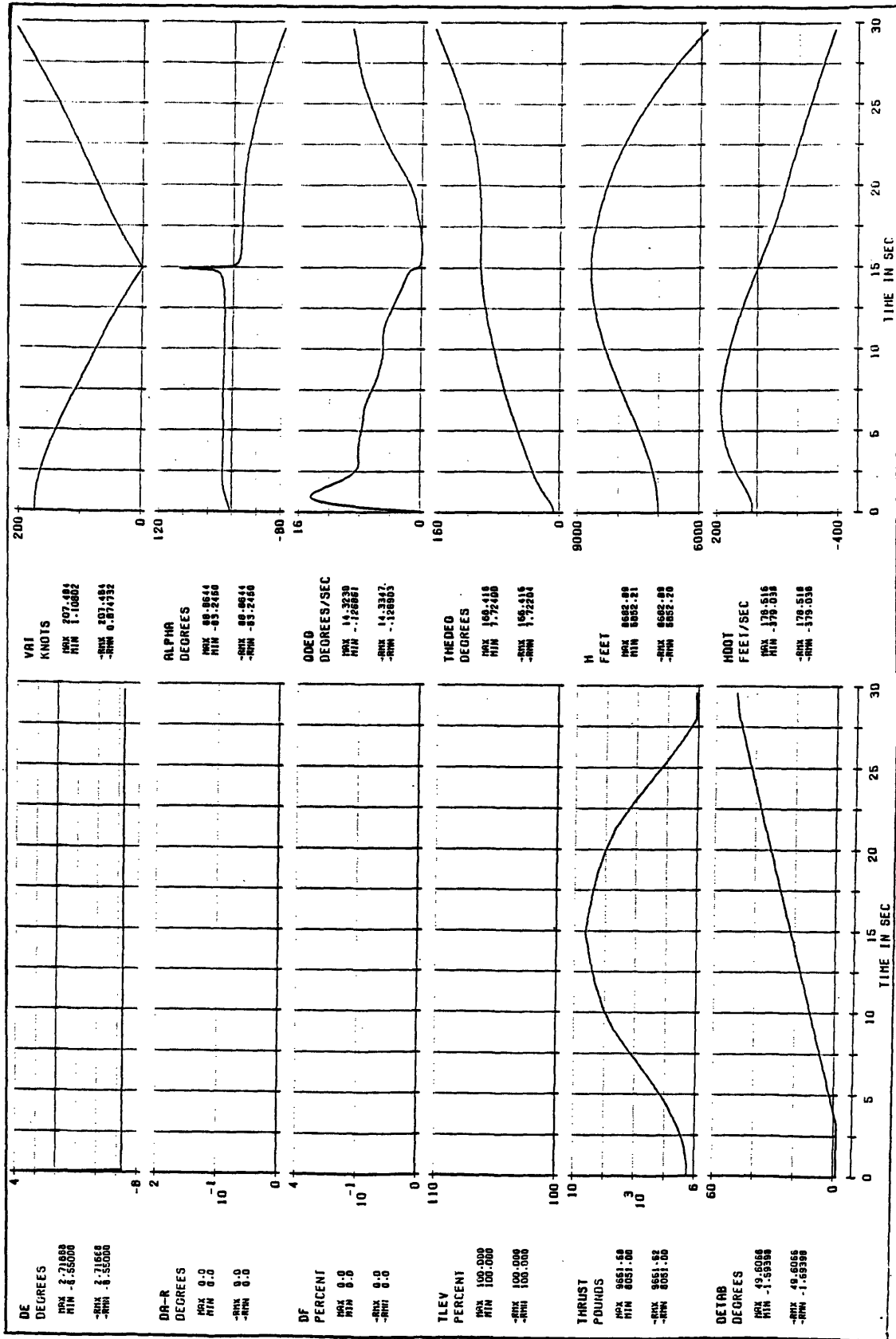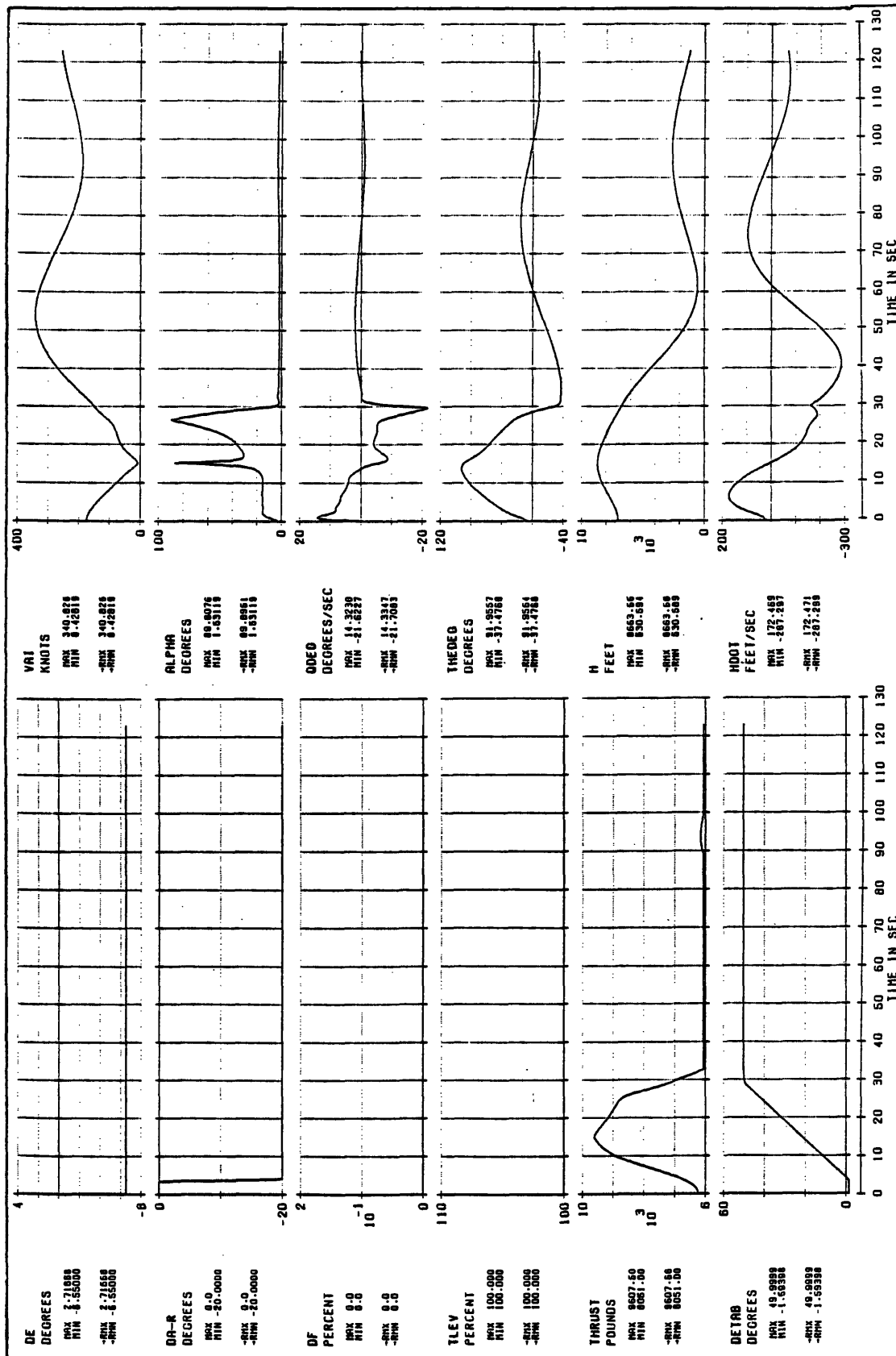
Figure 3.9, cont'd

(Trial 4: Figure 3.10c)
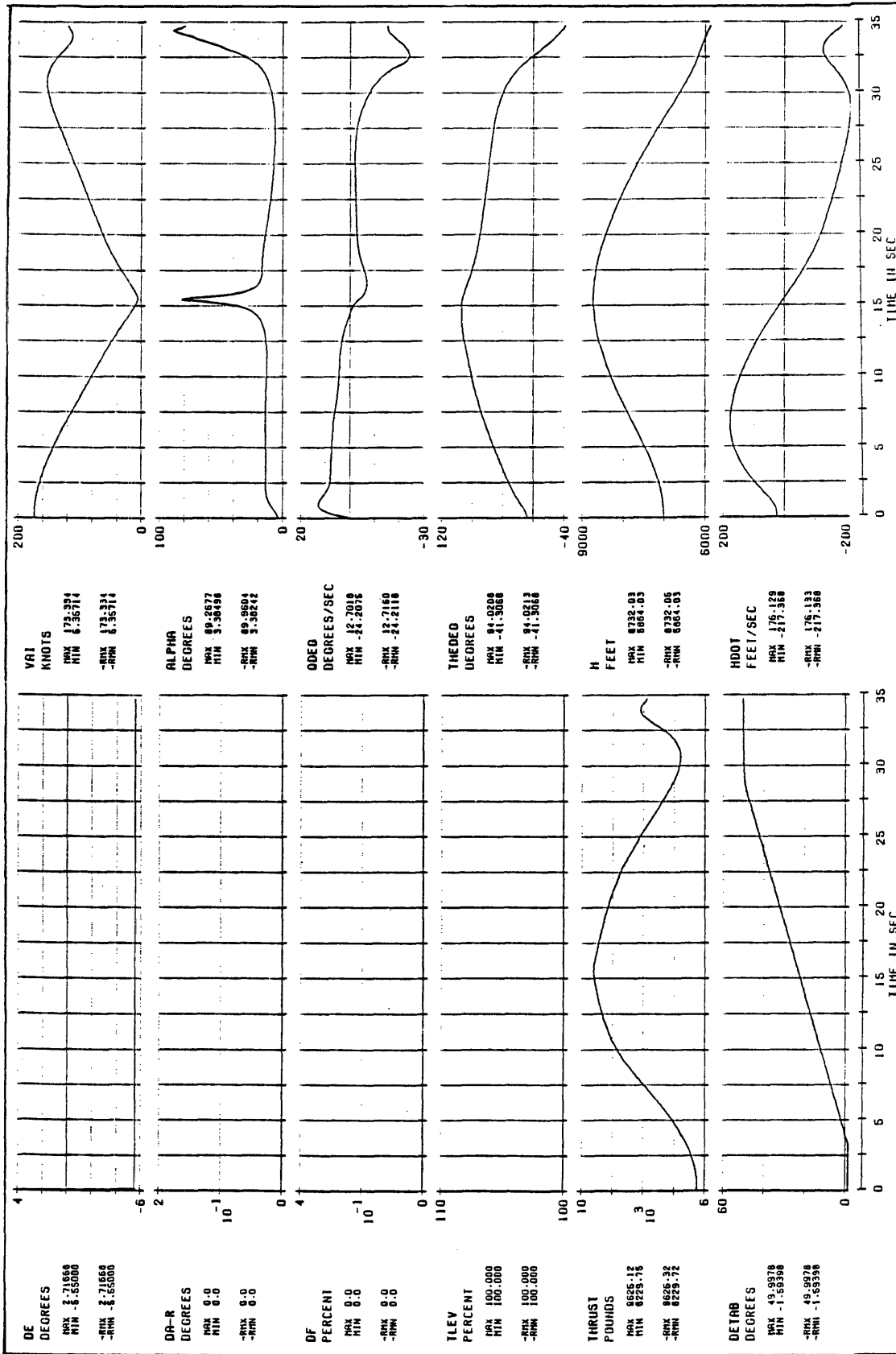
Figure 3.10a

Figure 3.10b

82

Figure 3.10c

83
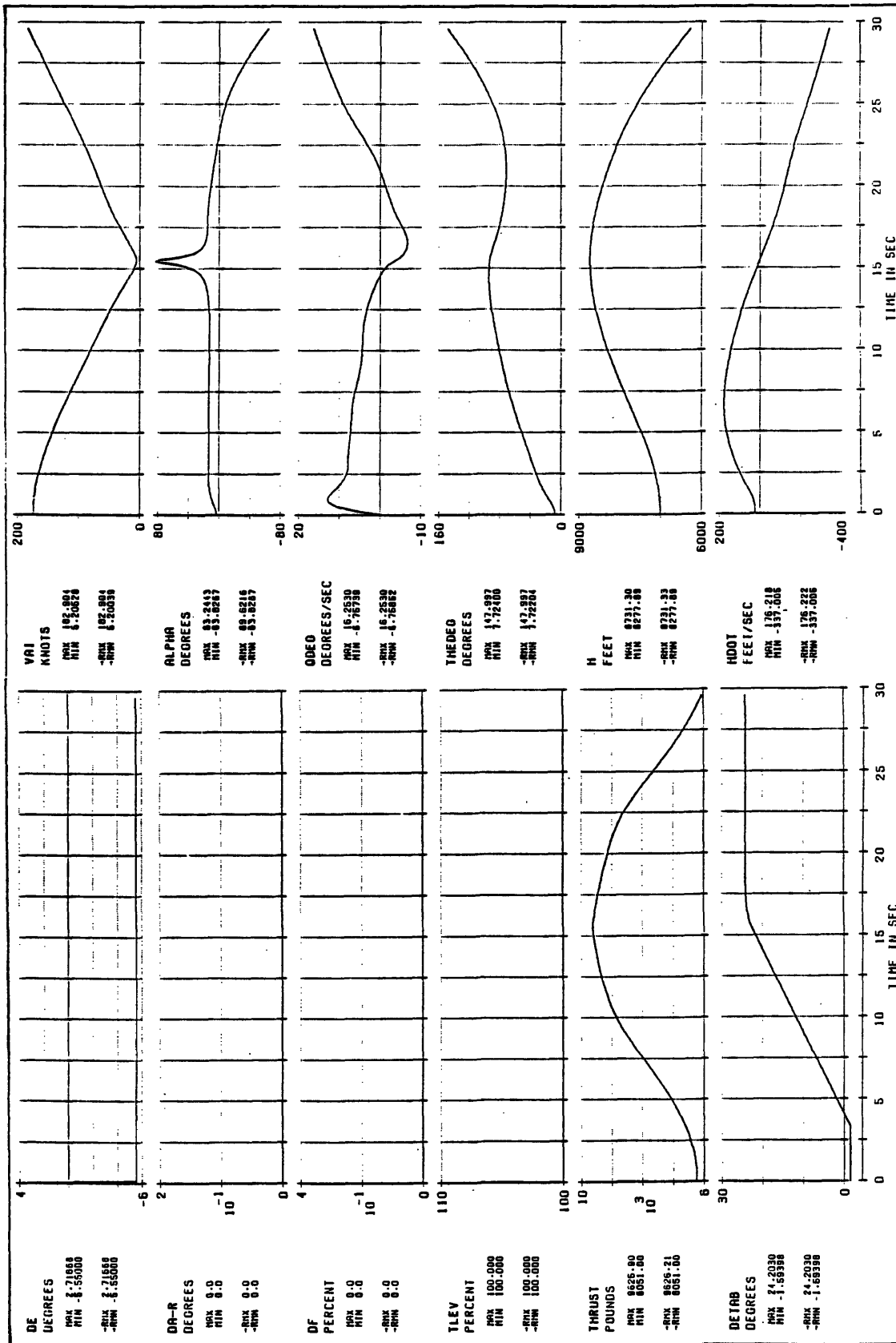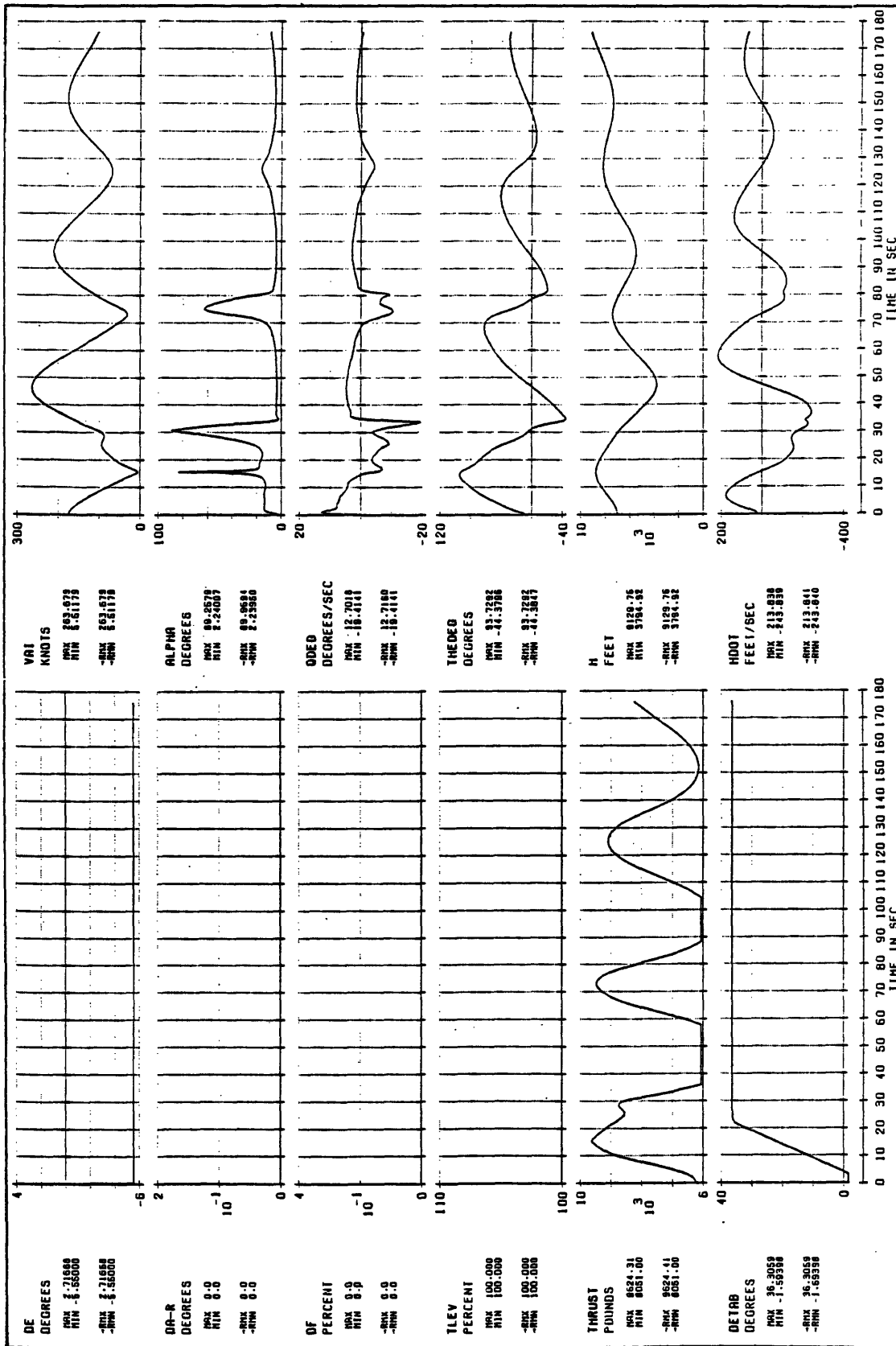
3.3.6.5. -9° Off-Nominal Elevator Jam (Pitch Up) During Flight at 147 KIAS at 1000', with 50% Flaps Deployed

Compensation: Hardover pitch down elevator tab and collective ailerons deployment, then both backed off

The expert system has the capability of interpolating on later control *un*deployment as well as on initial deployment. Figure 3.11 shows the expert system usage with this example case. The unaided aircraft looped with the failure. Hardover pitch-down elevator tab deployment led to an unusual-looking struggle with stall recovery. Figure 3.12a shows that angle of attack does decrease through 25° but that pitch rate does not display the characteristic minimization and break toward pitch up. Figure 3.12b shows a much more satisfying response after full pitch-down collective aileron was added. In order to get flight path angle to increase to a positive value and thus effect climb-out, aileron was backed off completely and then elevator tab, to an intermediate value. The highlighted exchange in the transcript points to the surmisal and recommendation that some pitch down should be relieved after pitch rate recovery. In all of the cases considered in this study, it was a winning strategy to first try reversing deployments to their initial values (although with some initial conditions one must consider reversing past these values), starting at the time at which pitch rate minimized. Three additional iterations (Figures 3.12c, d, and e) were required before the successful intermediate elevator tab deployment was found (Figure 3.12f). The interpolation on these undeployments proceeded on the basis of familiar criteria on looping and on recovery of flight path angle.

As other reasons arise for changing control setting later in the recovery, one can trust that there will be similar heuristic- (and, as implemented, rule-) based ways of bracketing, at least, the time for changing the setting. Once the time interval for likely needed changes is identified, one could always interpolate via successive halving of the time interval, if other guidelines lack (even if one can do no better than subdividing the total sim time span). One of the unexpected but fortunate things about finding a workable strategy for recovering this aircraft after elevator failures is that in no case was more than one control change point indicated. There is indeed a large capture region for the stabilized state. The number of control switch points could be much greater for a more control-bound aircraft.

;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft--
;can recover on its own.
;Did pitch rate ever cross zero?   (Trial 1)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Try the addition of immediate hardover elevator tab--------------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?   (Trial 2: Figure 3.12a)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes
;
;Did angle of attack remain below 25. deg.-or-
;if angle of attack ever exceeded this level did
;pitch rate reach a minimum before the end of the
;simulation and within 5. seconds after angle of
;attack last decreased through 25. deg.?
no
;
;Add immediate hardover collective aileron deflection------------------------------
;to -20. deg.
;Did pitch rate ever cross zero?   (Trial 3: Figure 3.12b)

Figure 3.11: Interaction with Expert System, -9° Off-Nominal Elevator Jam, Flying at 147 KIAS

yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes
;
;Did angle of attack remain below 25. deg.-or-
;if angle of attack ever exceeded this level did
;pitch rate reach a minimum before the end of the
;simulation and within 5. seconds after angle of
;attack last decreased through 25. deg.?
yes
;
;Did pitch rate cross back from negative to positive
;if angle-of-attack remained below 25. deg. or after
;angle-of-attack last decreased through 25. deg.?
yes
;
;Did flight path angle remain positive in the initial
;stall recovery-or-if it was negative at some point
;did it later cross from negative to positive?
no
;
;Backing off on the last pitch-down input later
;should be tried. In the last simulation
;if pitch rate achieved a
;minimum after angle of attack decreased to 25. deg.
;state the time in seconds that this minimum
;occurred. Otherwise state the time at which angle
;of attack decreased through 25. deg. If angle of
;attack never exceeded 25. deg. state the time at
;which pitch rate was minimized for the entire run.
28.
;
;Back off collective aileron hardover to 0. deg. at--
;28. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally

(Trial 4: Figure 3.12c)

```
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes

;
;Did flight path angle remain positive in the initial
;stall recovery-or-if it was negative at some point
;did it later cross from negative to positive?
no

;
;Back off elevator tab hardover to 3.65  deg. at-------------------------------------
; 28. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch angle remain below 111.  deg.-and-if it did
;so but crossed 30.  deg. did it decrease and recross
;this level later?
no

;
;Back off elevator tab hardover to 26.825  deg. at------------------------------------
;28. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch angle remain below 111.  deg.-and-if it did
;so but crossed 30. .deg. did it decrease and recross
;this level later?
no

;
;Back off elevator tab hardover to 38.4125  deg. at----------------------------------
;28. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

;
;Was the aircraft settling into an apparent descent?
no

;
;A successful recovery strategy has been found.-----------------------------------
;End -- no production true

;
;(64  productions (560  // 1560  nodes))
;(286  firings (987  RHS actions))
;(10.  Mean working memory size (18  maximum))
;(1.  mean conflict set size (8  maximum))
;(36.  mean token memory size (207  maximum))
;(36.  "mean token memory size" (207  "maximum"))
```

(Trial 5: Figure 3.12d)

(Trial 6: Figure 3.12e)

(Trial 7: Figure 3.12f)

Figure 3.12a

88

Figure 3.12b

89

Figure 3.12c

90

Figure 3.12d

91

Figure 3.12e

92

Figure 3.12f

93
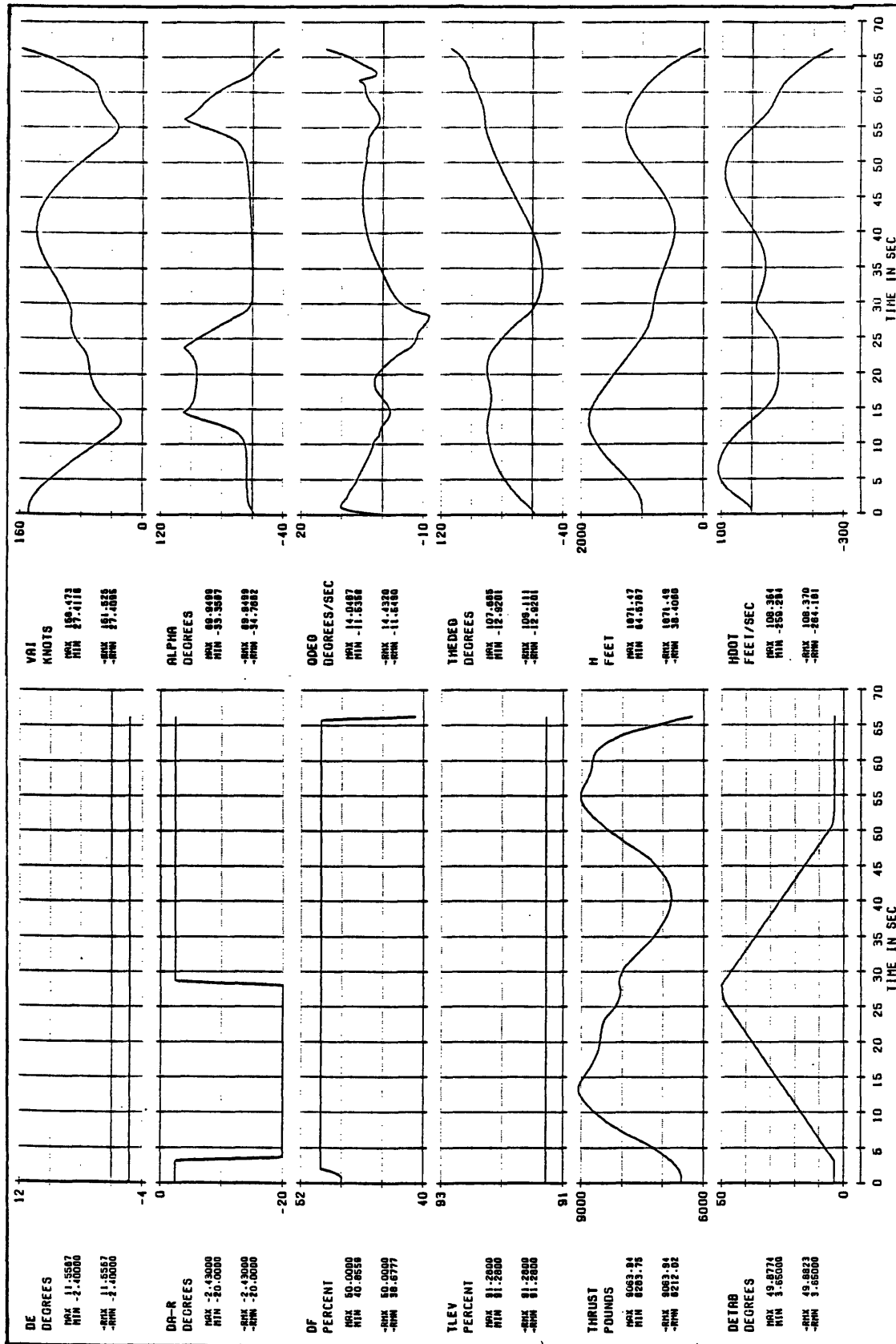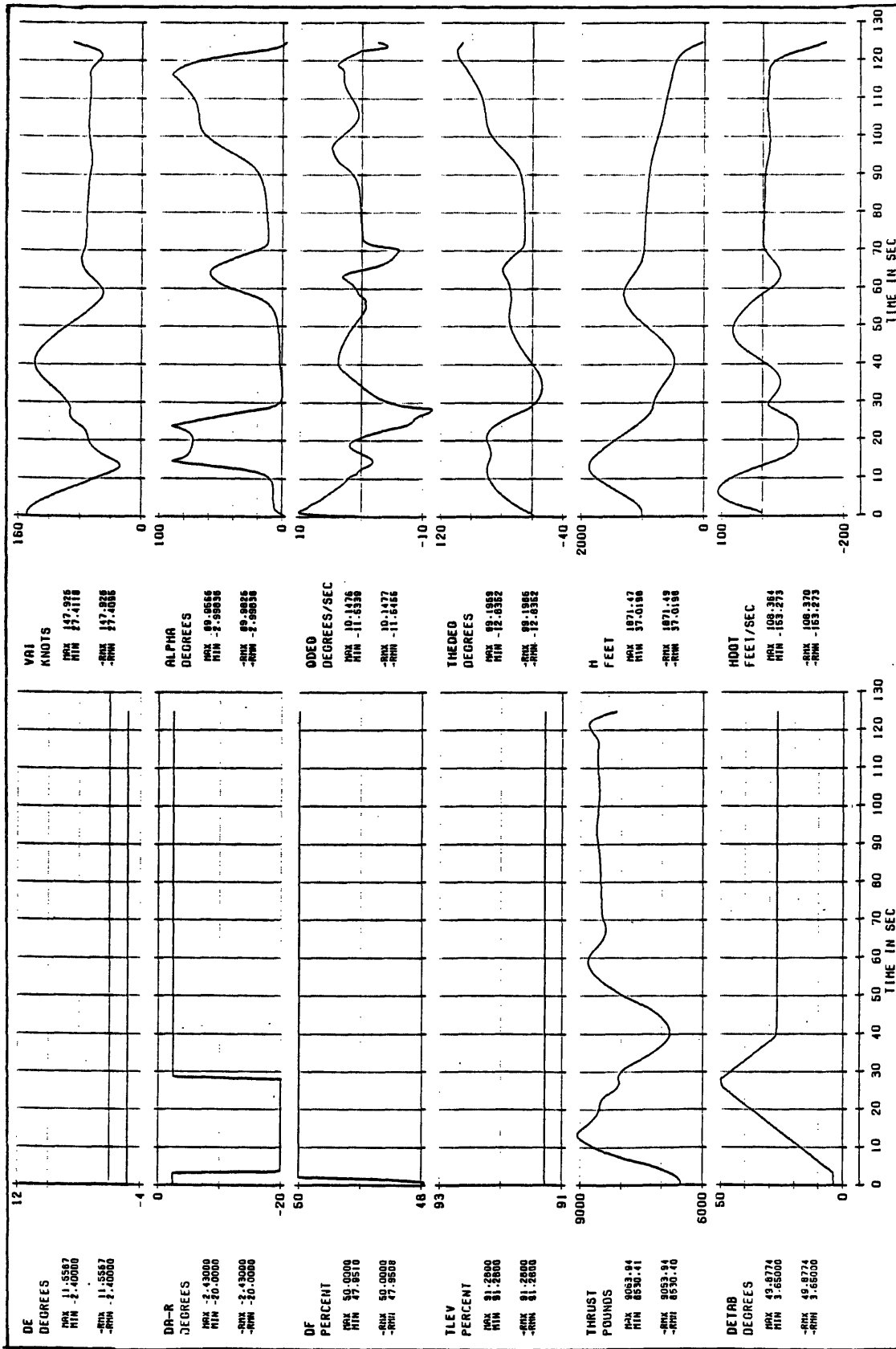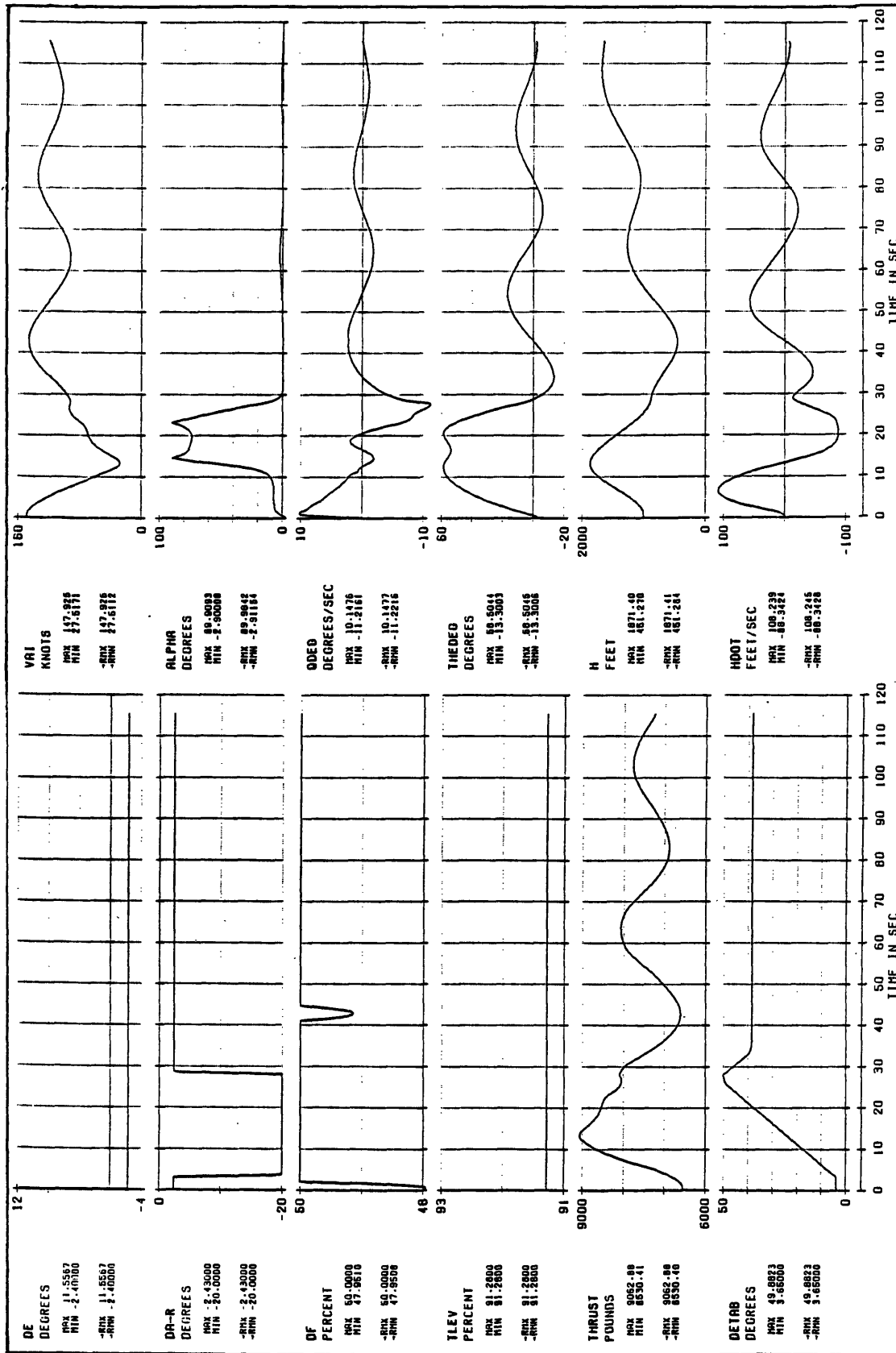
3.3.6.6. -12° Off-Nominal Elevator Jam (Pitch Up) During Flight at 147 KIAS at 1000', with 50% Flaps Deployed

Compensation: Hardover pitch down elevator tab and collective aileron deployment, flaps retracted somewhat then re-extended

In this case, hardover pitch-down elevator tab and collective aileron were insufficient to keep the aircraft from looping. The flaps had been extended, however, prior to the time of failure. Since retracting them would be a source of pitch-down moment, the expert system suggests full retraction of flaps next--see Figure 3.13, the transcript of interaction with the system. Figure 3.14a show the response of the aircraft to hardover pitch-down elevator tab, aileron, and flap retraction. The pitch rate did not recover to a positive value after its minimization and break, again general indication of initial overcompensation. The expert system suggests that the flaps be only halfway retracted, and Figure 3.14b shows the full pitch rate recovery. However, the pitch up in this case was still insufficient to facilitate the flight path angle reaching a positive value, and the aircraft soon impacted the ground. In this case (see Figures 3.14c and d), the re-extension of flaps had to be accompanied by full neutralization of collective ailerons in order to get successful recovery to stabilized ascent. The expert system uses the strategy of reversing controls in the order they were originally applied, although it might be considered preferable to reverse elevator tab deployment before the ailerons because of the larger pitch moment that it can provide.

```
;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft----------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?                                    (Trial 1)
no

;
;Try the addition of immediate hardover elevator tab-------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?                                    (Trial 2)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Add immediate hardover collective aileron deflection------------------------------
;to -20. deg.
;Did pitch rate ever cross zero?                                    (Trial 3)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Modify the last strategy to include immediate-------------------------------------
;hardover flap reduction to 0. %.
;Did pitch rate ever cross zero?                                    (Trial 4: Figure 3.14a)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
```

Figure 3.13: Interaction with Expert System, -12° Off-Nominal Elevator Jam, Flying at 147 KIAS

```
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes
;
;Did angle of attack remain below 25. deg.-or-
;if angle of attack ever exceeded this level did
;pitch rate reach a minimum before the end of the
;simulation and within 5. seconds after angle of
;attack last decreased through 25. deg.?
yes
;
;Did pitch rate cross back from negative to positive
;if angle-of-attack remained below 25. deg. or after
;angle-of-attack last decreased through 25. deg.?
no
;
;Try immediate hardover flap deployment to only----------------------------------
;25. %.
;Did pitch rate ever cross zero?
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes
;
;Did angle of attack remain below 25. deg.-or-
;if angle of attack ever exceeded this level did
;pitch rate reach a minimum before the end of the
;simulation and within 5. seconds after angle of
;attack last decreased through 25. deg.?
yes
;
;Did pitch rate cross back from negative to positive
;if angle-of-attack remained below 25. deg. or after
;angle-of-attack last decreased through 25. deg.?
yes
;
;Did flight path angle remain positive in the initial
;stall recovery-or-if it was negative at some point
;Did it later cross from negative to positive?
```

Figure 3.13, cont'd

(Trial 5: Figure 3.14b)

no

;
;Backing off on the last pitch-down Input later
;should be tried. In the last simulation
;If pitch rate achieved a
;minimum after angle of attack decreased to 25. deg.
;state the time In seconds that this minimum
;occurred. Otherwise state the time at which angle
;of attack decreased through 25. deg. If angle of
;attack never exceeded 25. deg. state the time at
;which pitch rate was minimized for the entire run.
24.

;
;Restore flap hardover to 50. % at 24. sec.---
;Was the aircraft stabilizing by our definition
;at the end of the sim?   (Trial 6: Figure 3.14c)
no

;
;Did pitch angle remain below 11.1. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes

;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
yes

;
;Did flight path angle remain positive In the Initial
;stall recovery-or-if it was negative at some point
;Did it later cross from negative to positive?
no

;
;Back off collective aileron hardover to 0 deg. at-----------------------------------
;24. sec.
;Was the aircraft stabilizing by our definition   (Trial 7: Figure 3.14d)
;at the end of the sim?
yes

;
;Was the aircraft settling Into an apparent descent?
no

;
;A successful recovery strategy has been found.------------------------------------
;End -- no production true

;
;(64 productions (537 // 1386 nodes))
;(43 firings (127 RHS actions))
;(9. Mean working memory size (9 maximum))
;(1. mean conflict set size (3 maximum))
;(32. mean token memory size (54 maximum))
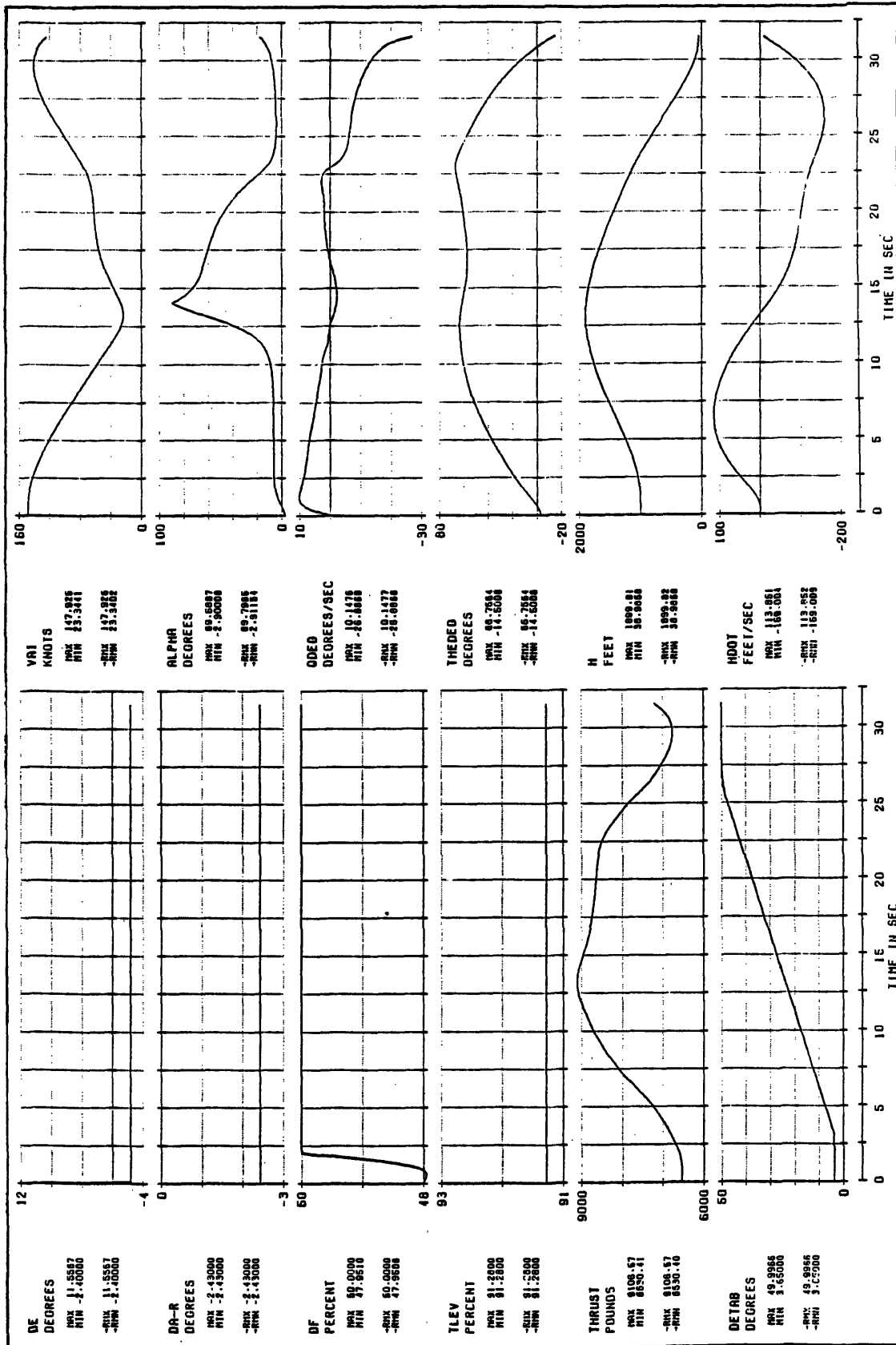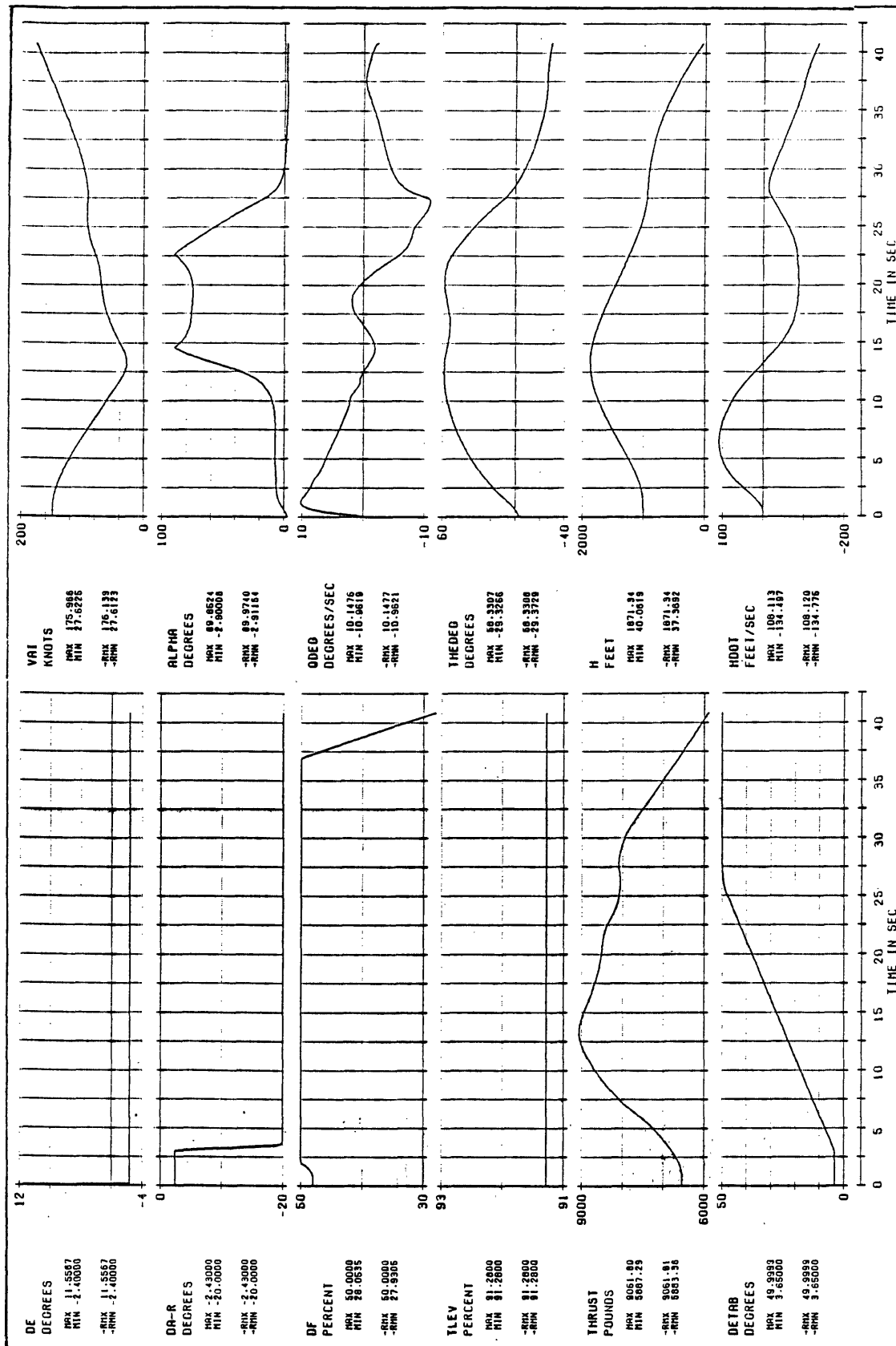;(32. "mean token memory size" (54 "maximum"))

Figure 3.13, cont'd

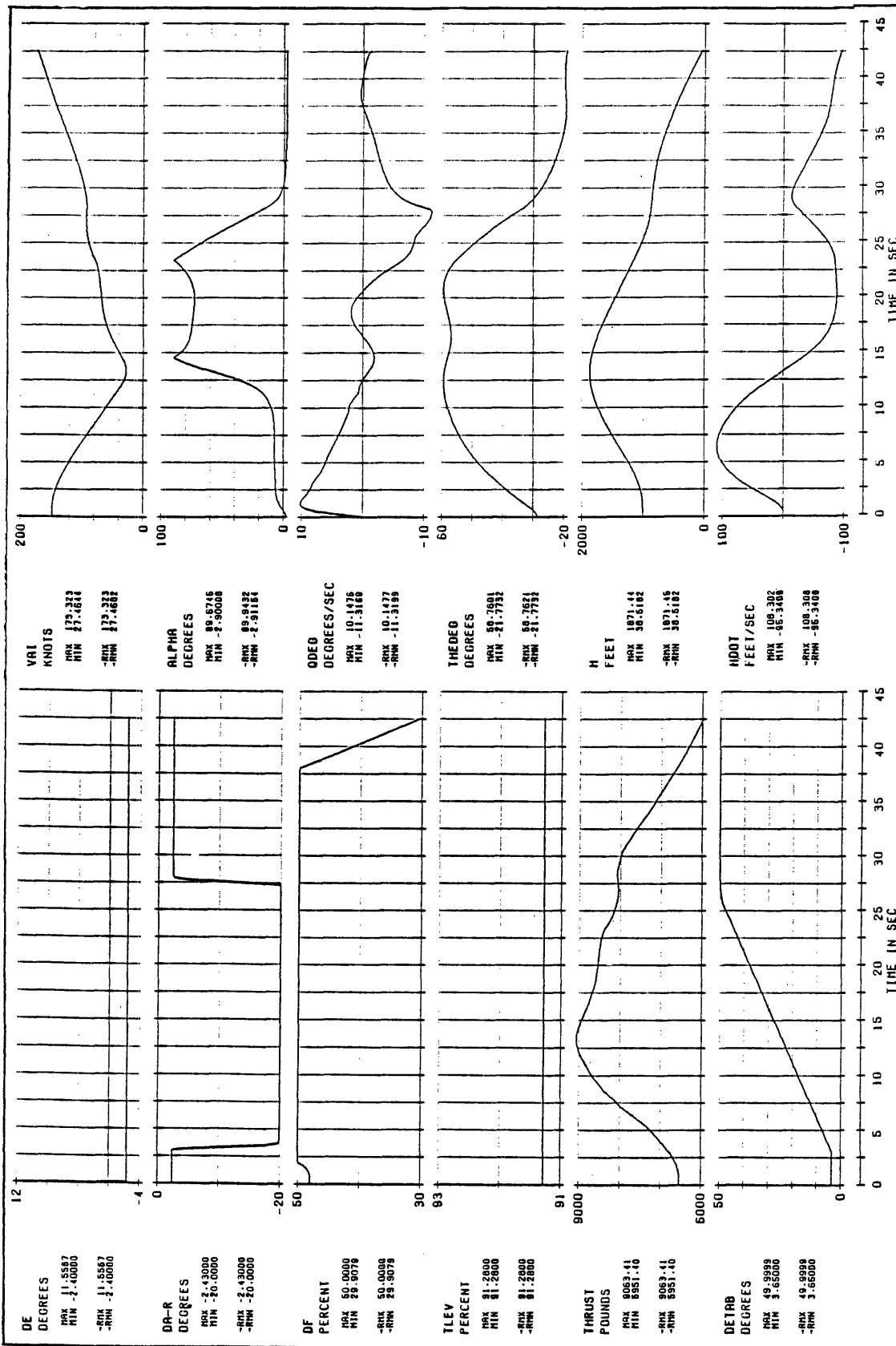Figure 3.14a

98

Figure 3.14b

99

Figure 3.14c

100

Figure 3.14d

101
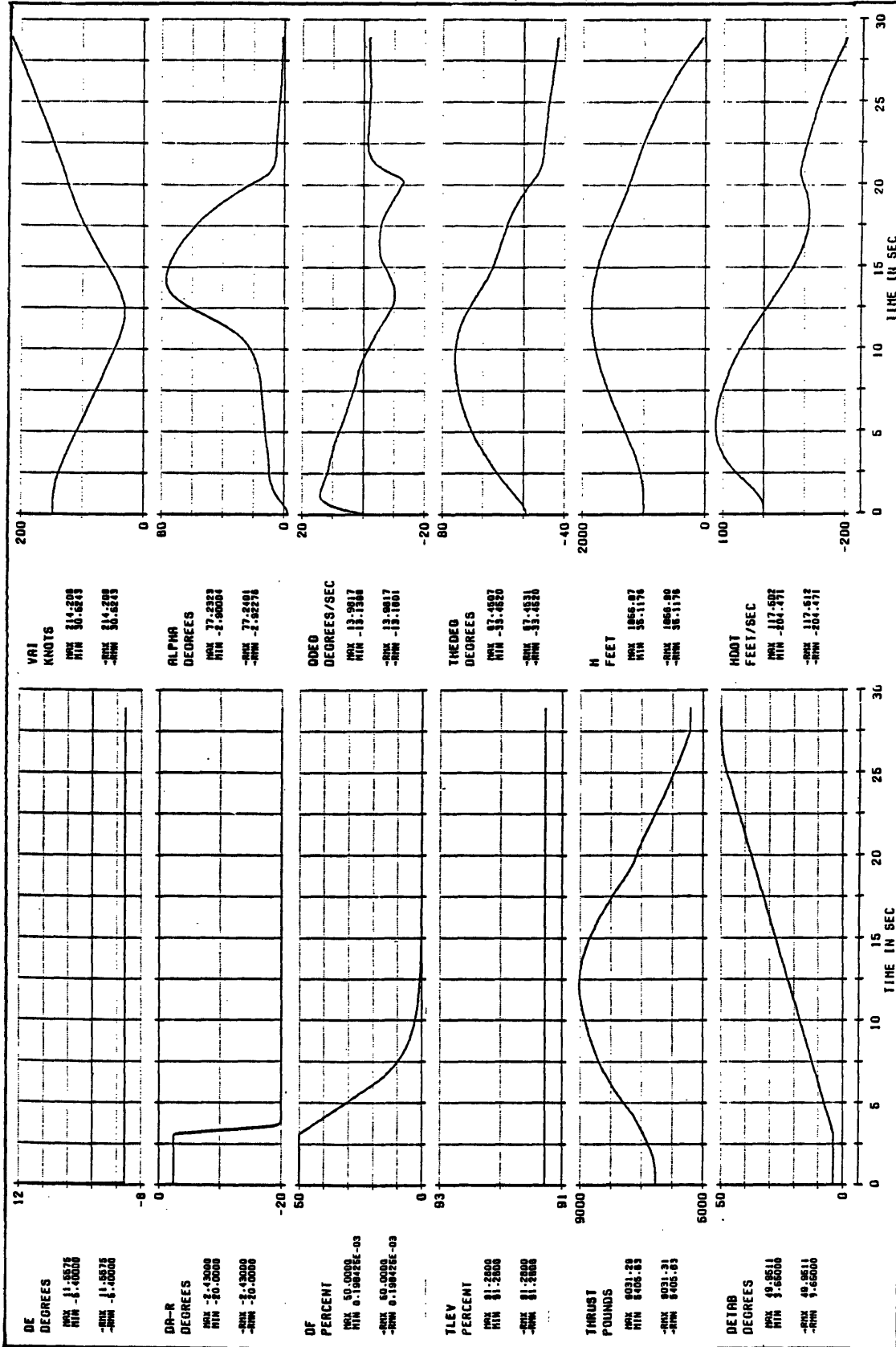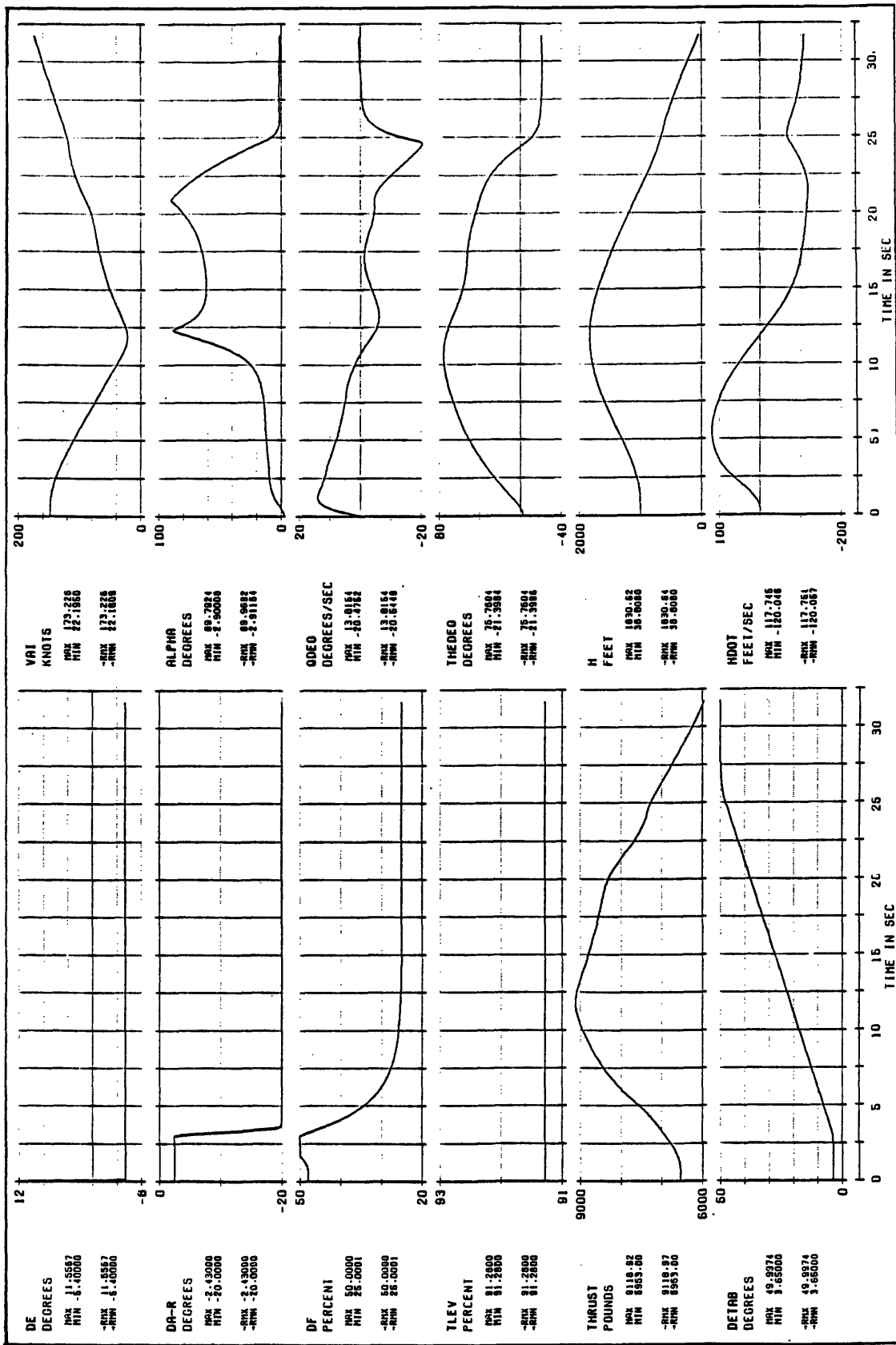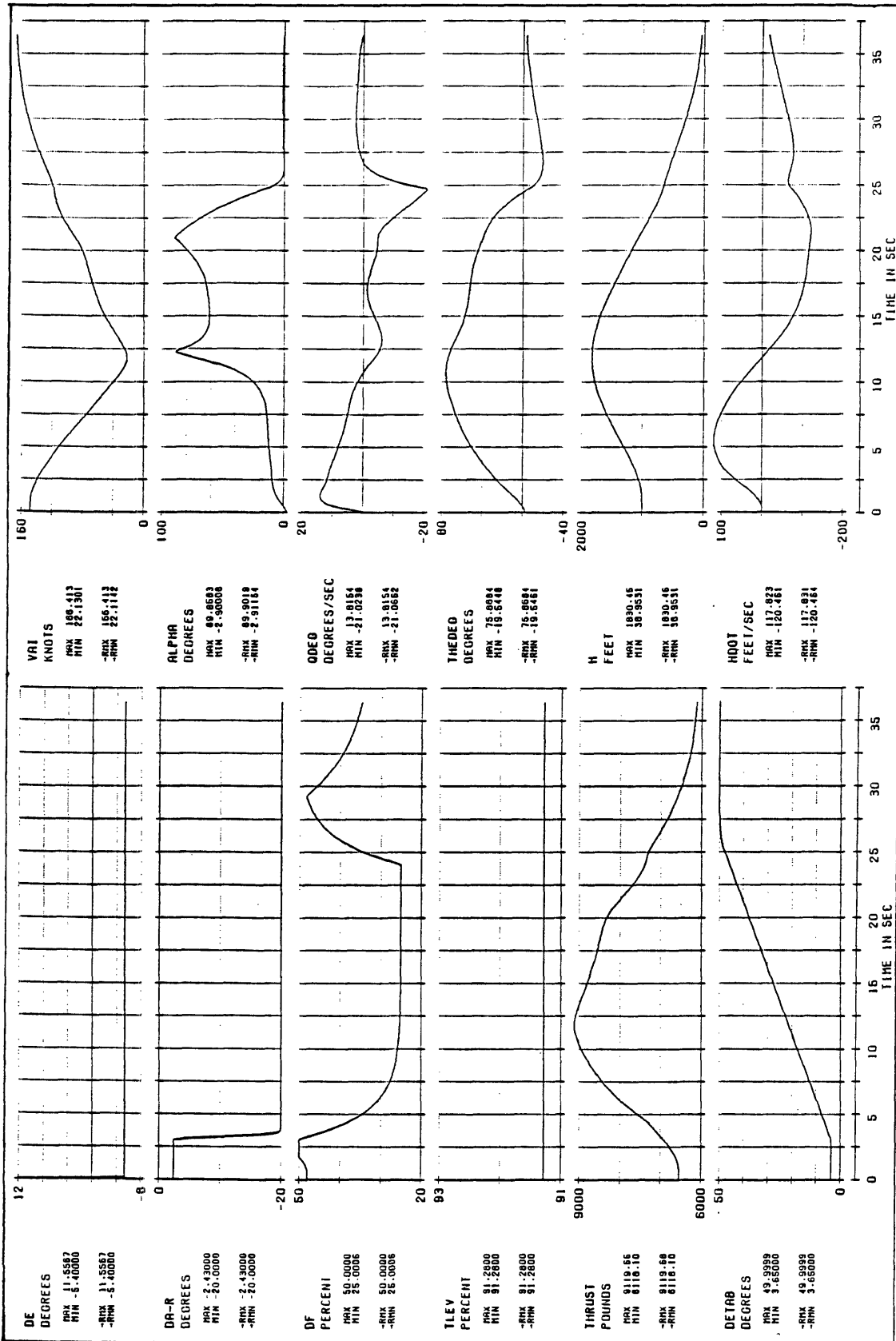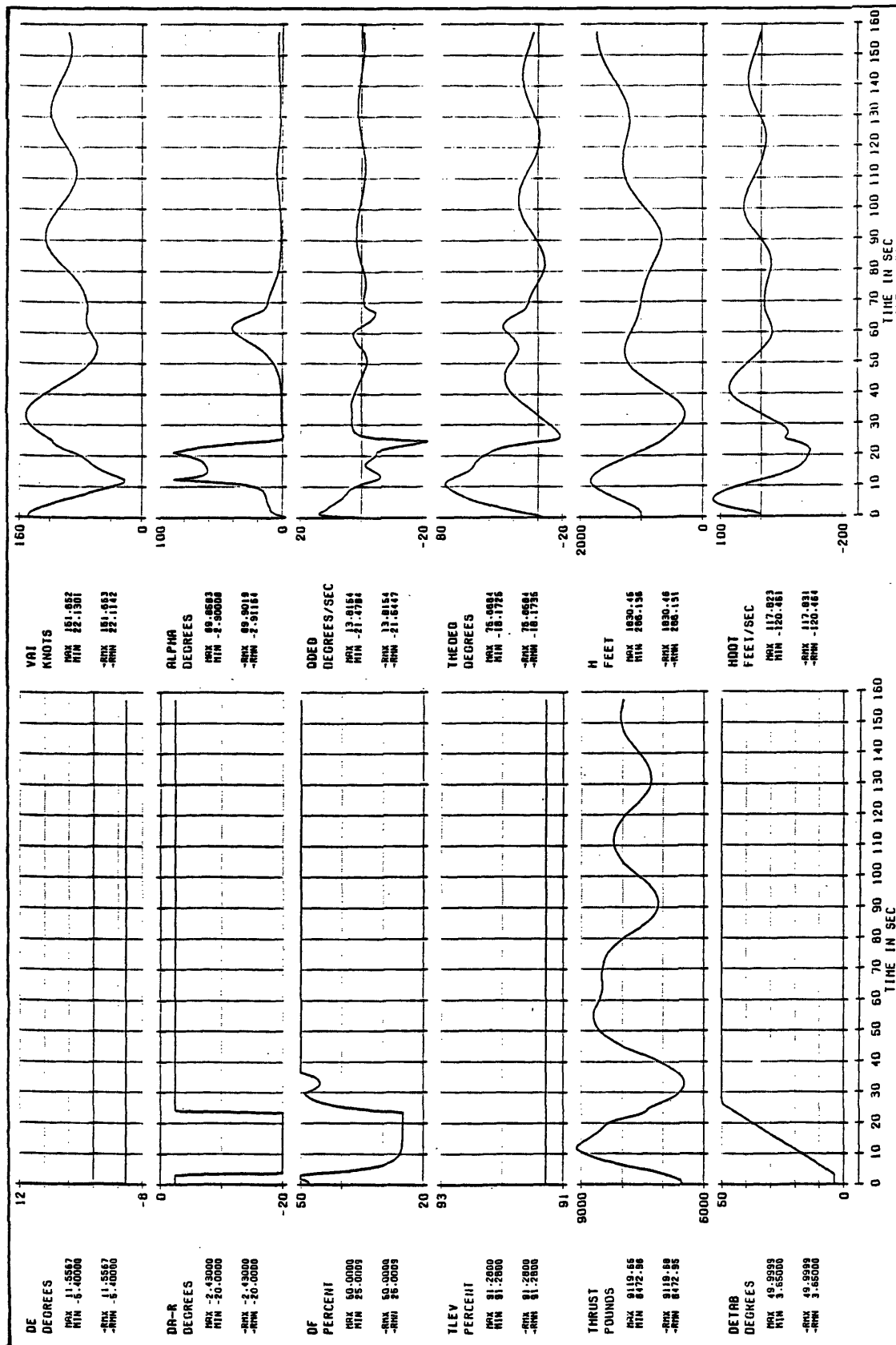
3.3.6.7. -12° Off-Nominal Elevator Jam (Pitch Up) During Flight at 120 KIAS at 7000'

Compensation: Hardover pitch down elevator tab, collective aileron, and thrust to full idle but later increased to full power

When the failure is severe enough, the pitch-down potential of thrust decreases must be called upon. In general, this will result in insufficient thrust later for allowing transition to climb.

There are certain rules in the expert system developed for this thesis that correct the recovery strategy when the aircraft pitch-stabilizes through use of aerodynamic surfaces, but stabilizes in a *descent*. It is clear that, for certain cases, the aerodynamic surface deployments could simply be changed to give more pitch up. For some degree of change, this will result in the aircraft stabilizing in a climb, but at a lower airspeed. For other cases, however, power must be increased at some point, when the pre-failure power setting was already low, for example (in which case pitch up changes in control surface deployments alone would only lead to dangerously low airspeeds or stall) or when the pitch-compensating control induces considerable additional drag (e.g., flaps are deployed). For all cases in this study, thrust increases could be used to stop stabilized descent, and the expert system was designed to suggest only this means. Because maximum climb rate is associated with full power, when power setting was changed, it was to get as close to 100% as possible, and thrust was increased with the other initial deployments if at all possible. When thrust increases had to be delayed (too much initial pitch up or acceleration in a dive otherwise) it was elected to do so when pitch rate minimized for pitch-up failures and when flight path angle first safely reached zero for pitch-down failures. In order to avoid thrust changes whenever possible, the expert system concentrates on pitch stabilization first, changing the thrust setting only when deploying aerodynamic controls gives stable descent. If additional pitch-down is required and available to compensate for the thrust-induced pitch up, it is added.

In the example case here, the expert system recommended full thrust decrease (Figure 3.15) when the aircraft looped after the pitch-down resources of elevator tab and collective aileron had been exhausted (Figure 3.16a). Because this thrust decrease leads to pitch-stabilized descent (Figure 3.16b), the expert system recommends full thrust restoration at time of pitch rate minimization. Figure 3.16c shows the successful outcome.

;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft----------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?   (Trial 1)
no
;
;Try the addition of immediate hardover elevator tab-------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?   (Trial 2)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Add immediate hardover collective aileron deflection------------------------------
;to -20. deg.
;Did pitch rate ever cross zero?   (Trial 3: Figure 3.16a)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
no
;
;Modify the last strategy to include immediate---------------------------------
;hardover thrust reduction to 0. %.
;Did pitch rate ever cross zero?   (Trial 4: Figure 3.16b)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

Figure 3.15: Interaction with Expert System, -12° Off-Nominal Elevator Jam, Flying at 120 KIAS

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```
;
;Was the aircraft settling into an apparent descent?
yes
;
;Restoring thrust later in the simulation should
;be tried. In the last simulation
;if pitch rate achieved a minimum after
;angle of attack decreased to 25. deg. state the
;time in seconds that this minimum occurred.
;Otherwise state the time at which angle of attack
;decreased through 25. deg. If angle of attack
;never exceeded 25. deg. state the time at which
;pitch rate was minimized for the entire run.
22.
;
;Modify the last strategy by increasing thrust to---------------------------------------
;100. % at 22. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.------------------------------------
;End -- no production true
;
;(64 productions (557 // 1518 nodes))
;(146 firings (531 RHS actions))
;(9. Mean working memory size (9 maximum))
;(1. mean conflict set size (2 maximum))
;(31. mean token memory size (59 maximum))
;(31. "mean token memory size" (59 "maximum"))
```

Figure 3.15, cont'd

(Trial 5: Figure 3.16c)

Figure 3.16a

105
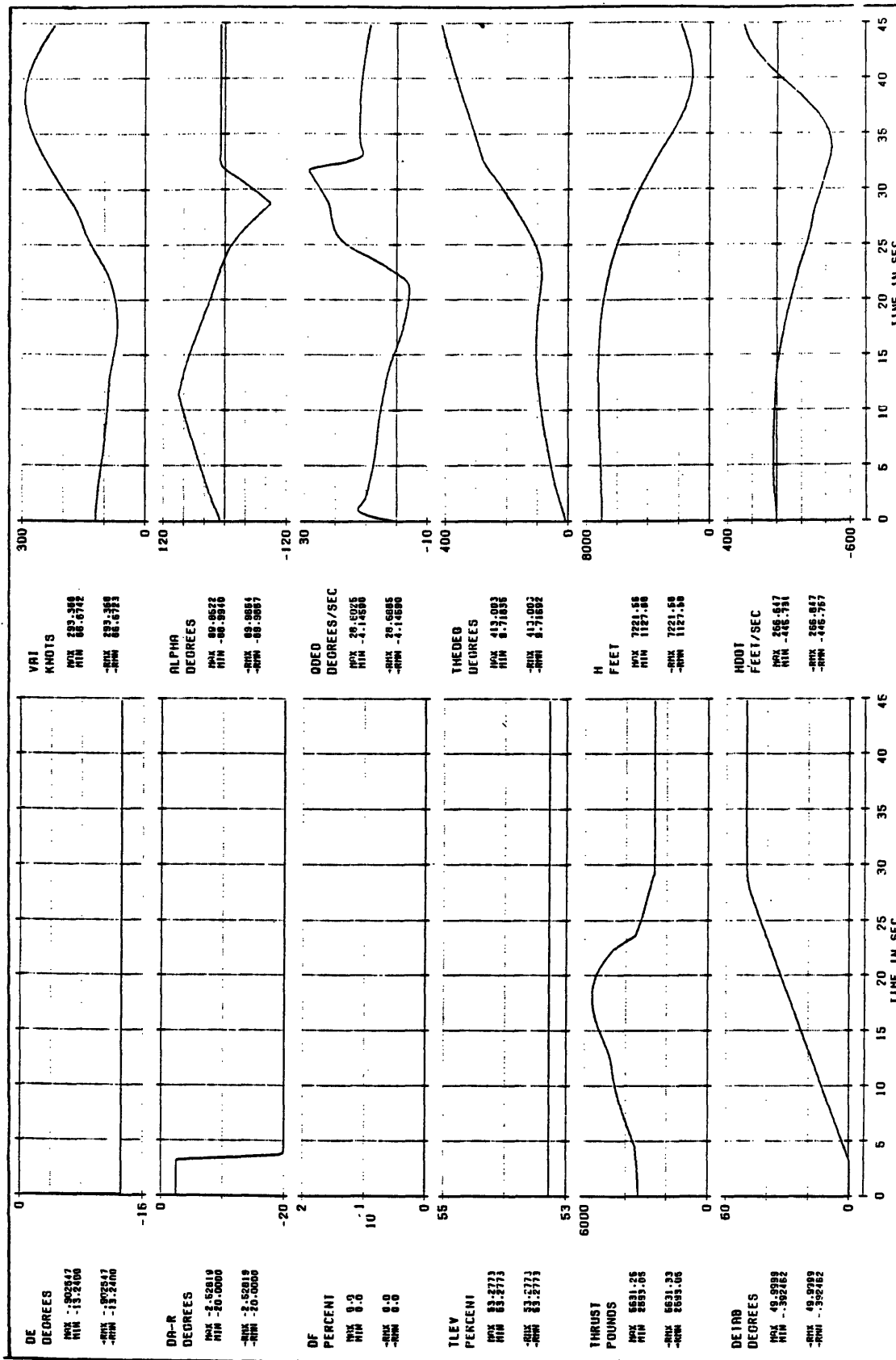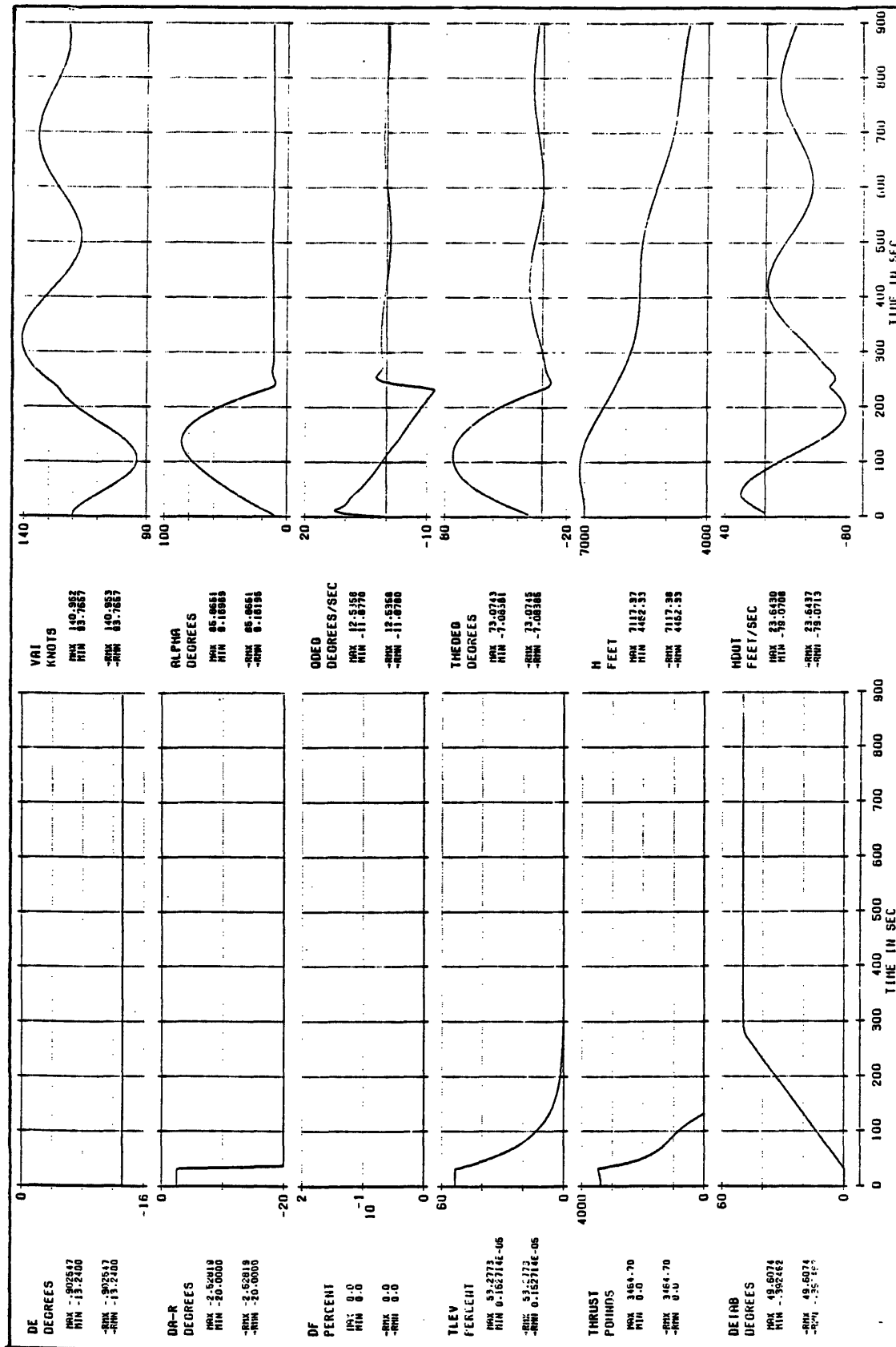
Figure 3.16b

Figure 3.16c

107
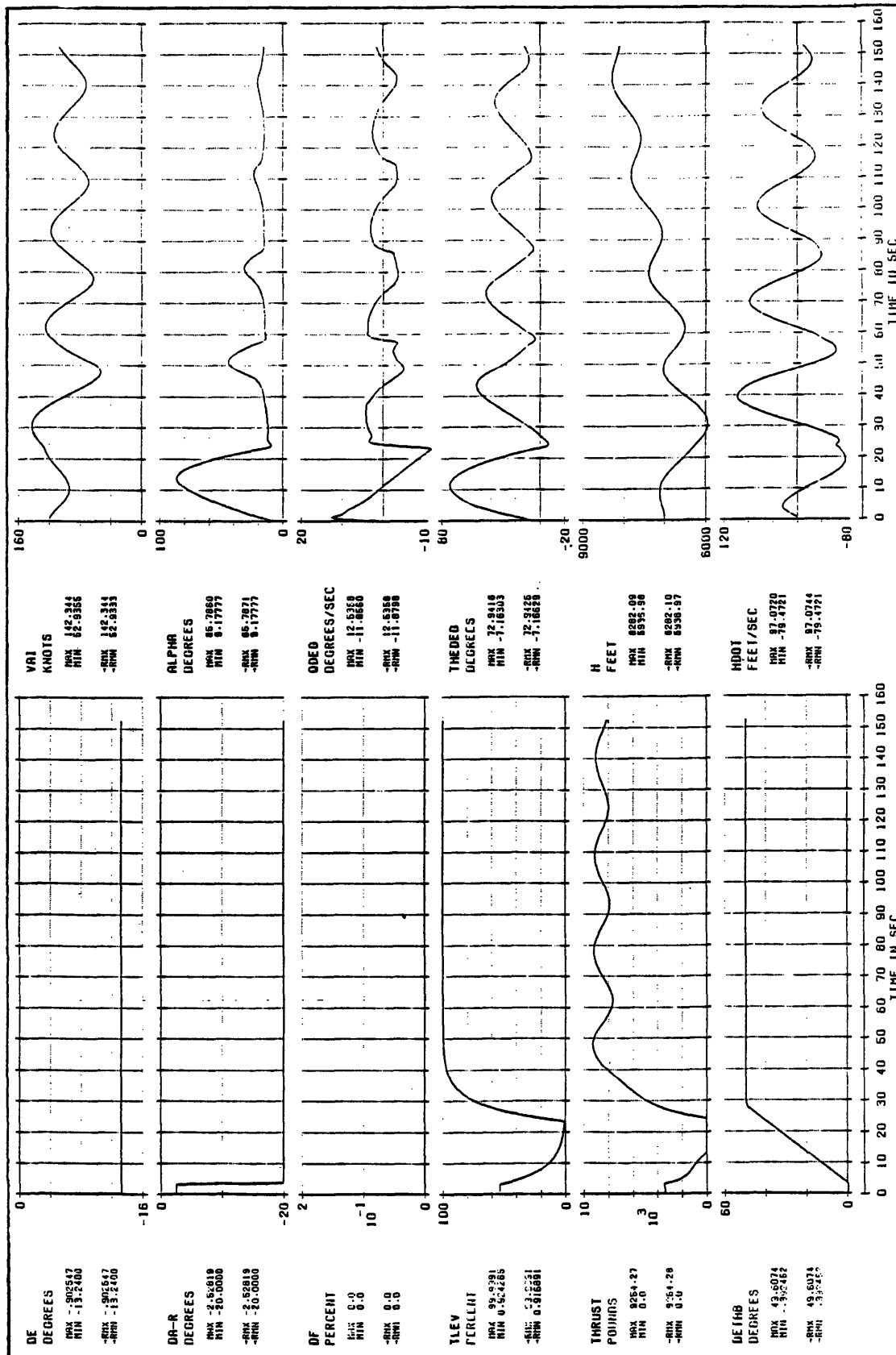
3.3.6.8. -22° Off-Nominal Elevator Jam (Pitch Up) During Rapid Descent, at 4000', with Landing Gear Extended and 50% Flaps

Compensation: Landing gear raised, hardover pitch-down elevator tab, aileron, and flap retraction, plus delayed thrust increase to stop descent

When there is a possibility of imposing thrust increases *initially* to stop eventual descent of the pitch-stabilized aircraft, the expert system will recommend it. This was successful with many cases. Sometimes, however, the pitch-up moment associated with thrust increases precludes preventing early aircraft looping.

In the case here, hardover elevator tab, collective aileron, and full flap retraction were all required to keep the aircraft from looping with the pitch-up failure. Figure 3.17 records the user interaction with the expert system in arriving at this strategy. Figure 3.18a shows that the aircraft pitch-stabilizes in descent (not surprising given that the initial condition was descent). The expert system stores this strategy, including the time at which pitch rate minimized, for possible backtracking (see highlighted text in output). When thrust is increased at the beginning of the recovery, its pitch-up influence does cause the aircraft to loop (Figure 3.18b), and the system suggests delaying the thrust increase instead to the time pitch rate minimizes. Figure 3.18c shows that this results in a successful recovery to climb.

Landing gear was raised immediately with this pitch-up failure. Whether landing gear was retracted or not did not impact significantly the pitch up of this aircraft. Landing gear retraction did help, however, in increasing pre-stall altitude gain--desirable on general principle.

It should be noted that the most severe pitch-stabilizeable pitch-up failures will force descent. Thrust increases sufficient to climb always induce pitch up for which there can be no compensation.

;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Raise landing gear immediately and see if the-------------------------------------
;aircraft can recover on its own.
;Did pitch rate ever cross zero?   (Trial 1)
no
;
;Try the addition of immediate hardover elevator tab---------------------------------
;deflection to 50. deg.
;Did pitch rate ever cross zero?   (Trial 2)
no
;
;Add immediate hardover collective aileron deflection-------------------------------
;to -20. deg.
;Did pitch rate ever cross zero?   (Trial 3)
no
;
;Modify the last strategy to include immediate------------------------------------
;hardover flap reduction to 0. %.
;Did pitch rate ever cross zero?   (Trial 4: Figure 3.18a)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
yes
;
;In case we have to backtrack later--
;in the last simulation
;if pitch rate achieved a minimum after angle of
;attack decreased to 25. deg. give the time in
;seconds that this minimum occurred. Otherwise
;give the time at which angle of attack decreased
;through 25. deg.
36.
;
;Add immediate hardover thrust increase to 100. %--------------------------------
;Did pitch rate ever cross zero?
yes   (Trial 5: Figure 3.18b)
;
;Was the aircraft stabilizing by our definition

Figure 3.17: Interaction with Expert System, -22° Off-Nominal Elevator Jam, on Descent, 145 KIAS

;at the end of the sim?
no
;
;Did pitch angle remain below 111. deg.-and-if it did
;so but crossed 30. deg. did it decrease and recross
;this level later?
yes
;
;Did angle of attack remain below 25. deg. originally
;-or-if it did cross this level did it always later
;decrease through it at least before rising above it
;again?
no
;
;Thrust increases will probably have to be delayed.----------------------------
;Unless nil
;apply immediate hardover elevator tab   (Trial 6: Figure 3.18c)
;deflection to 50. deg.
;hardover aileron deflection to -20. deg.
;hardover flap deflection to 0 % and
;hardover thrust increased only later--
;to 100. % at 36. sec.
;Did pitch rate ever cross zero?
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.----------------------------------
;End -- no production true
;
;(64 productions (560 // 1560 nodes))
;(236 firings (828 RHS actions))
;(10. Mean working memory size (18 maximum))
;(2. mean conflict set size (8 maximum))
;(37. mean token memory size (207 maximum))
;(37. "mean token memory size" (207 "maximum"))

Figure 3.18a

111
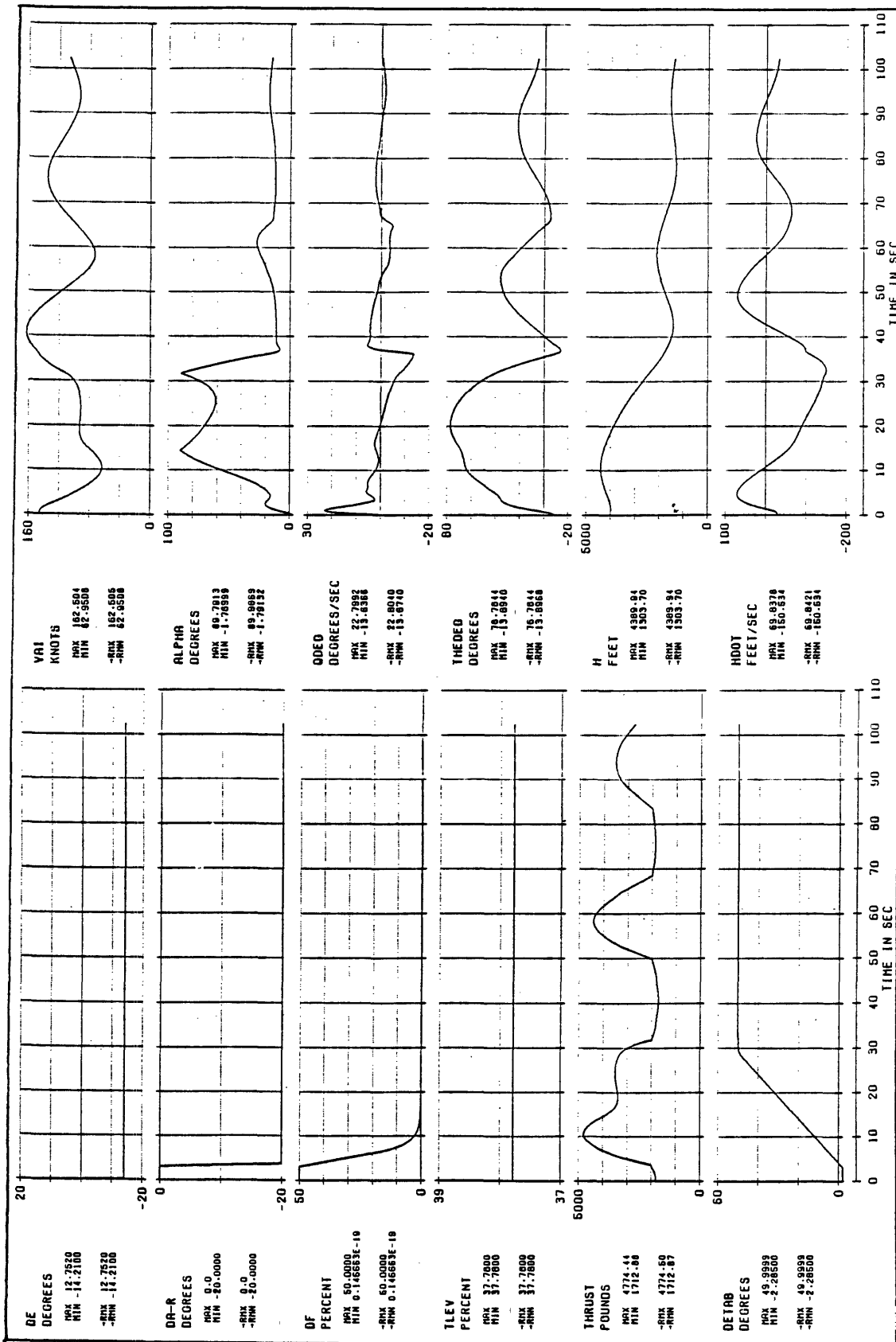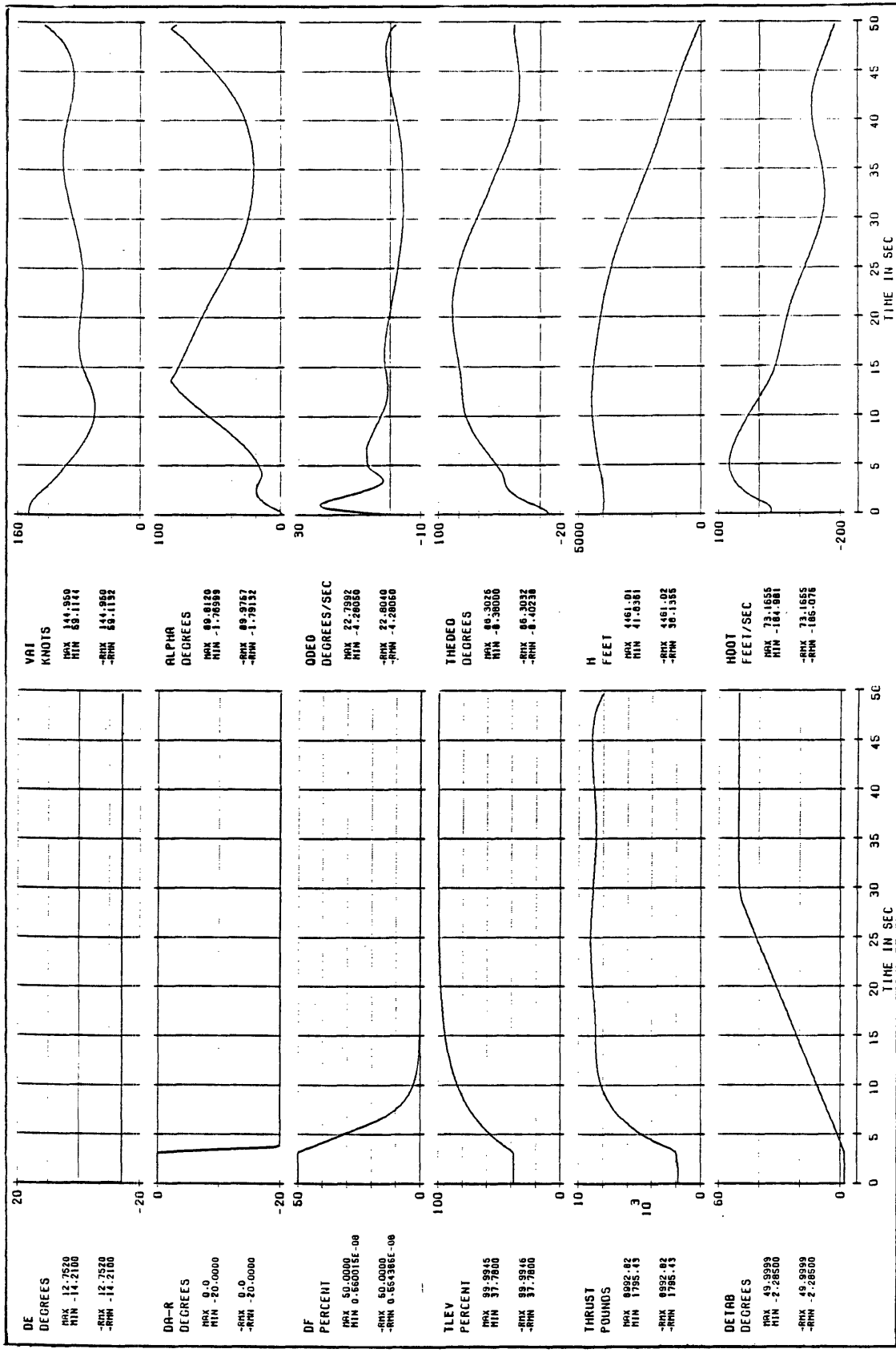
Figure 3.18b

Figure 3.18c

113
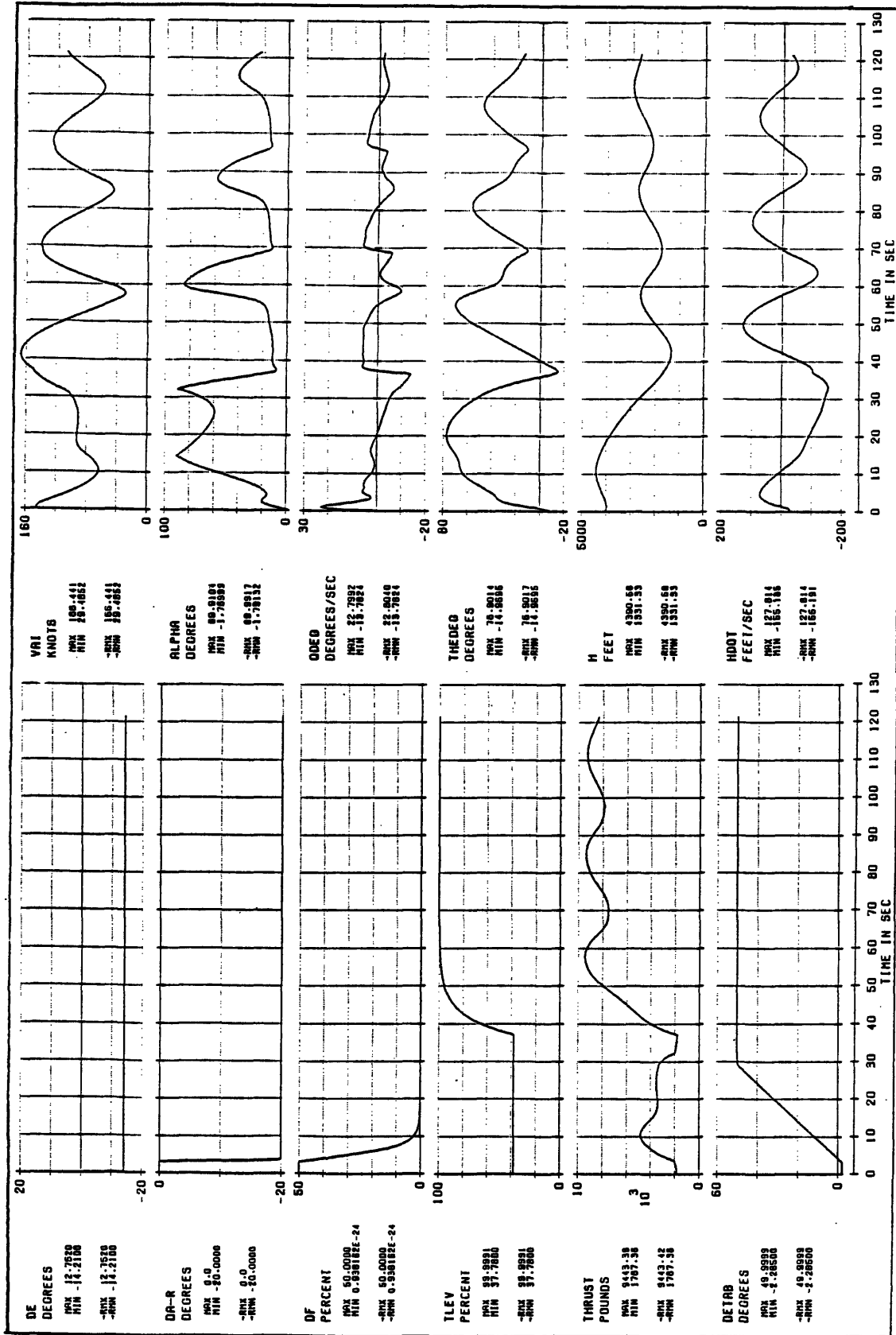
3.3.6.9. +1 Off-Nominal Elevator Jam (Pitch Down) During Flight at 147 KIAS at 1000', with 50% Flaps Deployed

Compensation: Hardover pitch-down elevator tab and collective aileron

The expert system developed to find emergency control strategies works for pitch-down failures similarly as for pitch-up failures. Initial opposing control is added sequentially, and certain aspects of the response are examined with the expert system to evaluate the control strategy and obtain a new trial strategy.

The effects of pitch-down failures for certain cases in this study were successfully opposed with no control changes or with hardover pitch-up elevator tab alone. In the case here, elevator tab deployment is not sufficient to oppose the failure-induced pitching moment. After ruling out overcompensation—clear when both pitch rate and flight path angle are positive at the end of the simulation—the system is looking to determine whether pitch rate remained above its first minimum. The relevant questions are highlighted in Figure 3.19. Here it did not (see Figure 3.20a), and this could be taken as a general sign of undercompensation. The addition of hardover collective aileron, however, gave successful recovery, as shown in Figure 3.20b.

```
;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft----------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?                          (Trial 1)
no
;
;Try the addition of immediate hardover elevator tab------------------------------
;deflection to -6. deg.
;Did pitch rate ever cross zero?                          (Trial 2: Figure 3.20a)
yes
;
;Was the aircraft stabilizing by our definition
;At the end of the sim?
no
;
;Did pitch rate overshoot zero to take a positive
;value and flight path angle also achieve a positive
;value at the end of the simulation?
no
;
;After it initially crossed zero did pitch rate
;remain greater than its first minimum?
no
;
;Add immediate hardover collective aileron deflection-----------------------------
;to 20. deg.
;Did pitch rate ever cross zero?                          (Trial 3: Figure 3.20b)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
no
;
;A successful recovery strategy has been found.------------------------------------
;End -- no production true
;
;(47 productions (332 // 810 nodes))
;(27 firings (93 RHS actions))
;(9. Mean working memory size (9 maximum))
```

Figure 3.19: Interaction with Expert System, $+1°$ Off-Nominal Elevator Jam, Flying at 147 KIAS
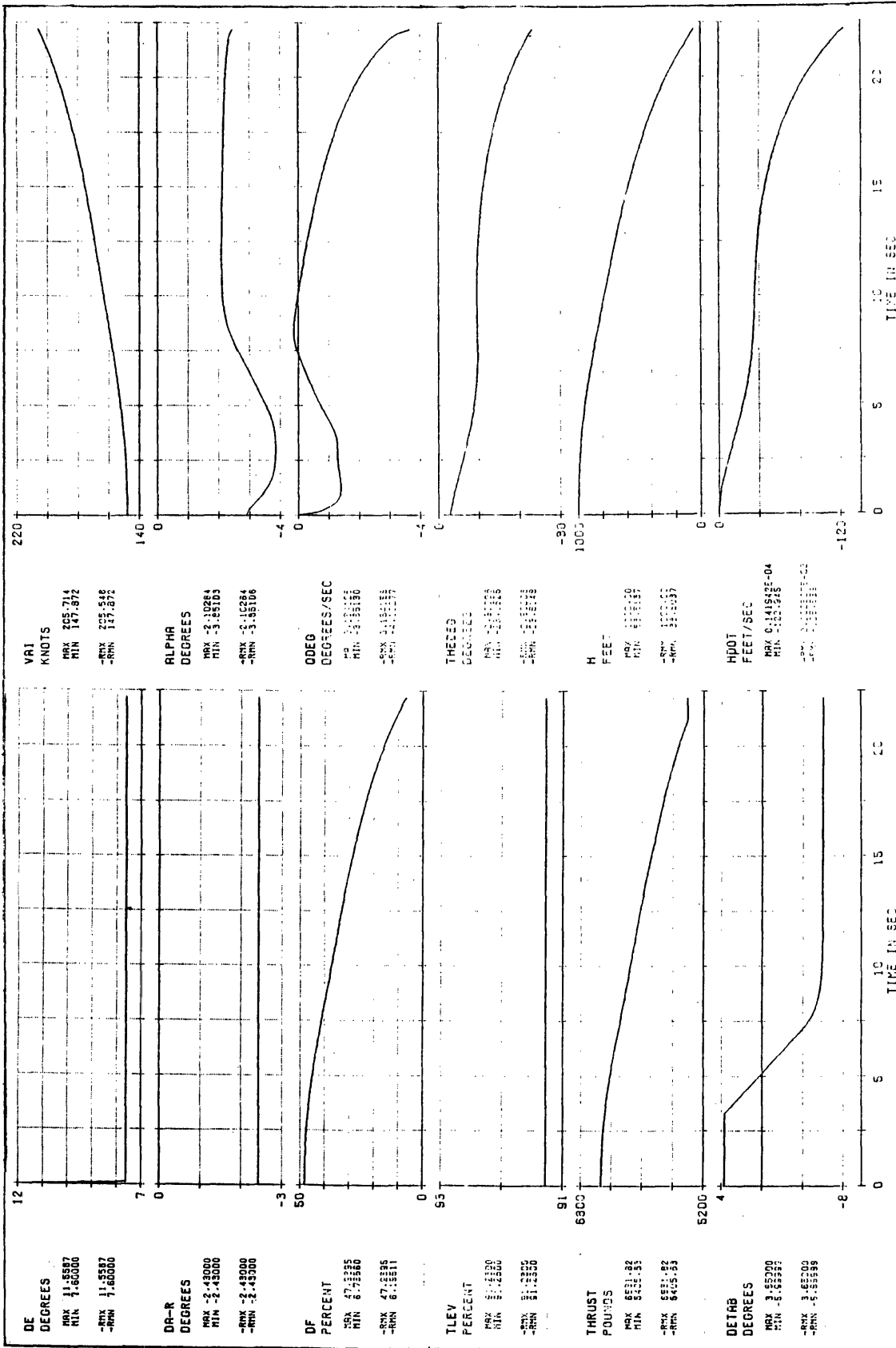
Figure 3.20a

Figure 3.20b

117
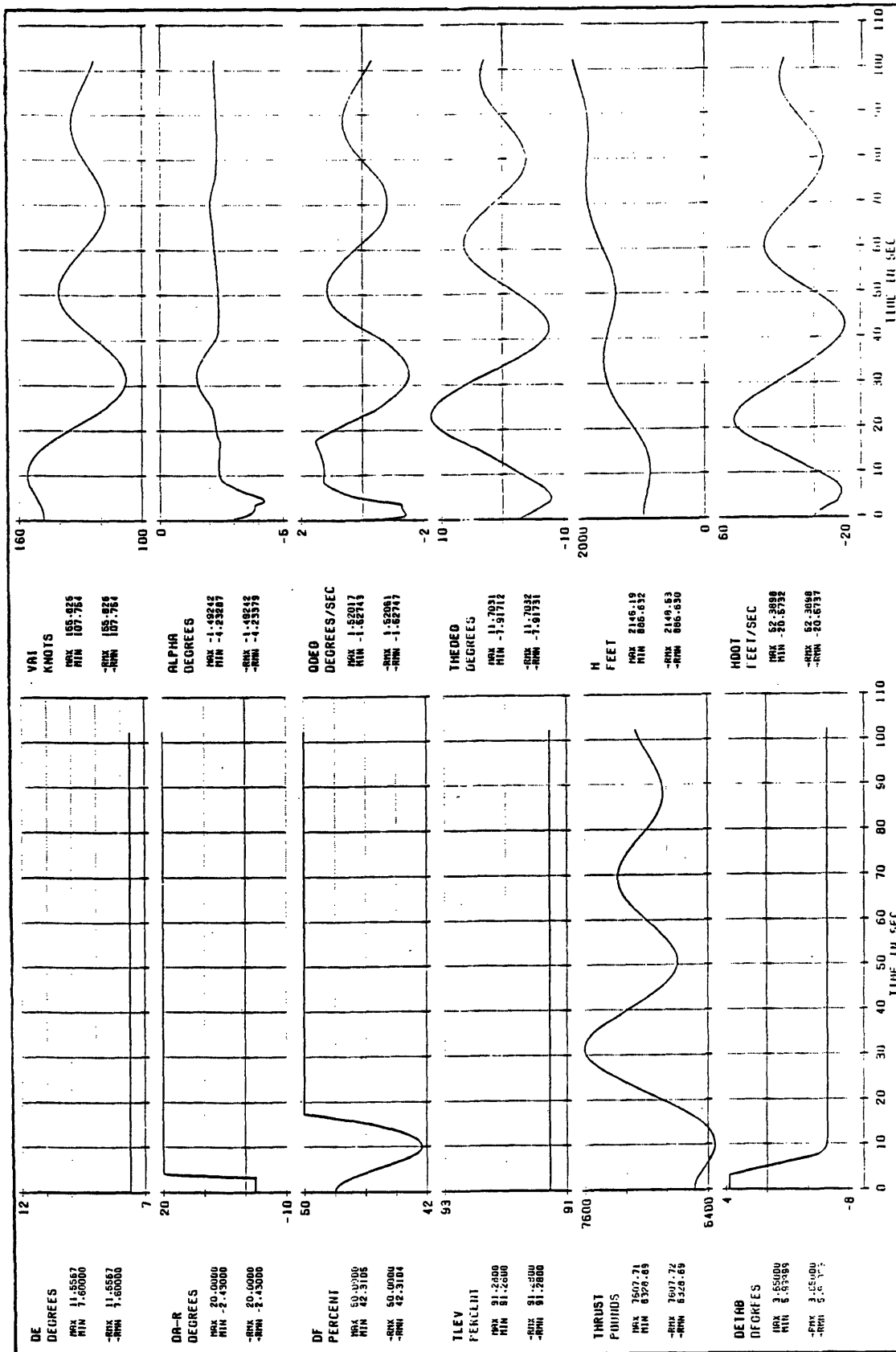
3.3.6.10 +4° Off-Nominal Elevator Jam (Pitch Down) During Ascent, at 7000'

Compensation: Hardover pitch-up elevator tab and aileron, flaps extended somewhat together with thrust reduction to idle, then thrust increase later

In this example case, hardover pitch-up elevator tab and collective aileron together could not provide sufficient pitch-up to bring the flight path angle to a positive value. Figure 3.21 shows that the expert system asks about this flight path angle recovery (highlighted in text). It infers undercompensation in the response of Figure 3.23a and suggests deployment of flaps next, exploiting their pitch-up effect.

The flaps on this aircraft are large and can contribute considerable pitch up control. They are restricted as to airspeeds at which they can be deployed, however, because of structural limitations. Figure 3.22 shows the allowable deployment airspeeds. In all cases studied for this research, flap deployments greater than 75.% led to unsuccessful results: the flaps contribute much more drag than potentially compensating pitch moment with larger deployments. In Figure 3.23b, the flap deployment to 75.% had to be aborted as the airspeed rose above allowable deployment speeds. The flaps could not deploy enough and quickly enough to prevent the pitch down and airspeed gain.

In order to limit the acceleration in the dive and thus enhance the prospects for flap deployment, the expert system suggests that thrust be reduced in this strategy--hardover to idle at first, anyway. Figure 3.23c shows that the aircraft responds with a pitch-stabilized descent. To correct this, it is recommended that thrust be reinstated to full power at the point at which flight path angle first recovers to zero (also highlighted in the output), but this together with the other deployments represents too much pitch up, and the aircraft loops (Figure 3.23d). As Figures 3.23e and f show, when the initial flap deployment is halved, as suggested by the expert system, the aircraft still pitch-stabilizes in descent, but the descent is nicely corrected with power reinstated to full power later.

This combination of thrust reduction to enhance flap deployment possibilities was a successful feature of successful emergency control for several pitch-down failure cases.

118

;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft--------------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?   (Trial 1)
no

;
;Try the addition of immediate hardover elevator tab--------------------------------------
;deflection to -6. deg.
;Did pitch rate ever cross zero?   (Trial 2)
no

;
;Add immediate hardover collective aileron deflection--------------------------------------
;to 20. deg.
;Did pitch rate ever cross zero?   (Trial 3: Figure 3.23a)
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch rate overshoot zero to take a positive
;value and flight path angle also achieve a positive
;value at the end of the simulation?
no

;
;After it initially crossed zero did pitch rate
;remain greater than its first minimum?
yes

;
;Did flight path angle remain positive in the initial
;stall recovery-or-if it was negative at some point
;did it later cross from negative to positive?
no

;
;Modify the last strategy to add immediate hardover--------------------------------
;flap deployment to 75. % subject to airspeed
;restrictions.   (Trial 4: Figure 3.23b)
;Did pitch rate ever cross zero?
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch rate overshoot zero to take a positive

Figure 3.21: Interaction with
Expert System,
+4° Off-Nominal
Elevator Jam, on
Ascent, 173 KIAS

;value and flight path angle also achieve a positive
;value at the end of the simulation?
no

;
;After it initially crossed zero did pitch rate
;remain greater than its first minimum?
yes

;
;Did flight path angle remain positive in the initial
;stall recovery-or-if it was negative at some point
;did it later cross from negative to positive?
no

;
;Include immediate hardover thrust reduction to 0. %---------------------------------
;in the last strategy.
;Did pitch rate ever cross zero?
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

;
;Was the aircraft settling into an apparent descent?
yes

;
;Restoring thrust later in the simulation should
;be tried. Give the time in seconds that flight
;path angle first crossed zero.
15.

;
;Modify the last strategy by increasing thrust to---------------------------
;100. % at 15. sec.
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch rate overshoot zero to take a positive
;value and flight path angle also achieve a positive
;value at the end of the simulation?
yes

;
;Modify the last strategy to have hardover flap-------------------------------------
;deployment to only 37.5 % subject to airspeed
;restrictions and suppress later thrust increase.
;Did pitch rate ever cross zero?
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

;
;Was the aircraft settling into an apparent descent?
yes

;
;Restoring thrust later in the simulation should
;be tried. Give the time in seconds that flight
;path angle first crossed zero.

Figure 3.21, cont'd

(Trial 5: Figure 3.23c)

(Trial 6: Figure 3.23d)

(Trial 7: Figure 3.23e)

120

16.

;

;Modify the last strategy by increasing thrust to-------------------------------------

;100. % at 16. sec.

;Was the aircraft stabilizing by our definition

;at the end of the sim?

yes

;

;

;Was the aircraft settling into an apparent descent?

no

;

;

;A successful recovery strategy has been found.-------------------------------------

;End -- no production true

;

;(52 productions (347 // 905 nodes))

;(77 firings (251 RHS actions))

;(9. Mean working memory size (9 maximum))

;(1. mean conflict set size (4 maximum))

;(20. mean token memory size (36 maximum))

;(20. "mean token memory size" (36 "maximum"))

Figure 3.21, cont'd

(Trial 8: Figure 3.23f)

Figure 3.22a

122
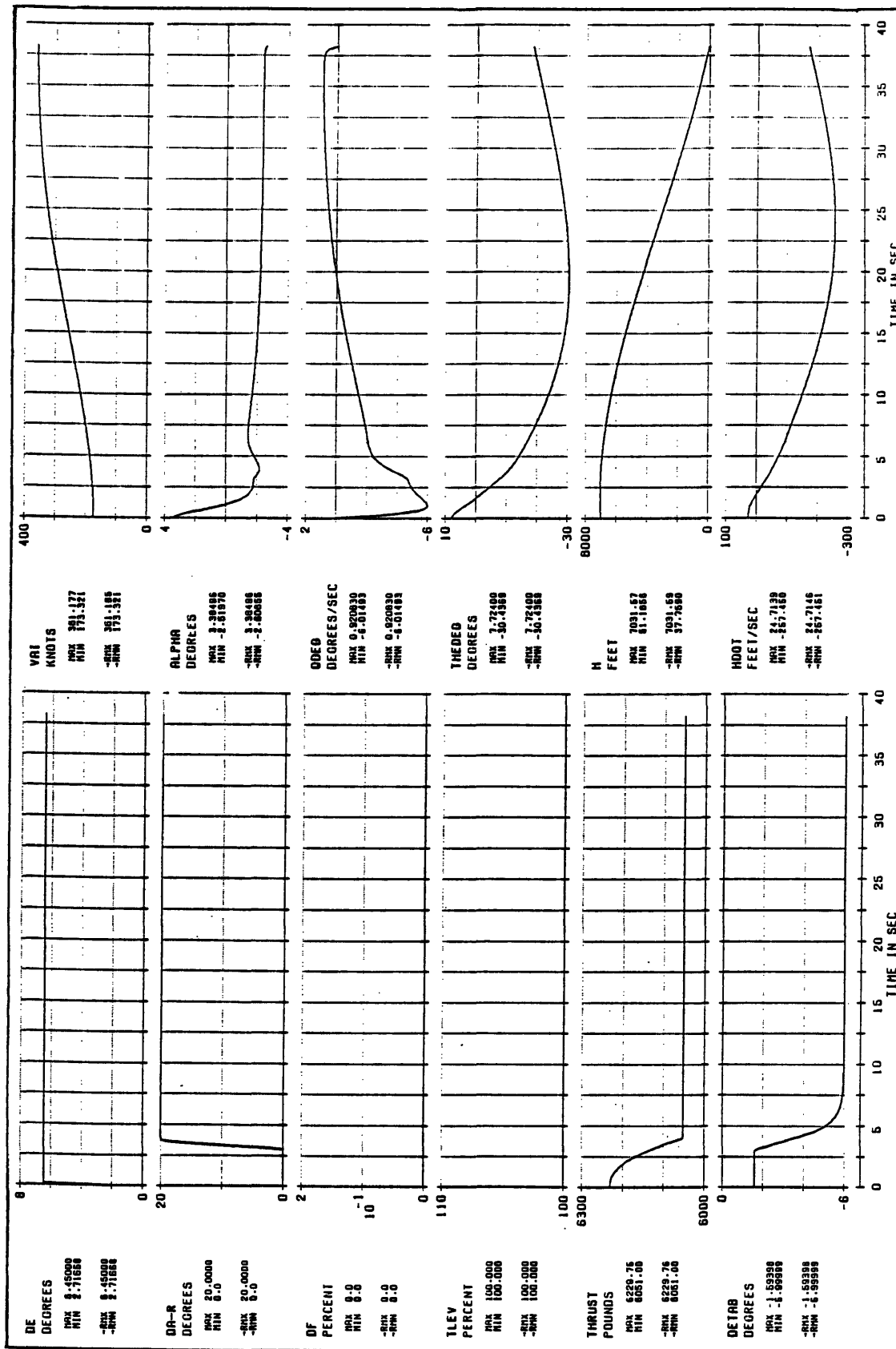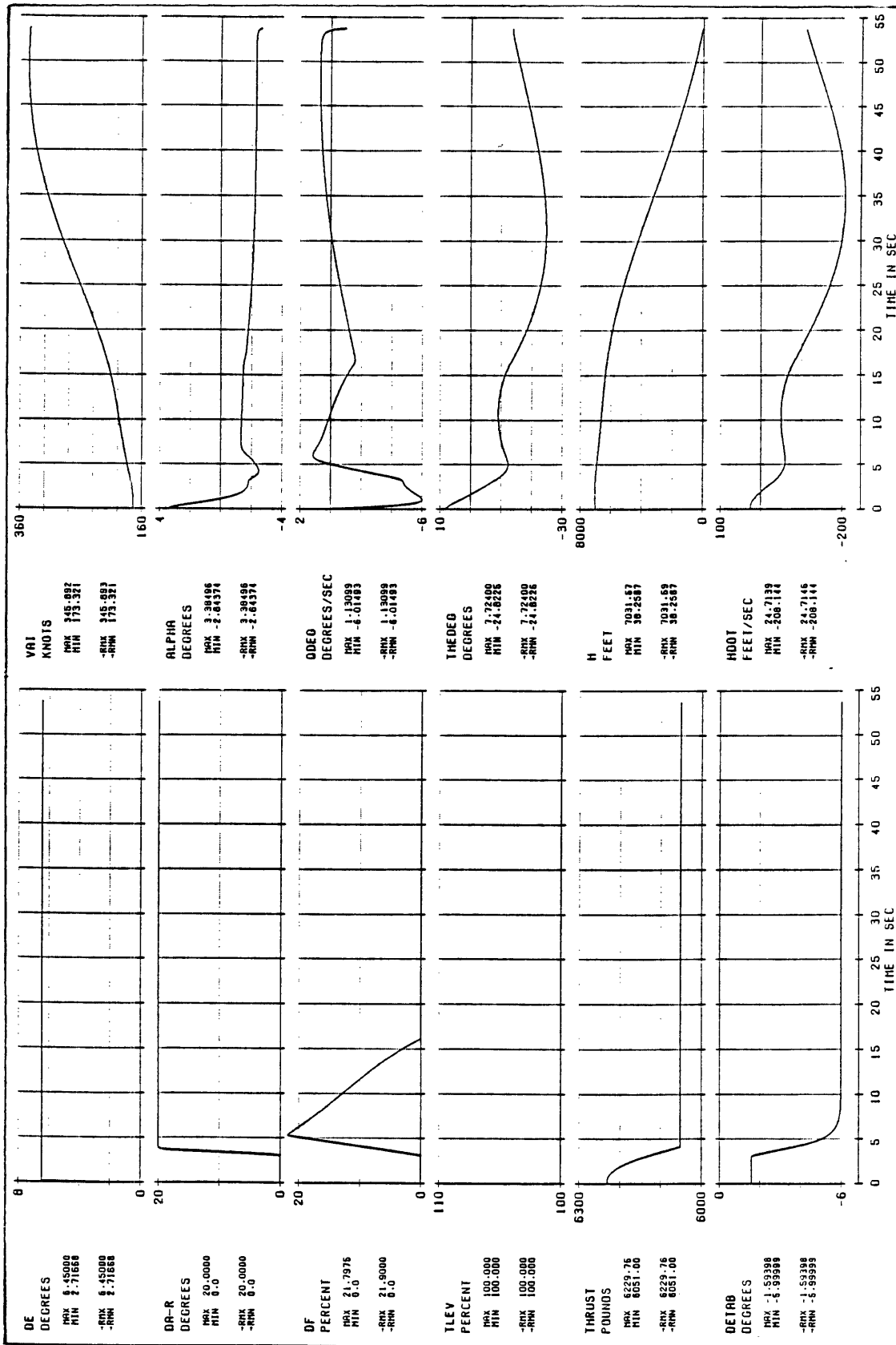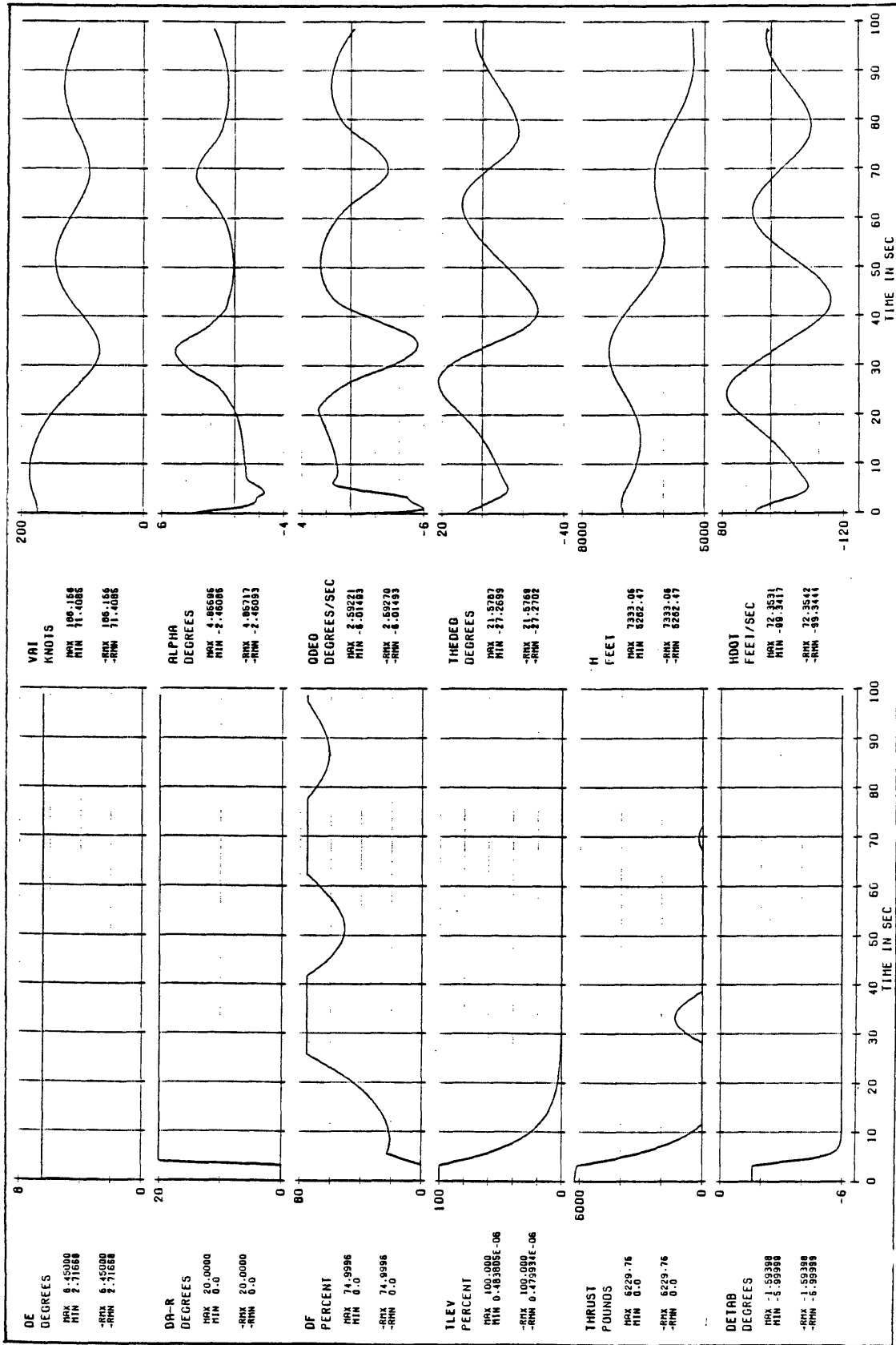
Figure 3.22b

Figure 3.22c

Figure 3.22d

125

Figure 3.22e

126

Figure 3.22f

127
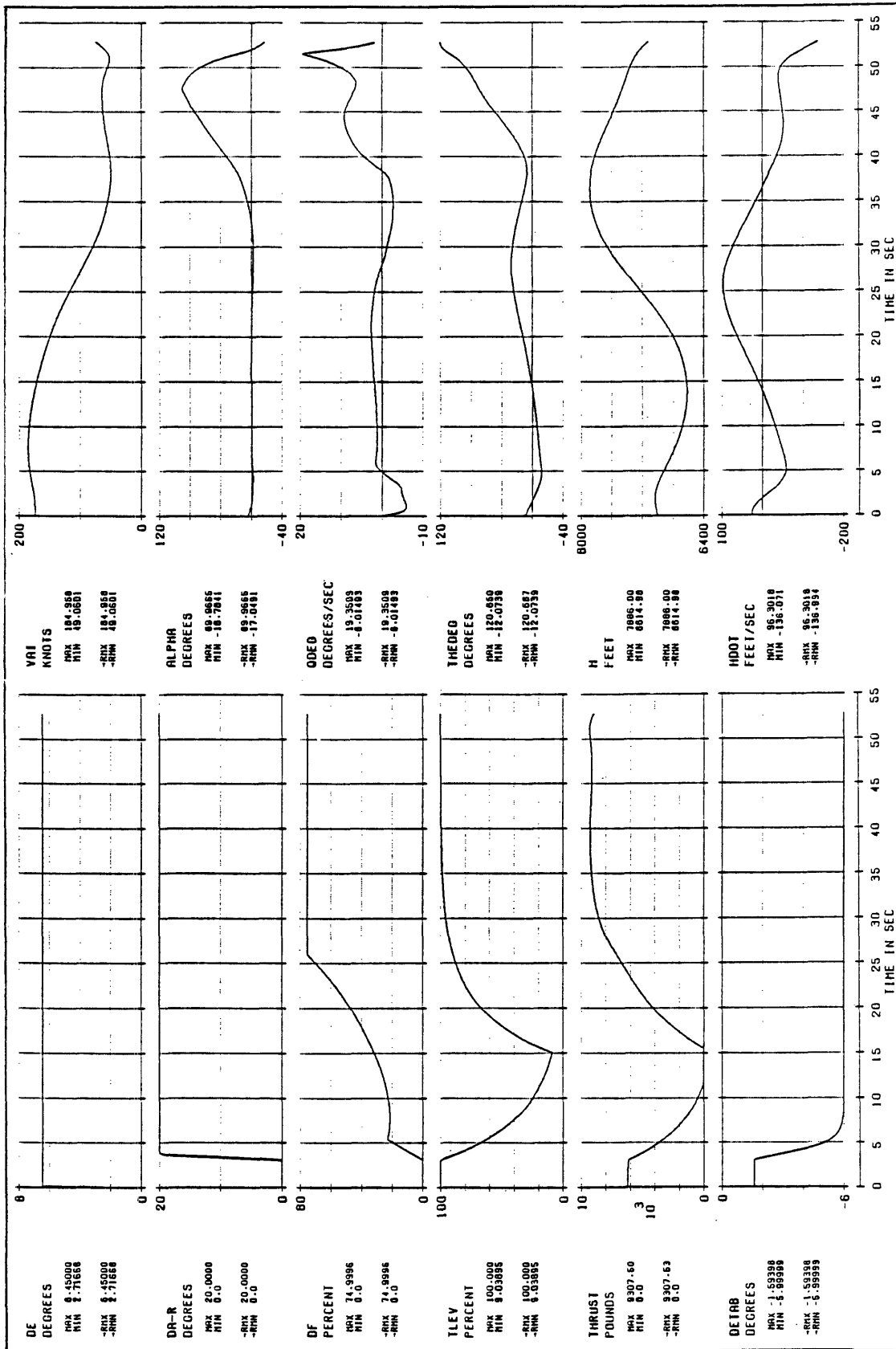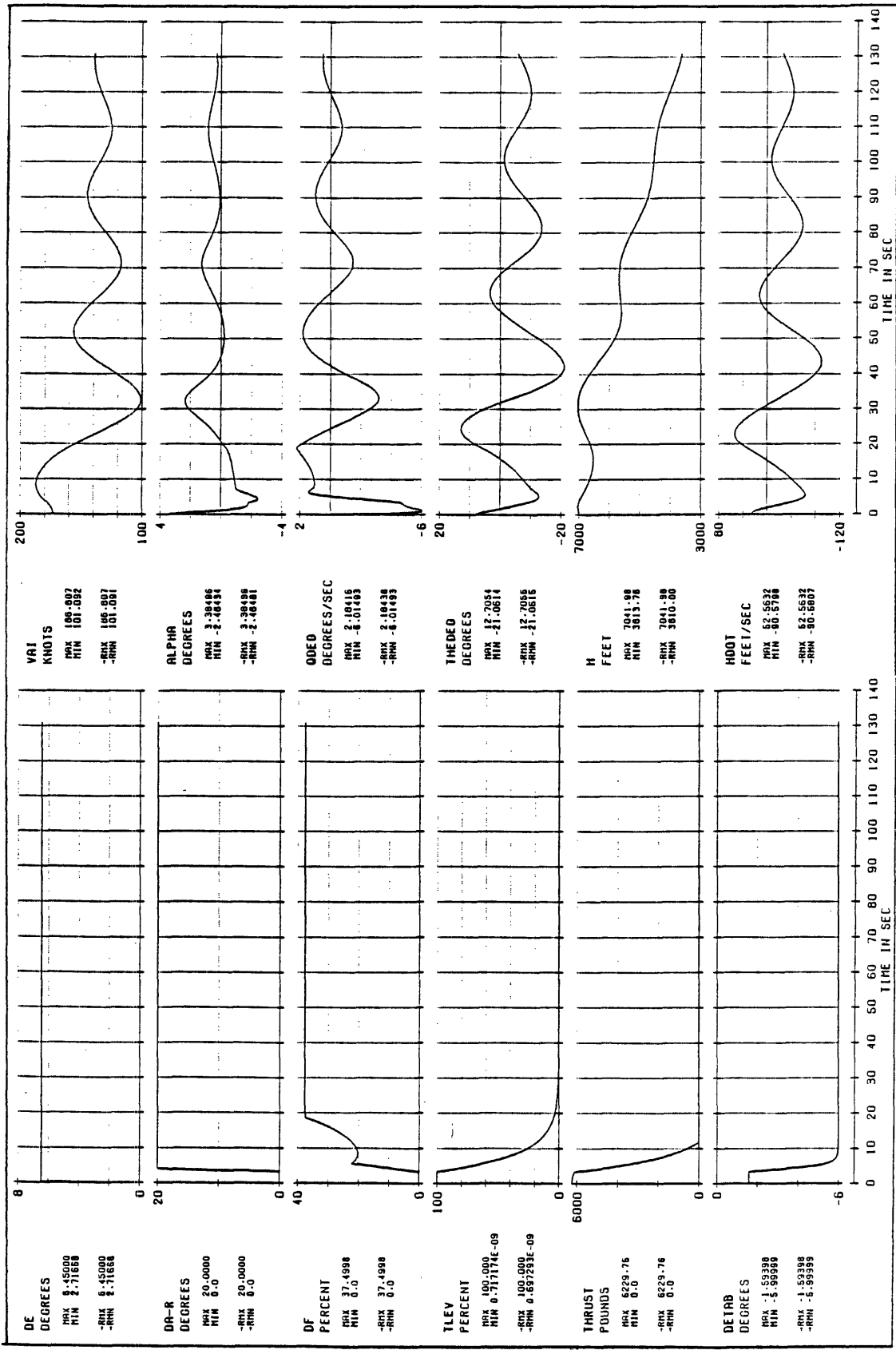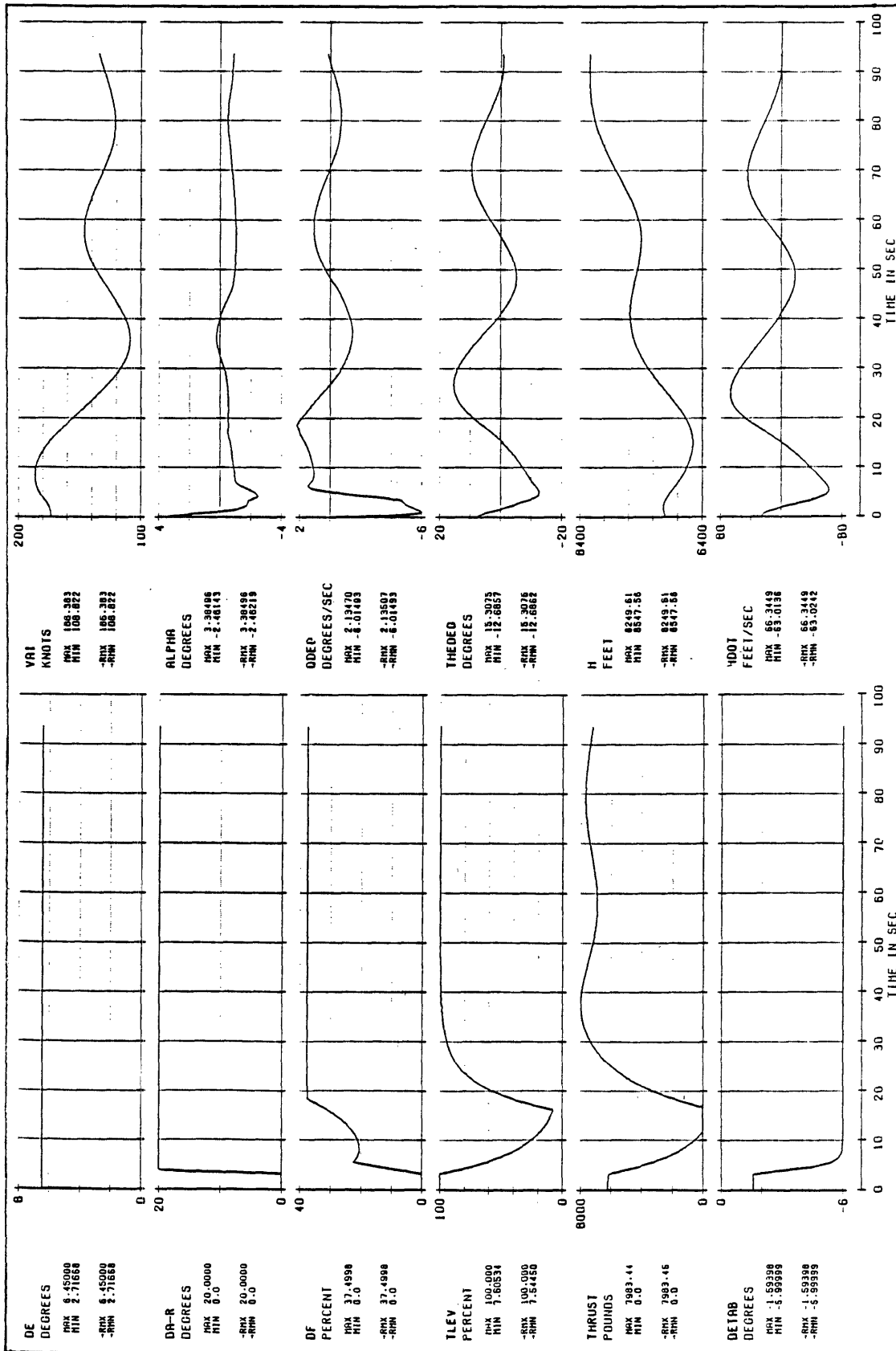
**Figure 3.23: C-130 Flap Deployment
Airspeed Limits**

Indicated Airspeed, Knots

Flap Deployment, Percent
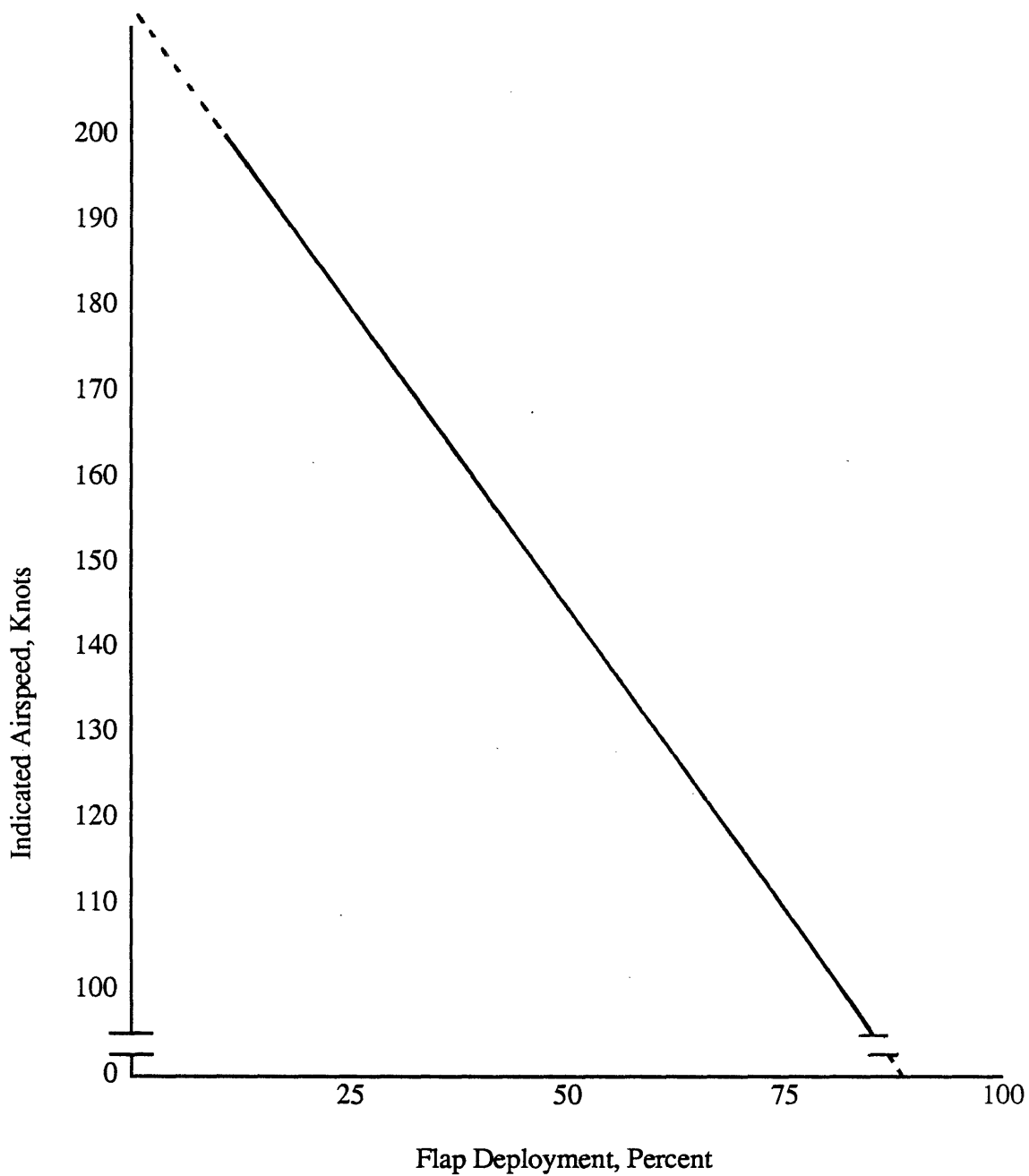
3.3.6.11. +1.° Off-Nominal Elevator Jam (Pitch Down) During Rapid Descent, at 4000', with Landing Gear Extended and 50% Flaps

Compensation: Landing gear left extended, hardover pitch-up elevator tab and collective aileron, flaps extended further, thrust increased; gear raised later--Recovery to forced descent.

Another type of recovery was discovered through considerable work with a very small pitch-down failure occurring when the aircraft was in a state of rapid descent. The summary difficulty here was in bringing enough pitch-up resources to bear in order to go beyond pitch stabilization and get the aircraft to transition to climb; the aircraft could at best be pitch-stabilized in a forced descent.

Figure 3.24 is the transcript of the interaction with the expert system concerning this failure case. As Figure 3.25a shows, hardover pitch-up elevator tab deployment is not sufficient to have pitch rate become positive. When hardover pitch-up collective aileron is added, the aircraft pitch-stabilizes in a descent of about 32 ft/ sec., as Figure 3.25b shows. Increasing the initial thrust to 100% merely causes the aircraft to accelerate in its dive, with flaps retracting as their deployment airspeed limits are broached (see Figure 3.25c). It seems clear that immediate flap deployment increases along with this thrust increase would result in a similar unsuccessful recovery. Based on these simulations, either initial thrust increase to an intermediate value will allow the flaps to remain extended and still facilitate climb-out, or moderate increase of thrust might be tried along with further extension of flaps to give that much additional pitch up.

Figure 3.25d shows the aircraft response to hardover pitch-up collective aileron and elevator tab and a thrust increase of 50% of the available range. The aircraft is stabilizing in a descent of approximately 12 ft/ sec. The airspeed has remained low enough that the flaps can remain extended. An increase in flap extension to 75% was added, and the aircraft pitch-stabilized again in a descent (Figure 3.25e). Thrust increase of 87.5% of the original upper range led to an accelerated dive to the ground again, as flaps retracted (Figure 3.25f). With thrust increase of 75% of the range between nominal and full thrust, the aircraft failed to pitch-stabilize, as angle of attack and pitch angle decreased dramatically (Figure 3.25g). Halving this increase in flap extension led to aircraft stabilization in a descent of approximately 3 ft/ sec. (Figure 3.25h).

Figure 3.25i shows the result of a trial raising of the landing gear immediately with the last control strategy. The decreased drag allows even greater acceleration, and the aircraft impacts the ground several seconds earlier. The landing gear had been left extended initially in all of the simulations with this case. The airspeed in the more successful of these did not

```
;
;The advisory is beginning.
;A simulation may be terminated when...
;The aircraft pitch angle starts to exceed 111. deg.
;with a pitch-up failure or
;Ground impact is imminent or
;Stable oscillations in all states are apparent
;and you can determine the approximate
;steady climb rate of stabilized flight.
;Answer all questions below with yes or no.
;Please be careful with your answers: there is
;no explicit checking for inconsistencies.
;
;Try no compensating control to see if the aircraft--------------------------------------
;can recover on its own.
;Did pitch rate ever cross zero?                                    (Trial 1)
no
;
;Try the addition of immediate hardover elevator tab--------------------------------------
;deflection to -6. deg.
;Did pitch rate ever cross zero?                                    (Trial 2: Figure 3.25a)
no
;
;Add immediate hardover collective aileron deflection-------------------------------------
;to 20. deg.
;Did pitch rate ever cross zero?                                    (Trial 3: Figure 3.25b)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;
;Was the aircraft settling into an apparent descent?
yes
;
;Give the time at which the flight path angle first
;crossed zero.
4.
;
;Try the last strategy but with immediate hardover---------------------------------------
;thrust increase to 100. %
;Did pitch rate ever cross zero?                                    (Trial 4: Figure 3.25c)
yes
;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no
;
;Did pitch rate overshoot zero to take a positive
;value and flight path angle also achieve a positive
;value at the end of the simulation?
no
;
;After it initially crossed zero did pitch rate
;remain greater than its first minimum?
no
```

Figure 3.24: Interaction with Expert System, $+1°$ Off-Nominal Elevator Jam, on Descent, 145 KIAS

```
;
;Try the last strategy but with immediate hardover------------------------------------
;thrust increase to 68.89 %.
;Did pitch rate ever cross zero?                                    (Trial 5: Figure 3.25d)
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

;
;Was the aircraft settling into an apparent descent?
yes

;
;Modify the last strategy to add immediate hardover----------------------------------
;flap deployment to 75. % subject to airspeed
;restrictions.                                                      (Trial 6: Figure 3.25e)
;Did pitch rate ever cross zero?
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes

;
;Was the aircraft settling into an apparent descent?
yes

;
;Try the last strategy but with immediate hardover-----------------------------------
;thrust increase to 84.445 %.
;Did pitch rate ever cross zero?                                    (Trial 7: Figure 3.25f)
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
no

;
;Did pitch rate overshoot zero to take a positive
;value and flight path angle also achieve a positive
;value at the end of the simulation?   .
no

;
;After it initially crossed zero did pitch rate
;remain greater than its first minimum?
no

;
;Modify the last strategy to have hardover flap-------------------------------------
;deployment to only 62.5 % subject to airspeed
;restrictions.                                                      (Trial 8: Figure 3.25h)
;Did pitch rate ever cross zero?
yes

;
;Was the aircraft stabilizing by our definition
;at the end of the sim?
yes
;;Was the aircraft settling into an apparent descent?
yes
```

```
;-------------------------------------------------------------------------------
;End -- no production true
;
;(49  productions (353  // 871  nodes))
;(42  firings (148  RHS actions))
;(10.  Mean working memory size (10  maximum))
;(1.  mean conflict set size (2  maximum))
;(21.  mean token memory size (34  maximum))
;(21.  "mean token memory size" (34  "maximum"))
```

Figure 3.24, cont'd

exceed airspeeds allowing structural safety of the landing gear, although this could become a lower-priority consideration in recovering from other cases of this type. Raising the landing gear at the time flight path angle first crossed zero led to a measurable improvement of this situation, and the aircraft stabilized with descent of only 1 ft/ sec. Figure 3.25j shows this. It is clear that this is probably about the best that can be done in recovering from this failure. Had the pre-failure flap deployment been less, increasing flap extension considerably could have been very useful in recovering in cases like this one. Other cases of this type were not found among those investigated, so tests concerning whether the flaps remained deployed at their original level did not need to be included in the expert system. It is clear, however, that this is an objective feature of the aircraft response which could be expected to be useful in the expert system's finding a successful recovery from similar cases.
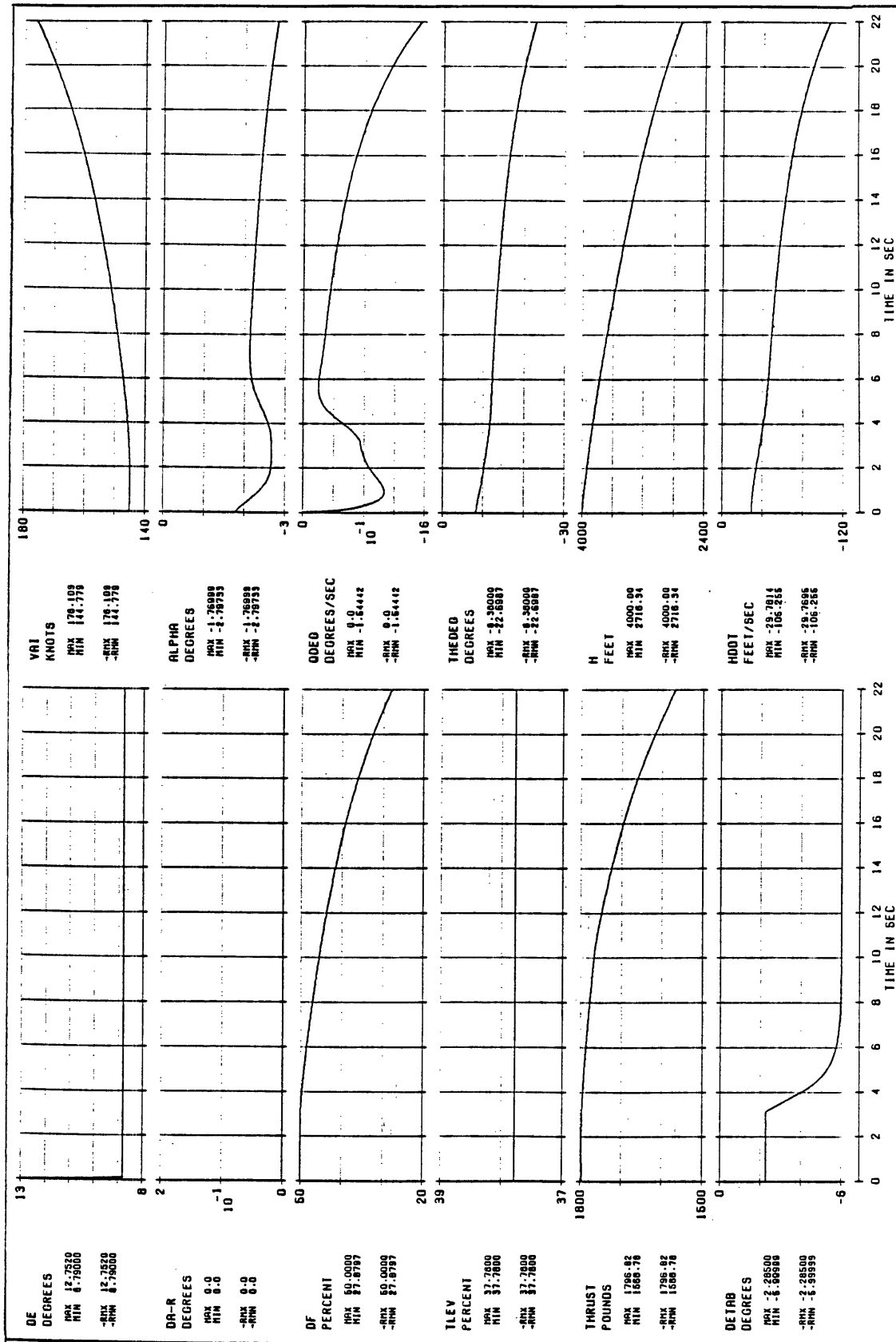
Figure 3.25a
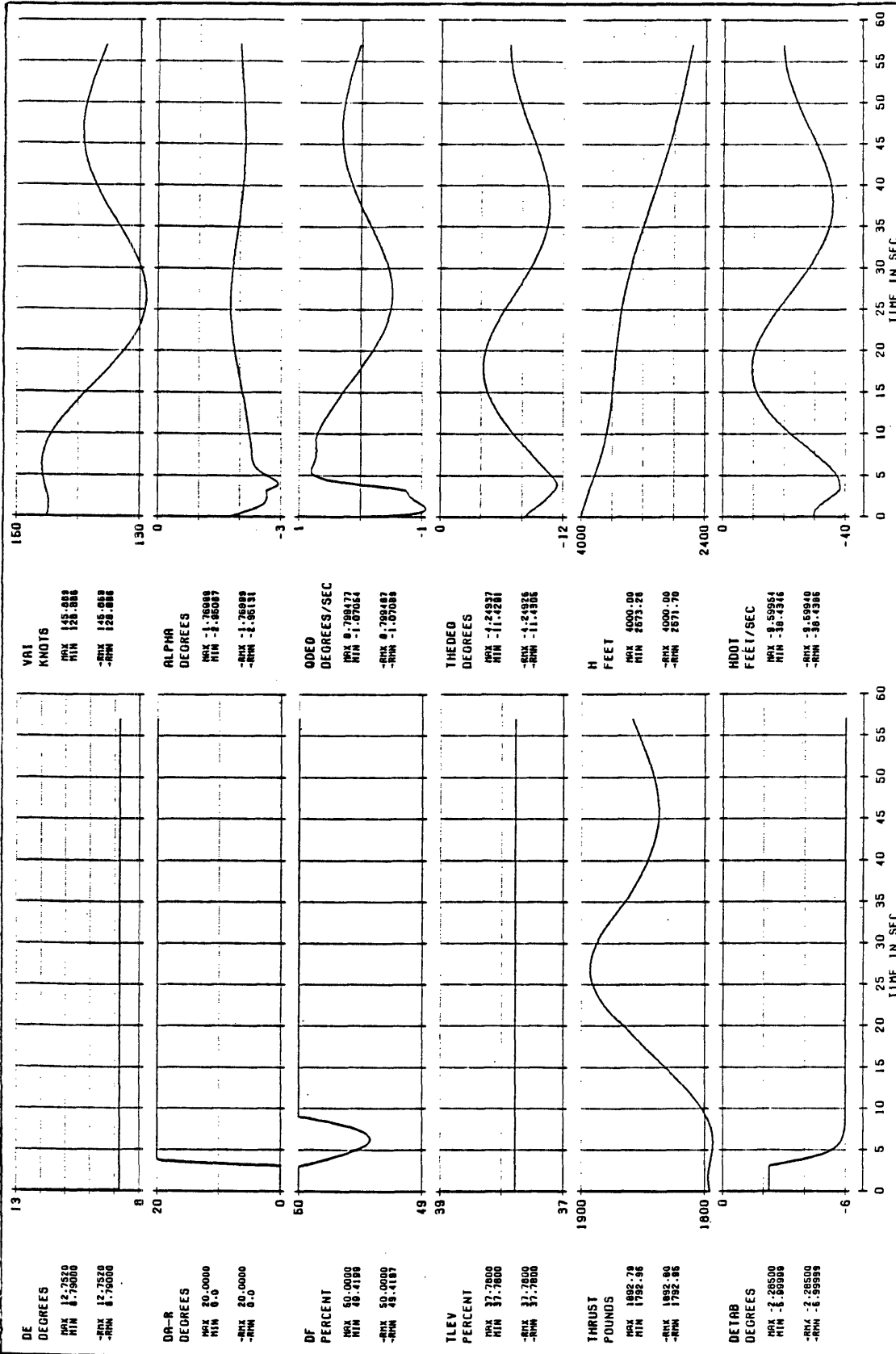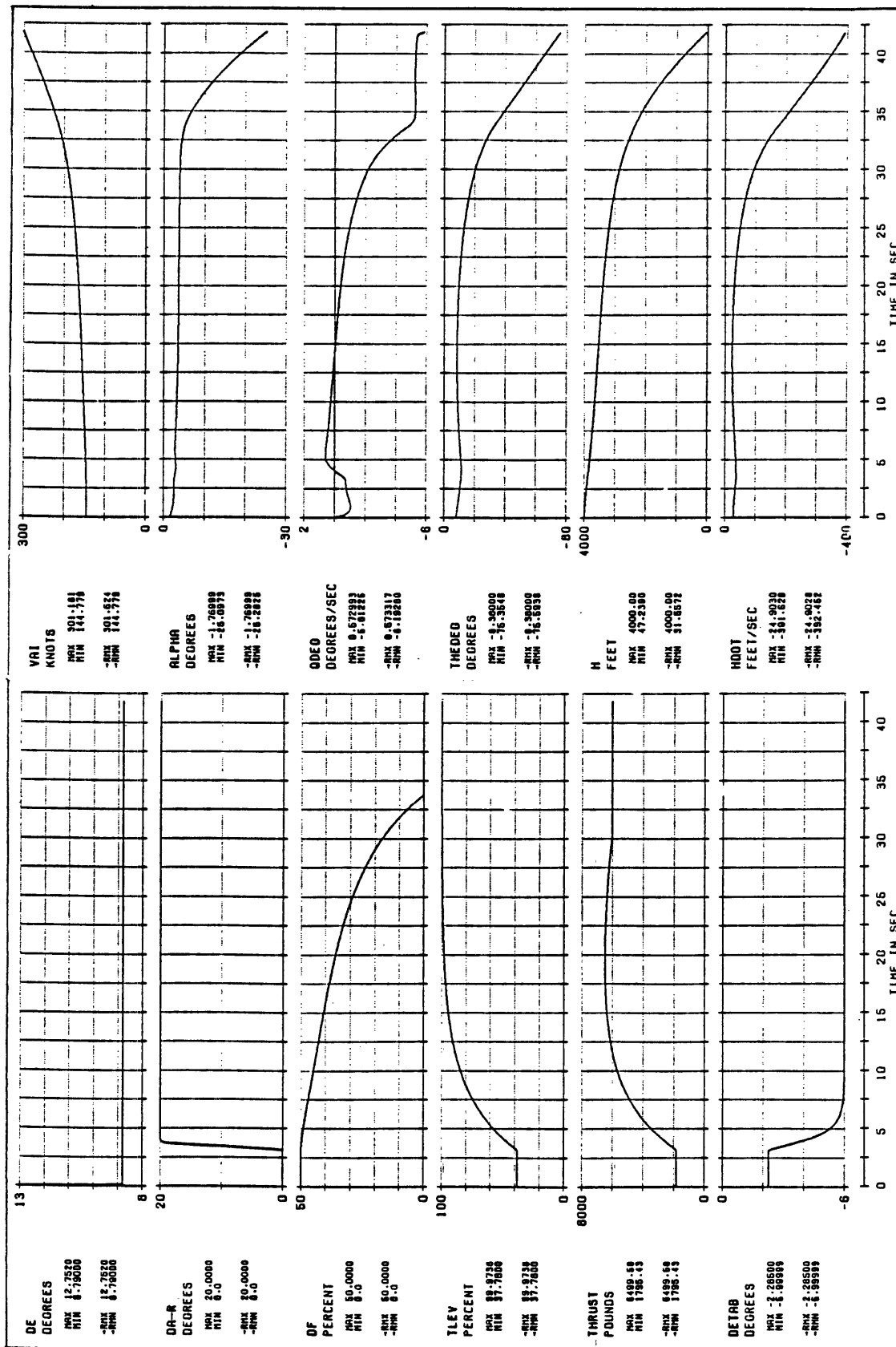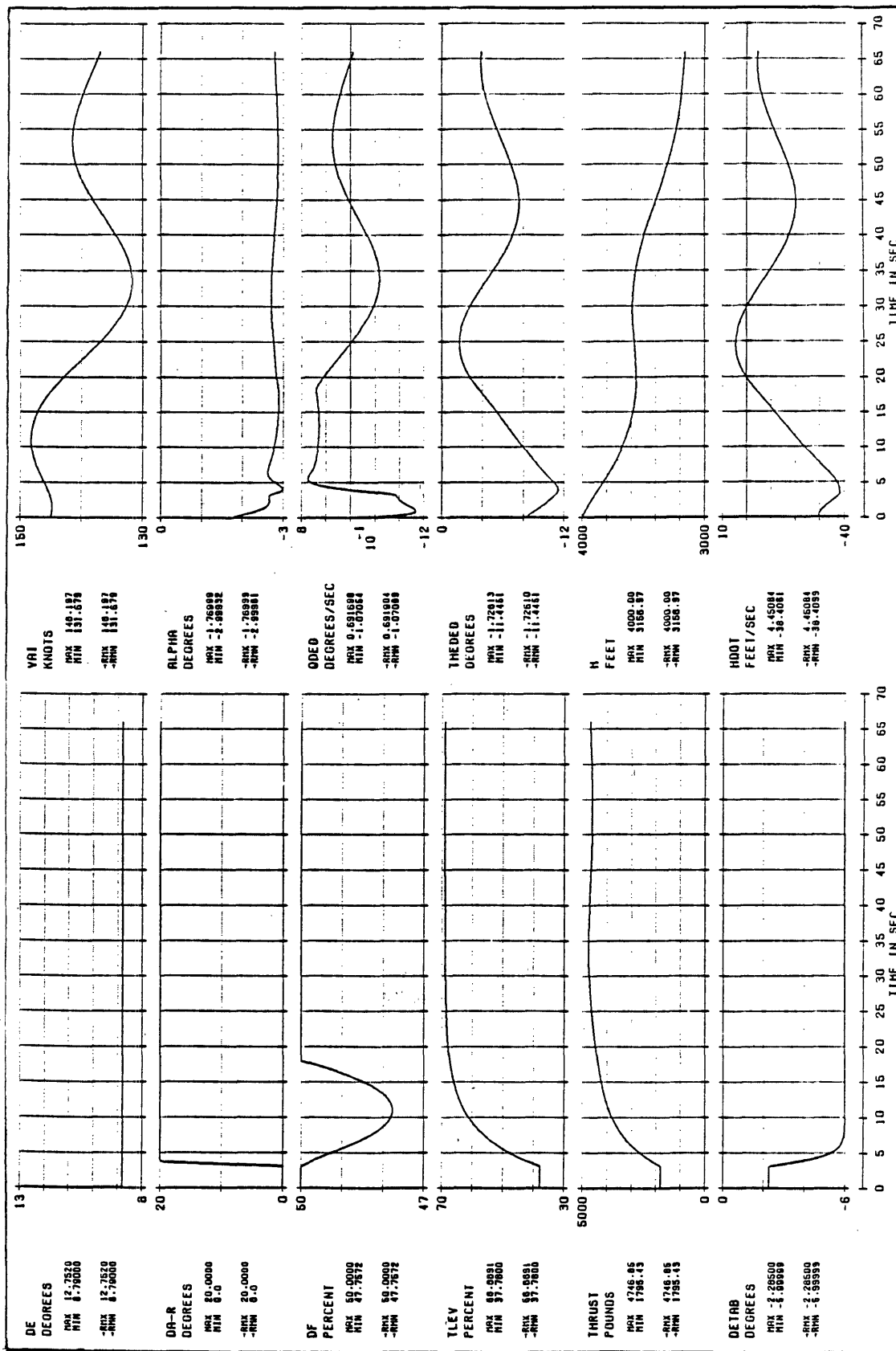
134

Figure 3.25b

135

Figure 3.25c

136

Figure 3.25d

137

Figure 3.25e

138

Figure 3.25f

139

Figure 3.25g

140

Figure 3.25h

141

Figure 3.25i

142

Figure 3.25j

143
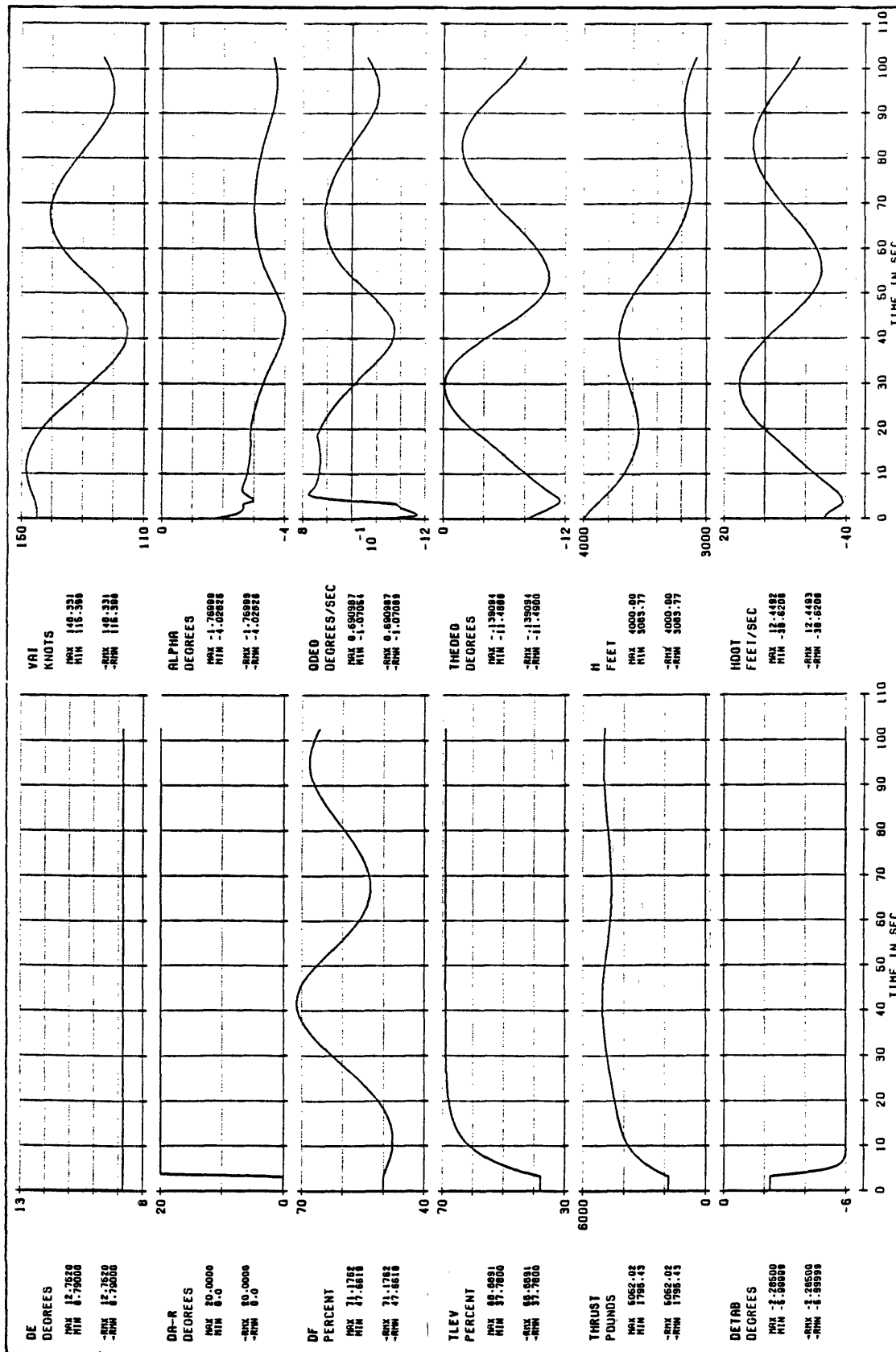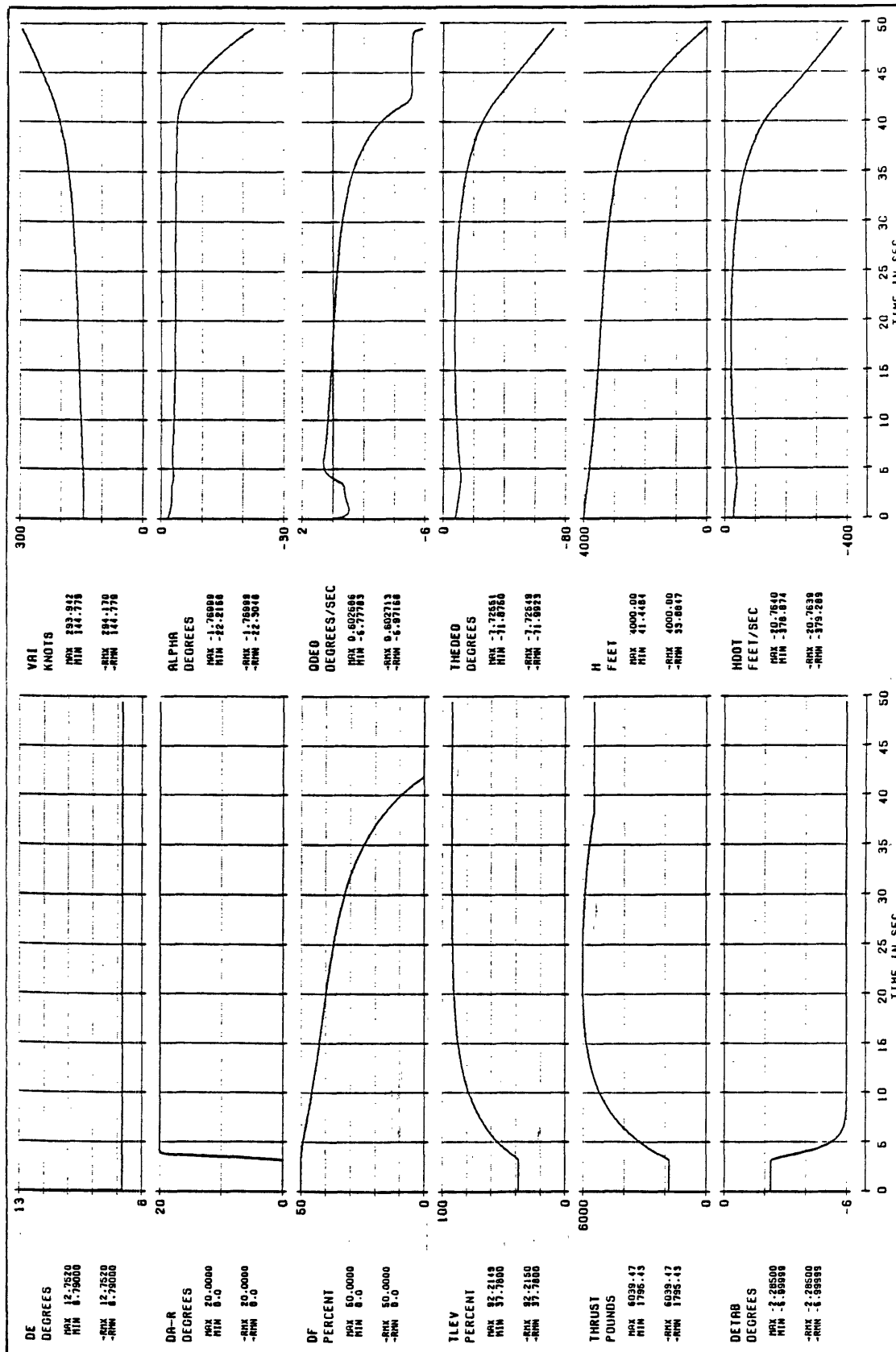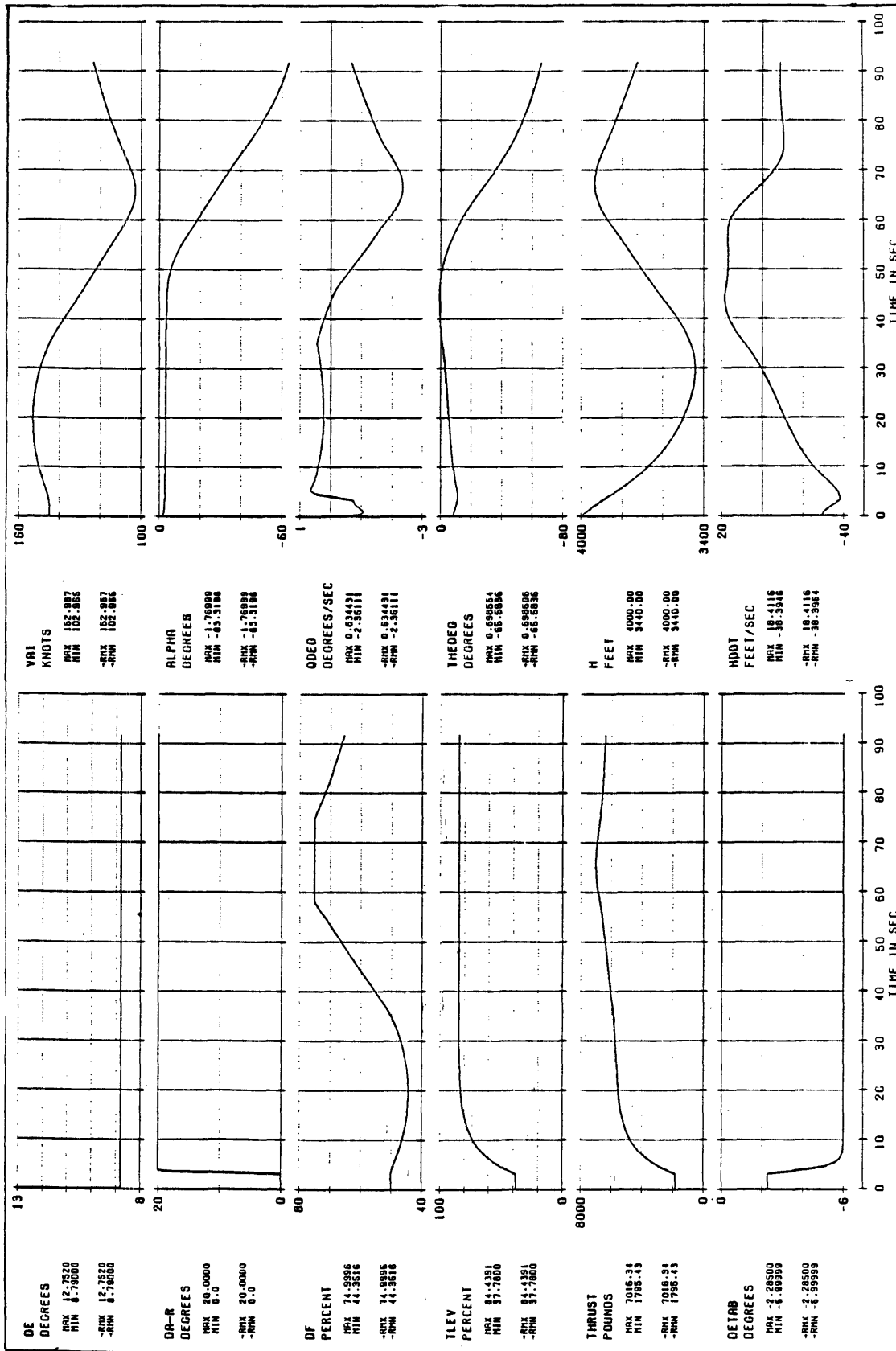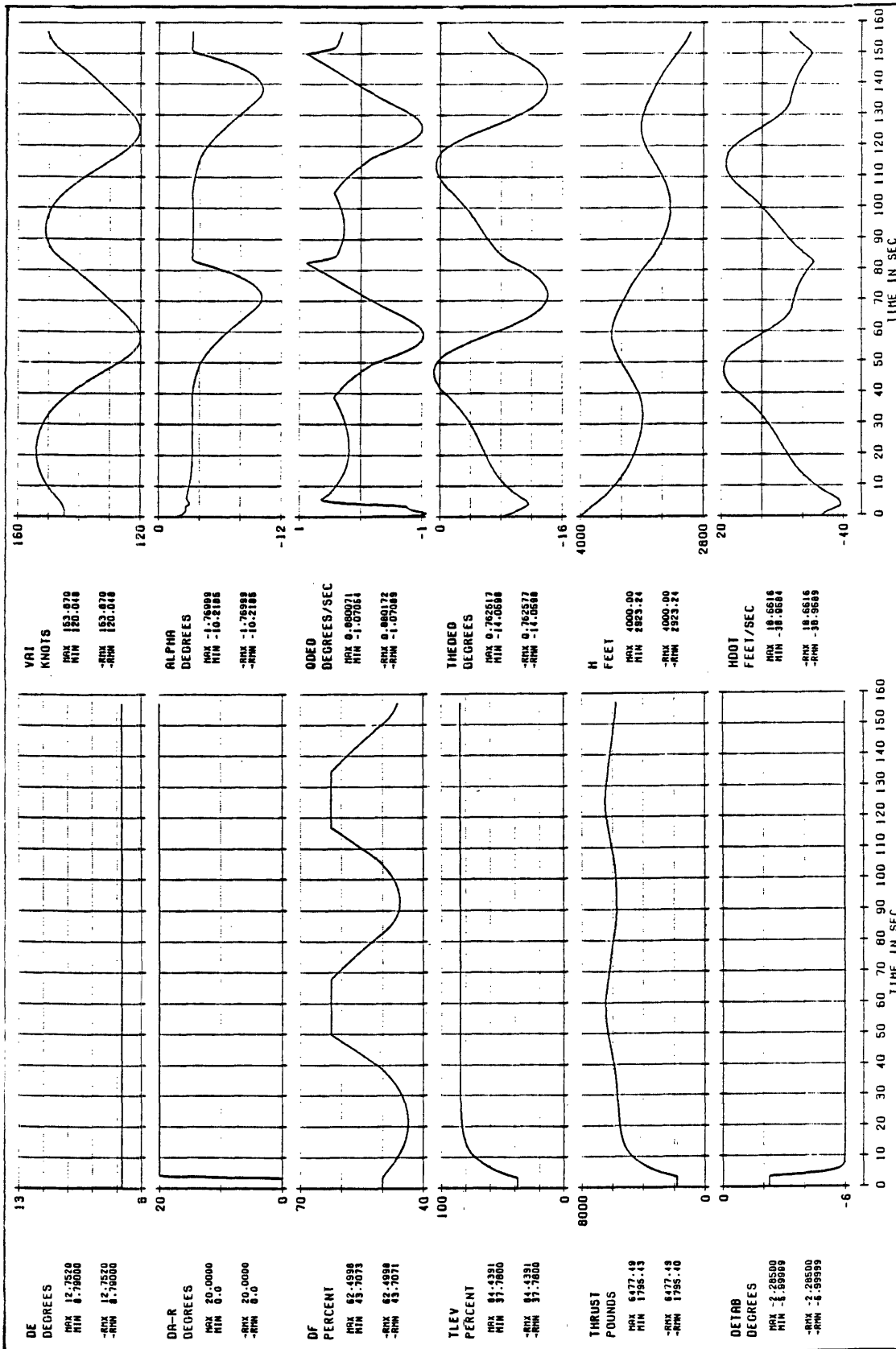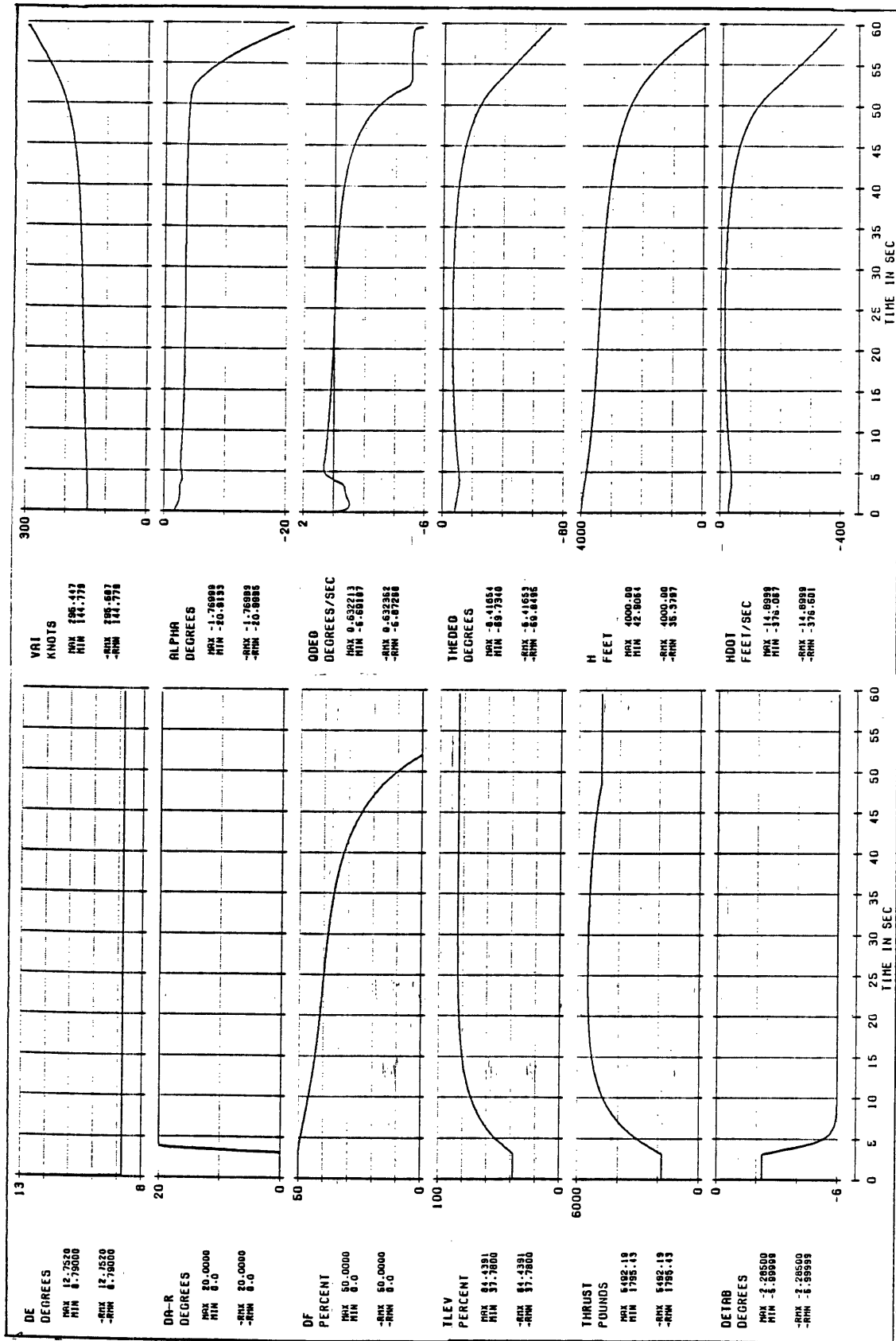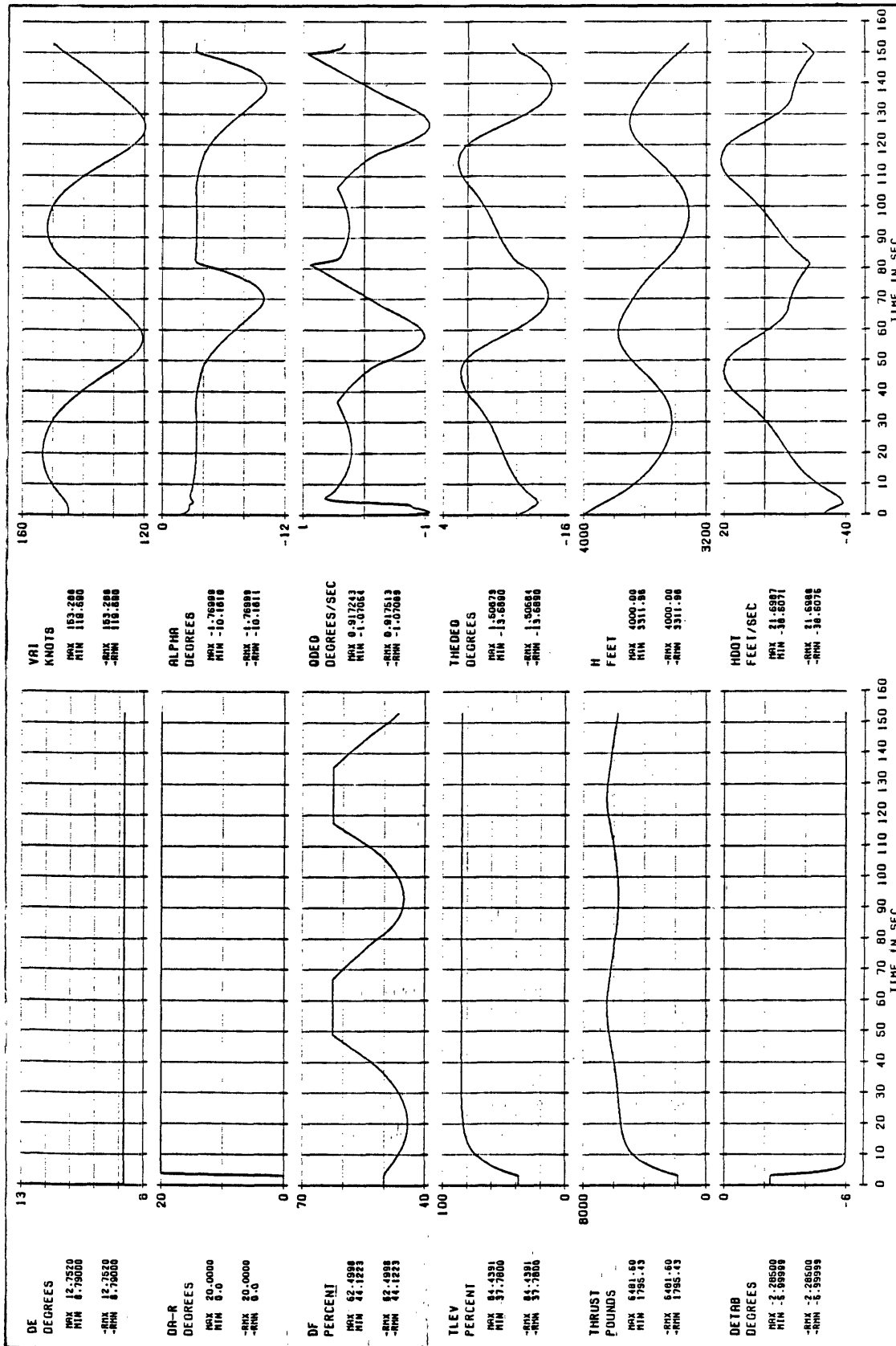
3.4. Suggested Extensions to This Type of System

3.4.1. Minimizing Altitude Lost in a Failure Recovery

The goal of minimizing altitude lost in a failure recovery can always be taken to be of very high priority. It is clear that *not* being able to minimize altitude loss will simply preclude success with certain failures. The perils of almost any failure that occurs when the aircraft is close to the ground have already been discussed, and tall obstacles can be present in the immediate vicinity in post-failure flight, of course. Since the general goal after initial stabilization is to climb to a safe decision altitude (10,000 ft. has been mentioned in this regard), getting a head start on reaching that altitude in the initial recovery period would obviously be more efficient and thus highly desirable.

Trying to minimize altitude loss in the recovery can introduce some significant complications into the procedure for solving for the recovery. In particular, thrust usage, as the fundamental determinant of climb rate, must be carefully considered. Consider the case of pitch-up elevator jam failures. For less severe failures, it is clear that *increasing thrust* to some degree can enhance the initial pitch up and make the most of the initial post-failure altitude gain. But *increasing the thrust too much* could be harmful when pitch-up inducing thrust increases lead to a stall, in the recovery of which altitude will be lost. (Further complicating matters, of course, is the question of whether this altitude lost in stall recovery-- it may be only a "mild" stall--wipes out the preceding gains made with high power and pitch.) For more severe failures, *any initial thrust increases* will preclude recovery entirely. In the example of Section 3.3.6.7, it was seen that certain pitch-up failures will lead to aircraft looping and loss unless considerable pitch-down resources are applied, including, in some cases, *thrust decreases*. Obviously minimizing altitude loss could mean trying to minimize thrust reduction, and there were cases in this study in which minimizing thrust reduction with pitch-up failures was essential in making any recovery possible. Knowing, then, when to reverse this pitch down, as is often needed, is problematic.

Altitude loss-minimizing stall recovery can be quite difficult: In applying pitch down opposition to the effects of the failure, enough must be applied so that additional stalls will be avoided. By applying *more* deliberate pitch down, up to a point, the aircraft can be recovered with less total altitude loss. Later, pitch up must be applied as soon as possible after angle of attack recovers, so that the descent incurred in stall recovery can be stopped. Optimum stall recovery is well known to be difficult.

Recoveries from pitch-down elevator jam failures also present complications when one is trying to minimize altitude losses. For example, thrust increases with very mild

failures can add some very beneficial pitch up moment. But increasing power with more severe failures just leads to acceleration of the aircraft in its dive to the ground, at the same time likely precluding much deployment of flaps for their pitch-up effects. Backing off on thrust--perhaps even to idle--can be needed--as has been seen--in order to have recovery at all. For these types of failures, however, there will be a time later in the recovery for restoring thrust if altitude loss is to be minimized. Ideally, one would like to lead and further flight path angle becoming positive as much as one can by applying thrust early for its pitch-up effects.

It is clear that true minimum altitude loss could involve pulsing thrust, backing off as the flight path angle goes negative and restoring it after flight path angle has recovered. One would also have to be very careful about minimizing recovering pitch-down control in many types of failure cases, whether pitch up or down or even involving failures of lateral/directional controls, and biased toward maximizing pitch-up control in the recovery, even to the point of applying considerably more at any point in the flight than the aircraft can finally stabilize with. The process of discovering the optimum minimum altitude loss control strategy--even guidelines for doing so--is probably nontrivial. Obtaining the true minimum-altitude loss recovery for a failure case would likely require considerable iteration, and thus would probably be worthwhile with only the most strenuous cases.

Attempts at minimizing altitude loss in a recovery were only approximate in the expert system developed for this thesis. Among the cases that could *not* be recovered in the study, there was no evidence that minimizing altitude loss would have allowed recovery. No failures on takeoff were simulated in this study, however, and this would likely encourage more attention to altitude loss. When restoring pitch up after stall--either by thrust usage or by other pitch-up control--it was elected to do so at the time at which pitch rate minimized after angle of attack decreased through 25 deg. Only when thrust increases were needed anyway for ultimate transition to an ascent from nominal or otherwise unavoidable descent was it elected to change the throttle setting. The decision was made to try to apply the thrust increases immediately, the opportunistic choice. If this induced aircraft looping, then the thrust increases were begun at the time at which pitch rate minimized. In a more complex system, slow thrust increases from the beginning could have worked better. As discussed previously, a similar choice was made in pitch-down cases, except that the thrust increases were applied at the time flight path angle first crossed zero. The power increases in several cases obliged additional pitch compensation after time of increase. These choices worked fine for all cases considered. One might want to try to move time of switch point forwards, in general, in trying to minimize altitude loss. Achieving true minimum altitude loss in the

recovery could oblige less than hardover control changes and perhaps eliminate the simplification of control switch points entirely.

It is clear that, good as an altitude-loss-minimizing emergency control strategy could be, other obstacles in the vicinity might oblige that maximum climb performance (maximum climb angle) be achieved as soon as possible. Here again one can foresee considerable work both in calculating the new airspeed for optimal climb and achieving it optimally with the emergency control strategy.

3.4.2. Extensions for Recoveries where Operating and Performance Constraints are Significant

3.4.2.1. Introduction

This type of system should be readily extendable to cover failures of other controls. The need to incorporate additional types of information in compounding a recovery control strategy is illustrated in the cases discussed in the next two sections.

3.4.2.2. An Asymmetric Flap Failure Case

As can be concluded from the Table 1.1 cases, asymmetric flap failures are not unusual among control failures (even though there are airworthiness regulations designed to prevent this). Among single failures of aerodynamic controls on the C-130, it can be expected that elevator and flap failures at larger asymmetric displacements would have the most devastating effect on flight. The case below will help to point toward other types of reasoning that should be at least implicit in some recovery strategies suggested by an expert system. In compensating for asymmetric flap failures, it can be noted that there is nothing to *reconfigure* here as in the usual attempts to deal with the loss of a primary control in the automatic control loop, since flaps are not part of any nominal loop.

The failure case to be considered here is a failure with the right flap extended 60% and the left flap unextended at 0%. The starting condition was steady straight and level flight of the C-130 at 123 KIAS at 1000', with both flaps unextended. An asymmetric flap failure here might be considered to have occurred when the pilot was in the process of transitioning (although 1000' is a bit low for this) to an approach configuration.

Figure 3.26 shows the response of the aircraft to the failure with stability augmentation (SAS) and control wheel steering (CWS) loops (see Appendix II) left engaged, in an attempt to enhance the prospect that, through the authority of these loops, the aircraft
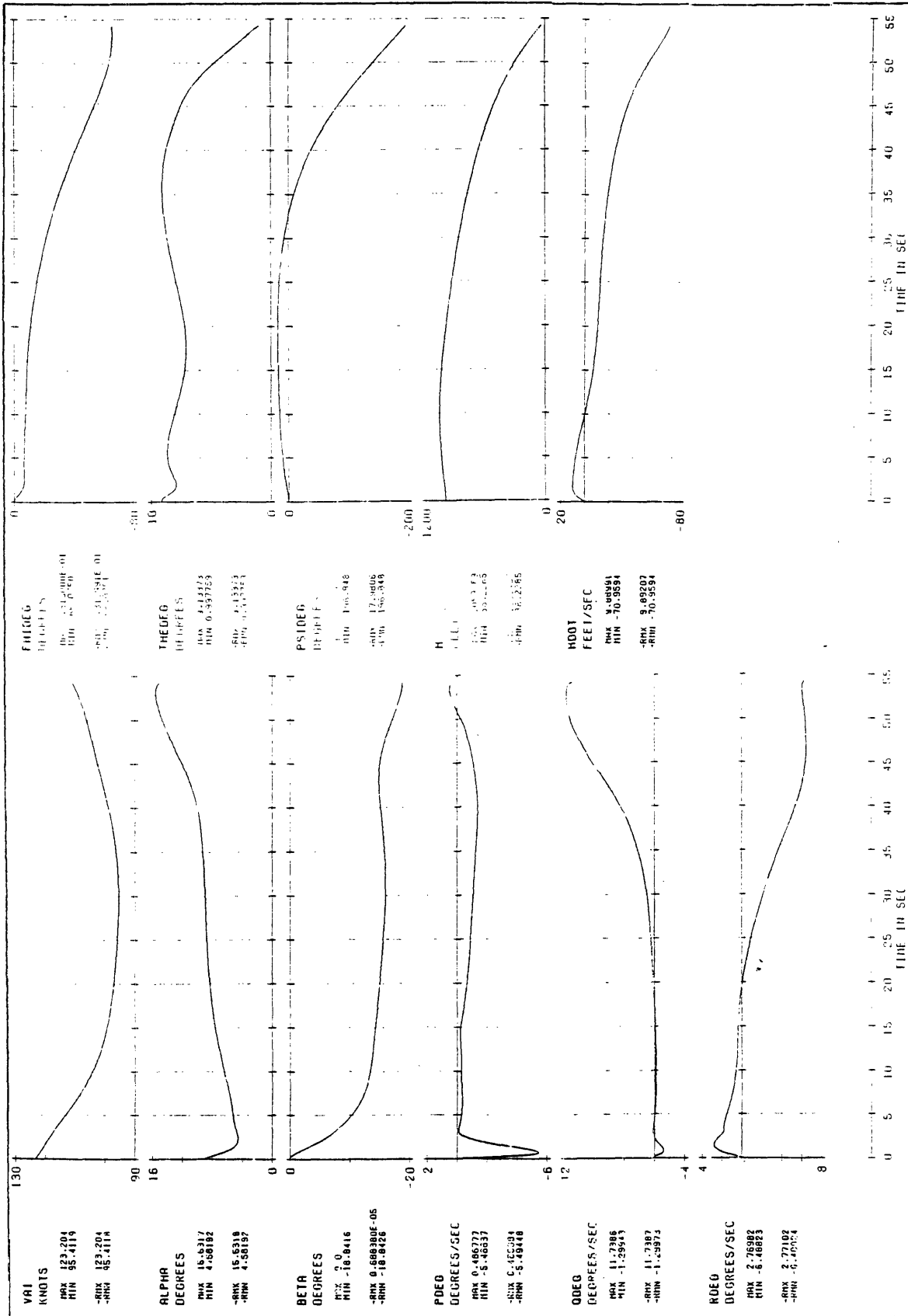
Figure 3.26 (Aircraft States)
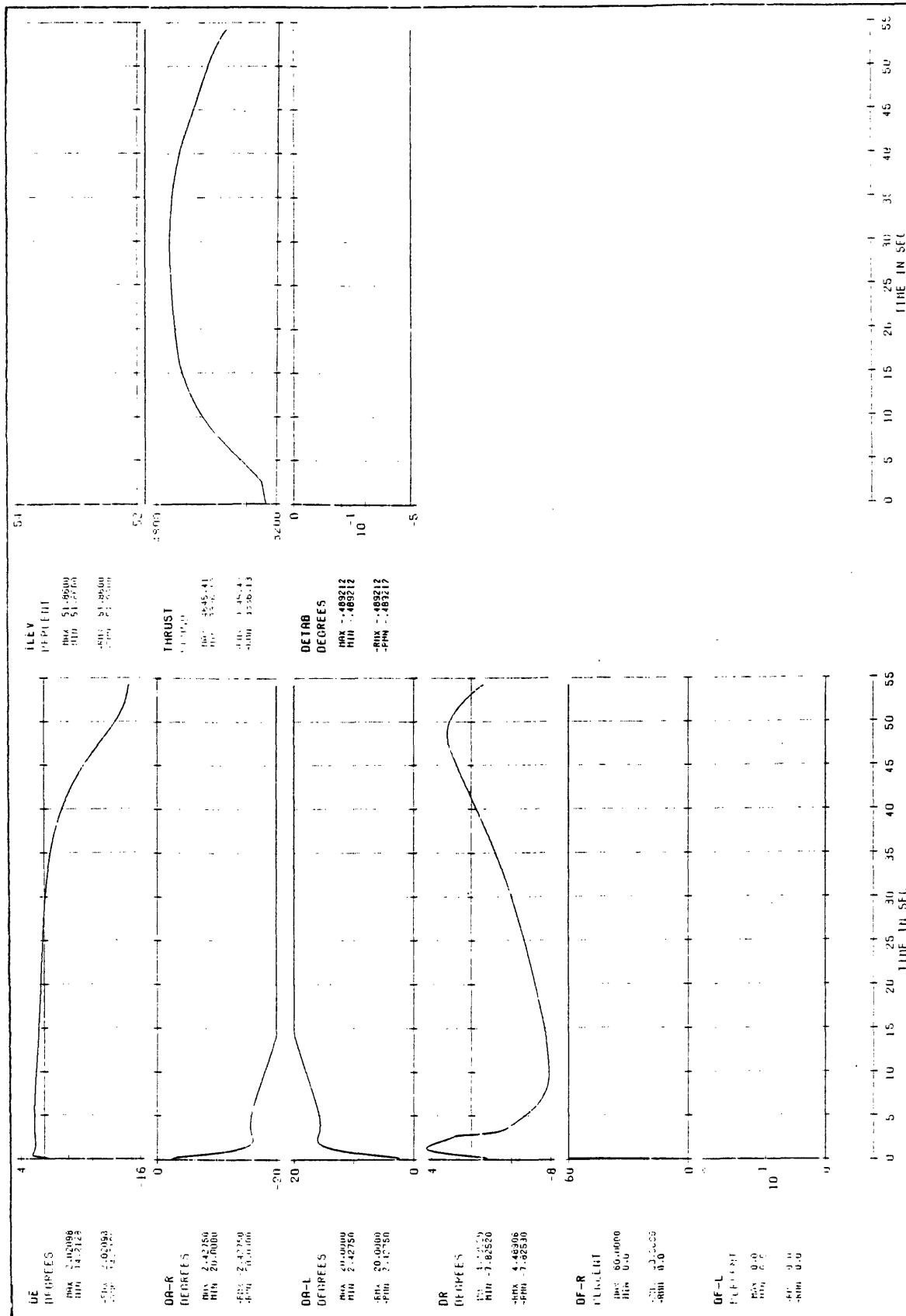
Figure 3.26, cont'd (Control Inputs)

could be brought to a stabilized post-failure phase without extraordinary action being needed. As Figure 3.26 shows, however, the aircraft impacted the ground 54 sec. after failure onset. The airspeed had dipped to about 95 KIAS before starting a late, slow increase as the aircraft dived. The bank angle reached 70° from failure-induced left roll before ground impact.

Consider again the controllability analysis for flap failures presented earlier, in Figure 2.2. This shows that asymmetric flap failures of this magnitude are not controllable at lower airspeeds (the ailerons are not sufficiently effective in providing opposing roll moment). Although Figure 2.2 does not reflect the beneficial effect of using moderate right sideslip to help in opposing the left roll (through dihedral), after higher-resolution evaluation for trim, it was clear that this failure will not be roll-controllable at airspeeds below approximately 110 KIAS.

The largely uncontrolled rolling of this aircraft with this failure was the causative factor behind uncontrolled ground impact, and, if one is to follow the guidance of a primary heuristic, namely, oppose the initial disturbance stringently, then one must make the strongest efforts to keep the airspeed above about 110 KIAS. The airspeed decayed rapidly to levels below this after the failure, as Figure 3.26 shows.

In a conservative effort to keep airspeed up during the recovery, pitch CWS was disengaged at the time of deliberate recovery action (three sec. after the failure). This was done in order to let pitch angle sag freely from its pre-failure value and thus help keep airspeed up. Roll-axis CWS was kept engaged (roll SAS alone being relatively low-gain for this aircraft), and it commanded quick, large aileron deployment to speed the sensitive stabilization in roll. Yaw and pitch SAS loops were left engaged throughout. Stability augmentation would of course be engaged whenever possible in flight, and the continued engagement eased the recovery by keeping yaw and sideslip angles small and by keeping pitch angle small while the failed-extended flap was contributing some not inconsiderable pitching moment. Part of finding a workable recovery strategy could naturally involve determining autopilot usage.

Disengaging pitch CWS alone gave a marked improvement in the response: airspeed was kept above 103 KIAS and bank angle stabilized at about 8° left bank, as Figure 3.27 shows. The aircraft was descending, however, and there was no indication of converging oscillation of the aircraft states.

Increasing the airspeed further might be attempted by increasing thrust or lowering the pitch (TEMPORARILY, as the aircraft is already very close to the ground) to get a quick (forceful) airspeed increase. It is understood that use of the elevator would be more effective in increasing airspeed but would necessarily increase altitude loss. The nice thing about increasing thrust is that, if it were sufficient to produce the necessary airspeed gain, then one
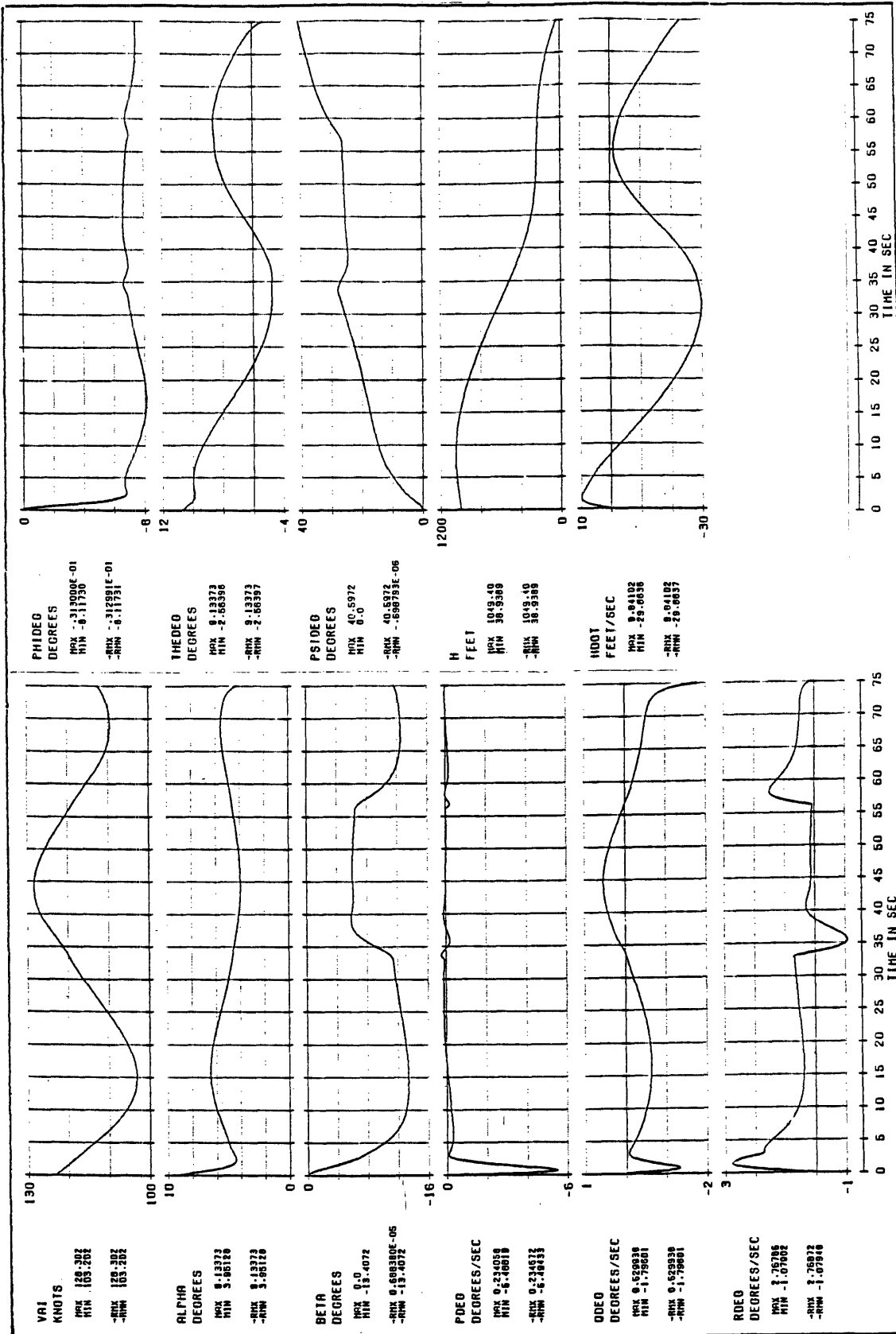
Figure 3.27 (Aircraft States)

150
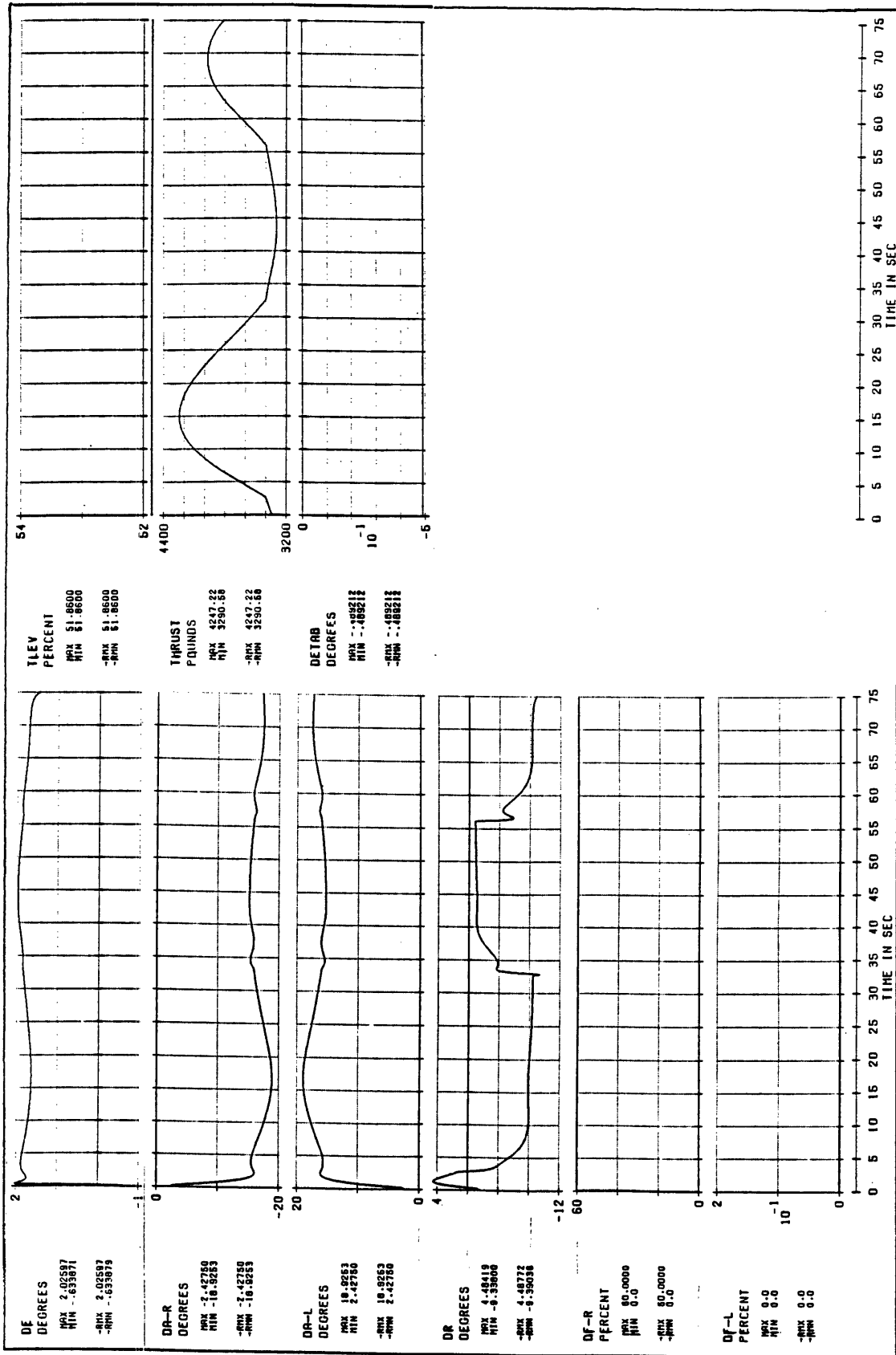
Figure 3.27, cont'd (Control Inputs)

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would already be in a better position to climb and reach a safer altitude after the aircraft was roll-stabilized.

It was found that thrust increases, from 30% added through increase to full power, resulted only in *decreases* in airspeed relative to this last response. Figure 3.28 shows for thrust increased to 100.% that airspeed could be dramatically reduced because of the overpowering pitch-up effects of thrust increase. It was clear then that recovery depended on timely pitch-down elevator usage. Figure 3.29 shows that the aircraft pitch-stabilizes very nicely in a climb when only a small (2.5°) immediate pitch-down command is sent to the elevator, along with the thrust increase to 100.% to give some acceleration in the initial dive and thus with an eye toward (hopefully) minimizing the altitude required to gain the necessary airspeed. These efforts have kept the airspeed above 110 KIAS. The aircraft stabilized in a climb at approximately 134 KIAS, with -9° left bank, approximately 8° of left sideslip, and with gradually re-neutralizing yaw angle.

The initial motivation for working with this flap failure case was the expectation that it would highlight the need for knowledge of the failure-controllable airspeed in compounding recovery strategies for some cases. As with the intermediate objective of keeping airspeed down to enhance flap deployment with pitch-down failures, there can be another type of intermediate objective in the recovery, involving, in this case, the need to satisfy a hard operating constraint. **It should be noted that a force-moment mapping reconfiguration or indeed other types of loop redesign could *not* be expected to do the sort of trade-off that led to this successful combined control recovery strategy.** This case shows that just giving the pilot an aim point (i.e., telling him that he could re-equilibrate at airspeeds above 110 KIAS with this failure) would very probably not suffice for him to make a recovery. In this case, providing only this information would probably leave too much room for the pilot's making a catastrophic choice of means to increase airspeed. Strengthening this, one might conclude that knowing about a new safer or more desirable operating point and knowing *only* that is likely *really* useful only after the aircraft has reached a fairly quiescent state and, thus, when the new point is clearly, simply reachable.

It can be understood that larger asymmetric flap failures may at best lead to roll-stabilized descent, since the lower airspeed associated with climb with so much drag may be below the roll-controllable airspeed for this failure. Stabilized moderate descent would of course be preferable to an uncontrolled rolling dive to the ground.
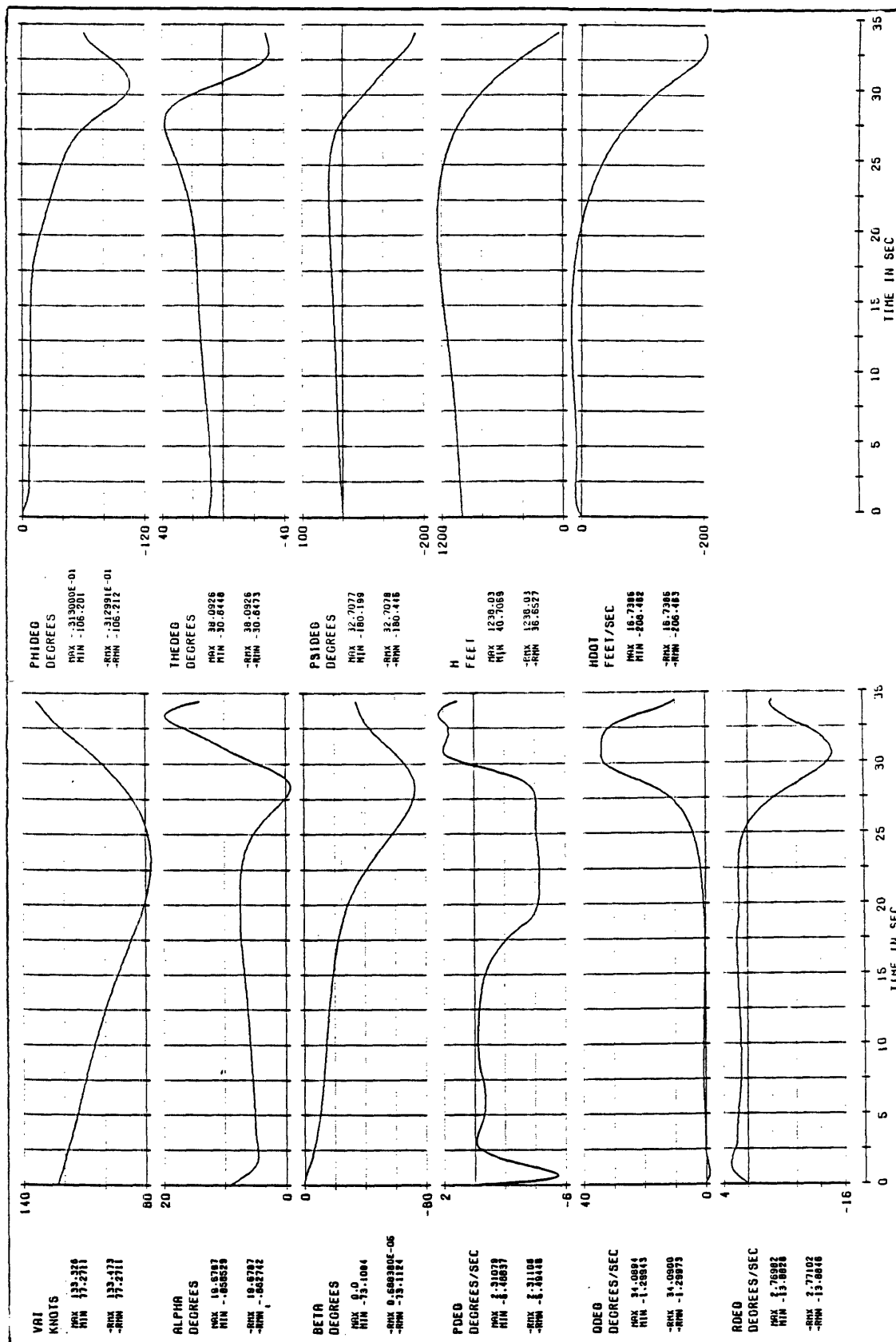
Figure 3.28 (Aircraft States)

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TELEV
PERCENT

MAX 99.9061
MIN 51.8600

-RMX 99.9061
-RMN 51.8600

THRUST
POUNDS

MAX 9000.81
MIN 3336.13

-RMX 9000.81
-RMN 3336.13

DETAB
DEGREES

MAX -.489212
MIN .489212

-RMX -.489212
-RMN .489212

DE
DEGREES

MAX 2.02098
MIN -24.8925

-RMX 2.02098
-RMN -24.8925

DA-R
DEGREES

MAX -2.42750
MIN -20.0000

-RMX -2.42750
-RMN -20.0000

DA-L
DEGREES

MAX 20.0000
MIN 2.42750

-RMX 20.0000
-RMN 2.42750

QR
DEGREES

MAX 13.9478
MIN -9.69461

-RMX 13.9478
-RMN -9.69461

QF-R
PERCENT

MAX 60.0000
MIN 0.0

-RMX 60.0000
-RMN 0.0

QF-L
PERCENT

MAX 0.0
MIN 0.0

-RMX 0.0
-RMN 0.0

TIME IN SEC

TIME IN SEC

Figure 3.28, cont'd (Control Inputs)
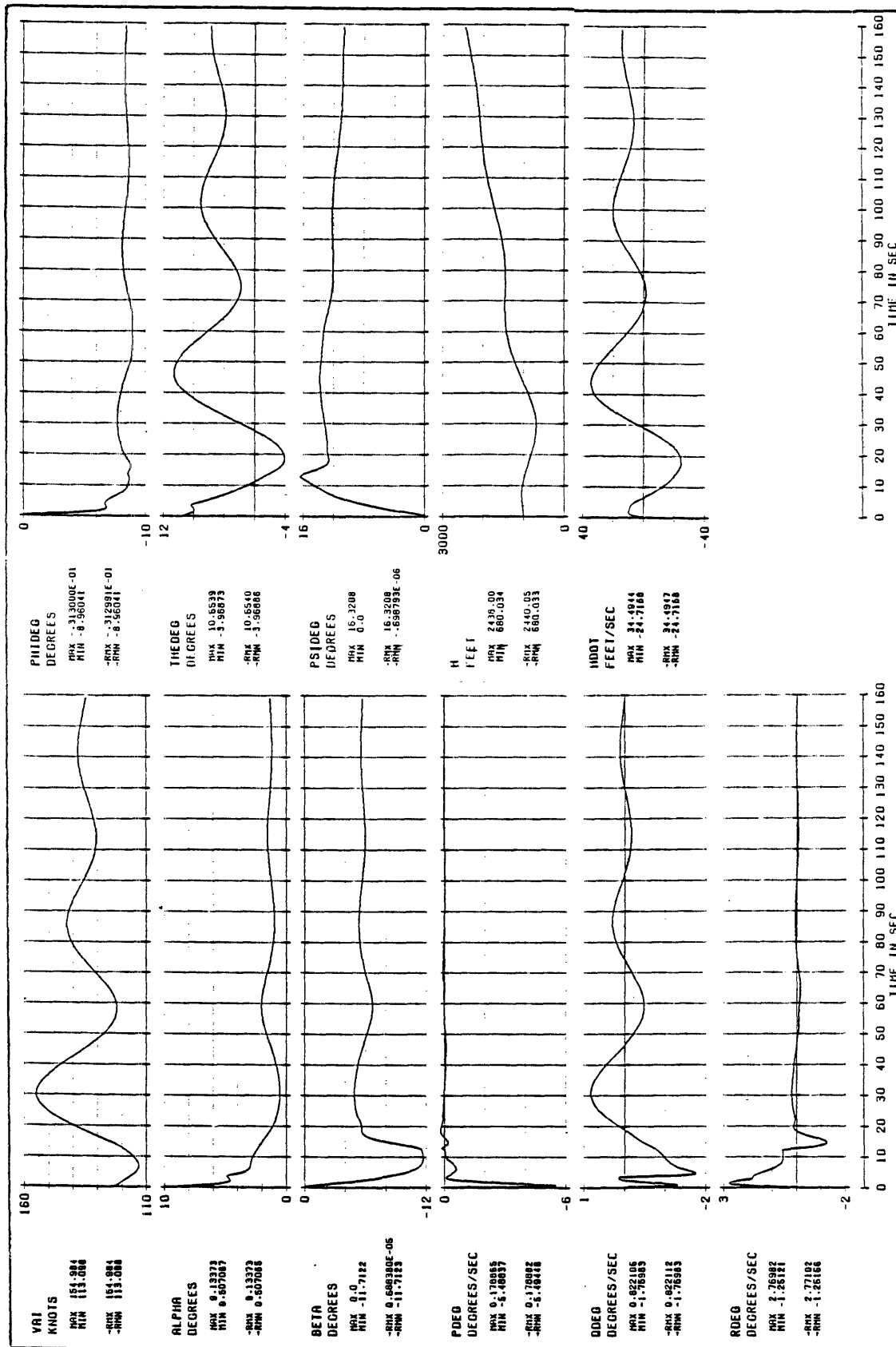
Figure 3.29 (Aircraft States)

155
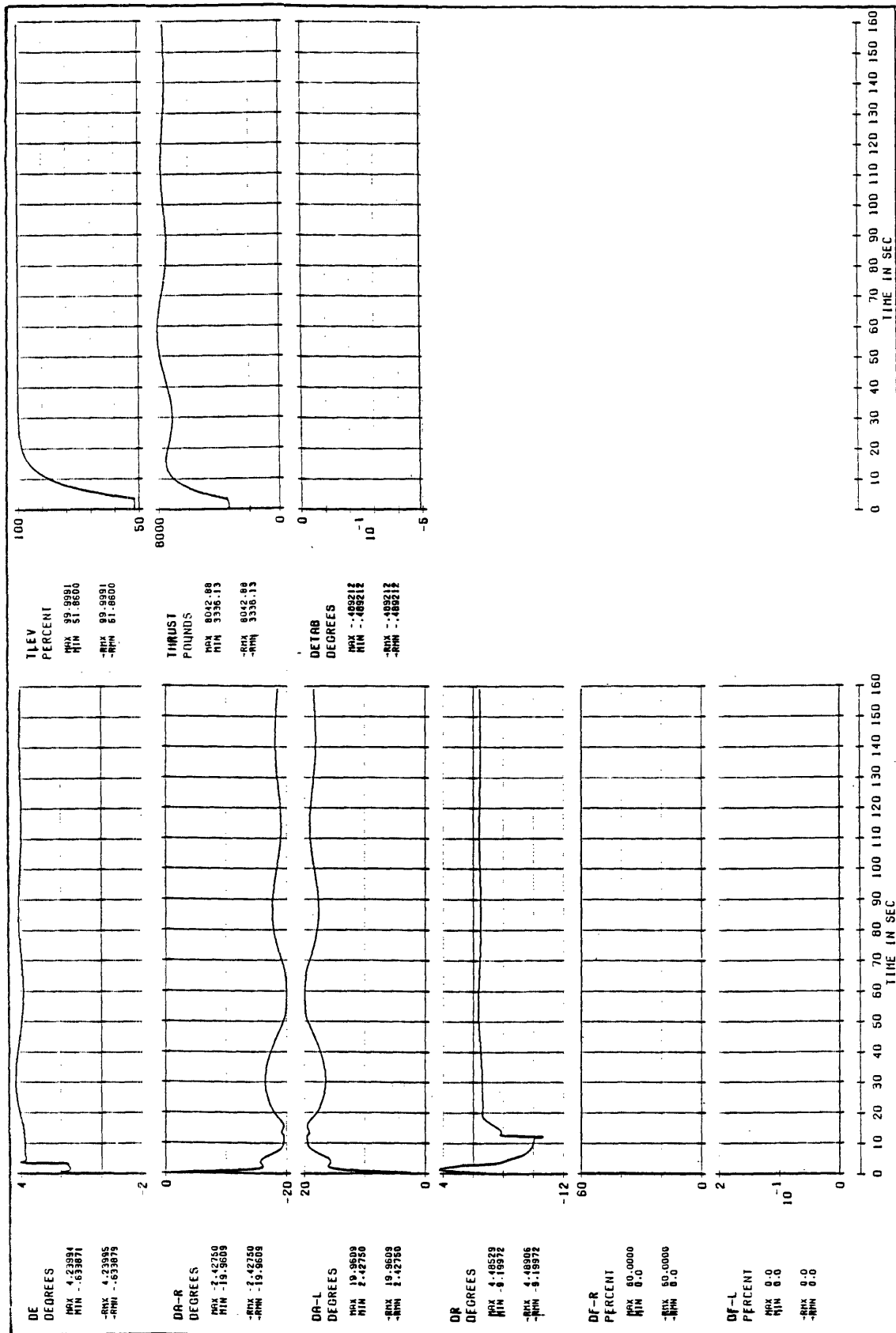
Figure 3.29, cont'd (Control Inputs)

3.4.2.3. Other Failure Cases Illustrating Need for Constraint Information in Recovery

In the flap failure case of the last section, it was clear that knowing controllability airspeed-type post-failure operating constraints played a crucial role in formulating successful emergency control. With other types of failures, other types of constraints could be important in compounding the emergency strategy. Consider cases 8 and 9 of Table 1.1. The slat failure of the first case and the engine failure of the second both would have obliged a new takeoff trajectory at higher airspeed and lower pitch because the failure induced a higher control-reversal airspeed and higher maximum lift-to-drag airspeed. As is well-known when one is flying behind the power curve, direct opposition to the effect of the failure makes the situation even worse. In these cases, performance-based constraints would become important in the recovery. Including these considerations must be part of formulating the recovery strategy. When two or more constraints apply, the one obliging the higher airspeed becomes the important one, of course. Certain types of constraints will always be more binding, e.g., the control reversal airspeed will always be higher than the stall airspeed for the impaired aircraft.

Case 22 is another example of the need to incorporate trim information in the recovery. In this case, although the elevator had detached on approach, the aircraft could have been safely trimmed at an airspeed safe for a fast landing. In Case 25, performance constraints would again have become important in recovering the aircraft: with two of four engines failed, the aircraft would have had only a narrow airspeed envelope for flight with minimum descent.

3.4.3. Other Extensions

It should be clear that the operation of the aircraft prior to the failure can substantially complicate the effects of the failure, both aircraft state and control setting. For example, suppose that, as in case 3 of Table 1.1, there is a rudder failure during non-obligatory three-engine operation. The recovery strategy should, of course, include thrust resymmetrization or even opposite asymmetrization, so the recovery aid system would need to know that the engine was optionally de-activated.

There is another type of elaboration and extension that would be included in more adept expert systems of this type. Suppose, for example, that a workable strategy has been found. There could be several reasons for going back and attempting to refine it. If this strategy involved hardover deflection of the ailerons, then one might consider trying to back off on their usage in order to increase turn capability in the immediate post-recovery flight.

Any sort of minimization of deflection of compensating control might similarly be desired in order to hedge against additional failures, especially as they might be expected after the given primary failure. Another type of strategy that might call for refinement is one with control changes at numerous times later in the recovery. One could expect to accumulate, in many cases, more than the minimum number of such changes. For higher-performance aircraft especially, one could expect numerous control change points if the expert system is oriented toward trying maximum control values first. Thus this process of streamlining the strategy could be very important. The need for refinement and the way in which it might be approached could be inferred through rules written in the expert system.

The strategy to find successful post-failure control for the cases in which thrust was reduced to facilitate flap deployment reflects backward chaining from a goal (flap deployment) to a subgoal (airspeed decrease) to the facilitating action of thrust decrease. Similarly, finding a strategy for successful recovery from the asymmetric flap failure involved backward chaining from the goal of keeping airspeed up to one at which failure-induced roll could be controlled by the ailerons to the facilitating forced early pitch-down using the elevator (a control, by the way, that could be readily undeployed--a dimension contributing to general control effectiveness as described in Section 3.4.3). By doing considerable manual simulation of recovery strategies, there is some possibility that this sort of inference might never need be explicit. On the other hand, the capability to do explicit backward chaining, particularly when the rules reflect less manual work with failure cases, might be a useful part of a complete system. It is not clear at this time what types of learning possibilities can or should be embedded in the alternate emergency control-type expert system, i.e., writing new rules. OPS5 as well as other expert systems shells will support new rule-writing.

3.4.4. Concerning Learning in Systems of this Type

Several extensions to the expert system are indicated if it is to be endowed with possibilities of *learning*. The system must have more *general* information linking cause with effect, that is, linking undesirable features in the response with possible cause and with changes that could be useful in remedying these undesirable features. There must be some possibility of inducing subgoals in achieving a successful response. The choice of what to try must be predicated on reasoning that chooses something that is expected to improve the response ("Means-End" problem-solving in AI theory [42]). Then there must be some metrics for evaluating whether the change has actually improved the response, and the system must be able to backtrack if the response has degraded. Because many of the rules will have

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empirical threshold state values embedded, the system must be able to change the thresholds in rules already established. The system must be able to formulate rules as it goes--some generalizing, some specializing. Some failure cases may have to be re-run in order to check the new rules.

3.5. Prospectus for Use of This Type of System

It seems clear from this development of a rule-based system to discover emergency control strategies that

--**A more elaborate system of this type should very easily be able to deal with multiple simultaneous control failures.**

--**A more elaborate system will very likely be able to perform as well as pilots (or even better in some respects)--the knowledge is not deep.**

It is not clear whether a system to do outright pre-simulation in real time of the recovery strategy could be implemented, or that it need be. An expert system that could discover the correct recovery strategy for different failure cases could quite naturally be used as the basis for generating--**on the ground**--broad recovery guidelines over large ranges of aircraft failure cases and failure circumstances. It is easy to understand that lack of generalizing information about successful emergency control strategies has mitigated against the use on board of some automated emergency control. It is intuitive, though, that broad ranges of failures and failure circumstances would yield to the same basic recovery strategy, or *type* of recovery strategy, anyway. To simplify, one can look for strategy "change" boundary points only. The ability to generalize the strategy would be especially pronounced if one did not insist on an optimal strategy in a strong sense, and thus one more likely to need to be specifically tailored to a given case. If some near-optimum recovery were being sought, the iterated recoveries would be tedious at best for a pilot. If it could be developed, an automated system to do the iterations could quite possibly do a better job, anyway, since it could probably be more sensitive to the trends of improvement or degradation of the recovery strategy. The final result of such a broad pre-simulation study could be the creation of a

system with enough information to allow its processing to consist of straight-through paths from information about the failure to the successful recovery strategy.

$$\left\{ \begin{array}{l} \text{The control failure} \\ \text{(what has failed and how)} \\[6pt] \text{Indicated airspeed} \\[6pt] \text{Altitude} \\[6pt] \text{Other initial states} \\ \text{(as required)} \\[6pt] \text{Initial control settings} \end{array} \right\} \longrightarrow \text{Recovery strategy}$$
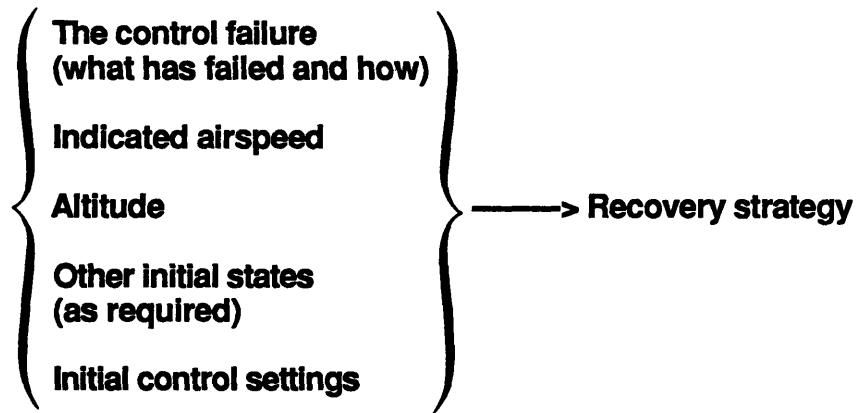
A system that could do this processing would be extremely attractive for inclusion on board most types of aircraft. One can foresee that

> --A more elaborate system of this type could be an important resource for aircraft design, certification, and pilot training.

Even if there were planned loop reconfiguration after the failure, this type of system could give some rough idea of the basic redundancy of the aircraft configuration alone, as the expert system looks for control strategies that show rate and state zero-crossings but without stabilization being asked for. This type of system could be quite useful even if used for only the most likely failure modes, like full hardover failures.

One of the especially appealing things about a pre-simulation survey of failure recoveries is that it could also lead to rational support of decision-making about emergency control where there is uncertainty about the failure and even the aircraft dynamics. Anyone would want to establish a "fail-safe" emergency control. It is clear from the work with C-130 elevator failures that there will be no one absolutely fail-safe control to the point of aircraft stabilization in climb for every failure situation. Shortening the time span for required automatic response before the pilot could be expected to respond correctly would likely contribute to easier robustness, however.

It could be another issue in robustness in actual on-board usage when and whether one makes the decision to try gradually increasing inputs for less serious-looking cases, hoping (encoding this would be nontrivial) that one has the right idea about what control would be workable. It is very possible that one will have to implement a two-tiered initial response: the-best-that-can-be-recommended-given-information-at-hand vs. there's-time-to-

do-some-calculations. There are other foreseeable guidelines for quick response based on qualitative ideas of probable cause, and this has been overlooked in traditional failure-accommodating control research. As an example of a "robust" guideline that might be applied before the failure is identified, if the aircraft is rolling after an attempt to put the flaps down again, a split flap condition has probably been induced. Action to attempt to raise the flaps again may be automatic or may be something that the pilot can be expected to do.

3.6. Summary

A demonstration rule-based expert system to discover successful post-control failure emergency control strategies has been developed. The philosophy adopted here in establishing emergency post-failure control is quite different from, although not incompatible with, that taken in usual failure-accommodating control research. Comparisons are difficult. Systems of this type can call for use of unusual controls: remember that we are talking about life and death issues, so form and conventionality are superfluous. Systems of this type can take into account saturation of controls in a situation in which it is very important. Finally, they can find the rather counterintuitive strategies that are sometimes required. They can be taught to recover where coupling between control of different axes is involved, for example, where temporary rolling to let the aircraft nose fall through is required in recovering from a large pitch-up *longitudinal* control failure. Their usefulness without control reconfiguration probably depends on the aircraft being of medium- or low-performance. The result is more or less qualitative control of a quantitative system, an established area of interest in artificial intelligence work. Extensions to the system have been discussed. It is believed that this type of system could be an extremely valuable resource.

Chapter 4

Preliminary Integration of a Recovery-Aiding System:

Initiating Emergency Control
Pilot Advisory System
Pilot-System Interaction Issues

4.1. Introduction

This chapter will indicate how a complete recovery aid and advisory system might be used during the span of post-control failure flight. Initiation of system usage and pilot-system interface will be examined. The suggested *pilot advisory* function will be given a narrative introduction and considerably more treatment.

In the following, it will be assumed without loss of generality that the failure manifests itself, as is common, soon after commitment to takeoff. The following discussions are intended to be general and not to refer only to a certain type of aircraft; however, when the type of aircraft makes a difference, note is made of this. In formulating the material in this chapter, imagination faltered somewhat as to what might be involved in implementing a post-failure aid and advisory system. Incremental accumulation of information through treatment of a large spectrum of failure cases, as with the development of the expert system in Chapter 3, would obviously be a part of the development. This chapter, then, is intended more to introduce some foreseeable issues than solve problems of more or less detail involved in a full-up system.

4.2. Phases of Post-Failure Flight

Periods of recovery flight can be categorized with respect to generic types of flight phases, as presented below. At each point, achieving the next of these flight phases would correspond to achieving the next of the highest-level subgoals on the way to achieving the highest goal of saving as many lives as possible. For most aircraft, saving as many lives as possible means getting the aircraft on the ground in the least traumatic way, and this will be considered the only possibility here because it incurs the more inclusive analysis. For certain other types of aircraft, there is the option of abandoning the vehicle, of course, although, with better assessment of the remaining capabilities, fewer bailouts than ever before will be required.

Phases of post-control failure flight:

1. Regaining (maintaining) control of the aircraft
2. Getting to a safe "decision" altitude
3. Stabilizing at altitude, determining landing capabilities
   and deciding where to land

   ----------------------possible bailout at this point, with certain aircraft

4. Nearing landing site
5. Making approach and landing

There were only five cases amongst those listed in Table 1.1 in which a successful recovery was made: cases numbered 5, 10, 16, 19, and 24. In each of these, after control of the aircraft was regained, post-failure flight proceeded with climb to altitudes on the order of 10,000' except where the failure occurred with the aircraft already at altitude. In all of these cases, descent to landing was generally effected as soon as possible. One can infer in each that some determination of landing capabilities was made, although this could clearly have been done without much consideration where the failure was not too strenuous. The fourth flight phase in the list above is intended to cover *extended* cruise flight in the debilitated aircraft, especially when landing is to be attempted at a distant location. For military aircraft for which the option of extensive post-failure maneuvering is to be retained, the following general "flight phase" is added for purposes of discussion:

6. High-maneuvering flight

As subgoals, achieving these flight phases successively reflects the "planning islands" idea, a very human heurism in the best sense, because driving toward islands greatly simplifies the "calculations" involved in the overall strategy. This idea is also clearly embodied in the high-level emergency procedures in flight manuals. Figure 4.1 helps to illustrate the fact that piloting, especially emergency piloting, involves mostly forward, short-time-horizon planning. When the failure manifests itself early, a very fast-thinking pilot could conceivably be able to see that a truly opportunistic plan to regain the airport of origin would be successful, but it is clear that the calculations to support this are much more difficult. Intuitively, there is the feeling that the pilot simply probably would not have enough information about the ramifications of such a complicating thing as a control failure

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for much significant, quick action. Implicit in later phases of post-failure flight is that the ramifications if not the identity of the failure are better understood.

Decision altitude
reached

Control of aircraft
re-established

Immediate
post-failure
state

Safest
Possible
Landing
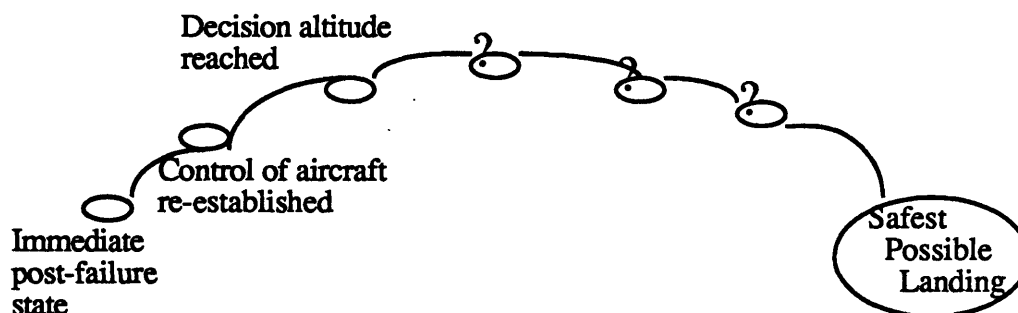
**Figure 4.1 : Forward, Islands-Based Planning
in Post-Control Failure Piloting**

4.3. Issues in the Initiation of Emergency Control

Failures of control surfaces are usually catastrophic because they generally come in such a way that they represent a large disturbance to the aircraft. The first goal of post-control failure flight in most cases would be to re-establish control of the aircraft. Doing so defines the first flight phase and can be thought of as culminating with the aircraft stabilizing in a climb.

As has been suggested earlier in this thesis, a recovery-aiding system will generally need to play its most dominant role just after the time of the initial failure manifestation. This assistance may be expected to consist of either or both of the following:

--Loop reconfiguration/ restructuring
--Recommending and/ or imposing emergency control

As has also been suggested, assistance may need to be high- or full-authority, wherein control is largely temporarily taken from the pilot.

Because FDI can be expected to identify the failure in many cases, initiation of the reconfiguration/ emergency control could be on the basis of a thresholded failure indication.

A clearly appropriate basis for initiating emergency control, however, would be a recognizable verbal request for assistance by the pilot, e.g., "HELP!". No misunderstanding about automatic recovery initiation could arise with this. In order to use this information in the most useful way, of course, the automated aid system should be tracking aircraft response beforehand so that the emergency control it imposes could be well-grounded and quickly applied. It remains to be determined whether the time involved for pilots to recognize that they need help actually leaves much workable time to formulate and impose emergency control in some useful number of failure circumstances.

Considering the cases in Table 1.1, the initial (dynamical) manifestation of a control failure can be expected to take any of the following types of forms:

1. Decreasing airspeed/ subnormal climb, particularly on takeoff
   (slats retracted, flaps retracted, pitch mistrim, engine failure)

2. Excessive pitch up or down
   (elevator or stabilizer failure, pitch mistrimming)

3. Excessive rolling
   (aileron failure, spoiler failure, flap asymmetry)

4. Excessive yawing (afterwards, optionally, rolling)
   (rudder failure, flap asymmetry, engine failure)

5. Slow divergence in pitch or other axes
   (e.g., uncontrollable climb--elevator failures)

The manifestations of a control failure **can** be very distinct and significant. But can one do anything prior to full failure identification? Being able to give early notification of danger to the pilot, certainly if explicit FDI is not available, or of rendering pilot assistance prior to explicit failure detection is a very tantalizing prospect. Initiating and performing correct initial emergency control will generally be the hardest aspect of recovery from control failures, and any extra time for formulating the emergency response would clearly be highly desirable. There is some precedent for response only-based danger notification, for example, with the ground proximity warning devices that have been installed on most military and commercial transport aircraft. It has been noted before now that on takeoff and departure, traditionally the time the aircraft is most liable to have a control failure, commercial transport aircraft will have remarkably consistent trajectories. This may be an exploitable feature in this regard. It is clear that there is *something* that could be done along these lines. Besides, this response information is all that pilots have been able to use in the past in control-failure situations to become aware of danger and act in a rational way to restore the aircraft to safety--sometimes

successfully. Consider the Flight 1080 case again. The most compelling initial failure manifestation was the airspeed decrease, which the pilot projected to stall long before the aircraft was near an unsafe operating state. McMahan asked himself what was affecting airspeed--drag, what was affecting drag--pitch, and what might affect pitch--thrust. McMahan "knew" to try thrust changes because, based on climb performance and the failure manifestation, and presumably from cockpit engine gauges, he verified that the engines were working. There are perhaps many interesting issues to be exploited in the focused qualitative-quantitative trajectory projection that pilots do and the backward chaining to establish a response. There is the possibility of automating some of this.

Because the issue has not been given explicit attention before, a word should be added about the probable masking of the effects of a failure by the automatic control. By its nature, automatic control could be expected to begin quickly to try to oppose the effects of a control failure. With most failures, however, this response would soon fall short of the needs, because of its generally too-low authority or the number and general effectiveness of the controls it can deploy. To help the dynamics-based FDI system in its job of comparing intended with actual aircraft trajectory, pilot commands (or other high-authority commands, e.g., autopilot ILS intercept commands) should be disentangled from signals due to inner-loop-type stabilization functions of the automatic control. This separation will be more or less difficult, depending upon design aspects of the automatic control, but by doing the separation, significant additional time for failure FDI could be made.

It has been noted previously in this thesis that reconfiguration of the automatic control of certain types of aircraft would very definitely be desirable or even positively needful after certain failures. It has also been noted, however, that all indicated recovering control changes could not be be expected from most standard types of automatic control, reconfigured or not (remember that use of secondary controls can be essential in recovering), and that, for certain types of aircraft, more manual-type--less *precise*--control changes would be all that was necessary to effect recovery in the immediate post-failure period. For high- or low-performance aircraft, at least some large manual-type control changes would be indicated. For a medium-performance aircraft like the C-130, this type of emergency control deployments could predominate, regardless of the "background" control reconfiguration.

Several clear reservations can be put forth concerning the notion of expecting the pilot to effect emergency control deployments himself, even in medium-performance aircraft such as the C-130 and even if the pilot were prompted. As was seen in Chapter 3, recovery from elevator failures on the C-130 often involved very rapid deployment of numerous controls simultaneously. In addition, although the required deployment of a given control clearly not need be terribly precise with this aircraft, less than hardover deployment of a given control

was often necessary. Rather than simply prompting the pilot to deploy one to many controls simultaneously, some to intermediate deployment, the following is suggested.

When automatic recovery control is to be initiated...

1. Indicate by the strongest *visual* indication which control has failed. Aural indication might be an important supplement.

2. State the needed control response and indicate by a red light that the control response will be automatic.

3. Begin automatic deployment with feedback to move the cockpit controls, including throttles.

4. **The implementation should be such that there remains the possibility of the pilot's *overpowering* the automatic inputs.**

By using this feedback, however inconvenient to arrange in current fly-by-wire aircraft, the pilot is given the opportunity for pseudo-input to the controls or input following. The pilot is discouraged from possibly intuitive but wrong response. Considering standard pilot response times, it can be expected that most pilots in most cases will not provide damaging input before an FDI system can identify a failure and (one can anticipate) before the best response is established. A decision must ultimately be made as to whether the pilot should actually be prevented from supplying inputs to the critical recovery controls after he would likely become aware of the failure manifestations but still during some period of real vulnerability of the aircraft to improper inputs. For the C-130, this period of vulnerability could be expected to extend roughly 45 seconds after time of failure (obligatory emergency control switches occurring at about 30 sec.). Even though it will be unnecessary to invoke full automatic control with some identified failures, early definite *automatic* action should probably be taken. If the failure has not been detected or identified by some point but diverging response is clear, it is probably wisest to offer and carry through automatically on some control strategy rather than hedge in any passive way.

It should be mentioned that automatic emergency control may need to be re-instated at any point after initial re-stabilization, as suggested by the Flight 1080 case. There may be suggestive ways of recording what worked last time. Note that re-initiating automatic recovering control later must proceed on the basis of pilot request or trajectory information, not FDI.

4.4. Automated Post-Failure Pilot *Advisory*--for Later Flight Phases

4.4.1. Introduction

As has been discussed, after an initial period in which the aircraft is brought substantially back under control, probably with notified-automatic-type assistance, there would likely follow phases of relatively quiescent flight. This is evident in the few successful cases of Table 1.1 and is the result of the pilot's natural inclination to reduce most performance demands on a handicapped aircraft. The transition between flight phases in later flight would generally be slow and careful. The pilot should definitely be strongly engaged in later flight, and given the fullest possible authority. After all, there is the greatest incentive to keep the pilot involved--he will be the best general problem-solver on board for the foreseeable future, and good problem-solving obliges interaction. However, based on the considerations established in Chapter 2, a system to *support* the pilot with advisory information for the rest of the flight would clearly be helpful and indeed truly needful in many cases. A reference giving pilots' remarks showing general support for post-failure advisory (while establishing a context for AI in the *nominal* piloting task) is [43]. Advice--if only by conspicuous intended absence--could provide a useful degree of security for the pilot. To pursue the idea of pilot advisory does require some faith, since most control failures do seem to result in disaster. One will have to believe that increasing control redundancy utilized better in control failure emergencies will begin to allow more safe initial stabilization.

As discussed in Chapter 2, there would be several bases for any potential advising. Some aspects of advising would come into more pronounced use in only certain flight phases. An advisory system could at least list and reference standard flight manual checklists for the most common types of failures (e.g., *engine failures* or wing surface failures). But it could also reasonably be expected to calculate pertinent information and assemble advice from more fundamental information.

Capt. McMahan demonstrated a very high level of "expertise" in the recovery of the Flight 1080 case (case 10, Table 1.1). One of the properties of an expert is that knowledge can be applied by the expert to solve problems efficiently and effectively, using the shortcuts that eliminate useless or unnecessary calculations [44]. This sort of efficiency via "focusing" must be a property of the advisory system. Experts also display "robustness" in problem-solving--their problem-solving degrades gracefully at the boundaries of their capability, reflecting breadth and depth of relevant knowledge. This property would be nice to have

throughout the aid and advisory system, since pilots are potentially responsible for dealing with any type of or circumstance for control failure.

Probably the key required capability for a post-failure advisory system is that of deciding which types of information to focus on, which types are important in safely continuing the flight to landing, which of these are subject to significant change, which the pilot needs to be most explicitly made aware of. Obviously not everything can or need be re-evaluated in the light of the failure.

Piloting is an expert behavior and thus has evolved to being relatively efficient from an information standpoint, so it makes sense to consider recovery information as pilots would like it. The view taken in this thesis is that it would be expedient to emulate pilot-type thinking about recovery in the recovery-advising system. When faced with a significant failure, for example, a good pilot would know when to evaluate for more precise information, but really on the basis of a *qualitative* assessment of the situation (i.e., fundamentally, when is "high-drag" high-drag?). Then, too, for best comprehension and use, the advice should be presented via expressions already familiar to the pilot. Piloting is at once a "qualitative" and "quantitative" skill. Of course, many of the original quantitative-type aspects of a novice pilot's flying are subsumed in more qualitative-type thinking later. The purpose here is not to belabor the distinction between the two types of pilot thinking but to point out that certain types of guidelines for recovery will involve some calculation and some will not.

One can anticipate that the knowledge involved in supporting the advisory would probably be more broad than deep, and probably not extensive. It is clear that a few well-placed bits of advice would generally suffice, and this is fortunate when considered from the standpoint of complexity of the intended system. The questions are *what* to calculate and *when*. The *why* is implicit in the knowledge base provided to the system. *How* to calculate will also be explored a little in what follows.

The overall aid/ advisory system will be a hybrid: data-driven processing but with sizable chucks of computation for which strong sequencing is necessary. This again suggests use of a production system approach to implement the advisory system, since most production-system languages, like the one already used in this study, have some mechanism for calling functions in a standard programming language as rule right hand side-type ("THEN") actions.

4.4.2. Expected Types of Contributions by the Advisory System

The following is a description of suggestive types of advisory system contributions during various phases of post-failure flight after the aircraft is brought back under control. The following discussion is intended to present types of advice that do seem practical and needful for at least some sorts of failures. Not all of these would be indicated for a given flight in which a control failure occurs.

Flight phase 2: Getting to a safe decision altitude. At some early point after the aircraft is stabilized, altitude should be gained if the aircraft is at all in danger of ground impact. Altitude (like airspeed) *is* safety in a pilot's mind. Flight manuals typically specify 10,000' as a desirable goal altitude in the event of a structural failure.

Gaining altitude safely and efficiently could in many cases require information concerning climb performance and how it should be optimized. Since there may be special goals on climb-out--clearing looming obstacles, in particular--the advisory system should be able to provide information on different types of optimized climb. Because hard operating constraints are of utmost concern, the advisory system should calculate and inform the pilot of these, as judged helpful or necessary, as early as possible.

Flight phase 3: Stabilizing at altitude, determining landing capabilities... One of the initial goals of recovery for most cases would be reaching steady straight and level flight at a safe altitude. Reaching equilibrium can certainly give additional time to decide the next, perhaps longer-term course of action. Equilibration is a standard idea in emergency piloting. Stabilization at a safe altitude traditionally is the point at which a decision about whether and how to proceed with a landing is made. If enabled to look for safe approach-type trim points for the impaired aircraft, the advisory system could be of considerable benefit. A possible additional help would be a discrete expert-system-type subsystem to help a pilot with safe check of remaining control capabilities. A subsystem allowed to do automatic, perhaps heuristic-based checking for remaining control capabilities at this time--examining aircraft response to system-directed quick, small amplitude test inputs, for example--could also be an asset. Whether flaps should be extended on landing and whether the deployment of landing gear would be significantly harmful should as best as possible be foreseen here. These considerations will also factor into the decisions concerning landing site.

...and deciding where to land. It is at the point where landing is being considered that the ability to calculate and explicate maximum range and/ or endurance for the handicapped aircraft could be extremely useful. For example, a pilot flying a failed aircraft over hostile territory (or an ocean) could benefit from knowing what destinations he can make. A nice extra for military aircraft would be the ability to calculate runway requirements

for the aircraft, if significantly changed, since potential landing sites might be significantly damaged and thus marginal, especially for the handicapped aircraft. Retrimming possibilities for enhanced cruise performance could also be evaluated at this point.

Flight phase 4: Nearing landing site. The pilot can proceed to the configuration change obliged by descent on the basis of cruise-type information already provided.

Flight phase 5: Making approach and landing. Descent is probably the least strenuous phase for control-impaired aircraft. As with the climb-out, however, descending safely and efficiently could in many cases require information concerning descent performance and how it should be optimized. The aircraft may need to be trimmed for the types of maneuverability possibly called upon in making a landing (i.e., trimmed to obtain some turn capability in the landing pattern and some degree of potential control over pitch and thus airspeed). As the landing is neared, it can be anticipated that certain discrete-type information would be especially helpful (e.g., whether fuel should be dumped, and other details about landing with or without spoilers, etc.).

It soon became clear from talking with pilots that what was generally most recommended were some very pedestrian, very general sorts of reminding advice, like "avoid (adverse) sideslipping" when there has been an engine failure. This will have a place in the system, although it should not at all be overdone. This sort of advice would come from more *qualitative* bases. As has been seen, however, this sort of advice really must be augmented with more quantitative advice. Most of the support needed seems to be quantitative "first-principle knowledge" using theory and the aircraft model, as opposed to empirical experiential knowledge (heuristics and rules of thumb) or commonsense knowledge. *The pilot's knowledge should be corrected only when acting according to it would be dangerous.* The goal is selective *substitution* in the pilot's first-principle and experiential knowledge and support of pilot judgment.

Remember that pilots fly by the numbers—and preferably by as few numbers as possible, e.g., stall speeds for only a limited number of configurations; airspeeds more or less roughly associated with optimum climb, cruise, and descent; and optimum turn speeds for a fighter aircraft. Pilots are accustomed to watching indicated airspeed very closely in general and most flying is done according to airspeed guidelines. Pilots do tend to—really, must—cling tenaciously to these numbers, so changes judged large by the advisory system probably must be put forward very clearly. Pilots want to be able to use nominal and standard emergency procedures (which have been practiced and are more automatic) as much as possible.

The following are some questions about residual control capability pilots interviewed for this research put forward as being those they would ideally want answered:

--How much roll capability remains?

--How much control do I have over vertical acceleration?

--How much can I affect airspeed?

--How much control do I have over sink rate?

--How much sideslip can I use?

--How much can I change angle of attack?

--Am I "committed to land"?

--Can I put the flaps down for a landing?

Control capability is, of course, best assessed in the context of what is needed in a given flight situation. That would apply to the answers wanted.

One of the compelling facts about aiding pilots post-failure is that they would ask for very simple-sounding types of information on remaining control capabilities, information which turns out to be impossible to convey, or nearly so, much less calculate. First of all, it must be clearly accepted that any truly strong notion of "control capability" in the dynamic sense has to be a function of the aircraft operating state, and even at a given state, it has to be a function of the position of the controls, their available range and allowable rate of deployment, the "artifact" of controls used to compensate for the failure, and the structural limitations on deployment. Furthermore, one must factor in the considerations that use of a control may be limited by whole-aircraft structural limitations or by other operating constraints, perhaps induced by the failure. This complexity is unavoidable. These sorts of things apply in nominal aircraft operation, too, of course, but then truly precise available control capability need not be assessed, because it is generally "known" by the pilot beforehand from training and experience.

What is ideally wanted is transferral of information on the level at which pilots prefer to operate and indeed operate best, namely the quasi-reflex skill level. Experienced pilots simply have a "feel" for the nominal capabilities of their aircraft. This simply cannot be provided wholesale for the handicapped aircraft. When pressed, however, pilots want less to be apprised of the new values of the quantitative maneuvering figures-of-merit--like new roll rate, how many g's can be pulled now--as knowing simply whether or not the capabilities are significantly degraded and the airspeeds and configurations at which these are optimized. Probably the best approach to transferral of information about operating a handicapped aircraft is via the parameters that even experienced pilots continue to use explicitly, if

possible, or, when absolute necessary, via parameters that underlay the original teaching of the skills, and inform via these parameters. As an extreme example of the latter, suppose that the pilot needs to make a steep, fast descent to landing in an aircraft with a significant elevator failure, perhaps after belated visual contact of a (small) landing site in bad weather or because of very urgent fuel problems. Or suppose that the pilot wants to avoid jarring an ordnance-laden aircraft on landing. Being able to flare could be very important in these circumstances. Knowing how to flare has long since become reflexive to some extent, anyway, for an experienced pilot. But now he is forced to use auxiliary controls if there has been a drastic elevator failure. Parameters are 1) new aim point, 2) height above the ground at flare initiation, and 3) what controls should be used, and at what rate they should be deployed. But first, one must determine that it is feasible to flare with the auxiliary controls in the first place.

4.4.3. Calculating Information for the Advisory

In the next few sections, there will be some preliminary discussion on how the need to assemble certain advisory information might be established. This will be suggested by diagrams indicating inference paths. If these diagrams look simple, it is because the difficult thing, again, is deciding when the next lowest node in the inference really should be concluded. In most cases, the decision would be based on judgment obtained through experience with many failure cases. These diagrams can only be vaguely suggestive in the absence of more experience with post-failure piloting. Keying for information would very likely be considerably aircraft-dependent.

It should be clear that these sorts of explicit calculation may only presage stronger, generalizing rules about what the pilot should be apprised of. The spirit of this is like that discussed in connection with the initial emergency post-failure control-discovering system:

Failure—>Guidelines, for initial phase and later phases

4.4.3.1. Calculating Operating Constraints

The appropriate time for beginning to induce operating constraints is *as soon as possible.* This must be initiated entirely by the advisory system.

The diagrams in Figure 4.2 suggest keying for calculating operating constraints after elevator, asymmetric flap, and slat failures. New stall speeds due to quite different flow over the wing in the case of the slat failure, for example, probably cannot be computed on-line

(this would be wind tunnel test data). It is a conservative solution to provide a blanket 10-20 kts above the nominal speed, and this is typical of conservative piloting. Obviously this could impinge on performance or other desires, however. A viable option would be using and presenting pre-calculated stall airspeeds for certain limited and less uncommon types of failures, especially leading edge slat problems.

Figure 4.2: Failures from Standpoint of Operating Constraint Calculation

Elevator Failure ⟶ Calculate Pitch-Controllable Airspeed

Asymmetric Flap Failure ⟶ Calculate Roll-controllable Airspeed

Slat Failure ⟶ Calculate Stall Airspeed(s)
        ↘ Calculate Control-Reversal Airspeed(s)

4.4.3.2. Calculating Performance

One of the important underlying considerations for the advisory is that the failure of a given control results not only in the loss of at least some of its own controlling functions but in the degradation of those of the compensating controls. This degradation can

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understandably be very significant in terms of its effect on performance and calculating it should begin as soon as possible. The diagrams in Figures 4.3-4.5 show the cascading implications on performance of control involvement in compensating for elevator, asymmetric flap, and slat failures on a generic aircraft. Calculations to support post-failure advising need to be keyed to both failed *and* compensating controls, particularly *primary* compensating controls.

Obviously, one really needs to compute for degraded capability only when reasonably sure that the control involvement means nominal performance cannot be approached. Determining the meaningful extent of control involvement in failure compensation for the purpose of anticipating significant degradation of capability is not trivial, so indication of control involvement (at least locally) might proceed on the basis of deflections of the control whose potential contributions are in question, or, perhaps, evaluating the deflections after a trim with best desired properties has been calculated. If the failure is known, this can be done readily. Important generic periods of performance assessment are climb, cruise, and descent. It seems likely that knowing which phase would be the most strenuous could be done on the basis of a qualitative-type assessment. Anticipating the involvement of compensating control at future points in the flight, preferably worst-case, is a little more difficult. An obvious recourse is to compute the trim associated with anticipated state rates, and again look at deflection of the controls. This could only be an approximate solution, however, because of reachability issues and because the future course of the flight cannot be anticipated entirely.

The best way to convey range or endurance capabilities is to state *maximum* range or endurance for the impaired aircraft and how it could be achieved. Typically, achieving maximum range or maximum endurance would involve climbing to an altitude *above* 10,000' because of engine performance characteristics. Whether climbing the impaired aircraft would consume too much fuel to make worthwhile the greater operating efficiency at altitude could be unclear and thus potentially a matter for computation, especially when unusual controls would be involved in making the climb and the desired landing site was very distant. Note, too, that whether the altitude for optimal cruise can be reached is perhaps also a reachability question. Following this advice cannot get the pilot into difficulties, although he may want to elect not to heed this advice when an intended landing site is well within the maximum available range. For military aircraft, especially in cases where compensating for the failure does not tie up thrust usage for compensating pitch or yaw, just converting the failure's effects to a given increase in the drag index can be considered a useful type of information, because the pilot can use this to compute range, and new optimal cruise and climb airspeeds using charts available in the standard flight manual, which are tabulated in drag index (see

Elevator Failure

Angle of attack and pitch changes

Flap usage
(if large failure)

Thrust usage
(if large flap deployment)

Thrust usage
(if large angle of attack)

Thrust usage
(if large elevator deflection)

Performance calculations

Dotted Lines--Indefinite inferences
Solid Lines--Definite inferences

-- minimum airspeed with power available
-- maximum airspeed
-- maximum attitude
-- maximum range and associated airspeed
-- maximum endurance and airspeed
-- maximum climb rate and airspeed
-- maximum climb angle and airspeed
-- minimum fuel standard-type climb and airspeed
[+ above with single engine out]

Figure 4.3: Potential Advisory System Inferences from Known Elevator Failure to Possible Need for Revised Performance Calculations

Asymmetric Flap Failure

Sideslip

Thrust usage
(if large sideslip)

Rudder usage
(if large failure)

Thrust usage
(if large rudder deflection)

Thrust usage
(if large flap deflection)

Performance calculations

-- minimum airspeed with power available
-- maximum airspeed
-- maximum altitude
-- maximum range and associated airspeed
-- maximum endurance and airspeed
-- maximum climb rate and airspeed
-- maximum climb angle and airspeed
-- minimum fuel standard-type climb and airspeed
[+ above with single engine out]

Dotted Lines--Indefinite inferences
Solid Lines--Definite inferences

**Figure 4.4: Potential Advisory System Inferences from Known Asymmetric
Flap Failure to Possible Need for Revised Performance Calculations**

Slat Failure -------------------------------> Changes in basic aerodynamics
                                               (if significant slat failure)

Dotted Lines--Indefinite inferences
Solid Lines--Definite inferences

Performance calculations

-- minimum airspeed with power available
-- maximum airspeed
-- maximum altitude
-- maximum range and associated airspeed
-- maximum endurance and airspeed
-- maximum climb rate and airspeed
-- maximum climb angle and airspeed
-- minimum fuel standard-type climb and airspeed
[+ above with single engine out]

Figure 4.5: Potential Advisory System Inferences from Known Slat Failure to Possible Need for Revised Performance Calculations

Figure 4.6). There are similar charts for three-engine performance, so some interpolation when thrust is moment-compensating is possible. Information about new performance will probably be easy to calculate--perhaps if would even be flight manual-type information--but for precision and convenience and timeliness, one may want to consider automating the calculation and presentation.

4.4.3.3. Calculating Explicit Retrim Information

Recall from Chapter 2 that, given even a modest degree of control redundancy, the same trajectory could be achievable with greater efficiency or with more potential for maneuvering reserved. This could arise in any flight phase, and this is especially relevant after the initial stabilization. It has been seen that the more appropriate time for searching for possible retrim possibilities is during relatively quiescent flight (or slow divergence), when the more powerful heuristic "oppose the disturbance" is usually much less relevant. It is to be understood that the pilot would probably not often be in the position of knowing to ask the system for better trim points. The system should probably just infer needs on the basis of apparent steady-state flight and make only *sparing* retrim recommendations, and only if clear improvements are involved. An exception to this sparingness could be recommendations made during the 10,000' break, when more explicit information is more justified, and one is more likely to have the pilot's attention. In some cases, the upcoming needs might be inferred and retrim proceed on that basis.

The following are three types of goals in retrimming. Of course, these may conflict in a given situation.

--Off-load compensation burden from controls needed otherwise--needed for maneuvering, for example.

--Move away from dangerous state constraints

--Obtain outright better performance, especially better efficiency

There will be circumstances where certain aspects of the current trajectory can be foregone in favor of obtaining a trajectory close to it but more desirable in other respects. It is clear that, in considering certain types of changes, pilot intentions would have to be known. If there is an obstacle ahead, for example, then a retrim that would involve a large reduction in climb performance in favor of general airspeed increase would be unwanted. On the other hand, if it is known that better climb is needed, then this can be sought through retrimming.
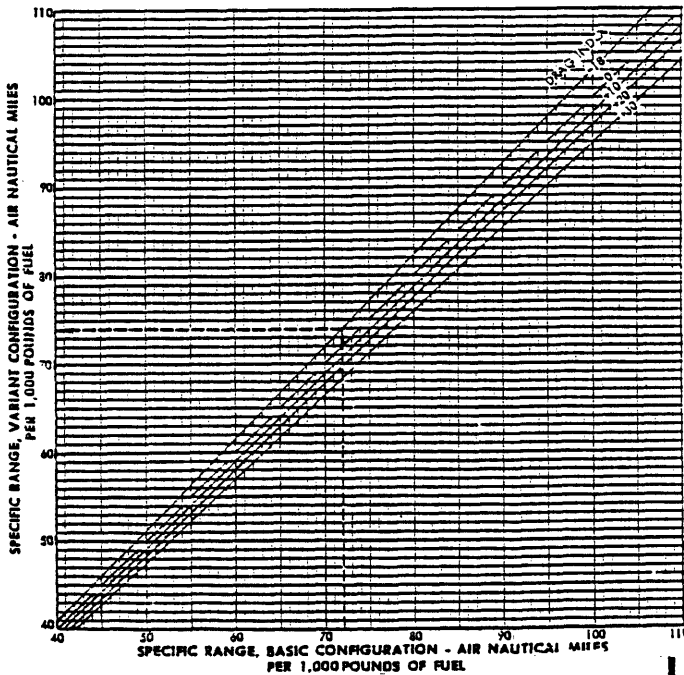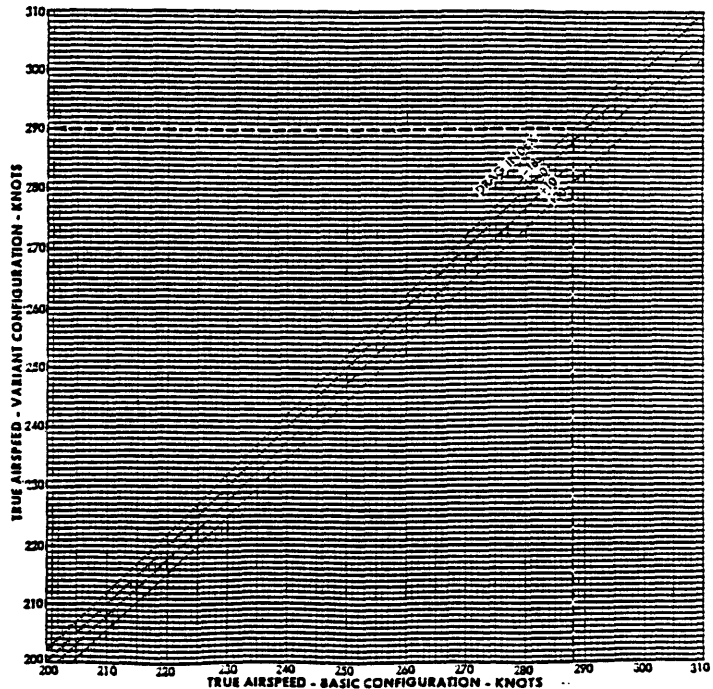
Figure 4.6: C-130 Flight Manual Performance Information Specified Through Drag Index [45] (Maximum range information)

In the retrim for better performance suggested by the example in Section 2.4.2 and in the retrim for better maneuvering in the Flight 1080 case (stabilizer burden shifted onto flaps during approach), retrim was explicit and could have been prompted. The possibility of doing some retrim automatically on an on-going basis should also be considered, however, particularly for more complex, higher-performance aircraft. In such a scheme, continuous trim to, perhaps, a general condition of some weighted balance of fuel economy and control centering (especially for more "effective" controls) could proceed on a slow, background basis, perhaps with informed pilot acquiescence. This again would be most effective if allowed to proceed during more quiescent flight. As in all retrim, reachability issues must be addressed, preferably before the retrim point is suggested. As part of the retrim information, one might need to specify the order in which changes in control deployment should be done, especially for more complicated cases. This is another area for possible knowledge-basing.

4.4.3.4. Calculating Maneuver Capability

Figure 4.7 illustrates the implications of asymmetric flap and slat failures from the standpoint of maneuvering capability. Highest-performance turns in a fighter aircraft are executed at the lowest velocity at which limit load can be obtained. This is the "corner velocity" of Figure 4.8. Where stall speeds change, the corner velocity will change. With the aim of advising pilots about changes in configuration associated with optimal post-failure maneuvering, the new corner velocity could be supplied to the pilot. Similarly, when stall and buffet speeds change, so may the gust penetration airspeed, at which airspeed the expected gust loadings cannot result in the aircraft limit load being exceeded. This airspeed, too, would be useful advisory information.

It can be, of course, an entirely different matter whether the angle of attack associated with maximum lift can be achieved by the control-impaired aircraft. With a very debilitating elevator failure, for example, it may not be achievable, since basic control authority would lack. It is unclear at this time whether most reachability issues should be addressed by simple retrim or whether propagation in a simulation will be required.

When the mission is to be aborted on the basis of flying quality, it should be noted that evaluating flying quality quantitative criteria to support this could well proceed on the ground. A wide, automated survey can be envisioned as useful in this regard.

Asymmetric Flap Failure

Bank and beneficial sideslip

Ailerons
(if large flap deflection)

Rudder usage

Advise: "Turns limited in ___ direction,"
"___ crosswind landing limited"

Slat Failure

Calculate "Corner Velocity"
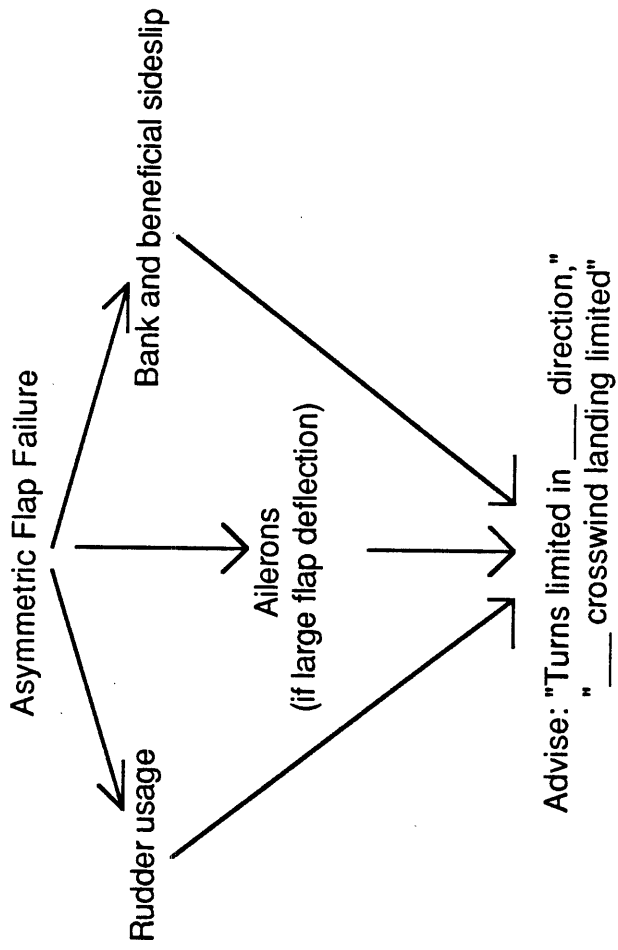
Figure 4.7: Asymmetric Flap and Slat Failures from a Maneuvering Standpoint
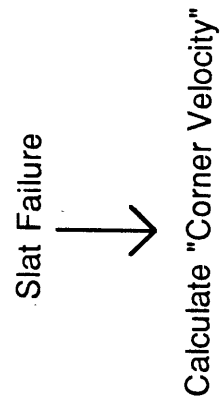
Figure 4.8: "Corner Velocity"--Important in High-Performance Post-Failure Maneuvering
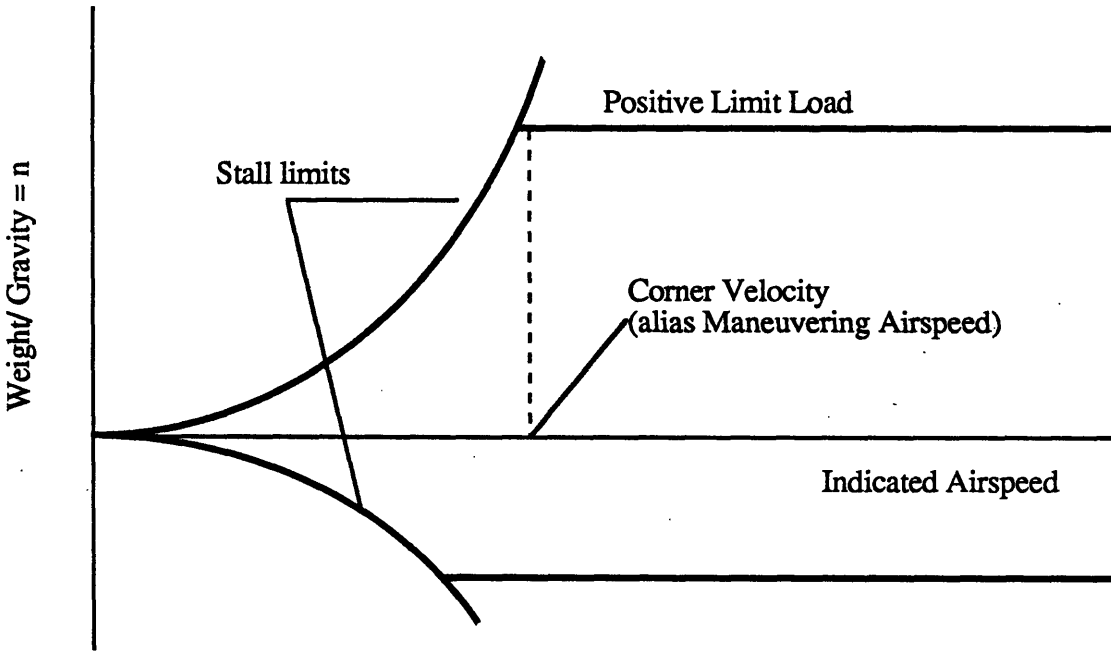
4.4.4. Issues of Pilot Interface During the Advisory

The ideal pilot advising might be expected to have the following features:

--The most important information--about significantly new operating constraints like new stall airspeeds, new controllable airspeed, other new state constraints--is *persistent.*

--Other information about each general flight phase is *kept updated* and is available to the pilot *on demand.*

With the second feature, the pilot is able to exercise any option at any time and be provided with good information. Remember that the state at which true optimal performance can be achieved can be expected to vary over the course of the flight. After a period of cruise flight at one altitude, for example, the pilot may need to climb again to a new assigned altitude. The pilot's thinking would not be overloaded or his memory strained, and much of the later flight conditions would not be clearly foreseeable, anyway. Obviously the level of information would need be less extensive if the pilot's intentions were known. Trying to guess his intentions would greatly complicate the system at best, however, probably without ever being entirely satisfactory. The advisory system as envisioned here is mostly *passive.*

Warnings here are considered to be the urgent, high-priority items that should be put before the pilot when immediate corrective action must be taken. There is some possibility that there may be significant need for a warning system. That there may be new constraints on controllable operation of an aircraft has already been discussed. Obviously it could be very important to warn the pilot as one of these constraints is being approached. The same sorts of considerations apply here as in the problem of issuing warning with the initial failure manifestation, and one wants to avoid false alarms as much as possible. But it makes more sense to risk being overbearing in issuing warnings after it has been established that a failure exists. After all, conservative flying would generally be expected. Warnings as needed could be based on more or less grandiose supporting capabilities.

The military pilots interviewed all suggested that there be a pilot aid that annunciates when minimum bail-out altitude is being approached. This minimum altitude is a function of aircraft attitude, airspeed, and descent rate. Although pilots will have studied this information in advance, it is complex, and it can easily be appreciated that the dangerous region for bail-out might be quickly penetrated by an aircraft that has a high rate of descent. One pilot suggested that a good way of presenting this information to the pilot is by a persistent whisper in his ear. Bail-out information is the information of ultimate importance to the pilot of an aircraft that can and must be abandoned.

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Being able to implement any of the proposed recovery aid and advisory system would require some computational and display capability, but not at a level more than that available in current medium-performance aircraft like the updated C-130 versions, in today's newer commercial transports, and certainly in all higher-performance military aircraft. The goals and features of this aid and advisory system would mesh extremely well with the future high-performance aircraft installations to be developed in the Pilot Associate program [46].

In [25], a reference which became available during the time this chapter was being prepared, it is suggested that some of the most important pilot advisory information of the type being recommended in this thesis be superimposed on a head-up display when possible. Figure 4.9 illustrates this. The information at the top indicates both that a flight control failure has occurred and a resultant general severity classification. In addition, an abort criterion is assumed to have been met and the pilot is advised to restrict aggressive maneuvering. There could be, similarly, recommendation to eject. It should be noted that in most AI work it is considered almost obligatory that an explanation be available for advice given by a system playing such a role. An angle of attack limit of 20° has been imposed, as shown. In this reference, it is recommended that there be optional menu-driven display on some multi-function display terminal for information on "Flight Status," "Flight Control System Status," as in Figures 4.10 and 4.11, and for "Emergency Procedures," as in Figure 4.12. In the first of these example cockpit displays, severity classification is given for basic flight phases, and some restrictions on operating and performance are shown. In the second, there is an assessment of the control system elements and of the automatic flight modes; it might be noted that important information about control reconfiguration, as used, should be provided in this display. In the "Emergency Procedures" here, only landing information is given. As has been discussed in this thesis, information about other flight phases should also be made available. The following Figures 4.13-4.16 suggest the breadth of the on-demand flight phase advisory information for climb, cruise, descent, and landing phases. Certain background calculations of the types listed but anticipating reasonably likely additional failures should also be performed. Again, it is recommended that this sort of information be kept updated throughout the flight, as needed.

4.5. Summary

This completes an elementary description of how a complete recovery aid and advisory system might be used during a post-failure flight. It seems clear that emergency control should generally be fully automatic, feeding back to cockpit control movement. The

suggestive advisory information for different flight phases should be available continuously or on demand, depending upon criticality.

WARNING

FLT CONTROL

ABORT

RESTRICT AGGRESSIVE MANUEVERING

```
          ┌─120─┐           ┌1000┐R
   20 ▶    200                      ─5
                    ⊕
          16       ─         ─
                  :         :
          <      :         : >
          100              ─5

AOA        10      10
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> o <
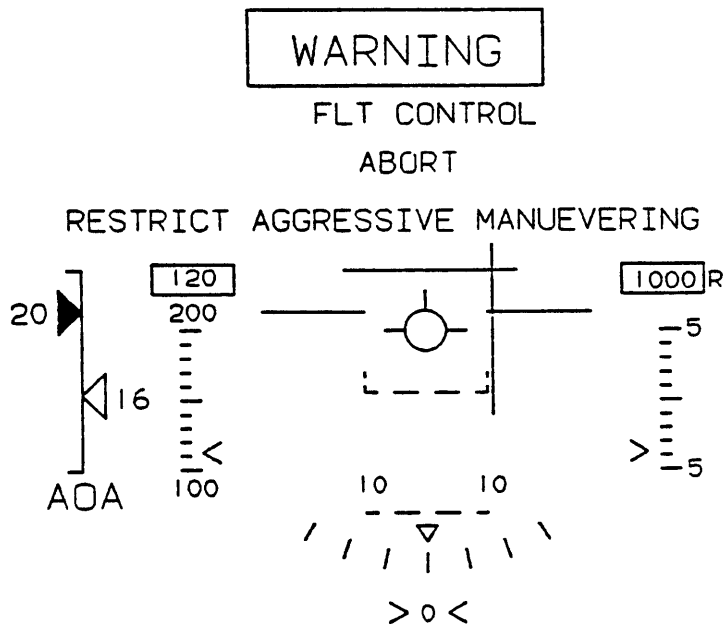
Figure 4.9: Automatic Pilot Advisory System Display Superimposed on Head-Up Display [25]

```
AUTO                    ABORT              FLT STAT
          PITCH CONTROL REDUNDANCY           ○
                FLT MODE STATUS
ENG                                        FCS STAT

       COMBAT   CRUISE    LAND     AUTO

       (RED)   (AMBR)    (RED)   (AMBR)    EMER PROC
FUEL
                  RESTRICTIONS

HYD       AOA        KIAS       RANGE
        15 ▶        ◁ 350     ◁ REQD
          ◁ 8              AVAIL ▶
FCS    -4 ▶       150 ▶
  ○
        PITCH CONTROL------LIMITED BELOW 250KTS.
        ROLL--------------LIMITED
        RESTRICT AGGRESSIVE MANUEVERING
```
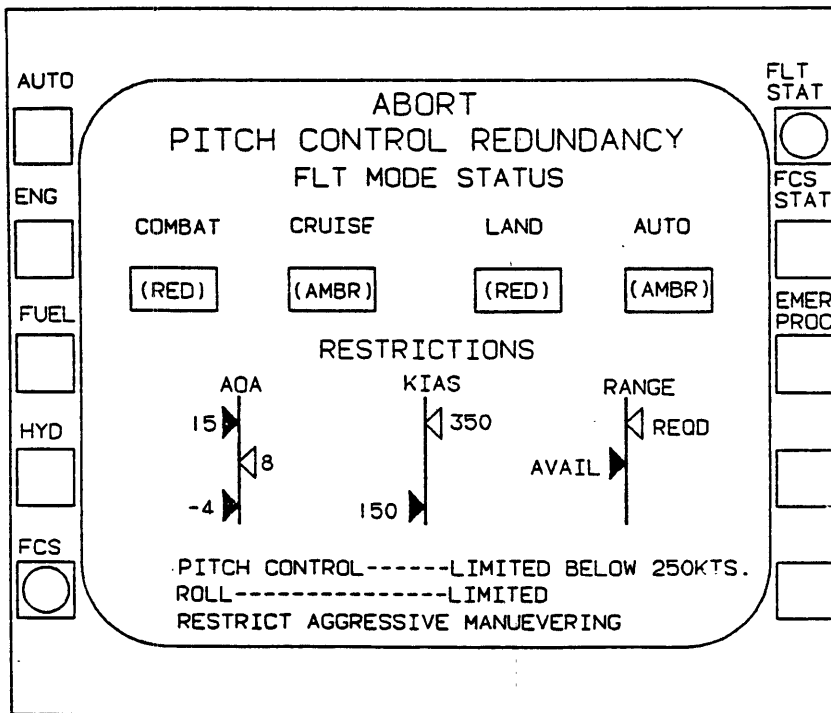
Figure 4.10: On-Demand Flight Status Display [25]

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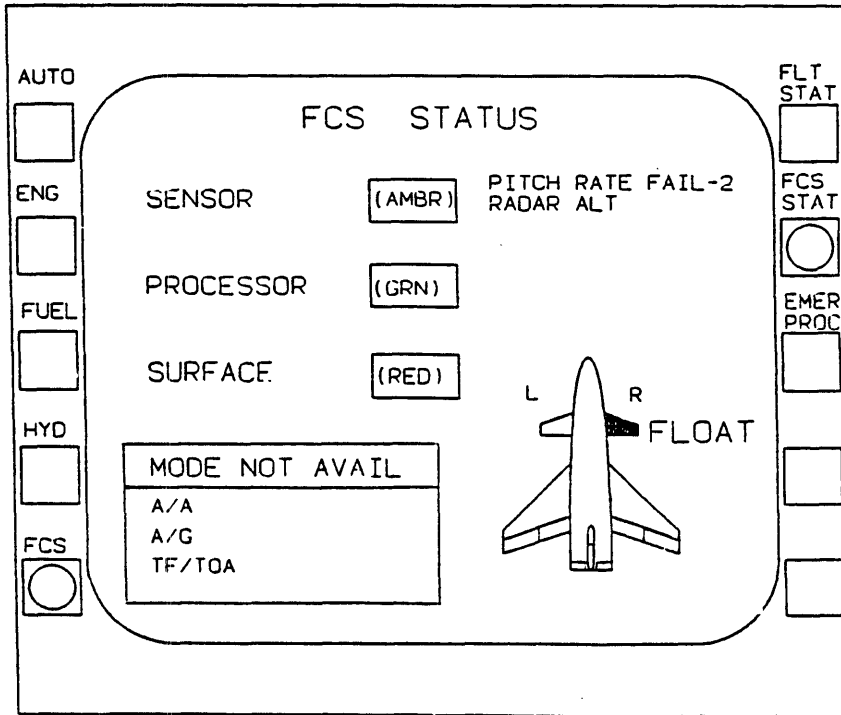
Figure 4.12: On-Demand Emergency Procedures Display [25]
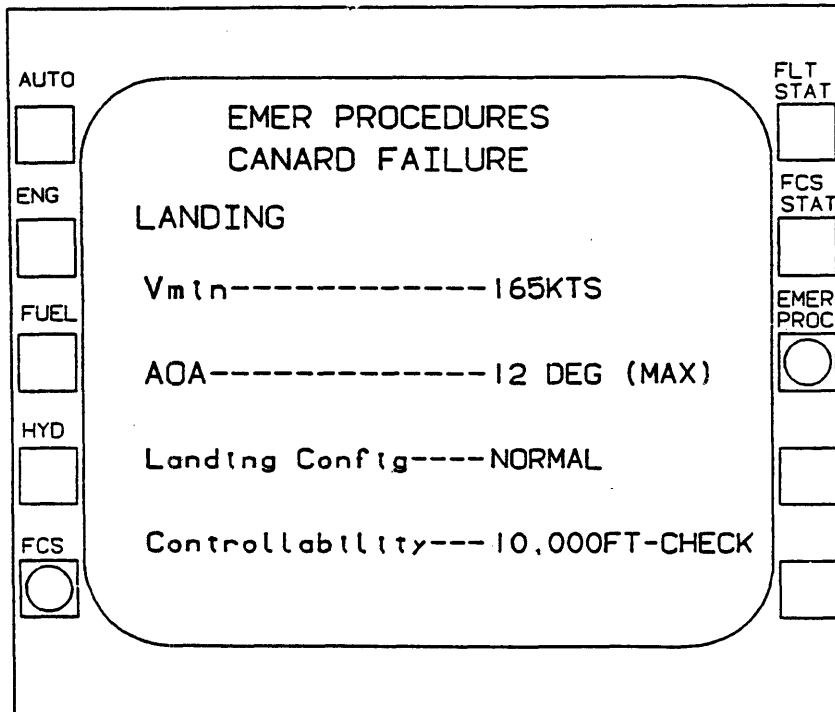
Figure 4.11: On-Demand Flight Control System Status Display [25]

Figure 4.13 : On-Demand Climb Information

- Flap retraction airspeed schedule
- Maximum climb rate and airspeed
- Maximum climb angle and airspeed
- Minimum-fuel standard-type climb rate and airspeed

Figure 4.14 : On-Demand Cruise Information

- Maximum range and strategy
- Maximum endurance and strategy
- Minimum cruise airspeed
- Maximum cruise airspeed
- Ceiling on cruise operations

Figure 4.15 : On-Demand Descent Information

- Maximum range standard-type descent and airspeed
- Standard 5°, 10° descent profiles possible?
- Standard rate turn possible?
- Range with current descent

Figure 4.16 : On-Demand Landing Information

- How to make landing:
  -- Flap usage
  -- Gear usage
  -- Approach speed
  -- Threshold speed
  -- Touch-down speed
  -- (How to flare with alternate controls, if necessary)
- Committed to land?
  If not, go-around information:
  -- Flap retraction airspeed schedule
  -- Final deployment limits on controls (esp. thrust)
  -- Control reversal airspeed

Chapter 5

Summary and Recommendations for Additional Research

5.1. Summary and Contributions of the Thesis

The main contribution of this thesis has been the categorization of the capabilities that a recovery-aiding system should have. This categorization is a general one and expected to be basically aircraft-independent. It was natural to cast these capabilities into the format of pilot *advisory*, all the while with the recognition that for certain types of (especially, higher performance) aircraft, automatic aid beyond control loop redesign and along the lines of the capabilities proposed here would be at least highly desirable. Each major element of this categorization was supported from actual aircraft accident cases and through simulations of post-failure flight of a C-130 aircraft.

Some of the elements of the categorization of the recovery-aiding system have gotten relatively fuller treatment. In particular, a rule-based system guiding pre-simulation to find successful post-failure emergency control has been developed. How automatic assistance could be initiated and to what degree it should be used were discussed. The advisory function of the system has been described by flight phase. The issues of pilot interface were discussed. There was a treatment of the important question of what to calculate for the advisory, and how to calculate it. There was a discussion on post-failure retrimming on constant-rate surfaces and some demonstrations of the real impact of this which the author believes to be novel. The frustrating attempt to get any leverage on solving any of the significant problems in this area is also briefly summarized, so as to make clear the real need for further work. The author has addressed the difficult problem of evaluating and conveying precise post-failure control capabilities in a way that is accessible to the pilot. A by-product of the early C-130 work was the extension of a certain very basic type of reconfiguration--the remapping of the intended forces and moments of a failed control--to allow for rate and position saturation of the controls, and other control dynamics. Finally, the simulations of piloted post-failure flight of the aircraft used in this study should help to point to the strenuousness of even relatively small failures of primary control surfaces--few such simulations are available.

5.3. Recommendations for Additional Work

There is clearly much theoretical work that can be done in the area of automatic control reconfiguration and redesign. Designing automatic control that is already strongly disturbance-rejecting (especially for disturbances associated with control failures) could be of considerable benefit. Beyond this, it seems clear that fully developing and implementing a recovery aid and advisory system will be a mostly straightforward process, and there is on-going development work in industry. Further development of a rule-based system to discover emergency control with or without underlying automatic control reconfiguration or, as suggested, to determine basic control redundancy of an aircraft should be able to proceed on the lines of the demonstration system of this thesis and the suggested extensions. Particular attention should be focused on achieving maximum robust emergency response to trajectory-only information. There are perhaps interesting issues in implementing emergency control to augment automatic control and when lateral/ directional failure cases are treated. Considerable broad-based work with a specific aircraft--best done in an industrial setting--will be required before the goal of a straight-through path from failure to needful automatic assistance and mixed qualitative and quantitative advisory information will be a reality.

One area for further academic-type work is the exploration of the idea of a scheme to do automatic testing of the remaining control capabilities, something which would be particularly useful in those inevitable cases where FDI will be somehow ineffective. This type of scheme might be based on pilot emulation, since it is a natural thing to test for response to quick, small-amplitude inputs. There will be some caveats that must be followed in order to avoid loss of the aircraft because of the testing, particularly for more control-sensitive aircraft. Trial deployment of controls whose reversal may be difficult is to be avoided, for example. Controls nominally coupled may need to be decoupled for the test.

More theoretical research into the area of constant-rate regions for aircraft nonlinear dynamics also seems justified. Considerable interesting work could probably be begun with a thorough-going survey for equilibrium region(s) for a specific aircraft, an investment that should be made, however computationally expensive such a survey would be.

It would clearly be very desirable to make inroads in the unexplored problem of metric-based ways of identifying control redundancy of a given aircraft configuration. It seems clear that any metrics developed can only be suggestive, not precise.

References

1. Rubertus, Duane P., "Self-Repairing Flight Control Systems Overview," Proceedings of the National Aerospace and Electronics Conference, 1983, pp. 1280-1286.

2. Tench, William H., Safety is No Accident, Collins, London, 1985.

3. National Transportation Safety Board, Aircraft Accident Report 71-12, Washington, D.C., August 1971.

4. NTSB, Aircraft Accident Report 72-18, June 1972.

5. NTSB, Aircraft Accident Report 73-02, February 1973.

6. NTSB, Aircraft Accident Report 75-08, May 1975.

7. NTSB, Aircraft Accident Report 77-06, September 1977.

8. McMahan, Jack, "Flight 1080," Air Line Pilot, July 1978.

9. NTSB, Aircraft Accident Report 78-10, August 1978.

10. International Civil Aviation Organization, Aircraft Accident Digest, 1982, pp. 1-27.

11. ICAO, Aircraft Accident Digest, 1982.

12. NTSB, Aircraft Accident Report 79-08, June 1978.

13. ICAO, Aircraft Accident Digest, 1983, pp. 57-91.

14. NTSB, Aircraft Accident Report 79-17, December 1979.

15. NTSB, Aircraft Accident Report 81-02.

16. NTSB, Aircraft Accident Report 82-05, June 1982.

17. NTSB, Aircraft Accident Report 83-11.

18. NTSB, Aircraft Accident Report 83-07, October 1983.

19. NTSB, Aircraft Accident Report 84-03, March 1984.

20. "Inquiry Committee Analyzes JAL 747 Flight Data Recorder," Aviation Week and Space Technology, September 9, 1985, p. 97.

21. NTSB, Aircraft Accident Report 86-04, June 1986.

22. "Dangerous Souvenir," Time, November 10, 1986, p. 63.

23. Kaufman, Michael T., "Pilot in Jet Crash Praised in Poland," New York Times, May 11, 1987.

24. O'Lone, Richard G., "NTSB Evaluates Factors in Detroit MD-82 Crash," Aviation Week and Space Technology, August 24, 1987, pp. 18-20.

25. Weinstein, Warren, et al., Control Reconfigurable Combat Aircraft Development, Phase 1--R&D Design Evaluation, AFWAL-TR-87-3011, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, May 1987.

26. Montoya, R.J., ed., "Restructurable Controls," NASA CP-2277, August 1983.

27. Flight Manual, USAF Series T-37B Aircraft, Secretary of the Air Force, T.O. 1T-37B-1, July 1982.

28. Federal Aviation Administration, Airworthiness Standards for Normal, Utility, and Acrobatic Category Airplanes, Federal Aviation Regulations Part 23; for Small Airplanes Capable of Carrying More Than 10 Occupants, Special FAR 23; and for Transport Category Airplanes, FAR Part 25, U.S. Department of Transportation, June 1974.

29. "Military Specification: Flying Qualities of Piloted Aircraft," MIL-F-87858, November 1980.

30. Grumman Aerospace Corp., "Dispersed and Reconfigurable Digital Flight Control System," (Vol. I), AFFDL-TR-79-3125, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, December 1979.

31. Chandler, Phillip R., "Self-Repairing Flight Control System Reliability and Maintainability Program Executive Overview," Proceedings of the National Aerospace and Electronics Conference, 1984, pp. 586-590.

32. Sadeghi, T. and Rosenthal, G., "A Control Law for the Self-Repairing/ Digital Flight Control System," Proceedings of the National Aerospace and Electronics Conference, 1984, pp. 591-595.

33. NTSB, Aircraft Accident Report 85-04, March 1985.

34. Motyka, P., Bonnice W., Hall, S., and Wagner, E., "The Evaluation of Failure Detection and Isolation Algorithms for Restructurable Control," NASA CR-177983, November 1985.

35. Weiss, Jerold L., et al., "Detection and Isolation of Control Surface Effectiveness Failures in High Performance Aircraft," Proceedings of the National Aerospace and Electronics Conference, 1985, pp. 552-559.

36. Dole, Charles E., Flight Theory and Aerodynamics, Wiley, New York, 1981.

37. Weiss, Jerold L., et al., "Initial Design and Evaluation of Automatic Restructurable Flight Control System Concepts," NASA CR-178064, June 1986.

38. Brownston, Lee, Farrell, Robert, et al., Programming Expert Systems in OPS5, Addison-Wesley, Reading, Massachusetts, 1985.

39. "Trinka, '78, Earns 1987 Jabara Award," Checkpoint [USAF Academy Alumni Magazine], August 1987, p. 28.

40. SAIC, ExperOPS5 for the Apple Macintosh, Version 1.5.

41. ExperTelligence, Inc., ExperLisp for the Apple Macintosh, Version 2.0.

42. Cohen, Paul R. and Feigenbaum, Edward A., ed., Handbook of Artificial Intelligence, William Kaufmann, Los Altos, California, 1982

43. Baron, Sheldon and Feehrer, Carl, "An Analysis of the Application of AI to the Development of Intelligent Aids for Flight Crew Tasks," NASA CR-3944, October 1985.

44. Waterman, D.A., A Guide to Expert Systems, Addison-Wesley, Reading, Massachusetts, 1986.

45. Flight Manual, USAF Series C-130B, C-130E, and USCG HC-130B Aircraft, T.O. 1C-130B-1-1, Naval Air Systems Command, December 1979.

46. Kinnucan, Paul, "Building a Better Cockpit," High Technology, January 1986, pp. 49-54.

Appendix I

C-5A Flight Manual Emergency Procedures
Concerning Control Failures

The following C-5A flight manual extract [A1.1] has the most extensive procedural information concerning control failures found during the course of this research. Its inclusion here is intended to point up that very limited information is explicitly available, that both scope and depth are limited, and that this information is not in a form suitable for particularly speedy use by a pilot.

Reference

A1.1. Flight Manual, USAF C-5A Aircraft, T.O. 1C-5A-1.

Engine Oil Filter Differential Pressure Warning Light.

If the engine oil filter differential pressure light comes on, it indicates that the scavenge oil filter is approaching a blocked condition. Crosscheck the applicable oil pressure gage to ascertain that the oil pressure is within the normal operating range. If the oil pressure is not within the normal range, the engine should be shut down, using the Precautionary Engine Shutdown checklist, unless its operation is essential to maintain flight. The applicable oil pressure gage should be periodically checked until the malfunction has been corrected. Continued engine operation with a blocked filter can result in a contaminated oil system. Under the contaminated condition, the likelihood exists of clogging internal oil screens and jets, resulting in loss of lubrication to bearings and seals. Consequences could be similar to those following the loss of oil pressure. Make a safety of flight entry in the Form 781.

High Oil Temperature.

High temperature (pressure normal) can usually be reduced by advancing the throttle to increase fuel flow through the fuel-oil cooler. Excessive temperatures or significant variations between engines can warn the pilot in time to shut down the engine and prevent an oil system or engine failure. If the shutdown is required, use the Precautionary Engine Shutdown checklist.

FLIGHT CONTROL SYSTEM FAILURES.

Flight Control Methods To Be Used After Loss of Normal Flight Controls (Massive or Mulitiple Flight Control Failures)

If all or a portion of normal flight controls are lost, the following information may be used to control and recover the airplane. There has been no flight test or structural analysis to confirm this information; however, it is considered the best available guidance for the extreme emergency of mulitiple flight control failures.

The items presented in these failure cases can possibly be used to control the C-5. The effectiveness of these items will vary with the center of gravity, weight, airspeed, and phase of flight at the time of failure, in addition to the extent of flight control system failure. Each item selected for use should be evaluated at altitude to test its effectiveness in possibly controlling the airplane.

Upon complete loss of a flight control, the pilot should first attempt to regain control of the airplane. Once the airplane has been brought under control, the failure should be analyzed and a determination made of what additional capability is available for control in an attempted landing of the airplane.

It is essential that the results of each action taken be anticipated and understood before initiation. Specific tasks should be discussed and coordinated between pilot and copilot prior to accomplishment.

Complete Loss of Elevator Pitch Trim Control; Additional Means of Pitch Control.

The following additional means of pitch control are presented for use by the pilot when all normal means of pitch control are lost.				
TO PITCH THE AIRPLANE UP	**SPEED EFFECT**	**TO PITCH THE AIRPLANE DOWN**		**SPEED EFFECT**
IMMEDIATE ACTIONS		**IMMEDIATE ACTIONS**		
a. Increase Thrust	INC	a. Descrease Thrust		DEC
b. Decrease Bank Angle	DEC	b. Increase Bank Angle		INC
ADDITIONAL CONTROLS		**ADDITIONAL CONTROLS**		
c. Uprig Ailerons (LDCS)	DEC	c. Downrig Ailerons (LCDS)		INC
d. Pitch Augmentation - ON (If Available)		d. Pitch Augmentation - ON (If Available)		
e. Engage Pitch Autopilot		e. Engage Pitch Autopilot		
f. Shift CG Aft Transfer Fuel to Outbd Tanks Jettison Inbd Fuel	DEC	f. Shift CG Forward Transfer Fuel to Inbd Tanks Jettison Outbd Fuel		INC
g. Extend Symmetrical Flight Spoilers	DEC	g. Retract Symmetrical Flight Spoilers		INC

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The following information will be helpful in configuring and landing an airplane that does not have normal itch controls.

Approach and Landing

The following procedure is recommended in preparation for landing:

    a. Establish final configuration at altitude.

      (1) Extend landing gear at or near 10,000 feet AGL.

The lanaing gear increases the drag which requires the use of higher thrust to regain the initial flight path angle.

      (2) Extend flaps directly to 100 percent at or near 6,000 feet AGL.

Normal airspeed restrictions apply if possible; however, flap extension may be initiated at speeds up to 200 KCAS.

WARNING

If hydraulic systems 1, 2, and 3 have failed, do not extend the flaps. Lowering flaps will introduce an uncontrollable nose-down pitch moment due to elevator float.

Note

If the failure occurs at intermediate flap settings, attempt to stabilize at that configuration. If controllability is adequate, subsequent flap configuration changes may not be necessary.

      (3) Position additional controls so that adequate pitch-up control is available for flare or go-around.

      (4) Evaluate the new trimmed airspeed for controllability, the ability to flare or recover from upset and its relationship to the charted approach speed.

Note

The minimum trimmed airspeed should be at least charted approach speed plus 10 knots, if possible.

    b. Determine where to land. Select an airport having an ILS, minimum terrain obstacles on final approach, and maximum runway length, if landing at an airport is feasible. The ILS should be used as a guide nly. If landing at an airport is not feasible, select flat terrain for landing.

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Note

This phase of the recovery process must receive thorough evaluation to determine suitability of considered recovery location(s), ability to adequately control the airplane during the final approach, and the best combination/selection of control options.

The following procedure is recommended for landing

    a. Establish long flat final approach.

Note

Minimize the use of roll control for heading changes, as this will disturb the airplane in pitch. Pitch disturbances may be minimized by making minor heading changes with rudder, if available, or by use of asymmetric thrust.

    b. Flare. Anticipate airplane nose-down pitch due to ground effect. Counteract this pitch-down tendency by beginning a high gradual flare using a combination of the following controls:

      (1) Symmetric flight spoilers

      (2) Thrust

      (3) LDCS

    c. Use ground spoilers as soon as possible after touchdown to ensure the airplane does not become airborne again.

WARNING

Ground spoilers shall not be deployed in flight. Complete loss of control can occur if ground spoilers are used in flight.

Note

Inboard ground spoiler panels must be reactivated by symmetrically turning Ground Spoiler Left and Right Hand Sys A then B hydraulic power switches to ON immediately after touchdown.

Use of Additional Means of Pitch Control

Large bank angles, sometimes exceeding 30 degrees, may be initially required to reduce a nose-up attitude while recovering from a failure transient.

The pitch axis of the autopilot should be engaged to aid in damping the airplane pitch oscillations. Several

attempts may be required to engage the autopilot. To alleviate the movement of the pilot's column, shear the interconnect between the pilots' control columns with the procedures described in this section. After shear out, the copilot column will continue to follow the autopilot.

If conditions permit it is advisable to establish an aft CG (approximately 38 percent) because less pitch control is required to maneuver the airplane with an aft CG. With an aft CG, the trimmed airspeed is reduced. From a full fuel condition, as much as a 7 percent aft or 5 percent forward CG shift can be obtained.

WARNING

Do not exceed the aft CG limit or the airplane may become uncontrollable.

The flight spoilers may be deployed symmetrically in flight by the following procedure:

a. Ground Spoiler Left and Right Hand Sys A and B Hydraulic Power switches - OFF. (Allow 3 seconds for system pressure to bleed off.)

b. Symmetrically retard throttles No. 1 and 4 sufficiently to allow the use of the ground spoiler handle.

WARNING

Ensure hydraulic power is off to the ground spoilers or complete loss of control can occur if the ground spoiler handle is used.

c. Use the ground spoiler handle override lever to disengage the ground spoiler handle locking pin.

d. Slowly and smoothly deploy the flight spoilers to achieve the desired pitch up (slow down).

e. Normal roll control spoilers with flaps up are limited to 22.5 degrees. As a guide when using this symmetrical deployment procedure, 60 percent of ground spoiler handle travel will cause the flight spoilers to deploy approximately 22 degrees. Further application of the ground spoiler handle beyond the 60 percent position at speeds above flap placard speed should only be accomplished as a last resort to control pitch and reduce trim speed.

WARNING

Application of symmetric flight spoilers has not been flight tested or structurally analyzed and could possibly result in higher than normal loads in the wing, flaps, or spoiler system. Also deployment of spoilers

produces drag, loss of lift, and aircraft nose up pitch; therefore, causing a change in the flight path angle and possibly stall at slow speeds.

Establishing an acceptable configuration at any given flight condition may require partial spoiler deployment to provide desired flight path, which may then make it possible to deflect spoilers in both directions from this partially deployed position to provide some pitch control.

Pitch oscillations may be excited by wind gusts, airplane maneuvering, or configuration changes. While attempting to control the airplane in pitch, keep bank angle excursions to less than 10 degrees where possible.

Under most flight conditions, stopping at intermediate flap positions will cause pitch down and associated speed increase.

WARNING

If hydraulic systems 1, 2, and 3 have failed, do not extend the flaps. Lowering the flaps will introduce an uncontrollable nose down pitch moment due to elevator float.

Having accomplished control of pitch oscillations induced by the failure, wind gusts, airplane maneuvering, or configurational changes, the pilot must be constantly aware of the possibility of exciting further pitch oscillations. These motions are the result of the natural tendency of the airplane to oscillate in pitch This motion is termed phugoid and is characterized by a cyclic variation in the rate of climb/descent with a period of 40 to 80 seconds depending on flight conditions. The key to proper use of throttles for phugoid control is through VVI information. Suppressing the phugoid with throttle requires that the throttle setting be retarded just after the VVI reaches its maximum sink rate and advanced just after the VVI reaches its maximum climb rate. The amount of throttle change required to control the phugoid is dependent on the amplitude. Initially, for large variations, full throttle movement may be needed. Phugoid oscillations are stable and may not need to be fought during flight at cruise altitude. It is important to learn how to reduce the amplitude of these oscillations by use of throttles, bank angle, symmetrical flight spoilers or other controls because these pitch excursions should be damped on final approach.

Loss of Roll Control; Additional Means of Controlling Roll.

a. Roll control with trim

b. Yaw

c. Asymmetric thrust

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Note

The following procedure should only be used when additional roll control means listed above are not considered adequate for approach and landing. A 40 percent flap approach and landing is recommended.

d. Alternate roll control using ground spoiler handle.

(1) Turn OFF Ground Spoiler Left and Right Hand Sys A and B Hydraulic Power switches.

(2) Turn OFF Sys A and B Hydraulic Power switches for Flight Spoilers on the right wing. (NOTE. The resultant roll can be counteracted with yaw and aileron trim. If aileron trim is not available, pull back the ground spoiler handle to maintain wings level).

(3) Symmetrically retard throttles 1 and 4 to allow use of ground spoiler handle.

(4) Replace yaw and aileron trim by slowly pulling back ground spoiler handle to maintain wings level.

Note

Ground spoiler handle lock override lever must be used to disengage the ground spoiler handle locking pin.

Note

If additional spoiler deflection is needed to balance the left and right roll control available, use the trim system to produce the desired effect.

CAUTION

Apply handle motion slowly until desired roll response is obtained.

(5) Add aileron trim and maintain wings level by slowly adjusting ground spoiler handle. Using ground spoiler handle, evaluate roll capability and adjust aileron trim until acceptable roll rate in both directions is achieved.

WARNING

If a missed approach, go-around, or additional thrust is required, No. 1 throttle must remain in its last position. Advancing No. 1 throttle will close ground spoiler handle

and result in an immediate roll. Remaining roll capability (rudder and aileron trim) may not be sufficient for recovery.

WARNING

Except in an actual emergency, never remove all hydraulic power from any flight controls. Under no circumstances will the Flight Spoiler Sys A and Sys B Power switches be turned OFF simultaneously. To do so will allow all flight spoilers on the wing to float up.

CAUTION

In the event hydraulic system 2 or 3 is not providing adequate pressure for elevator control, placing the Inbd Elevator Hydraulic Power switches for the adequate system to NORM and placing the power switches for the inadequate hydraulic system to OFF should provide adequate system pressure. The elevator should be returned to neutral prior to switching hydraulic systems to prevent abrupt elevator inputs and damage to the airplane.

Note

The master caution system will not be activated when the Inbd Elevator Left Sys 3 and Right Sys 2 Hydraulic Power switches are placed in the OFF position. Subsequent elevator system hydraulic failures will activate the master caution system and the elevator power light will flash.

Note

If one aileron will not uprig, or after uprigging it will not retrim to a faired condition, the operative trim should be selected and positioned to the same position as the inoperative trim.

Jammed Roll Control System.

The roll control system contains two interconnect rods, each equipped with a shear pin. One interconnect rod and shear pin connects the pilot's and copilot's forward quadrants. The other interconnect rod connects the pilot's and copilot's aft quadrant.

If a jam occurs in either the pilot's or copilot's roll control system, sufficient force exerted at the control wheels will shear both pins, permitting use of the operable portion of the roll control system.

WARNING

Disengage the autopilot roll axis. If possible, reduce airspeed before shearing pins, and always turn both control wheels toward the airplane centerline to minimize control overshoot and prevent overstressing the airframe.

After shear out, exercise caution since the remaining one-wing roll system will have unsymmetrical characteristics.

If the right wing is the operable system, the copilot will also experience higher breakout forces and a very low force gradient. Over controlling may easily result.

Jammed Pitch Control System.

The pitch control system contains two interconnect rods, each equipped with a shear pin. One interconnect rod and shear pin connects the pilot's and copilot's forward quadrants. The other interconnect rod connects the pilot's and copilot's aft quadrants. If a jam occurs in either the pilot's or copilot's pitch control system, sufficient force exerted on the control columns will shear both pins permitting use of the operable pair of symmetric elevators.

To shear the pins, accomplish the following:

a. Disengage the autopilot pitch axis.

b. Reduce airspeed, if possible, and shut off hydraulic power to both outboard elevator system 3.

c. Ensure that the inboard left and right elevators are each powered by a single system.

d. Trim as needed.

e. Perform shear-out with minimal overshoot to prevent excessive stress on the airframe.

f. Reactivate outboard elevator system 3 power. If the pilot has control, the force gradient will be low. If the copilot has control, forces will be near normal. In either case, response to elevator commands will be reduced since either the inboard or outboard elevators will not be operable.

Jammed Directional Control System.

The pilot's and copilot's rudder pedals are connected by a common cable system to the upper and lower rudders. Interconnect rods and shear pins are not provided. If a jam occurs in the rudder cable system, the rudders may be controlled to 20 degrees either side of center by use of the Yaw Aug Man Trim controls on the flight augmentation panel. To obtain emergency rudder control, the yaw augmentation system must be engaged, and the guarded Yaw Aug Man Trim switch placed to ON. Rotating the Yaw Aug Man Trim knob then provides signals to the rudder servo valves to displace the rudders in the desired direction.

WARNING

Do not use the yaw augmentation manual trim for normal operation. This device provides up to 20 degrees of rudder deflection in approximately 1/2 second and bypasses the normal rudder stop system. Slowly apply the rudder necessary to control the airplane. Rapid rudder input may cause structural damage.

Jammed Feel Springs.

Each of the pitch, roll, and yaw control systems incorporate a feel spring which is equipped with a shear pin. If a feel spring jams, sufficient force on the affected controls will shear the pin, disconnecting the feel spring from the system. In the case of the pitch and roll systems, less force is required to shear the feel spring pin than is required to shear the interconnect rod pins.

Because the pilot is unable to differentiate between a jammed flight control and a jammed feel spring, refer to the Jammed Roll/Pitch Directional Control System procedures in this section prior to application of corrective force.

WARNING

When any Flight Control Hydraulic Power switch (except inboard elevator) is turned OFF or a flight control hydraulic sys off light (except inboard elevator) comes on, airspeed is limited to no more than 350 KCAS or Mach 0.825. If the inboard elevator is not powered on the left and right by system 2 or 3, airspeed is limited to no more than 350 KCAS or Mach 0.825.

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Uncommanded Flight Control Inputs.

If uncommanded flight control inputs are experienced and the malfunctioning system cannot be determined, recommend the pilot disengage the flight augmentation systems. This action will isolate most electrical inputs to the flight controls. After the airplane has stabilized, re-engage/reset systems one at a time, as required and determine the malfunctioning system.

High Control Forces (Inflight).

If higher than normal control forces are experienced in the pitch axis, attempt to isolate the problem as follows: Determine that the autopilot is disconnected and the AFCS Master Power pushbutton is OFF. If no change is noted, place the Pitch PACS switch to OFF. If no effect is noted, return the switch to NORM. A possible cause may be an elevator variable feel unit abnormality. Remove the elevator feel hydraulic power, one system at a time, by placing the appropriate Elevator Feel switch to OFF. If no effect is noted, return the switch to NORM. If higher control forces are still present, place both Elevator Feel switches to OFF. If no change is noted, return both switches to NORM.

> **CAUTION**
>
> Extreme caution must be observed when flying with both elevator feel systems off.

If higher than normal control forces are experienced in the lateral axis, ensure that the autopilot is disconnected and the AFCS Master Power pushbutton is OFF. Place the Roll PACS switch to OFF; if no effect is noted, return the switch to NORM.

Cable Tension Regulator Lockout.

The cable tension regulator is spring loaded to the C (COLLD) position, and it includes a surge lock device which will lock the two drums together when a sudden movement occurs between the one drum and the other. If a locked condition is suspected, grasp the two cables near the regulator and slowly bring them together simultaneously. Release them slowly and check that the regulator drums operate smoothly. The cable then should be tight; if not, repeat the procedure.

> **WARNING**
>
> It is not recommended that the cable tension regulator be reset in flight unless a safe platform (i.e., bulk cargo) is available. A ladder is not considered adequate.

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> **WARNING**
>
> Do not operate the autopilot with a cable tension regulator locked out.

FLIGHT CONTROL HYDRAULIC POWER FAILURE.

Note

The following flight control hydraulic power failure procedures are based on the assumption that a malfunction has occurred in a component and that the associated hydraulic power supply system(s) has not failed. For procedures to be used in the event of a total hydraulic system failure, refer to Hydraulic System Failure in this section.

Aileron Hydraulic Power Off Indication.

If an aileron hydraulic sys off light comes on, position the corresponding Aileron Hydraulic Power switch to OFF. If both hydraulic systems powering a single aileron have failed, or the corresponding switches are selected OFF, the aileron will float up and produce a mild roll in the direction of the failed or selected OFF aileron.

Rudder Hydraulic Power Off Indication.

If a rudder hydraulic sys off light comes on, position the corresponding Rudder Hydraulic Power switch to OFF. If both hydraulic systems powering a rudder have failed, and the corresponding switches are OFF, the rudder will float to an aerodynamic neutral position.

Should all hydraulic power be lost to one of the individual rudders, the Rudder Lim switch should be placed to MIN Q to obtain the maximum available rudder deflection from the remaining rudder.

> **WARNING**
>
> Use extreme caution when applying rudder inputs with the rudder stop system out of the normal configuration permitting more than the maximum allowable rudder deflection. More than the allowable rudder deflection could cause structural damage. Limit rudder input to that required to control the airplane.

Elevator Hydraulic Power Off Indication.

If an outboard elevator hydraulic system off light comes on, place the corresponding Elevator Hydraulic Power switch to OFF. If the inbd elevator left sys 2 off light comes on, place the Inbd Elevator Left Sys 3 Hydraulic Power switch to NORM and place the Inbd Elevator Left Sys 2 Hydraulic Power switch to OFF. If the inbd elevator right sys 3 off light comes on, place the Inbd Elevator Right Sys 2 Hydraulic Power switch to NORM and place the Inbd Elevator Right Sys 3 Hydraulic Power switch to OFF.

Elevator Feel Power Off Indication.

If an elevator feel sys off light comes on, place the associated Elevator Feel Hydraulic Power switch to OFF. The remaining elevator feel system will provide full elevator feel capability.

CAUTION

If both elevator feel systems are inoperative, use extreme caution while controlling pitch attitude. Structural damage could result from overcontrolling since the only force available is from the bobweights, friction, and centering springs.

Rudder Stop System Failure.

If a rudder limiter light comes on, first check indicated airspeed. If below 153 KCAS, the light indicates that the rudder is limited to less than full travel. For this condition, place the Rudder Lim switch to MIN Q. If between 153 KCAS and 238 KCAS, the light indicates that the rudder is either limited to 4 degrees travel or unlimited travel (35 degrees). For this condition, slow the airplane to below 153 KCAS and check whether the light goes out. If it does, the rudder is unlimited in travel. If the light does not go out, the rudder is limited to 4 degrees travel. For this condition, place the Rudder Lim switch to MIN Q if required.

If airspeed is above 238 KCAS, the rudder limiter light indicates that the rudder stop system will not limit rudder travel to the 4 degree maximum allowable deflection.

If rudder movement is restricted at airspeeds below 153 KCAS, even though the rudder limiter light is not on, place the Rudder Lim Switch to MIN Q if additional rudder travel is required.

If rudder travel is restricted on the ground with the Rudder Lim Switch in the AUTO position, and maintenance is not available, and it is essential to continue the mission, place the switch in MIN Q and check the rudder for full travel. If full rudder travel is available in this configuration, flight may be safely accomplished with the Rudder Lim switch in the MIN Q position throughout the flight. Limit rudder input to that required to control the airplane.

WARNING

Use extreme caution when applying rudder inputs with the rudder stop system out of the normal configuration permitting more than the maximum allowable rudder deflection. More than the allowable rudder deflection could cause structural damage. Limit rudder input to that required to control the airplane.

Pitch Trim Failure.

If a pitch trim failure is detected, disconnect both the normal and alternate pitch trim systems by depressing the Trim Disc button on the control wheel. The operating system may then be reset by selecting the proper system with the Pitch Trim Reset switch. The Manual Pitch Trim levers (on both sides of the center console) shall be used in case both normal and alternate pitch trim systems are inoperative.

Runaway Pitch Trim.

If a runaway pitch trim is detected, immediately depress the Trim Disc button on the control wheel. This will disconnect both the normal and alternate pitch trim systems. Use the manual pitch trim levers to retrim the airplane. The normal and alternate pitch trim systems may then be reset, one at a time, watching closely for another runaway. If the faulty system is discovered, leave it disconnected for the remainder of the flight.

WARNING

A pitch trim runaway to the 12-degree nose up stop, in all flaps-down configurations, will result in insufficient longitudinal control to prevent the airplane from entering a stall when the CG is aft of 33 percent MAC. Make a no-flap landing.

CAUTION

A pitch trim runaway to the full airplane nose-down setting may result in insufficient longitudinal control to generate desired positive load factor maneuvers. If additional elevator control is deemed necessary, it can be obtained by turning on hydraulic system No. 3 to the left inboard elevator and system No. 2 to the right inboard elevator. This should be accomplished with the elevator control column in the neutral position to prevent an abrupt elevator input which could result in structural damage.

Note

The Manual Pitch Trim lever may be used to override a hydraulic runaway that was not disconnected by the Trim Disc button.

Flight Augmentation Failure.

The flight augmentation system is fail operative in that no single fault in a pitch, lateral, or yaw subsystem can disable that subsystem. In case of multiple fault, the subsystem will disengage. A single fault in a subsystem is indicated by the appropriate pitch, lateral, or yaw aug fault lights and the master caution ghts. Complete failure of a subsystem will be indicated by the appropriate pitch, lateral, or yaw aug inop light and the master caution lights. The off light in the related Flight Augmentation Control pushbutton switch will also come on with a complete failure of the subsystem. The master auto lights and appropriate autopilot annunciator lights will come on if the augmentation subsystem faults or becomes inoperative while the autopilot is engaged.

Yaw Augmentation Inoperative.

If the yaw augmentation system should fail inoperative, as indicated by the yaw aug inop light, turn coordination is not provided and damping of the dutch roll is reduced. Airspeed must be restricted to 300 KCAS/ 0.825 Mach if the yaw augmentation remains faulted or inoperative. No abrupt rudder inputs, rudder reversals, or abrupt sideslip angles should be generated. Limit rudder input to that necessary to control the airplane. Manual recovery from dutch roll oscillations is best accomplished by using only small aileron control inputs to stop the rolling motion. Wheel angles should be limited to about ± 10 degrees. Rudder control inputs should not be used to damp the dutch roll

because of the possibility of aggravating the condition. Should turbulence be encountered at high altitude with the yaw augmentation system inoperative, the pilot should consider either a reduction in altitude, or a change in cruise speed, or both, to improve the natural damping characteristics. Conditions permitting, reduce altitude to approximately 31,000 feet or lower (reducing altitude will steadily improve dutch roll damping characteristics). Establish a cruise airspeed range of Mach 0.70 to 0.75.

Note

Yaw augmentation manual trim (emergency rudder trim) and roll axis of the autopilot are not available when the yaw augmentation system is inoperative.

Lateral Augmentation Inoperative.

If the lateral augmentation system should fail inoperative, as indicated by the lateral aug inop light, spiral stability and rudder coordination will not be provided in steady turns. The yaw augmentation system will provide rudder deflection for turn entry coordination and damping of dutch roll.

Note

The roll axis of the autopilot is not available when the lateral augmentation system is inoperative.

Pitch Augmentation Inoperative.

The pitch axis of the autopilot is not available with the pitch augmentation inoperative.

ALDCS Failures.

The ALDCS will disengage automatically and the ALDCS off annunciator light will come on as a result of failures within the ALDCS or disengagement of the pitch or lateral augmentation system. Refer to ALDCS OPERATING LIMITATIONS in section V.

Stallimiter System Failure.

If inadvertent shaker onset should occur during normal flight regimes where the airplane is not near the stall regime, immediately deactivate both stallimiter systems by placing the Stallimiter switches OFF. Determine which system has produced the malfunction by observing the stall lights and leave that system deactivated. Activate the good system for continued single protection in flight.

Appendix II

Concerning the C-130 Aircraft Simulation
Used in this Research

A2.1. General Information

Figure A2.1 is a photograph of the new updated version of aircraft used in this study. Exact dimensions were not available, but overall wingspan is approximately 133', overall length 98', and maximum normal takeoff weight approximately 155,000 lb. The C-130 is a military medium- to long-range transport powered by four turboprop engines. The simulation used during this research was of a (c. 1980) STOL version of the aircraft, which was built. *Explicit* information on most aspects of performance and *most* other *piloting-related* information specific to this aircraft were, unfortunately, proprietary at the time of this research. The aircraft simulation was designed for interface with a cockpit simulator, and thus for actual pilot usage. It is a high-fidelity nonlinear simulation of the standard type: Euler equations of motion with aerodynamic data in look-up tables, and all pilot cockpit-command-to-motion lags and other dynamics modelled. The simulation appears to give a reasonable and accurate simulation of aircraft motion in normal and extreme ranges of flight conditions.

The C-130 of the simulation had a fairly traditional group of controls--elevator plus elevator tab, differential ailerons, rudder, engines, and flaps--but this STOL aircraft differed from the conventional versions chiefly in that it was equipped with large leading- and trailing-edge flaps, which were quite instrumental in certain failure recoveries. The deployment of both sets of flaps was associated with a single flap control in the simulation, leading edge flaps being deployed first and trailing edge flaps after full extension of the leading edge surfaces. A change made in the simulation was the splitting of ailerons to allow independent deployment. The elevator tab was used independently of the elevator setting, potentially leading to large stresses in the actuation system but introducing a very important control degree-of-freedom.

The thrust model in the simulation was limited, with thrust a function of airspeed and throttle setting only, and independent of altitude.
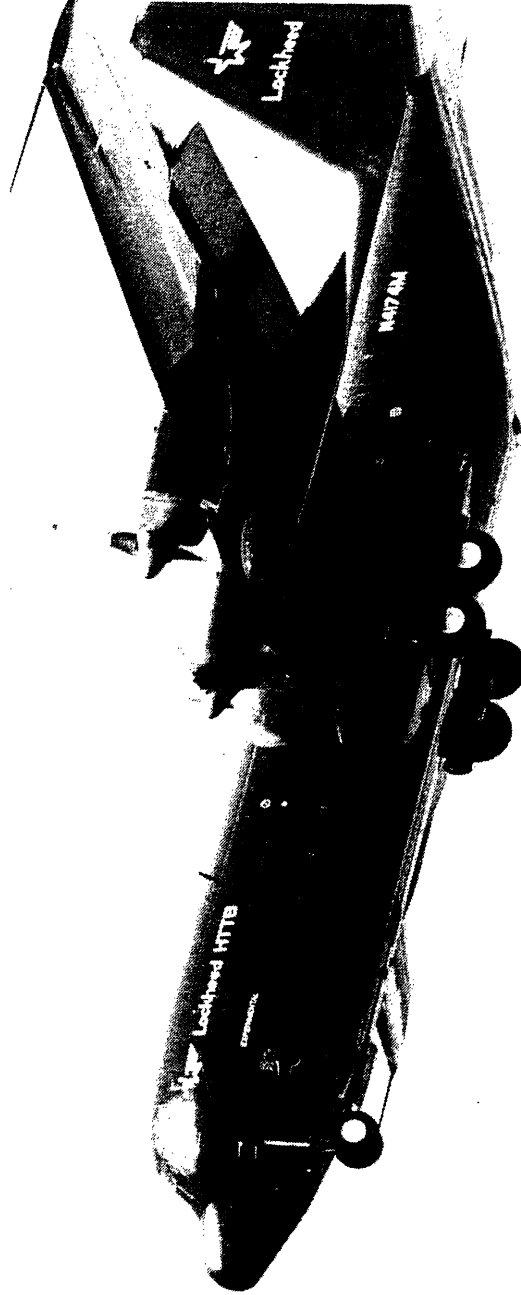
Figure A2.1: STOL C-130 (Updated Version)

Aircraft States in Simulation

V --true airspeed
α --angle of attack
β --sideslip angle
p --roll rate
q --pitch rate
r --yaw rate
φ --roll angle
θ --pitch angle
ψ --yaw angle
h --altitude

Aircraft Controls and Deployment Rates

de (elevator), 50. deg./sec.
da_r, da_l (right and left ailerons; da if collective), 35. deg./ sec.
dr (rudder), 35. deg./ sec.
df_r, df_l (right and left flaps; df if collective), 10.%/ sec.
tlev (thrust lever setting), 30.%/ sec.
detab (elevator tab), 2. deg./ sec.

A2.2. How the C-130 Simulation was Flown

The C-130 simulation was implemented on a VAX 11/780-5 computer. Dynamics and controls for the longitudinal axis only were used in part of this research. The simulation was "flown" using a terminal, *not* with conventional cockpit controls. The terminal display consisted of scrolling columns of output, with the output being completely user's choice. A typical choice is shown in the sample output fragment in Figure A2.2. The output interval chosen was generally 1.0 sec. The ratio of real to simulation time was anywhere from about 2-5 (5-12 with the force/ moment reconfiguration) to 1, depending upon overall computer load. The basic integration step size of the simulation was .02 sec.

The C-130 simulation has a very nice interrupt feature, which allowed essentially instantaneous access to the large global common block. Any quantity in this block could be reset at will through keyboard entry during the interrupt. The controls were commanded changed by keyboard-entered bias at a stage just prior to the point in the simulation where position and rate limiting and the generally fast first-order lag and second-order control dynamics were applied. This was the main method used in approximating what a pilot could do in controlling the aircraft, and it was considered a very satisfactory approximation in the use made of this simulation during this study. The direct access to the common was also used to switch autopilot modes and other settings as needed.

T SE	VA KNO	ALPHA DEGREES	QDEG DEGREES/SEC	THEDEG DEGREES	DA R DEGREES	DETAB DEGREES	TLEV PERCENT	HDOT FEET/SEC	H FEET	DA L DEGREES
0	180	3.126	0.0	3.126	-1.766	-1.985	72.85	0.3705E-04	7000.	1.766
1.0	179	16.04	23.38	20.07	-1.766	-1.985	72.85	23.47	7006.	1.766
2.0	171	25.05	13.79	30.36	-1.766	-1.985	72.85	73.57	7055.	1.766
3.0	161	28.32	10.60	50.21	-1.766	-1.985	72.85	112.2	7149.	1.766

```
*** HOLD ***
SET DETABTEST_R=60.
===> DETABTEST_R   changed from   0.0   to   60.000000
SET DETABTEST_L=60.
===> DETABTEST_L   changed from   0.0   to   60.000000
SET DATEST_R=-30.
===> DATEST_R   changed from   0.0   to   -30.000000
SET DATEST_L=-30.
===> DATEST_L   changed from   0.0   to   -30.000000
SET PCTTEST_1=-72.85
===> PCTTEST_1   changed from   0.0   to   -72.849998
SET PCTTEST_2=-72.85
===> PCTTEST_2   changed from   0.0   to   -72.849998
SET PCTTEST_3=-72.85
===> PCTTEST_3   changed from   0.0   to   -72.849998
SET PCTTEST_4=-72.85
===> PCTTEST_4   changed from   0.0   to   -72.849998
CP
*** COMPUTE ***
```

T SE	VA KNO	ALPHA DEGREES	QDEG DEGREES/SEC	THEDEG DEGREES	DA R DEGREES	DETAB DEGREES	TLEV PERCENT	HDOT FEET/SEC	H FEET	DA L DEGREES
4.0	149	30.98	9.017	60.08	-19.97	-0.4050	62.17	135.8	7275.	-19.89
5.0	136	33.57	7.268	68.21	-20.00	1.595	50.86	145.3	7416.	-20.00
6.0	122	35.85	5.264	74.66	-20.00	3.595	41.61	144.6	7562.	-20.00
7.0	109	38.16	4.214	79.59	-20.00	5.595	34.04	135.9	7703.	-20.00
8.0	95.	40.76	3.247	83.24	-20.00	7.595	27.85	121.9	7832.	-20.00
9.0	83.	44.20	2.989	86.32	-20.00	9.595	22.78	105.2	7945.	-20.00
10.	71.	49.30	2.950	89.30	-20.00	11.59	18.64	86.67	8042.	-20.00
11.	60.	56.64	2.116	91.93	-20.00	13.59	15.47	66.54	8118.	-20.00
12.	52.	66.06	0.3579	93.19	-20.00	15.59	12.47	45.22	8174.	-20.00
13.	46.	77.55	-1.432	92.65	-20.00	17.60	10.20	23.11	8208.	-20.00
14.	45.	89.83	-3.052	90.37	-20.00	19.60	8.349	0.3032	8220.	-20.00
15.	46.	78.63	-3.868	86.83	-20.00	21.60	6.831	-22.46	8209.	-20.00
16.	50.	69.68	-3.974	82.87	-20.00	23.60	5.589	-44.57	8175.	-20.00
17.	55.	62.73	-3.663	79.01	-20.00	25.60	4.573	-65.89	8120.	-20.00
18.	61.	57.17	-2.971	75.90	-20.00	27.60	3.741	-86.15	8044.	-20.00
19.	67.	52.39	-2.535	73.00	-20.00	29.60	3.061	-105.3	7948.	-20.00
20.	74.	48.55	-2.999	70.30	-20.00	31.60	2.505	-123.8	7834.	-20.00
21.	81.	46.36	-4.169	66.77	-20.00	33.60	2.050	-141.4	7701.	-20.00
22.	87.	46.51	-5.823	61.81	-20.00	35.60	1.678	-157.3	7551.	-20.00
23.	93.	49.68	-7.730	55.03	-20.00	37.60	1.373	-170.8	7387.	-20.00
24.	98.	56.44	-9.409	46.44	-20.00	39.60	1.124	-188.6	7211.	-20.00
25.	103	67.28	-10.86	36.29	-20.00	41.60	0.9201	-197.6	7026.	-20.00
26.	110	82.33	-12.28	24.73	-20.00	43.60	0.7533	-211.6	6833.	-20.00
27.	122	78.93	-14.12	11.58	-20.00	45.60	0.6169	-219.6	6629.	-20.00
28.	135	57.42	-16.48	-3.690	-20.00	47.60	0.5053	-218.9	6412.	-20.00
29.	145	33.02	-16.96	-21.42	-20.00	49.11	0.4140	-212.3	6192.	-20.00
30.	154	8.092	-12.61	-39.95	-20.00	49.68	0.3393	-225.7	5977.	-20.00
31.	166	5.068	-4.228	-42.57	-20.00	49.88	0.2782	-228.9	5758.	-20.00
32.	176	8.201	4.752	-36.81	-20.00	49.96	0.2283	-219.8	5550.	-20.00
33.	185	8.605	4.905	-31.58	-20.00	49.88	0.1874	-202.8	5305.	-20.00
34.	193	8.460	5.202	-26.81	-20.00	49.99	0.1539	-181.5	5094.	-20.00
35.	199	8.445	5.319	-21.74	-20.00	50.00	0.1265	-155.1	4901.	-20.00
36.	203	8.468	5.361	-16.47	-20.00	50.00	0.1042	-124.7	4732.	-20.00
37.	207	8.486	5.335	-11.13	-20.00	50.00	0.8585E-01	-91.89	4592.	-20.00
38.	206	8.513	5.237	-5.773	-20.00	50.00	0.7007E-01	-58.13	4484.	-20.00
39.	203	8.551	5.070	-0.4807	-20.00	50.00	0.5861E-01	-24.99	4409.	-20.00
40.	199	8.599	4.835	4.678	-20.00	50.00	0.4859E-01	6.101	4367.	-20.00
41.	199	8.660		9.636	-20.00	50.00	0.4038E-01		4358.	-20.00

```
*** HOLD ***
CP
*** COMPUTE ***
```

Figure A2.2: Example of Terminal Output from Which C-130 Aircraft was "Flown" (Shows commanded control changes made during sim. interrupt)

The author was licensed as a private pilot in 1978. Several pilots were consulted directly about piloting issues as they arose.

A2.3. About the C-130 Nominal Pitch Control Loops

The C-130 natural dynamics have certain poles that are only very lightly damped, so a three-axis stability augmentation system (SAS) was part of the original nominal aircraft model in the simulation. In the pitch axis, the SAS issues commands to the elevator only; this should be kept in mind for the elevator failure cases. In the roll and yaw axes, the SAS issues commands to aileron and rudder, respectively. The nominal C-130 also has the frequently-seen control wheel steering (CWS) autopilot mode. In the pitch axis, this mode is designed to translate control column position into a desired pitch angle, and is a pitch angle regulator loop. The loop also issues commands to the elevator only. In the roll axis, CWS is again a regulator loop, and issues commands to the ailerons.

Appendix III

An Extended Force/ Moment Remapping Reconfiguration

The reconfiguration described in this Appendix was used in the earliest attempts at recovering the C-130 after elevator failures. This reconfiguration was a remapping to the other longitudinal controls of pitch-moment effects of elevator deployment intended by the nominal automatic control loops. Use of this reconfiguration to recover the aircraft in the initial post-failure period was abandoned because the nominal automatic control for the C-130 has fairly low authority, so remapping its commands usually resulted in slow and generally inadequate opposition to the disturbance induced by off-nominal jam failures. This reconfiguration will be presented here, however, in order to describe its functioning, which could be well suited to give better initial emergency response in other applications. *The shortcomings of use of the standard pseudoinverse-type reconfiguration will be well demonstrated.* In two cases, the C-130 was recovered and flown to 10,000' using the reconfiguration described in this Appendix.

One of the fundamental ideas in reconfiguring control once the failure is identified is to map the forces and moments dictated by the nominal control onto the remaining unfailed controls. In terms of the linear model, one thus seeks to solve

$$B_f \, \Delta \underline{u}_f(t) = B \, \Delta \underline{u}(t)$$

where B_f represents the columns of the original B matrix associated with the remaining controls $\Delta \underline{u}_f$ (as in the standard usage, the B matrix is the linearization of model with respect to control inputs). Typically one solves for $\Delta \underline{u}_f(t)$ as

$$\Delta \underline{u}_f(t) = B_f^\dagger \, B \, \Delta \underline{u}(t)$$

where $B_f^\dagger$ is generally the least-squares Moore-Penrose pseudoinverse of B_f.

This approach to reconfiguration is less attractive from most standpoints than other approaches and certainly less than outright control loop redesign. By checking this type of control reconfiguration for stability using the well-known robustness tests of [A3.1], it is clear that stability of the loop reconfigured in this way cannot be guaranteed for all initial conditions unless there is full control redundancy, and thus rank B_f = rank B. This type of reconfiguration does have ease of immediate use in its favor where it does guarantee stability. It is the basis of reconfigured control that has been flight tested [A3.2]. Among its

limitations is that the nominal automatic control loops in typical lower-performance aircraft are somewhat low-gain, and thus have insufficient authority to oppose failure-induced disturbances on their own. Remapping low-gain commands can be futile. More simply, however, remapping commands to the unfailed controls as above does not take into account the dynamics of the unfailed controls--including limitations on rate of deployment--or position limits.

This appendix demonstrates the advantages of abandoning the standard pseudoinverse (PSINV)-type reconfiguration in favor of a scheme that uses, *at any given time*, those working controls that more exactly duplicate the intended effects of the failed control.

Figure A3.1 shows the (simulated) uncompensated longitudinal response to a 5° off-nominal nose-down elevator jam on the C-130 aircraft when the aircraft was flying at 197 KIAS at 1000'. The C-130 stability augmentation system and the separate pitch-hold (control wheel steering) autopilot loop issued intended elevator commands. A simple proportional-integral-differential altitude-hold loop that uses the engines was added for this study and was in use during this run, to further encourage recovery from the failure.

The C-130 is *not* a particularly sensitive aircraft from a stability and control viewpoint, yet a 5° off-nominal elevator jam was enough to cause the aircraft to dive from 1000' to the ground in 8 sec. Figure A3.2 shows the response of the aircraft to the same failure, but with the usual type of pseudoinverse reconfiguration in place. To get the new reconfigured control, the equation

$$B_f \, S^{-1} \, \Delta\underline{u_f} = \underline{b_i} \, \Delta u_i$$

was solved; the input scaling S was half the total range of motion of the working controls except for the elevator tab, which was scaled by the smaller available nose-up range only. This scaling was introduced in order to encourage the use of ailerons, which are less effective incrementally in pitch but have a good-sized range of travel. Different scalings were also tried, however, with no substantial change in the effectiveness of this reconfiguration strategy in aiding recovery. Flight was not prolonged past the 8 sec. of the uncompensated case with this traditional-type pseudoinverse reconfiguration. The pseudoinverse reconfiguration in this case was a *best faith effort* to get the standard pseudoinverse reconfiguration to work. *The control dynamics were dropped in the simulation, as was the finite deployment time.*

Whether or not the equation $B_f \, \Delta\underline{u_f}(t) = B \, \Delta\underline{u}(t)$ can be solved exactly, pseudoinverse reconfiguration can ask for very large deployments of certain controls which are particularly
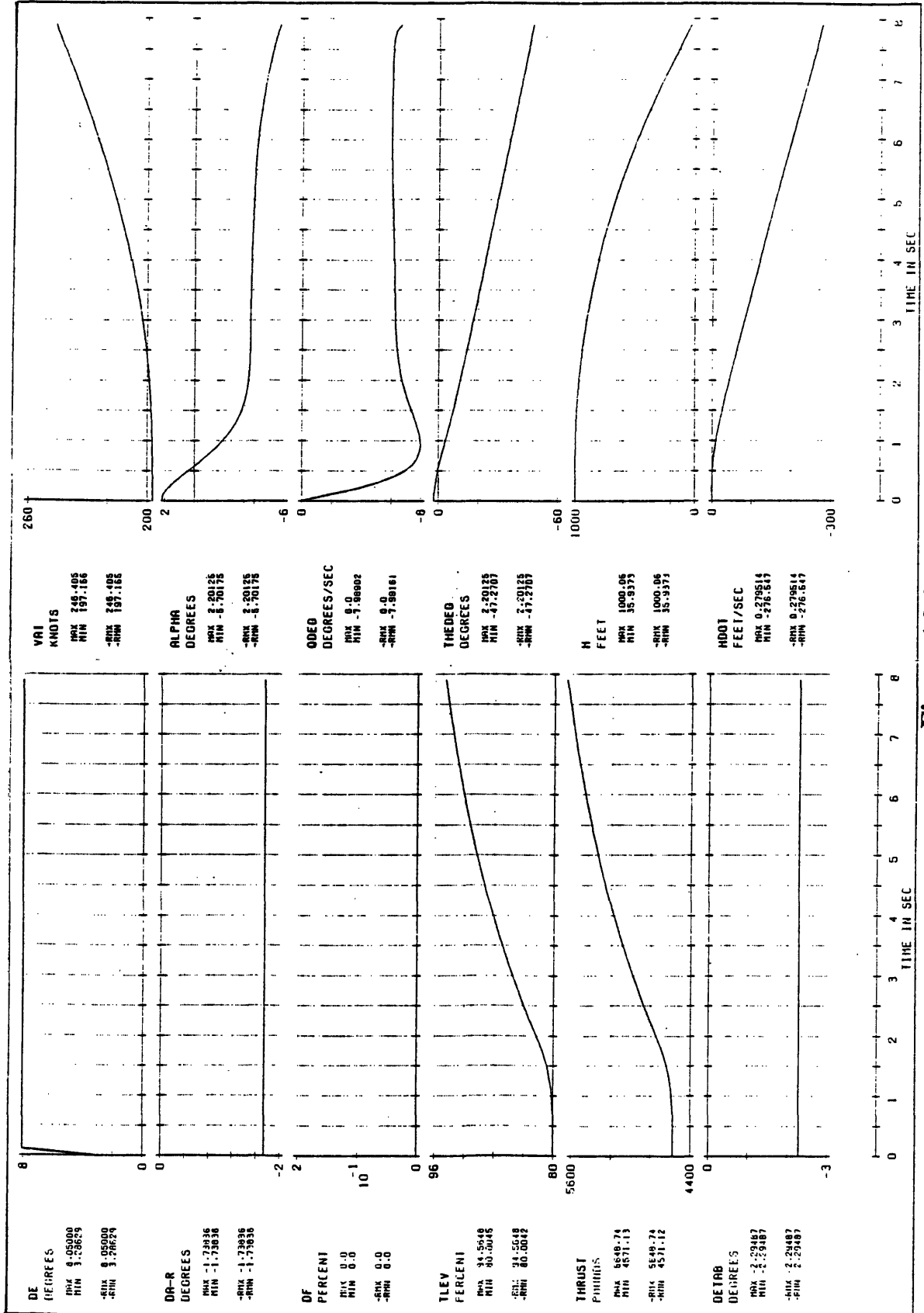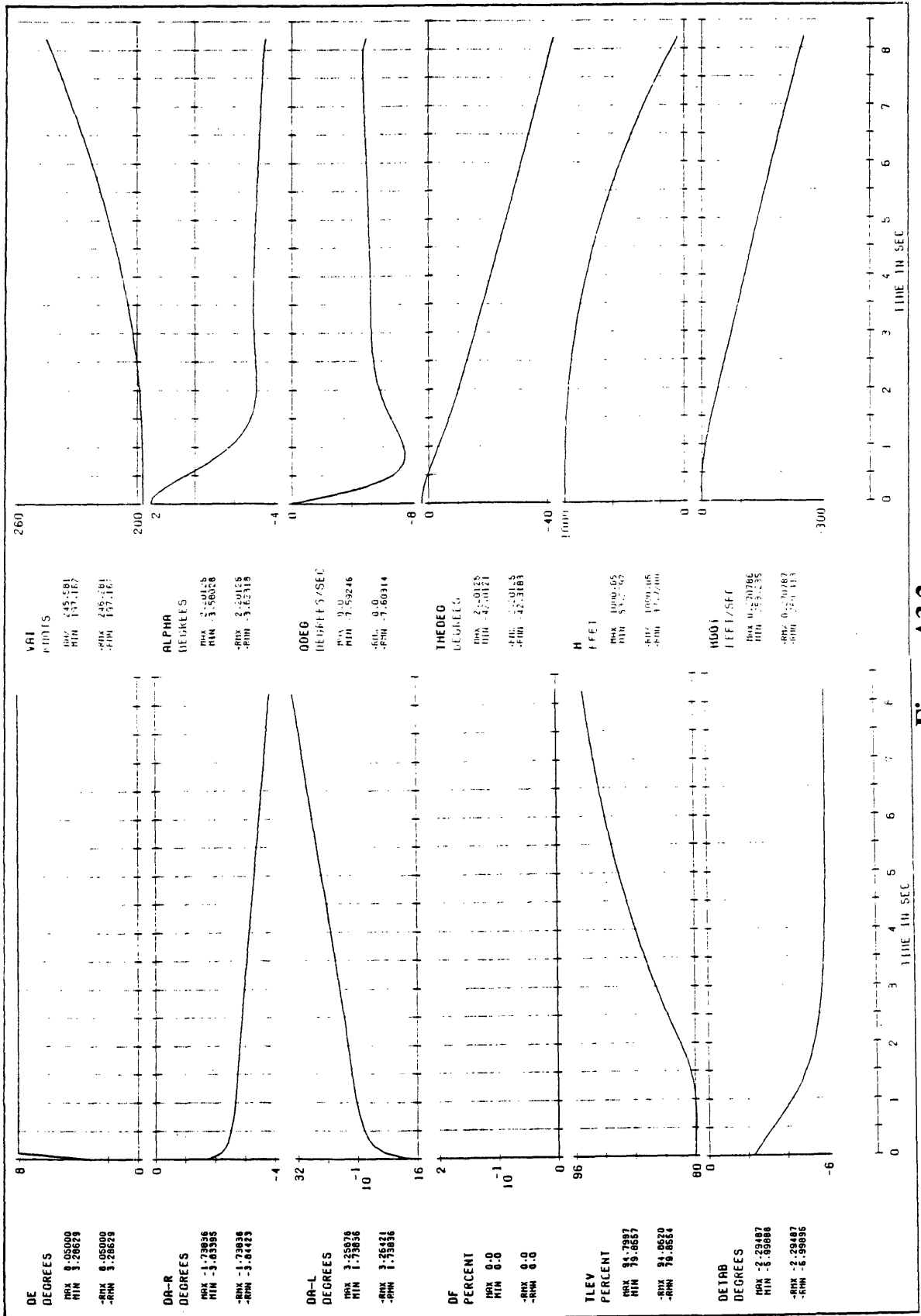
Figure A3.1

Figure A3.2

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or nearly solely effective in effecting changes in certain state rates. This flies directly in the face of rate and position saturation of the controls (not to mention the limitations of the linear model).

This failure case gave the first good indication that the standard pseudoinverse-type reconfiguration can have significant weaknesses when used on an aircraft with limited control redundancy. The PSINV reconfiguration caused quite different control movement than in a later successful manual recovery--in particular, the ailerons moved to give a pitch-*down* moment, not the needed pitch-up.

Figure A3.3 shows the successful recovery of the aircraft from this failure when the controls were reconfigured (instantaneously) to do the best job of matching the SAS- and CWS-commanded pitch moment, *but taking into account rate and position saturation of the working controls.* The aircraft recovered to a fairly stable 140 KIAS, 600 ft/ min. climb within approximately 25 sec. The salient features were immediate hard-over pitch-up aileron response, while the slower flaps and then the elevator tab (slowest to deploy) were brought in. A small pitch-up thrust increase was used in the intermediate time frame.

This successful emergency control was the solution to the problem below, solving for changes in the covering controls, Δu_f, given elevator command Δu_i:

$$\text{Min } [(B_f \Delta u_f - b_i \Delta u_i)^T Q (B_f \Delta u_f - b_i \Delta u_i) + \Delta u_f^T R \Delta u_f]$$
$$\text{subject to}$$
$$u_{f_{min}} \leq u_f \leq u_{f_{max}}$$
$$du_{f_{min}}/dt \leq du_f/dt \leq du_{f_{max}}/dt$$

It was clear in the first attempts at recovering the aircraft via the reconfiguration here that it would not be possible to duplicate exactly all of the intended elevator's effects on velocity, angle of attack, and pitch rate. The aircraft was not fully control-redundant with respect to this failure. By insisting on equal weighting of the differences in each of these directions (i.e., $Q = \text{diag } (1, 1, 1, 1, 1)$), the aircraft was lost. For the successful simulation of Figure A3.3, Q was a weighting on pitch rate only and R was a diagonal weighting matrix five orders of magnitude smaller than Q. This small weighting on the controls themselves helps retain potential authority for maneuvering or other purposes, but this weighting was kept relatively very small so that there would be no possibility of sacrificing maximum recovery potential. After it became clear that the functioning controls were truly effectively duplicating the intended effects of the failed control and the aircraft was stabilized, more extensive reshifting of control burden could proceed through larger R weighting. One other tested

Figure A3.3

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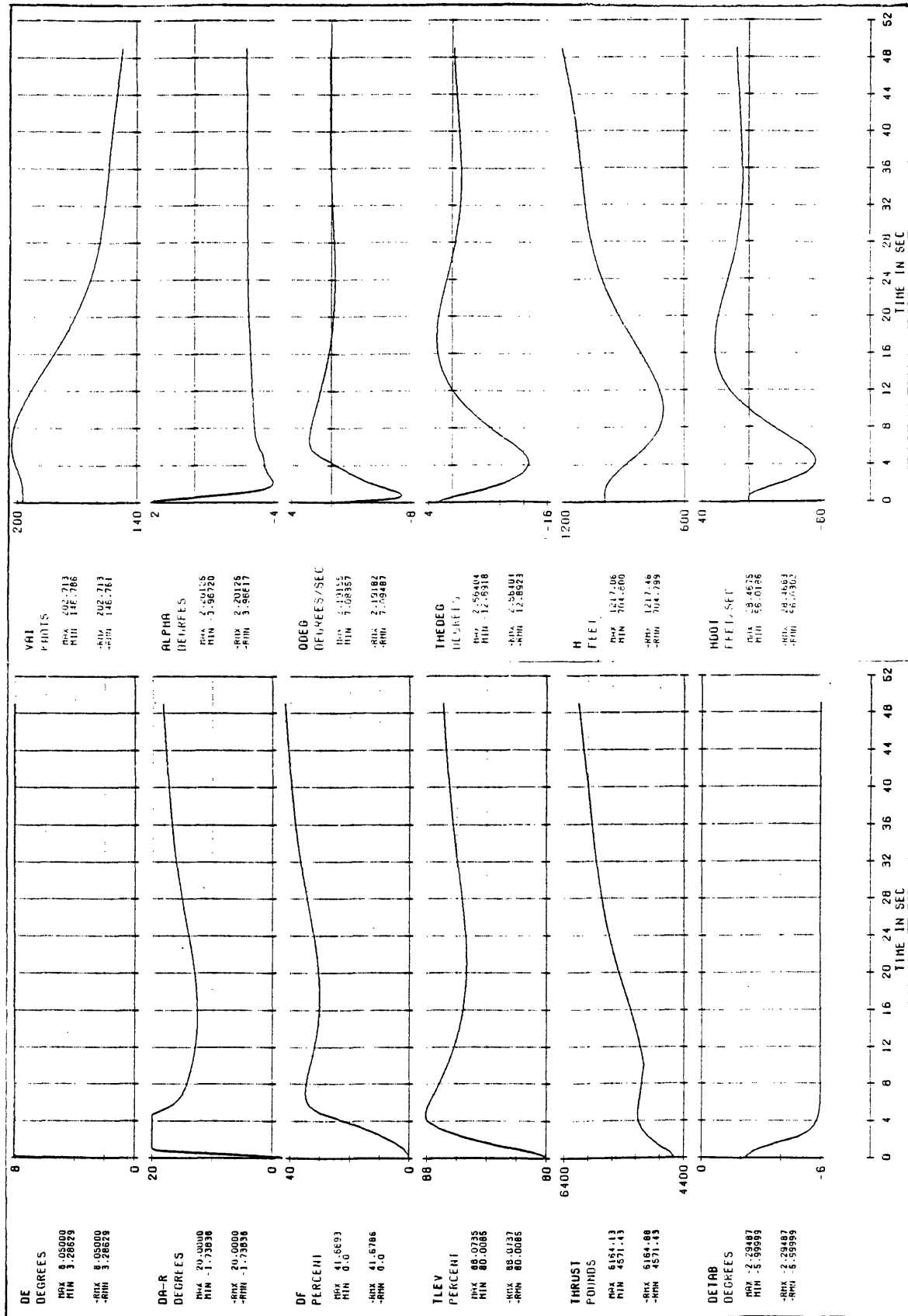
choice of Q was weighting according to the nominal effect of the elevator on the various state rates, that is, if $\underline{b}$ is the column of the B matrix associated with the elevator's effects,

$$Q = \text{diag} (b_1{}^2, b_2{}^2, ...)$$

One can think of this choice as a further step toward minimizing the effects of the disturbance generated by the failure or as preferring to duplicate the largest intended effects of the failed surface. This choice of weighting did not, however, allow for recovery from this failure. It simply diverted too many control resources from opposition of the failure-induced nose-down *pitch moment*. In all subsequent runs, the reconfiguration was based on pitch rate weighting only. This presumably leads to the lightly damped motion in the post-failure aircraft. But in the absence of more definitive work on the effects of different weighting choices, this is a tenable one.

Although any of a number of constrained *quadratic programming* techniques could have been used to solve the optimization problem above, a more general nonlinear programming approach was used in this study. This choice was made before there was a clear view of the cost to be minimized and how much of the control dynamics would be incorporated into the model. A general *conjugate gradient* optimization method was used, one which could solve the general problem

$$\text{Minimize } \Sigma \ f \ (\Delta\underline{u}_f \ (i), \Delta\underline{u}_{f_{rc}})$$
$$\text{subject to}$$
$$\Delta\underline{u}_f(i+1) = g \ (\Delta\underline{u}_f \ (i), \Delta\underline{u}_{f_{rc}} \ (i))$$

Here $\Delta\underline{u}_{f_{rc}}$ is the commanded control deployment rate. The constraints of control position and rate saturation were accounted for by having g() be a saturation function, as needed. The conjugate gradient method used was an Euler discretization of that method employed to minimize an integral nonlinear cost, in reference [A3.3]. Because of the requirements of smoothness of cost and propagation equations, the exact saturation functions were approximated (to possibly arbitrary exactness) by rounding off the corners, as for example when the actual (vs. commanded) deployment rate $\Delta\underline{u}_{f_{rc}}$ saturates or, similarly, when a limit is reached on control position.

Using this nonlinear programming method would allow straightforward incorporation of control dynamics. In the reconfiguration runs of this study, however, control dynamics beyond limitations on deployment rate were not incorporated. Because of the slowness of thrust dynamics, it is to be recommended that they be incorporated.

The pitch-up moment provided by the flaps was a crucial factor in the recovery and climb of this handicapped aircraft. Their deployment airspeed limitations (structural constraints) were exceeded for a time in the early part of the recovery. This aircraft cannot be recovered at this altitude without violating the flap deployment constraints for a time.

This reconfiguration was used to fly the aircraft with the elevator jammed at 8.05° and, in another case, with the elevator jammed at -9° to stabilization at 10,000' and then through to a pitch-stabilized slow descent that would have allowed the aircraft to be flown safely onto the ground in a no-flare landing. After the initial part of the recovery in the first case, because of the expected extended usage of flaps in the climb, the indicated airspeed limitations on flap deployment were more carefully considered. By being aware in advance of these airspeed limitations and by being apprised (through the terminal output) of the flap deployments that the reconfiguration was asking for, elevator inputs could be commanded that allowed the flap deployments to remain inside the constraints during the long climb and later descent. With this first case, the large flap deployments obliged a change in the linear model used in the reconfiguration, effected just prior to descent to the model associated with the stabilized point at 10,000'. In the second case, the linear model used throughout was that associated with the original pre-failure cruise flight. Figure A3.4 shows the ascent in the second case, with elevator jammed at -9°. The aircraft looped very soon when there was no compensation applied. This reconfiguration allowed a successful climb out and recovery to descent on the first try. At about 28 sec. post-failure, at a point when the aircraft had already substantially recovered via this Extended Force/ Moment Remapping (EFMR) reconfiguration, the thrust was increased to 100%, and a small commanded elevator bias was input, which was remapped to the other controls. The CWS autopilot mode was turned off so that pitch angle could more freely increase for the climb. Probably because of the pitch rate matching only but also due to the limitations on mode of control inputs and the author's own limitations as a pilot , the aircraft required a few hundred seconds to stop its pitch oscillations in the climb whenever a large control change was made, as Figure A3.4 shows. This made stabilization at altitude difficult, too, and it was hard to determine the magnitude and phasing of stabilizing changes in elevator and throttle settings. A pilot could be expected to *try*, at least, to limit these, even under the difficult circumstances.

Thrust had to do double duty in the climb. Decreasing thrust was the only remaining means of pitch-down control in the pitch-up (-9° elevator jam) case, but then it wasn't independently available for control over climb rate. A common scenario was that an increase in thrust to improve the climb performance would lead to angle of attack and pitch angle becoming so large that the airspeed would decrease and the climb rate would actually

Figure A3.4

DE
DEGREES

DA-R
DEGREES

DF-R
PERCENT

TLEV
PERCENT

THRUST
POUNDS

DETAB
DEGREES

VAI
KNOTS

ALPHA
DEGREES

QDEQ
DEGREES/SEC

THEDEQ
DEGREES

H
FEET

HDOT
FEET/SEC

TIME IN SEC
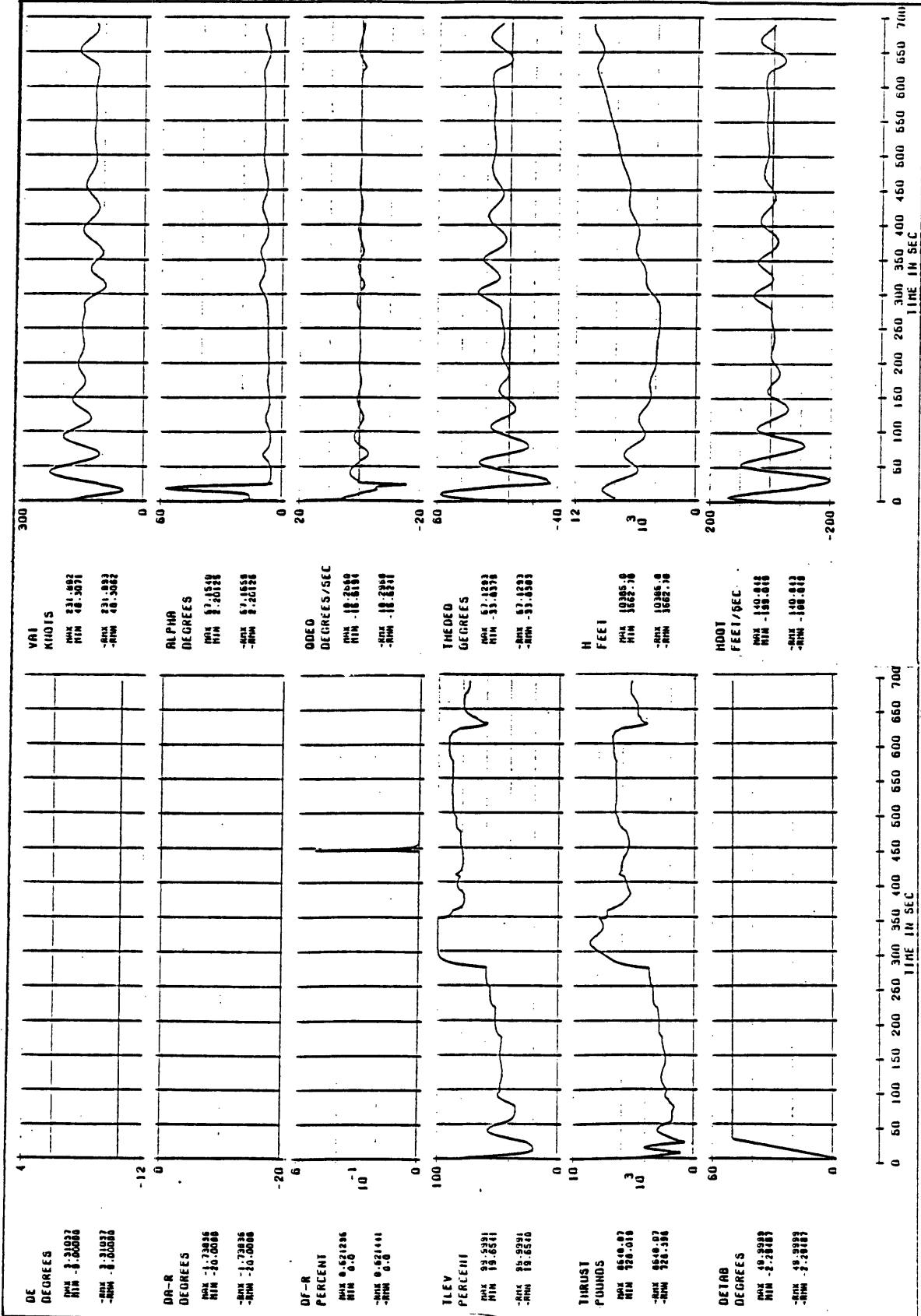
decrease. "Optimal" post-failure climb would have meant maximizing climb rate or minimizing fuel to altitude, probably preferably the latter.

The descent was initiated by dropping the throttle setting in this pitch-up failure case and commanding a couple of degrees of pitch-down elevator input, which was remapped. Very gradually, flight at 129 KIAS and with 5-6 ft/sec. sink rate was achieved. The descent was not difficult, although concentration was required. Large, quick control changes were avoided and oscillations were allowed to die so that a clear view of the effect of control changes was possible. It took 4-5 minutes to get the aircraft settled out on the descent. Being able to fly this long, slow final was a real luxury because of the limited aircraft range it allowed and because of the presumably relatively high fuel usage.

There arose a dilemma in interpreting pilot commands with this reconfiguration. If the pilot specifies some control input explicitly, should the reconfiguration be allowed to bleed off this input, or should it be allowed to stand unequivocated? This was an important issue where flap and thrust changes were involved. This was decided in favor of letting the command stand and the controls be deployed accordingly.

References

A3.1. Lehtomaki, N.A., et al., "Robustness Results in LQG Based Multivariable Control Designs," IEEE Transactions on Automatic Control, AC-26, February 1981.

A3.2. "Software Advances Fuel Optimism for 'Reconfigurable Aircraft'," Research and Development, October 1985, pp. 43-44.

A3.3. Hasdorff, Lawrence, Gradient Optimization and Nonlinear Control, Wiley, New York, 1976.

Appendix IV

Implicit Function Theorems Applied to Aircraft Equilibrium and Other Constant-Rate Regions

In flying the C-130 simulation, many times a closer equilibrium than a solved-for retrim was discovered by flying the aircraft. Scaling of the states and inputs in the retrim problem was *not* a satisfactory answer to this problem. An obvious recourse is to know many equilibria--perhaps even a general description of the equilibrium region. However, iterative methods are currently the only option for solving for roots of general nonlinear equations. These techniques can only be used to solve point-by-point for equilibria.

Even for an aircraft without much control redundancy, like the C-130, the equilibrium region can be quite large. To get the barest idea of its extent for this aircraft, the allowable longitudinal state and control space was gridded very coarsely and a point-by-point search made for (near-)equilibria among the grid node points. The survey could be expected to have included all of the equilibrium region, albeit very coarsely. The result of this was thirty-eight points with all state rates falling within (-.1, +.1). Among these and 14 other equilibrium points which were accumulated through other work, there were points with values of angle of attack, altitude, collective aileron, flap, and elevator tab at both extremes of their usable ranges and with true airspeed between 163 and 337 ft/sec., elevator between -12° and 8°, and thrust lever setting between 60% and 93%. This represents a considerable range, a range that was unexpectedly large, and one that argues well for potential recovery from a large range of control failures.

It would be of value to be able to discuss the properties of constant-rate regions for aircraft nonlinear dynamics. This information could then be used in certain post-failure situations, for example, to locate equilibrium points that have the failed input's value, particularly if one assumes that the coefficients in the governing differential equations have not significantly changed with the failure. It should be mentioned that this assumption is likely quite a good one with the most common type of failures, jam failures. It can be expected that floating or missing surfaces will induce a more radical change in the dynamics, and partial surface loss an effect on the dynamics that is probably somewhere in between.

Other advantages of knowing more about constant-rate regions for aircraft-type nonlinear systems are numerous. More general information regarding the map $(x,u) \leftrightarrow rates$ could be useful in many ways:

1. It could lead to better assessment of linearity assumptions used, among other things, for control and FDI design.

2. It could facilitate indicating overall control redundancy of a given aircraft. Related to this is indicating how the current control burden could be shifted more locally from one to other controls in order to free up the first for desired trajectory changes.

3. The information might provide a good basis for evaluating more static "reachability" of certain states, for example, as one contemplates bringing an aircraft with failures to a landing. The information could be expected to indicate when certain intermediate configurations necessary to this are impossible.

4. The $(x,u) \leftrightarrow rates$ and constraints representation could, in the long run, be expected to lead to suggestive control information in post-control failure recovery. (It could conceivably provide options even when the failure identification is uncertain.) The information could be used to give the static "performance" airspeeds and configurations that can be critical to recovery from first bases.

The information in the form of pairs $((x,u), rates)$ is voluminous and unwieldy. One is working here in n+m space, where number of states n = 10 and number of controls m = n or more (the higher the better from a control redundancy viewpoint). The forward map would reflect evaluation of the nonlinear dynamics $f(x,u)$. Useful information on the inverse map really means having to describe a high-dimensional surface, with as yet unknown curvature and extent. Unfortunately, it seems that the higher the dimension of the constant-rate regions and thus the harder to evaluate the region, the more useful it is, because of the indicated versatility of the aircraft to fly after control failures.

There are very few mathematical tools are available for application to describing and constant-rate regions of aircraft nonlinear dynamics. The following will give some theorems relevant to the problem of determining the properties of constant-rate regions, including equilibrium regions, for aircraft nonlinear dynamics. This researcher has attempted to gather the very few available theorems that seem relevant to problems of existence and uniqueness of solutions to general, and preferably underdetermined systems of nonlinear equations and

makes here a few statements that relate to the shape and extent of the constant-vectoral-valued regions of these equations.

Let the nonlinear dynamics of the system of interest be expressed as

$$d\underline{x} / dt = \underline{f}(\underline{x}, \underline{u})$$

where $\underline{f}$ is a mapping of an open set $S_x \times S_u \subseteq R^n \times R^m$ into R^n, and $\underline{f}$ is considered to have partials continuous in their arguments (one says that $\underline{f}$ is continuously differentiable, or C'). The open set $S_x \times S_u$ may for present purposes be considered to be the set of physically feasible states and controls. (That this feasible set is most readily thought of as being an open set plus its boundary presents no difficulties.)

One can consider, without loss of generality, for any $(\underline{x}_0, \underline{u}_0) \in S_x \times S_u$ (and thus for points on the equilibrium surface) that the matrix

$$[\, \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{x} \mid \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{u} \,] \equiv [A \mid B]$$

where A and B are the usual linear model matrices, has full rank, that is, rank n. In other words, the local linear model has no redundant states. This is usually an implicit assumption for a dynamic model.

Let $\underline{z}$ be the collection of n among n+m total states and controls such that

$$\text{Rank}\,[\, \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{z} \,] = n.$$

Let $\underline{w}$ be the remaining states and controls. This choice $(\underline{z}, \underline{w})$ will be called the *invertible Jacobian partition* (IJP). This partition need not be unique at $(\underline{x}_0, \underline{u}_0)$, and, in fact, unless either $m = 0$ or $[\, \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{w} \,] \equiv [\, 0 \,]$ (neither applicable for systems of interest here) it will *not* be unique.

Most of the available general properties of the equilibrium surface originate from the Implicit Function Theorem.

Implicit Function Theorem [A4.1]

Let $\underline{f}$ be a C'-mapping of an open set $S_z \times S_w \subseteq R^{n+m}$ into R^n, such that $\underline{f}(\underline{z}_0, \underline{w}_0) = \underline{0}$ for some point $(\underline{z}_0, \underline{w}_0)$ in $S_z \times S_w$. Assume that the matrix $[\, \partial\underline{f}(\underline{z}_0,\underline{w}_0) / \partial\underline{z}\,]$ is invertible. Then there exist open sets V in R^{n+m} and Y in R^n, with $(\underline{z}_0, \underline{w}_0) \in R^{n+m}$ and $\underline{w}_0 \in Y$, having the following property:

To every $\underline{w} \in Y$ corresponds a unique $\underline{z}$ such that
$$(\underline{z}, \underline{w}) \in V \text{ and } \underline{f}(\underline{z}, \underline{w}) = \underline{0}$$

If this $\underline{z}$ is defined to be $\underline{g}(\underline{w})$, then $\underline{g}$ is a C' mapping of V into R^n, $\underline{g}(\underline{w}_0) = \underline{z}_0$, $\underline{f}(\underline{g}(\underline{w}), \underline{w}) = \underline{0}$ for $\underline{w} \in Y$, and

$$[\, \partial\underline{g}(\underline{w}_0) / \partial\underline{w}\,] = -[\, \partial\underline{f}(\underline{z}_0, \underline{w}_0) / \partial\underline{z}\,]^{-1} \cdot [\, \partial\underline{f}(\underline{z}_0, \underline{w}_0) / \partial\underline{w}\,]$$

$\blacklozenge$

Reference [A4.2] gives a slightly stronger Implicit Function Theorem, which includes, among other things, information on the size of the domain of the implicit function $g(\underline{w})$ at all points of the equilibrium surface. This information did not seem very useful because the results, being general ones, are weak.

The following theorem expresses the general topology of the equilibrium surface, and WLOG (with $\underline{f}$ properly defined) the topology of *all constant-rate surfaces* associated with the assumed C' dynamics.

Theorem.

Let $\underline{f}(\underline{x},\underline{u})$ be a C' mapping from open set $S_x \times S_u \subseteq R^n \times R^m$ into R^n, and with the property that for any $(\underline{x}_0,\underline{u}_0) \in S_x \times S_u$

$$\text{Rank }[\, \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{x}\, |\, \partial\underline{f}(\underline{x}_0, \underline{u}_0) / \partial\underline{u}\,] = n$$

Then the set of all points $(\underline{x}_e,\underline{u}_e) \in S_x \times S_u$ for which $\underline{f}(\underline{x}_e,\underline{u}_e) = \underline{0}$ is the union of separated perfect sets (closed sets in which every point is a limit point). The complement of this set (the region outside the equilibrium region) is open and everywhere n+m-dimensional.

The first part of this theorem is basically a topological interpretation of the Implicit Function Theorem above, except for the additional "separated" closed sets property. This property follows from the n+m-dimensionality and openness of ES^C, the complement of ES.

That ES^c is open is immediate; the argument is as follows. Suppose that some point $(\underline{x}_1, \underline{u}_1)$ $\in ES^c$ were not an interior point. Then every neighborhood of $(\underline{x}_1, \underline{u}_1)$ contains a point in ES. Suppose that $\| \underline{f}(\underline{x}_1, \underline{u}_1) \| = \varepsilon'$. Then continuity of $\underline{f}$ is immediately violated, since for ε $= \varepsilon' / 2$ there is no δ such that $\| (\underline{x} - \underline{x}_1), (\underline{u} - \underline{u}_1) \| \leq \delta$ implies $\| \underline{f}(\underline{x}, \underline{u}) \| \leq \varepsilon$. So ES is closed in $S_x \times S_u$. This same continuity can be used to show that ES^c is n+m-dimensional.

♦

This theorem indicates that the equilibrium surface consists of one or more topologically separate pieces. It is easy to construct examples where the equilibrium surface is in separate pieces, particularly through limiting the domain of a variable. The surface does not branch, because of the local uniqueness property that one has from the Implicit Function Theorem above. To paraphrase from that theorem, when $\underline{f}$ meets the C' condition and with $(\underline{z}, \underline{w})$ the invertible Jacobian partition at $(\underline{x}_e, \underline{u}_e)$, then, for $\underline{z}_e'$ in some neighborhood of $\underline{z}_e$,

$$\underline{f}(\underline{z}_e', \underline{w}_e) = \underline{f}(\underline{z}_e, \underline{w}_e) = \underline{0} \implies \underline{z}_e' = \underline{z}_e.$$

When a single invertible Jacobian partition can be used throughout the domain of $\underline{f}$, then this can be strengthened, as in the theorem below.

Theorem [A4.3].

Let $\underline{f}$ be as above, and suppose that a single invertible Jacobian partition $(\underline{z}, \underline{w})$ can be used throughout the domain of $\underline{f}$. Let S_z be any convex set of points in $\underline{f}$'s domain in $\underline{z}$. Then, for any two points $\underline{z}'$ and $\underline{z}'' \in S_z$ and any $\underline{w}_e$ in $\underline{f}$'s domain in $\underline{w}$

$$\underline{f}(\underline{z}', \underline{w}_e) = \underline{f}(\underline{z}'', \underline{w}_e) = \underline{0} \implies \underline{z}' = \underline{z}''.$$

♦

If, for example, $\partial \underline{f} / \partial \underline{x}$ were invertible throughout the domain of $\underline{f}$, (and this disallows pure integrators in the dynamic system) and S_x is convex, then each control setting is associated with at most one equilibrium state of the system. Having the state dynamics matrix [A] invertible for the linearization at each operating point would doubtless simplify certain aspects of system re-equilibration, but from the standpoint of increased system redundancy one may not want this uniqueness: perhaps, for example, one of the equilibrium states associated with a certain control setting is closer than another to the system's nominal

condition. Experience strongly suggests that the equilibrium state associated with a given control setting is unique for aircraft.

Using a naive approach, the implicit function theorem could be used to construct pieces of the equilibrium surface--given a starting point on each piece. To be more specific, one can see that, on the equilibrium surface,

$$[\partial \underline{f} (\underline{z}_e, \underline{w}_e) / \partial \underline{z}] \cdot d\underline{z} + [\partial \underline{f} (\underline{z}_e, \underline{w}_e) / \partial \underline{w}] \cdot d\underline{w} = \underline{0}$$

so inifinitesimal movements along the surface must be in the direction of

$$\text{Span } \{ \text{Ker } [\partial \underline{f} (\underline{z}_e, \underline{w}_e) / \partial \underline{z} \mid \partial \underline{f} (\underline{z}_e, \underline{w}_e) / \partial \underline{w}] \}$$
$$= \text{Span } \{ \text{Ker } [\partial \underline{f} (\underline{x}_e, \underline{u}_e) / \partial \underline{x} \mid \partial \underline{f} (\underline{x}_e, \underline{u}_e) / \partial \underline{u}] \}$$
$$\equiv \text{Span } \{ \text{Ker } [A \mid B] \}$$

This kernal is m-dimensional, and, in fact, $\underline{f}^{-1} (\underline{0})$ is an m-dimensional manifold in R^{n+m}. Figure A4.1 illustrates this. One has defined with this span the local slope of the equilibrium surface. The equilibrium surface near any $(\underline{x}_e, \underline{u}_e) \in ES$ could be approximately established by juxtaposing the m-dimensional local tangent planes at successively more distant points. The following proposition relates to the span of this kernal.

Proposition.

Let $\underline{f}$ be as above. Let $\underline{e}_i$ be the direction of the axis associated with the i-th element of $(\underline{x},\underline{u})$, an element which will be called y_i. Let $\underline{f} (\underline{z}_0, \underline{u}_0) = \underline{0}$. Then

$$\underline{e}_i \in \text{Span } \{ [\partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial \underline{x} \mid \partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial \underline{u}] \}$$

if and only if

$$\partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial y_i = \underline{0}.$$

♦

One can expect that, in general, any single partition of m states and controls among n+m will not have a Jacobian that invertible throughout the entire domain of $\underline{f}$. To establish the approximate equilibrium surface as above, then, the partition must be changed at times. Because the matrix associated with a given IJP is invertible throughout an open set, say I_{p1}, there is no definite point at which the partition must change to a second. By working within

Figure A4.1: Constant-Rate Regions for Systems of Nonlinear Equations

$n = 1, m = 2$ —
two-dimensional sheet
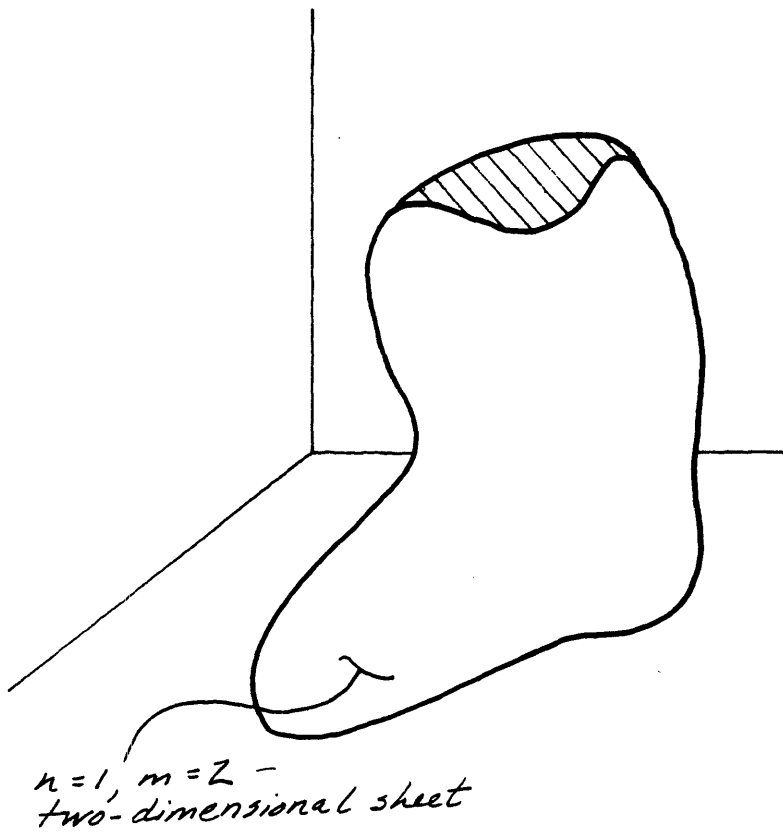
For an aircraft with n states, m inputs--

Constant-rate regions are
• m-dimensional in n+m-space
• Smooth

The regions can "bend" and
can have bounds within the
domain boundaries

One could establish the equilibrium surface for all $\underline{w}$ in some open set of previously established points, via the implicit function $\underline{w} = \underline{g}\ (\underline{z})$, but one must not be tempted to believe that the surface necessarily extends indefinitely in $\underline{w}$. It need not do so even if the domain of $\underline{f}$ is entire $R^n \times R^m$ and the same partition is invertible throughout this domain, as counter-illustrated by the function $f(x,u) = e^x - u$, for which there is no equilibrium solution for $u \leq 0$. It turns out that, except for constraints on the domain of $\underline{f}$, the end of the equilibrium region in a given state or control occurs if and only if the partial of $\underline{f}$ with respect to that state or control is becoming linearly independent of the other partials of the function.

One can formulate theorems similar to each of those above for the case where $\underline{x} = \underline{x}_0$ (the aircraft state here) is fixed. The equilibrium surface is locally of dimension m - r, where r = dim (Im [B]). The local tangent surface to the equilibrium surface is in this case spanned by Ker [B].

The existence theorem in [A4.3] is of theoretical but little practical value in determining whether an equilibrium exists for a given value of $\underline{w}$.

The following proposition states a simple observation.

Proposition.

Let $\underline{f}$ be as in the IFT above, and suppose that state or control $\underline{z}_i = \underline{g}_i\ (\underline{w})$ must be included in the invertible Jacobian partition of $(\underline{x},\underline{u})$ in the neighborhood of $(\underline{x}_0, \underline{u}_0)$ in ES. Then

$$\partial g_i\ /\ \partial \underline{w} = \underline{0}^T$$

on the equilibrium surface at $(\underline{x}_0, \underline{u}_0)$.

To show this, one knows that, on the equilibrium surface,

$$d\underline{f} = \partial \underline{f}\ /\ \partial z_i \bullet dz_i + ... + \partial \underline{f}\ /\ \partial w_i \bullet dw_i + ... = \underline{0}.$$

Using linear independence, $dz_i = 0$ and

$$dz_i = \partial g_i\ /\ \partial w_i \bullet dw_i + ... + \partial g_i\ /\ \partial w_m \bullet dw_m + ... = 0.$$

for all $d\underline{w}$ implies $\partial g_i\ /\ \partial w_j$ for all w_j.

♦

This last theorem shows that one is locally restricted in changes to states or controls that can be associated with system equilibrium. If control i, for example, must be included in the IJP, then one can say that the system is not locally control-i-redundant, and

$$\text{Rank} [A \mid b_1 \ b_2 \ ... \ b_{i-1} \ b_{i+1} \ ... \ b_m] = n - 1$$

The equilibrium surface has a local tangent plane spanned by Ker [A ∣ B], as has been seen. Any i-th column of matrix [A ∣ B] is either linearly independent or can be written as a linear combination of the other columns. In fact, there is a group of states and controls with maximum number of members whose associated columns can be used in expressing linear dependence:

$$\partial f / \partial z_i (\partial u_i) = \sum_{\substack{j=j_i, \, j \neq i}}^{\max j} \alpha_j \, \partial f / \partial z_i (\partial u_i)$$

The states and controls in this grouping plus state or control element i can be considered as composing redundancy group i, RG_i. This group is closed, that is, $RG_i = RG_j$ when element $i \in RG_j$. The larger the redundancy group, then, loosely speaking, the more inherent (local) redundancy among states and controls. More important in determining the degree of system redundancy is the dimension of the kernals of $[A \mid B]_{RG_i}$, the matrix of columns of [A ∣ B] associated with elements of RG_i. The larger the space spanned by these kernals, the greater the (local) system redundancy with respect to control i (or state i). Local redundancy among controls only can be evaluated through construction of redundancy groups among columns of [B] only where it is desired that re-equilibration not require a (permanent) change in the system state.

It makes sense that, provided the implicit equation for the ES gives x as a function of independent u, then nearby states on the ES are controllable, in the limit of infinitely small changes in u. To have $x = g (u)$ one must have local linear model matrix [A] invertible. The proposition below expresses this idea.

Proposition.

Let $\underline{f}$ be as above. Suppose that the matrix [$\partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial \underline{x}$] is invertible for some $(\underline{x}_0, \underline{u}_0)$ where $\underline{f} (\underline{z}_0, \underline{w}_0) = \underline{0}$. Let P be the (linear) mapping P $((\underline{x}, \underline{u})) \rightarrow \underline{x}$ for all $(\underline{x}, \underline{u}) \in S_x \times S_u$. For each vector $\underline{k}_i \in \text{Ker} \{[\partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial \underline{x} \mid \partial \underline{f} (\underline{x}_0, \underline{u}_0) / \partial \underline{u}]\}$ then

$$P(\underline{k}_i) \in \text{Im} [B \mid AB \mid ... \mid A^{n-1} B]$$

where [A] and [B] are the usual matrices of the linear model at $(\underline{x}_0, \underline{u}_0)$.

$\blacklozenge$

This idea of reachability cannot be extended in general to cases where A is not invertible.

References

A4.1. Rudin, Walter, <u>Principles of Mathematical Analysis</u>, McGraw-Hill, New York, 1976.

A4.2. Holtzman, Jack, <u>Nonlinear System Theory--A Functional Analysis Approach</u>, Prentice-Hall, Englewood Cliffs, New Jersey, 1970.

A4.3. Ostrowski, A.M., <u>Solution of Equations in Euclidean and Banach Spaces</u>, Academic Press, New York, 1973.

Appendix V

OPS5 Program for Expert System to Aid in
Discovering Elevator Failure Recovery Strategies
via Directed Pre-Simulation

The following program is an expert system for directing iterated simulation to discover workable emergency control after elevator failures on the C-130 aircraft, as discussed in Chapter 3.

```
;****************************************************************
; Expert System for Discovering Elevator Failure Recovery Strategies
; via Directed Pre-Simulation
;
;****************************************************************
;
(i-g-v) ;Initialization of OPS5 system
;
;****************************************************************
; Element Class Declarations
;****************************************************************
;
(remove *) ;Clearing working memory
(literalize Mode value)
(literalize Elevator-off-nominal-deflection value)
;
(literalize Failure-case-description
  elevator-jammed-at ;failed elevator position, degrees
  elevator-i ;elevator setting pre-failure, degrees
  aileron-i ;aileron setting pre-failure, degrees
  flap-i ;flap setting pre-failure, percent
  tlever-i ;throttle setting pre-failure, percent
  elevtab-i ;elevator tab setting pre-failure, degrees
  landing-gear-i) ;landing gear pre-failure, up or down
;
(literalize Tlever-master tlever-m counter-m)
(literalize Recovery-control aileron flap tlever elevtab
 apply-time-2 )
(literalize Recovery-control-2 aileron-2 flap-2 tlever-2 elevtab-2)
(literalize Recovery-control-save aileron-s flap-s elevtab-s
 apply-time-2s)
;
(literalize Scratchpad
  aileron-lower-bound aileron-upper-bound
  flap-lower-bound flap-upper-bound
  tlever-lower-bound tlever-upper-bound
  elevtab-lower-bound elevtab-upper-bound)
;
(literalize Sim-results pitch-compensated aircraft-stabilized
  pitch-overcompensated descent did-not-loop stall-recovered:alpha
  stall-recovered:pitch-rate-min stall-recovered:pitch-rate
  stall-recovered:gamma dive-recovered:pitch-rate
  dive-recovered:gamma)
;
;****************************************************************
; Productions
;****************************************************************
;
;-------------------------------------------------------------
; Initial production
;-------------------------------------------------------------
(p Start
 (Mode start)
```

```
(Failure-case-description ^ elevator-jammed-at <j>
                         ^ elevator-i <ic>)
-->
(modify 1 ^ value sim-advise)
(write (crlf) The advisory is beginning.)
(make Elevator-off-nominal-deflection ^ value (compute <j> - <ic>))
(write (crlf) A simulation may be terminated when...)
(write (crlf) The aircraft pitch angle starts to exceed 111. deg.)
(write (crlf) with a pitch-up failure or)
(write (crlf) Ground impact is imminent or)
(write (crlf) Stable oscillations in all states are apparent)
(write (crlf) and you can determine the approximate)
(write (crlf) steady climb rate of stabilized flight.)
(write (crlf) Answer all questions below with yes or no.)
(write (crlf) Please be careful with your answers: there is)
(write (crlf) no explicit checking for inconsistencies.))
;
```

```
.;-----------------------------------------------------------------
;Pitch Down failures
;-----------------------------------------------------------------
;
(p Pitch-down-failures::From-scratch
  (Mode sim-advise)
  (Recovery-control ^ elevtab nil)
  (Elevator-off-nominal-deflection ^ value {<v> > 0.})
  (Tlever-master ^ tlever-m nil)
  -->
  (write (crlf) Try no compensating control to see if the aircraft)
  (write (crlf) can recover on its own.)
  (modify 1 ^ value query))

;
(p Pitch-down::Uncompensated:too-much-pitch-down
  (Mode sim-advise)
  (Recovery-control ^ elevtab nil)
  (Sim-results ^ pitch-compensated no)
  (Elevator-off-nominal-deflection ^ value {<v> > 0.})
  -->
  (modify 2 ^ elevtab -6.)
  (write (crlf) Try the addition of immediate hardover elevator tab)
  (write (crlf) deflection to -6. deg.)
  (modify 1 ^ value query)
  (remove 3)
  (make Sim-results nil))

;
(p Pitch-down::Elevtab-hardover:too-much-pitch-up
  (Mode sim-advise)
  (Scratchpad ^ elevtab-lower-bound <n1> ^ elevtab-upper-bound <n2>)
  (Recovery-control ^ elevtab -6. ^ aileron nil)
  (Sim-results ^ pitch-overcompensated yes)
  (Failure-case-description ^ elevtab-i <n>)
  -->
  (modify 2 ^ elevtab-lower-bound -6. ^ elevtab-upper-bound <n>)
  (exec '(bind-average -6. <n>))
  (modify 3 ^ elevtab <t1>)
  (write (crlf) Try immediate hardover elevator tab deflection to)
  (write (crlf) <t1> deg.)
  (modify 1 ^ value query)
  (remove 4)
  (make Sim-results nil))

;
(p Pitch-down::Elevtab-hardover:insufficient-pitch-up
  (Mode sim-advise)
  (Recovery-control ^ elevtab -6. ^ aileron nil)
  (Sim-results ^ pitch-compensated no)
  -->
  (modify 2 ^ aileron 20.)
  (write (crlf) Add immediate hardover collective aileron deflection)
  (write (crlf) to 20. deg.)
  (modify 1 ^ value query)
  (remove 3)
  (make Sim-results nil))
```

```
;
(p Pitch-down::Elevtab-and-aileron-hardover:too-much-pitch-up
 (Mode sim-advise)
 (Scratchpad ^ aileron-lower-bound <n1> ^ aileron-upper-bound <n2>)
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
              ^ tlever nil)
 (Sim-results ^ pitch-overcompensated yes)
 (Failure-case-description ^ aileron-i <n>)
-->
 (modify 2 ^ aileron-lower-bound <n> ^ aileron-upper-bound 20.)
 (exec '(bind-average <n> 20.))
 (modify 3 ^ aileron <t1>)
 (write (crlf) Modify the last strategy to have hardover collective)
 (write (crlf) aileron deflection to only <t1> deg.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Elevtab-and-aileron-hardover:insufficient-pitch-up
 (Mode sim-advise)
 (Failure-case-description ^ flap-i {<n> < 75.})
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
              ^ tlever nil)
 (Sim-results ^ pitch-compensated no)
 -(Failure-case-description ^ flap-i {<n> > 0.})
-->
 (modify 3 ^ flap 75.)
 (write (crlf) Modify the last strategy to add immediate hardover)
 (write (crlf) flap deployment to 75.% subject to airspeed)
 (write (crlf) restrictions.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Elevtab-and-aileron-hardover-flap-already:insuff.
 (Mode sim-advise)
 (Failure-case-description ^ flap-i {<fi> > 0.}) .
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
              ^ tlever nil)
 (Tlever-master ^ tlever-m nil)
 (Sim-results ^ pitch-compensated no)
-->
 (modify 3 ^ tlever 0.)
 (write (crlf) Include immediate hardover thrust reduction to 0.%)
 (write (crlf) in the last strategy.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Elevtab-aileron-tlev-hardover-flap-already:insuff.
 (Mode sim-advise)
 (Failure-case-description ^ flap-i {<fi> < 75.})
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
              ^ tlever 0.)
```

```
(Sim-results ^ pitch-compensated no)
-->
(modify 3 ^ flap 75.)
(write (crlf) Modify the last strategy to add immediate hardover)
(write (crlf) flap deployment to 75.% subject to airspeed)
(write (crlf) restrictions.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-down::Elevtab-aileron-flap-hardover:too-much-pitch-up
(Mode sim-advise)
(Scratchpad ^ flap-lower-bound <n1> ^ flap-upper-bound <n2>)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.)
(Sim-results ^ pitch-overcompensated yes)
(Failure-case-description ^ flap-i <n>)
-->
(modify 2 ^ flap-lower-bound <n> ^ flap-upper-bound 75.)
(exec '(bind-average <n> 75.))
(modify 3 ^ flap <t1>)
(write (crlf) Modify the last strategy to have hardover flap)
(write (crlf) deployment to only <t1> % subject to airspeed)
(write (crlf) restrictions.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-down::Elevt.-ail.-fl.-tl.-h.o.-tlev-delayed-incr.:too-much
(Mode sim-advise)
(Scratchpad ^ flap-lower-bound <n1> ^ flap-upper-bound <n2>)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.
        ^ tlever 0. ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ tlever-2 100.)
(Sim-results ^ pitch-overcompensated yes)
(Failure-case-description ^ flap-i <n>)
-->
(modify 2 ^ flap-lower-bound <n> ^ flap-upper-bound 75.)
(exec '(bind-average <n> 75.))
(modify 3 ^ flap <t1> ^ apply-time-2 nil)
(modify 4 ^ tlever-2 nil)
(write (crlf) Modify the last strategy to have hardover flap)
(write (crlf) deployment to only <t1> % subject to airspeed)
(write (crlf) restrictions and suppress later thrust increase.)
(modify 1 ^ value query)
(remove 5)
(make Sim-results nil))

;
(p Pitch-down::Elevtab-aileron-flap-hardover:insufficient-pitch-up
(Mode sim-advise)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.
        ^ tlever nil)
(Sim-results ^ pitch-compensated no)
-->
(modify 2 ^ tlever 0.)
```

```
(write (crlf) Include immediate hardover thrust reduction to 0.%)
(write (crlf) in the last strategy.)
(modify 1 ^ value query)
(remove 3)
(make Sim-results nil))
;
(p Pitch-down::Elevtab-aileron-flap-tlever-h.o.:insuff.-pitch-up
(Mode sim-advise)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.
         ^ tlever 0.)
(Sim-results ^ pitch-compensated no)
-->
(write (crlf) At least small violations of the flap deployment)
(write (crlf) restrictions will have to be considered in order to)
(write (crlf) try to get a recovery.)
(modify 1 ^ value end))
;
(p Pitch-down::Descent-can-mean-not-pitch-compensated
(Mode sim-advise)
(Failure-case-description ^ tlever-i {<ti> > 55.})
(Elevator-off-nominal-deflection ^ value {<v> > 0.})
(Sim-results ^ descent yes)
-->
(modify 4 ^ pitch-compensated no ^ pitch-overcompensated nil
      ^ descent nil))
;
(p Pitch-down::Interpolation:Intermediate-elevtab:too-much
(Mode sim-advise)
(Elevator-off-nominal-deflection ^ value {<v> > 0.})
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab {<s> > -6.} ^ aileron nil)
(Sim-results ^ pitch-overcompensated yes)
-->
(modify 3 ^ elevtab-lower-bound <s>)
(exec '(bind-average <s> <ub>))
(modify 4 ^ elevtab <t1>)
(write (crlf) Try immediate hardover elevator tab deflection to)
(write (crlf) <t1> deg.)
(modify 1 ^ value query)
(remove 5)
(make Sim-results nil))
;
(p Pitch-down::Interpolation:Intermediate-elevtab:insufficient
(Mode sim-advise)
(Elevator-off-nominal-deflection ^ value {<v> > 0.})
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab {<s> > -6.} ^ aileron nil)
(Sim-results ^ pitch-compensated no)
-->
(modify 3 ^ elevtab-upper-bound <s>)
(exec '(bind-average <lb> <s>))
(modify 4 ^ elevtab <t1>)
(write (crlf) Try hardover elevator tab deflection to <t1> deg.)
(modify 1 ^ value query)
```

```
(remove 5)
(make Sim-results nil))
;
(p Pitch-down::Interpolation:Elevtab-and-intermed.-aileron:too-much
 (Mode sim-advise)
 (Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
 (Recovery-control ^ elevtab -6. ^ aileron {<s> < 20.} ^ flap nil
              ^ tlever nil)
 (Sim-results ^ pitch-overcompensated yes)
-->
 (modify 2 ^ aileron-upper-bound <s>)
 (exec '(bind-average <lb> <s>))
 (modify 3 ^ aileron <t1>)
 (write (crlf) Modify the last strategy to have immediate hardover)
 (write (crlf) collective aileron deflection to <t1> deg. only.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Interpolation:Elevtab-and-intermed.-ail.:insufficient
 (Mode sim-advise)
 (Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
 (Recovery-control ^ elevtab -6. ^ aileron {<s> < 20.} ^ flap nil
              ^ tlever nil)
 (Sim-results ^ pitch-compensated no)
-->
 (modify 2 ^ aileron-lower-bound <s>)
 (exec '(bind-average <s> <ub>))
 (modify 3 ^ aileron <t1>)
 (write (crlf) Increase hardover collective aileron deflection to)
 (write (crlf) <t1> deg.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Interpol.:Elevtab-ail.-inter.-flap:too-much-pitch-up
 (Mode sim-advise)
 (Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap {<s> < <ub>}
        ^ tlever nil)
 (Sim-results ^ pitch-overcompensated yes)
-->
 (modify 2 ^ flap-upper-bound <s>)
 (exec '(bind-average <lb> <s>))
 (modify 3 ^ flap <t1>)
 (write (crlf) Modify the last strategy to have immediate hardover)
 (write (crlf) flap deployment to <t1> % subject to airspeed)
 (write (crlf) restrictions.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Interpol.:Elevtab-ail.-inter.-flap:insuff.-pitch-up
 (Mode sim-advise)
```

```
(Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap {<s> < <ub>}
          ^ tlever nil)
(Sim-results ^ pitch-compensated no)
-->
(modify 2 ^ flap-lower-bound <s>)
(exec '(bind-average <s> <ub>))
(modify 3 ^ flap <t1>)
(write (crlf) Increase hardover flap deployment to <t1> % subject)
(write (crlf) to airspeed restrictions.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Attempting-full-dive-recovery-via-delayed-restored-thrust
 (Mode sim-advise)
 (Elevator-off-nominal-deflection {<v> > 0.})
 (Recovery-control ^ tlever 0. ^ apply-time-2 nil)
 (Sim-results ^ aircraft-stabilized yes ^ descent yes)
-->
(modify 4 ^ pitch-compensated nil ^ pitch-overcompensated yes)
(write (crlf) Restoring thrust later in the simulation should)
(write (crlf) be tried.  Give the time in seconds that flight)
(write (crlf) path angle first crossed zero.)
(modify 3 ^ apply-time-2 (accept)))

;
(p Pitch-down::Elevt.-ail.-opt.-flap-h.o.-tlev:insuff.-thrust-later
 (Mode sim-advise)
 (Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ tlever 0.)
 (Sim-results ^ pitch-overcompensated yes)
 (Recovery-control ^ apply-time-2 {<at> > 0.})
 (Recovery-control-2 ^ tlever-2 nil)
-->
(modify 2 ^ tlever-lower-bound 0. ^ tlever-upper-bound 100.)
(modify 6 ^ tlever-2 100.)
(write (crlf) Modify the last strategy by increasing thrust to)
(write (crlf) 100.% at <at> sec.)
(modify 1 ^ value query)
(modify 4 ^ aircraft-stabilized nil ^ pitch-overcompensated nil
       ^ descent nil))

;
(p Pitch-down::Descent-can-mean-insufficient-thrust
 (Mode sim-advise)
 (Elevator-off-nominal-deflection ^ value {<v> > 0.})
 (Failure-case-description ^ tlever-i {<ti> < 55.})
 (Tlever-master ^ tlever-m nil)
 (Recovery-control ^ elevtab <e> ^ aileron <a> ^ flap <f>
          ^ tlever nil)
 (Sim-results ^ aircraft-stabilized yes ^ descent yes)
 (Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
-->
(write (crlf) Give the time at which the flight path angle first)
(write (crlf) crossed zero.)
```

```
(make Recovery-control-save ^ apply-time-2s (accept)
        ^ elevtab-s <e> ^ aileron-s <a> ^ flap-s <f>)
(modify 4 ^ tlever-m 100.)
(write (crlf) Try the last strategy but with immediate hardover)
(write (crlf) thrust increase to 100.%)
(modify 7 ^ tlever-lower-bound <ti> ^ tlever-upper-bound 100.)
(modify 1 ^ value query)
(remove 6)
(make Sim-results nil))
;
(p Pitch-down::Immediate-thrust-incr.-brings-accel.-dive:interpolate
 (Mode sim-advise)
 (Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
            ^ tlever nil ^ apply-time-2 nil)
 (Sim-results ^ pitch-compensated no)
 (Tlever-master ^ tlever-m {<tm> > 55.})
 -(Tlever-master ^ tlever-m nil)
-->
 (modify 2 ^ tlever-upper-bound <tm>)
 (exec '(bind-average <lb> <tm>))
 (modify 5 ^ tlever-m <t1>)
 (write (crlf) Try the last strategy but with immediate hardover)
 (write (crlf) thrust increase to <t1> %.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Elevtab-aileron-hardover-thrust-incr:insuff.-pitch-up
 (Mode sim-advise)
 (Failure-case-description ^ flap-i {<n> < 75.})
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap nil
            ^ tlever nil)
 (Sim-results ^ aircraft-stabilized yes ^ descent yes)
 -(Tlever-master ^ tlever-m nil)
-->
 (modify 3 ^ flap 75.)
 (write (crlf) Modify the last strategy to add immediate hardover)
 (write (crlf) flap deployment to 75.% subject to airspeed)
 (write (crlf) restrictions.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
;
(p Pitch-down::Elevtab-ail.-flap-h.o.-thrust-incr:insuff.-pitch-up
 (Mode sim-advise)
 (Scratchpad ^ flap-lower-bound <n1> ^ flap-upper-bound <n2>)
 (Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.
            ^ tlever nil)
 (Sim-results ^ pitch-compensated no)
 (Failure-case-description ^ flap-i <n>)
 -(Tlever-master ^ tlever-m nil)
-->
 (modify 2 ^ flap-lower-bound <n> ^ flap-upper-bound 75.)
```

```
(exec '(bind-average <n> 75.))
(modify 3 ^ flap <t1>)
(write (crlf) Modify the last strategy to have hardover flap)
(write (crlf) deployment to only <t1> % subject to airspeed)
(write (crlf) restrictions.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-down::Immediate-thrust-incr.-is-insufficient:interpolate
(Mode sim-advise)
(Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
(Recovery-control ^ elevtab -6. ^ aileron 20. ^ flap 75.
           ^ tlever nil ^ apply-time-2 nil)
(Sim-results ^ aircraft-stabilized yes ^ descent yes)
(Tlever-master ^ tlever-m {<tm> > 55.})
-(Tlever-master ^ tlever-m nil)
-->
(modify 2 ^ tlever-lower-bound <tm>)
(exec '(bind-average <tm> <ub>))
(modify 5 ^ tlever-m <t1>)
(write (crlf) Try the last strategy but with immediate hardover)
(write (crlf) thrust increase to <t1> %.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-down::Attempt-power-transition-to-climb-later
(Mode sim-advise)
(Elevator-off-nominal-deflection {<v> > 0.})
(Recovery-control ^ tlever 0. ^ apply-time-2 <at>)
(Recovery-control-2 ^ tlever-2 nil)
(Sim-results ^ pitch-overcompensated yes)
(Recovery-control-save ^ elevtab-s <es> ^ aileron-s <as>
              ^ flap-s <fs> ^ apply-time-2s <ats>)
-->
(modify 4 ^ tlever-2 100.)
(write (crlf) Unless nil apply immediate hardover elevator tab)
(write (crlf) deflection to <es> deg.)
(write (crlf) hardover aileron deflection to <as> deg.)
(write (crlf) hardover flap deflection to <fs> %)
(write (crlf) thrust hardover to 0.% and then increased hardover)
(write (crlf) to 100.% at <ats> seconds. Raise landing gear at)
(write (crlf) the same time.)
(modify 1 ^ value query)
(remove 5)
(make Sim-results nil))
;
```

```
;-------------------------------------------------------------
;Pitch Up Failures
;-------------------------------------------------------------
;
(p Pitch-up-failures::From-scratch
 (Mode sim-advise)
 (Elevator-off-nominal-deflection ^ value {<v> < 0.})
 (Recovery-control ^ elevtab nil)
 (Failure-case-description ^ landing-gear-i up)
 (Sim-results ^ pitch-compensated nil)
 -->
 (write (crlf) Try no compensating control to see if the aircraft)
 (write (crlf) can recover on its own.)
 (modify 1 ^ value query))

;
(p Pitch-up-failures::From-scratch/raise-landing-gear
 (Mode sim-advise)
 (Elevator-off-nominal-deflection ^ value {<v> < 0.})
 (Recovery-control ^ elevtab nil)
 (Failure-case-description ^ landing-gear-i down)
 (Sim-results ^ pitch-compensated nil)
 -->
 (write (crlf) Raise landing gear immediately and see if the)
 (write (crlf) aircraft can recover on its own.)
 (modify 1 ^ value query))

;
(p Pitch-up::Uncompensated:too-much-pitch-up
 (Mode sim-advise)
 (Recovery-control ^ elevtab nil)
 (Sim-results ^ pitch-compensated no)
 (Elevator-off-nominal-deflection ^ value {<v> < 0.})
 -->
 (modify 2 ^ elevtab 50.)
 (write (crlf) Try the addition of immediate hardover elevator tab)
 (write (crlf) deflection to 50. deg.)
 (modify 1 ^ value query)
 (remove 3)
 (make Sim-results nil))

;
(p Pitch-up::Elevtab-hardover:too-much-pitch-down
 (Mode sim-advise)
 (Scratchpad ^ elevtab-lower-bound <n1> ^ elevtab-upper-bound <n2>)
 (Recovery-control ^ elevtab 50. ^ aileron nil ^ apply-time-2 nil)
 (Sim-results ^ pitch-overcompensated yes)
 (Failure-case-description ^ elevtab-i <n>)
 -->
 (modify 2 ^ elevtab-lower-bound <n> ^ elevtab-upper-bound 50.)
 (exec '(bind-average <n> 50.))
 (modify 3 ^ elevtab <t1>)
 (write (crlf) Try immediate hardover elevator tab deflection to)
 (write (crlf) <t1> deg.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))
```

;
(p Pitch-up::Elevtab:too-much-pitch-down-later
(Mode sim-advise)
(Scratchpad ^ elevtab-lower-bound <n1> ^ elevtab-upper-bound <n2>)
(Failure-case-description ^ elevtab-i <n>)
(Recovery-control ^ elevtab <e> ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ elevtab-2 nil)
(Sim-results ^ stall-recovered:gamma no)
-(Recovery-control ^ elevtab nil)
-->
(modify 2 ^ elevtab-lower-bound <n> ^ elevtab-upper-bound <e>)
(modify 5 ^ elevtab-2 <n>)
(write (crlf) Back off elevtab hardover to <n> deg. at <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
        ^ did-not-loop nil ^ stall-recovered:alpha nil))

;
(p Pitch-up::Elevtab-hardover:insufficient-pitch-down
(Mode sim-advise)
(Recovery-control ^ elevtab 50. ^ aileron nil)
(Sim-results ^ pitch-compensated no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 2 ^ aileron -20.)
(write (crlf) Add immediate hardover collective aileron deflection)
(write (crlf) to -20. deg.)
(modify 1 ^ value query)
(remove 3)
(make Sim-results nil))

;
(p Pitch-up::Elevtab-and-aileron-hardover:too-much-pitch-down
(Mode sim-advise)
(Scratchpad ^ aileron-lower-bound <n1> ^ aileron-upper-bound <n2>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap nil
            ^ tlever nil ^ apply-time-2 nil)
(Sim-results ^ pitch-overcompensated yes)
(Failure-case-description ^ aileron-i <n>)
-->
(modify 2 ^ aileron-lower-bound -20. ^ aileron-upper-bound <n>)
(exec '(bind-average -20. <n>))
(modify 3 ^ aileron <t1>)
(write (crlf) Modify the last strategy to have hardover collective)
(write (crlf) aileron deflection to <t1> deg. only.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-up::Elevtab-and-aileron:too-much-pitch-down-later
(Mode sim-advise)
(Scratchpad ^ aileron-lower-bound <n1> ^ aileron-upper-bound <n2>)
(Failure-case-description ^ aileron-i <n>)
(Recovery-control ^ elevtab 50. ^ aileron <a>
            ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ aileron-2 nil)

```
(Sim-results ^ stall-recovered:gamma no)
-(Recovery-control ^ aileron nil)
-->
(modify 2 ^ aileron-lower-bound <a> ^ aileron-upper-bound <n>)
(modify 5 ^ aileron-2 <n>)
(write (crlf) Back off collective aileron hardover to <n> deg. at)
(write (crlf) <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
      ^ did-not-loop nil ^ stall-recovered:alpha nil))
;
(p Pitch-up::Elevtab-and-aileron-hardover:insufficient-pitch-down
(Mode sim-advise)
(Failure-case-description ^ flap-i {<f> > 0.})
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap nil)
(Sim-results ^ pitch-compensated no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 3 ^ flap 0. )
(write (crlf) Modify the last strategy to include immediate)
(write (crlf) hardover flap reduction to 0.%.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))
;
(p Pitch-up::Elevtab-aileron-and-flap-hardover:too-much-pitch-down
(Mode sim-advise)
(Scratchpad ^ flap-lower-bound <n1> ^ flap-upper-bound <n2>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap 0.
            ^ tlever nil ^ apply-time-2 nil)
(Sim-results ^ pitch-overcompensated yes)
(Failure-case-description ^ flap-i <n>)
-->
(modify 2 ^ flap-lower-bound 0. ^ flap-upper-bound <n>)
(exec '(bind-average 0. <n>))
(modify 3 ^ flap <t1> )
(write (crlf) Try immediate hardover flap deployment to only)
(write (crlf) <t1> %.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))
;
(p Pitch-up::Elevtab-aileron-and-flap:too-much-pitch-down-later
(Mode sim-advise)
(Scratchpad ^ flap-lower-bound <n1> ^ flap-upper-bound <n2>)
(Failure-case-description ^ flap-i <n>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap <f>
            ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ flap-2 nil)
(Sim-results ^ stall-recovered:gamma no)
-(Recovery-control ^ flap nil)
-->
(modify 2 ^ flap-lower-bound <f> ^ flap-upper-bound <n>)
(modify 5 ^ flap-2 <n>)
```

(write (crlf) Restore flap hardover to <n> % at <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
        ^ did-not-loop nil ^ stall-recovered:alpha nil))

;
(p Pitch-up::Elevtab-aileron-opt.-flap-hardover:insuff.-pitch-down
(Mode sim-advise)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever nil
            ^ apply-time-2 nil)
(Sim-results ^ pitch-compensated no)
(Tlever-master ^ tlever-m nil)
-->
(modify 2 ^ tlever 0.)
(write (crlf) Modify the last strategy to include immediate)
(write (crlf) hardover thrust reduction to 0.%.)
(modify 1 ^ value query)
(remove 3)
(make Sim-results nil))

;
(p Attempting-full-climb-recovery-via-delayed-restored-thrust
(Mode sim-advise)
(Elevator-off-nominal-deflection {<v> < 0.})
(Recovery-control ^ tlever 0. ^ apply-time-2 nil)
(Sim-results ^ aircraft-stabilized yes ^ descent yes)
-->
(modify 4 ^ pitch-compensated nil ^ pitch-overcompensated yes)
(write (crlf) Restoring thrust later in the simulation should)
(write (crlf) be tried. In the last simulation)
(write (crlf) If pitch rate achieved a minimum after)
(write (crlf) angle of attack decreased to 25. deg. state the)
(write (crlf) time in seconds that this minimum occurred.)
(write (crlf) Otherwise state the time at which angle of attack)
(write (crlf) decreased through 25. deg. If angle of attack)
(write (crlf) never exceeded 25. deg. state the time at which)
(write (crlf) pitch rate was minimized for the entire run.)
(modify 3 ^ apply-time-2 (accept)))
;
(p Pitch-up::Elevt.-aileron-opt.-flap-h.o.-tlev:insuff.-thrust-later
(Mode sim-advise)
(Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever 0.
            ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ tlever-2 nil)
(Sim-results ^ stall-recovered:gamma no)
-->
(modify 2 ^ tlever-lower-bound 0. ^ tlever-upper-bound 100.)
(modify 4 ^ tlever-2 100.)
(write (crlf) Modify the last strategy by increasing thrust to)
(write (crlf) 100.% at <at> sec.)
(modify 1 ^ value query)
(modify 5 ^ aircraft-stabilized nil ^ did-not-loop nil
        ^ stall-recovered:gamma nil ^ descent nil
        ^ stall-recovered:alpha nil))
;

```
(p Pitch-up::Elevt.-aileron-opt.-flap-h.o.-tlev:descent-later
 (Mode sim-advise)
 (Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever 0.
        ^ apply-time-2 {<at> > 0.})
 (Recovery-control-2 ^ tlever-2 nil)
 (Sim-results ^ pitch-overcompensated yes)
 -->
 (modify 2 ^ tlever-lower-bound 0. ^ tlever-upper-bound 100.)
 (modify 4 ^ tlever-2 100.)
 (write (crlf) Modify the last strategy by increasing thrust to)
 (write (crlf) 100.% at <at> sec.)
 (modify 1 ^ value query)
 (remove 5)
 (make Sim-results nil))

;
(p Pitch-up::Elevt.-ail.-opt.-fl.-tlev.-h.o.:not-st.-rec.:pitch-rate
 (Mode sim-advise)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever 0.)
 (Sim-results ^ pitch-compensated no
        ^ stall-recovered:pitch-rate no)
 (Recovery-control ^ apply-time-2 nil)
 -->
 (write (crlf) It looks as if there has been poor stall recovery.)
 (write (crlf) If the simulation terminated with ground impact)
 (write (crlf) then the situation should be considered hopeless.)
 (modify 1 ^ value end)
 (remove 3)
 (make Sim-results nil))

;
(p Pitch-up::Elevtab-aileron-opt.-flap-tlev.-h.o.:insuff.-pitch-down
 (Mode sim-advise)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever 0.)
 (Sim-results ^ pitch-compensated no)
 -->
 (write (crlf) The situation looks hopeless--there are no more)
 (write (crlf) pitch-down resources.)
 (modify 1 ^ value end))

;
(p Pitch-up::All-controls-backed-off-later:insufficient-pitch-up
 (Mode sim-advise)
 (Failure-case-description ^ elevtab-i <ei> ^ aileron-i <ai>
            ^ flap-i <fi>)
 (Recovery-control ^ apply-time-2 {<at> > 0.})
 (Recovery-control-2 ^ tlever-2 100.)
 (Sim-results ^ stall-recovered:gamma no)
 -(Recovery-control-2 ^ elevtab-2 {<e2> > <ei>}
            ^ aileron-2 {<a2> < <ai>} ^ flap-2 {<f2> < <fi>})
 -->
 (write (crlf) The situation looks hopeless--there are no more)
 (write (crlf) pitch-up resources for delayed application.)
 (modify 1 ^ value end))

;
(p Pitch-up::Descent-can-mean-pitch-overcompensated
```

```
(Mode sim-advise)
(Failure-case-description ^ tlever-i {<ti> > 55.})
(Elevator-off-nominal-deflection ^ value {<v> < 0.})
(Sim-results ^ descent yes)
-->
(modify 3 ^ pitch-compensated nil ^ pitch-overcompensated yes
        ^ descent nil))

;
(p Pitch-up::Mixed-stall-recovery-means-pitch-overcompensated
(Mode sim-advise)
(Sim-results ^ stall-recovered:pitch-rate no
          ^ stall-recovered:alpha yes
          ^ stall-recovered:gamma nil)
-->
(modify 2 ^ pitch-compensated nil ^ pitch-overcompensated yes
        ^ stall-recovered:alpha nil))

;
(p Pitch-up::No-alpha-recovery-means-not-pitch-compensated
(Mode sim-advise)
(Sim-results ^ stall-recovered:alpha no
          ^ stall-recovered:gamma nil)
-->
(modify 2 ^ pitch-compensated no ^ pitch-overcompensated nil
        ^ stall-recovered:alpha nil))

;
(p Attempting-full-stall-recovery-via-delayed-control-action
(Mode sim-advise)
(Sim-results ^ pitch-compensated yes
          ^ stall-recovered:pitch-rate yes
          ^ stall-recovered:alpha yes
          ^ stall-recovered:gamma no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 2 ^ pitch-compensated nil)
(write (crlf) Backing off on the last pitch-down input later)
(write (crlf) should be tried. In the last simulation)
(write (crlf) If pitch rate achieved a)
(write (crlf) minimum after angle of atttack decreased to 25. deg.)
(write (crlf) state the time in seconds that this minimum)
(write (crlf) occurred. Otherwise state the time at which angle)
(write (crlf) of attack decreased through 25. deg. If angle of)
(write (crlf) attack never exceeded 25. deg. state the time at)
(write (crlf) which pitch rate was minimized for the entire run.)
(modify 3 ^ apply-time-2 (accept)))

;
(p Pitch-up::Interpolation:Intermediate-elevtab:too-much
(Mode sim-advise)
(Elevator-off-nominal-deflection ^ value {<v> < 0.})
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab {<s> < 50.} ^ aileron nil)
(Sim-results ^ pitch-overcompensated yes)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 3 ^ elevtab-upper-bound <s>)
```

```
(exec '(bind-average <lb> <s>))
(modify 4 ^ elevtab <t1>)
(write (crlf) Try immediate hardover elevator tab deflection to)
(write (crlf) <t1> deg.)
(modify 1 ^ value query)
(remove 5)
(make Sim-results nil))

;
(p Pitch-up::Interpolation:Intermediate-elevtab:too-much-later
(Mode sim-advise)
(Failure-case-description ^ elevtab -i <ei>)
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab <e> ^ aileron nil
           ^ apply-time-2 <at>)
(Recovery-control-2 ^ elevtab-2 {<el> > <ei>})
(Sim-results ^ stall-recovered:gamma no)
-(Recovery-control ^ elevtab nil)
-->
(modify 3 ^ elevtab-upper-bound <el>)
(exec '(bind-average <lb> <el>))
(modify 5 ^ elevtab-2 <t1>)
(write (crlf) Back off elevator tab hardover to <t1> deg. at)
(write (crlf) <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
        ^ did-not-loop nil ^ stall-recovered:alpha nil))
;
(p Pitch-up::Interpolation:Intermediate-elevtab:insufficient
(Mode sim-advise)
(Elevator-off-nominal-deflection ^ value {<v> < 0.})
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab {<s> < 50.} ^ aileron nil)
(Sim-results ^ pitch-compensated no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 3 ^ elevtab-lower-bound <s>)
(exec '(bind-average <s> <ub>))
(modify 4 ^ elevtab <t1>)
(write (crlf) Try hardover elevator tab deflection to <t1> deg.)
(modify 1 ^ value query)
(remove 5)
(make Sim-results nil))
;
(p Pitch-up::Interpolation:Intermediate-elevtab:insufficient-later
(Mode sim-advise)
(Failure-case-description ^ aileron-i <ai>)
(Scratchpad ^ elevtab-lower-bound <lb> ^ elevtab-upper-bound <ub>)
(Recovery-control ^ elevtab <e> ^ apply-time-2 <at>)
(Recovery-control-2 ^ elevtab-2 {<el> < <e>} )
(Sim-results ^ pitch-compensated no)
-(Recovery-control-2 ^ aileron-2 {<a2> < <ai>})
-->
(modify 3 ^ elevtab-lower-bound <el>)
(exec '(bind-average <el> <ub>))
```

```
(modify 5 ^ elevtab-2 <t1>)
(write (crlf) Back off elevator tab hardover to <t1> deg. at)
(write (crlf) <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ pitch-compensated nil
        ^ stall-recovered:gamma nil ^ did-not-loop nil
        ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interpolation:Elevtab-and-intermediate-aileron:too-much
(Mode sim-advise)
(Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron {<s> > -20.} ^ flap nil
        ^ tlever nil)
(Sim-results ^ pitch-overcompensated yes)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 2 ^ aileron-lower-bound <s>)
(exec '(bind-average <s> <ub>))
(modify 3 ^ aileron <t1>)
(write (crlf) Modify the last strategy to add immediate hardover)
(write (crlf) collective aileron deflection to <t1> deg.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-up::Interpolation:Elevtab-and-intermed.-ail.:too-much-later
(Mode sim-advise)
(Failure-case-description ^ aileron-i <ai>)
(Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron <a> ^ flap nil
        ^ tlever nil ^ apply-time-2 <at>)
(Recovery-control-2 ^ aileron-2 {<al> < <ai>})
(Sim-results ^ stall-recovered:gamma no)
-(Recovery-control ^ aileron nil)
-->
(modify 3 ^ aileron-lower-bound <al>)
(exec '(bind-average <al> <ub>))
(modify 5 ^ aileron-2 <t1>)
(write (crlf) Back off collective aileron hardover to <t1> deg. at)
(write (crlf) <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
        ^ did-not-loop nil ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interpolation:Elevtab-and-intermed.-ail.:insufficient
(Mode sim-advise)
(Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron {<s> > -20.} ^ flap nil
        ^ tlever nil)
(Sim-results ^ pitch-compensated no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 2 ^ aileron-upper-bound <s>)
(exec '(bind-average <lb> <s>))
```

```
(modify 3 ^ aileron <t1>)
(write (crlf) Modify the last strategy to add immediate hardover)
(write (crlf) collective aileron deflection to <t1> deg.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-up::Interpolation:Elevtab-and-intermed.-ail.:insuff.-later
 (Mode sim-advise)
 (Failure-case-description ^ aileron-i <ai>)
 (Scratchpad ^ aileron-lower-bound <lb> ^ aileron-upper-bound <ub>)
 (Recovery-control ^ elevtab 50. ^ aileron <a> ^ apply-time-2 <at>)
 (Recovery-control-2 ^ aileron-2 {<al> < <ai>})
 (Sim-results ^ pitch-compensated no)
 -(Recovery-control ^ aileron nil)
 -->
 (modify 3 ^ aileron-upper-bound <al>)
 (exec '(bind-average <lb> <al>))
 (modify 5 ^ aileron-2 <t1>)
 (write (crlf) Back off collective aileron hardover to <t1> deg. at)
 (write (crlf) <at> sec.)
 (modify 1 ^ value query)
 (modify 6 ^ aircraft-stabilized nil ^ pitch-compensated nil
        ^ stall-recovered:gamma nil ^ did-not-loop nil
        ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interpolation:Elevtab-aileron-intermed.-flap:too-much
 (Mode sim-advise)
 (Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap {<s> > 0.}
        ^ tlever nil)
 (Sim-results ^ pitch-overcompensated yes)
 (Recovery-control ^ apply-time-2 nil)
 -->
 (modify 2 ^ flap-lower-bound <s>)
 (exec '(bind-average <s> <ub>))
 (modify 3 ^ flap <t1>)
 (write (crlf) Modify the last strategy to add immediate hardover)
 (write (crlf) flap deployment to <t1> % subject to airspeed)
 (write (crlf) restrictions.)
 (modify 1 ^ value query)
 (remove 4)
 (make Sim-results nil))

;
(p Pitch-up::Interpolation:Elevtab-ail.-interm.-flap:too-much-later
 (Mode sim-advise)
 (Failure-case-description ^ flap-i <fi>)
 (Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap <f>
        ^ tlever nil ^ apply-time-2 <at>)
 (Recovery-control-2 ^ flap-2 {<fl> < <fi>})
 (Sim-results ^ stall-recovered:gamma no)
 -(Recovery-control ^ flap nil)
 -->
```

```
(modify 3 ^ flap-lower-bound <fl>)
(exec '(bind-average <fl> <ub>))
(modify 5 ^ flap-2 <t1>)
(write (crlf) Restore flaps hardover to <t1> % at <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ stall-recovered:gamma nil
        ^ did-not-loop nil ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interpolation:Elevtab-aileron-intermed.-flap:insuff.
(Mode sim-advise)
(Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap { <s> > 0.}
        ^ tlever nil)
(Sim-results ^ pitch-compensated no)
(Recovery-control ^ apply-time-2 nil)
-->
(modify 2 ^ flap-upper-bound <s>)
(exec '(bind-average <lb> <s>))
(modify 3 ^ flap <t1>)
(write (crlf) Try hardover flap deployment to <t1> % subject to)
(write (crlf) airspeed restrictions.)
(modify 1 ^ value query)
(remove 4)
(make Sim-results nil))

;
(p Pitch-up::Interpolation:Elevtab-ail.-intermed.-flap:insuff.-later
(Mode sim-advise)
(Failure-case-description ^ flap-i <fi>)
(Scratchpad ^ flap-lower-bound <lb> ^ flap-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap <f>
        ^ tlever nil ^ apply-time-2 <at>)
(Recovery-control-2 ^ flap-2 { <fl> < <fi>})
(Sim-results ^ pitch-compensated no)
-(Recovery-control ^ flap nil)
-->
(modify 3 ^ flap-upper-bound <fl>)
(exec '(bind-average <lb> <fl>))
(modify 5 ^ flap-2 <t1>)
(write (crlf) Restore flaps hardover to <t1> % at <at> sec.)
(modify 1 ^ value query)
(modify 6 ^ aircraft-stabilized nil ^ pitch-compensated nil
        ^ stall-recovered:gamma nil ^ did-not-loop nil
        ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interp.:Elevt.-ail.-opt.-fl.-inter.-tlev:too-much-later
(Mode sim-advise)
(Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever <t>
        ^ apply-time-2 <at>)
(Recovery-control-2 ^ tlever-2 <t2>)
(Sim-results ^ pitch-compensated no)
-(Recovery-control ^ tlever nil)
-(Recovery-control-2 ^ tlever-2 nil)
-->
```

```
(modify 2 ^ tlever-upper-bound <t2>)
(exec '(bind-average <lb> <t2>))
(modify 4 ^ tlever-2 <t1>)
(write (crlf) Reduce the delayed thrust increase to <t1> %.)
(modify 1 ^ value query)
(modify 5 ^ aircraft-stabilized nil ^ pitch-compensated nil
        ^ stall-recovered:gamma nil ^ did-not-loop nil
        ^ stall-recovered:alpha nil))

;
(p Pitch-up::Interp.:Elevt.-ail.-opt.-flap-inter.-tlev:insuff.-later
 (Mode sim-advise)
 (Scratchpad ^ tlever-lower-bound <lb> ^ tlever-upper-bound <ub>)
 (Recovery-control ^ elevtab 50. ^ aileron -20. ^ tlever <t>
            ^ apply-time-2 <at>)
 (Recovery-control-2 ^ tlever-2 <t2>)
 (Sim-results ^ pitch-overcompensated yes
            ^ stall-recovered:gamma no)
 -(Recovery-control ^ tlever nil)
 -(Recovery-control-2 ^ tlever-2 nil)
 -->
 (modify 2 ^ tlever-lower-bound <t2>)
 (exec '(bind-average <t2> <ub>))
 (modify 4 ^ tlever-2 <t1>)
 (write (crlf) Change the delayed thrust increase to <t1> %.)
 (modify 1 ^ value query)
 (modify 5 ^ aircraft-stabilized nil ^ pitch-overcompensated nil
        ^ stall-recovered:gamma nil ^ did-not-loop nil
        ^ stall-recovered:alpha nil))

;
(p Pitch-up:Descent-can-mean-insufficient-thrust:for-backtrack
 (Mode sim-advise)
 (Elevator-off-nominal-deflection {<v> < 0.})
 (Failure-case-description ^ tlever-i {<ti> < 55.})
 (Tlever-master ^ tlever-m nil)
 (Recovery-control ^ tlever nil ^ apply-time-2 nil)
 (Sim-results ^ aircraft-stabilized yes ^ descent yes)
 -->
 (write (crlf) In case we have to backtrack later--)
 (write (crlf) In the last simulation)
 (write (crlf) If pitch rate achieved a minimum after angle of)
 (write (crlf) atttack decreased to 25. deg. give the time in)
 (write (crlf) seconds that this minimum occurred. Otherwise)
 (write (crlf) give the time at which angle of attack decreased)
 (write (crlf) through 25. deg.)
 (modify 5 ^ apply-time-2 (accept)))

;
(p Pitch-up:Descent-can-mean-insufficient-thrust:detab-at-most
 (Mode sim-advise)
 (Elevator-off-nominal-deflection {<v> < 0.})
 (Failure-case-description ^ tlever-i {<ti> < 55.})
 (Tlever-master ^ tlever-m nil)
 (Recovery-control ^ elevtab <e> ^ aileron nil ^ tlever nil
            ^ apply-time-2 {<at> > 0.})
 (Recovery-control-2 ^ elevtab-2 <e2>)
```

(Sim-results ^ aircraft-stabilized yes ^ descent yes)
(Scratchpad ^ elevtab-lower-bound <lb>)
-(Recovery-control ^ elevtab 50.)
-->
(make Recovery-control-save ^ elevtab-s <e> ^ apply-time-2s <at>)
(modify 4 ^ tlever-m 100.)
(modify 5 ^ elevtab nil ^ apply-time-2 nil)
(modify 6 ^ elevtab-2 nil)
(write (crlf) Add immediate hardover thrust increase to 100.%)
(modify 1 ^ value query)
(remove 8)
(make Scratchpad nil)
(remove 7)
(make Sim-results nil))
;
(p Pitch-up:Descent-can-mean-insufficient-thrust:detab&aileron-only
(Mode sim-advise)
(Elevator-off-nominal-deflection {<v> < 0.})
(Failure-case-description ^ tlever-i {<ti> < 55.})
(Tlever-master ^ tlever-m nil)
(Recovery-control ^ elevtab 50. ^ aileron <a> ^ flap nil
        ^ tlever nil ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ elevtab-2 <e2>)
(Sim-results ^ aircraft-stabilized yes ^ descent yes)
(Scratchpad ^ elevtab-lower-bound <lb>)
-(Recovery-control ^ aileron -20.)
-->
(make Recovery-control-save ^ elevtab-s 50. ^ aileron-s <a>
                ^ apply-time-2s <at>)
(modify 4 ^ tlever-m 100.)
(modify 5 ^ aileron nil ^ apply-time-2 nil)
(modify 6 ^ elevtab-2 nil ^ aileron-2 nil)
(write (crlf) Add immediate hardover thrust increase to 100.%)
(modify 1 ^ value query)
(remove 8)
(make Scratchpad nil)
(remove 7)
(make Sim-results nil))
;
(p Pitch-up:Descent-can-mean-insuff.-thrust:detab&ail.&opt.flap-only
(Mode sim-advise)
(Elevator-off-nominal-deflection {<v> < 0.})
(Failure-case-description ^ tlever-i {<ti> < 55.})
(Tlever-master ^ tlever-m nil)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap {<f> > 0.}
        ^ tlever nil ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ elevtab-2 <e2>)
(Sim-results ^ aircraft-stabilized yes ^ descent yes)
(Scratchpad ^ elevtab-lower-bound <lb>)
-->
(make Recovery-control-save ^ elevtab-s 50. ^ aileron-s -20.
                ^ flap-s <f> ^ apply-time-2s <at>)
(modify 4 ^ tlever-m 100.)
(modify 5 ^ flap nil ^ apply-time-2 nil)

```
(modify 6 ^ elevtab-2 nil ^ aileron-2 nil ^ flap-2 nil)
(write (crlf) Add immediate hardover thrust increase to 100.%)
(modify 1 ^ value query)
(remove 8)
(make Scratchpad nil)
(remove 7)
(make Sim-results nil))
;
(p Pitch-up:Descent-can-mean-insuff.-thrust:detab&ail.&flap-h.o.
(Mode sim-advise)
(Elevator-off-nominal-deflection {<v> < 0.})
(Failure-case-description ^ tlever-i {<ti> < 55.})
(Tlever-master ^ tlever-m nil)
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap 0.
             ^ tlever nil ^ apply-time-2 {<at> > 0.})
(Recovery-control-2 ^ elevtab-2 <e2>)
(Sim-results ^ aircraft-stabilized yes ^ descent yes)
(Scratchpad ^ elevtab-lower-bound <lb>)
-->
(make Recovery-control-save ^ elevtab-s 50. ^ aileron-s -20.
                  ^ flap-s 0. ^ apply-time-2s <at>)
(modify 4 ^ tlever-m 100.)
(modify 5 ^ apply-time-2 nil)
(modify 6 ^ elevtab-2 nil ^ aileron-2 nil ^ flap-2 nil)
(write (crlf) Add immediate hardover thrust increase to 100.%)
(modify 1 ^ value query)
(remove 8)
(make Scratchpad nil)
(remove 7)
(make Sim-results nil))
;
(p Pitch-up::Immediate-thrust-incr.-gives-too-much-pitch-up:no-flaps
(Mode sim-advise)
(Failure-case-description ^ flap-i {<f> = 0.})
(Recovery-control ^ elevtab 50. ^ aileron -20.
          ^ tlever nil ^ apply-time-2 nil)
(Recovery-control-2 ^ tlever-2 nil)
(Recovery-control-save ^ elevtab-s <es> ^ aileron-s <as>
               ^ flap-s <fs> ^ apply-time-2s <ats>)
(Sim-results ^ pitch-compensated no)
-(Tlever-master ^ tlever-m nil)
-->
(write (crlf) Thrust increases will probably have to be delayed.)
(modify 4 ^ tlever-2 100.)
(write (crlf) Unless nil apply immediate hardover elevator tab)
(write (crlf) deflection to <es> deg.)
(write (crlf) hardover aileron deflection to <as> deg.)
(write (crlf) hardover flap deflection to <fs> % and)
(write (crlf) hardover thrust increased only later--)
(write (crlf) to 100.% at <ats> sec.)
(modify 1 ^ value query)
(remove 6)
(make Sim-results nil))
;
```

```
(p Pitch-up::Immed.-thrust-incr.-gives-too-much-pitch-up:max.-flaps
(Mode sim-advise)
(Failure-case-description ^ flap-i {<f> > 0.})
(Recovery-control ^ elevtab 50. ^ aileron -20. ^ flap 0.
          ^ tlever nil)
(Recovery-control-2 ^ tlever-2 nil)
(Recovery-control-save ^ elevtab-s <es> ^ aileron-s <as>
              ^ flap-s <fs> ^ apply-time-2s <ats>)
(Sim-results ^ pitch-compensated no)
-(Tlever-master ^ tlever-m nil)
-->
(write (crlf) Thrust increases will probably have to be delayed.)
(modify 4 ^ tlever-2 100.)
(write (crlf) Unless nil apply immediate hardover elevator tab)
(write (crlf) deflection to <es> deg.)
(write (crlf) hardover aileron deflection to <as> deg.)
(write (crlf) hardover flap deflection to <fs> % and)
(write (crlf) hardover thrust increased only later--)
(write (crlf) to 100.% at <ats> sec.)
(modify 1 ^ value query)
(remove 6)
(make Sim-results nil))
;
;
;
```

```
;-----------------------------------------------------------------
; Averaging Function
;-----------------------------------------------------------------
;
(defun bind-average (l u)
 (prog (temp li)
 (setq temp (/ (+ l u) 2.))
 (setq li (list 'bind '<t1> temp))
 (eval li)))
 ;
;-----------------------------------------------------------------
; Queries About Simulation Outcome
;-----------------------------------------------------------------
 ;
(p Query::Did-pitch-rate-cross-zero?
 (Mode query)
 (Sim-results ^ pitch-compensated nil)
 (Recovery-control ^ apply-time-2 nil)
 -->
 (write (crlf) Did pitch rate ever cross zero?)
 (modify 2 ^ pitch-compensated (accept)))
 ;
(p Query::Did-the-aircraft-stabilize?
 (Mode query)
 (Sim-results ^ aircraft-stabilized nil)
 -->
 (write (crlf) Was the aircraft stabilizing by our definition)
 (write (crlf) at the end of the sim?)
 (modify 2 ^ aircraft-stabilized (accept)))
 ;
(p Query::Pitch-down:Did-we-overcompensate?
 (Mode query)
 (Elevator-off-nominal-deflection ^ value { <v> > 0. })
 (Sim-results ^ aircraft-stabilized no ^ pitch-overcompensated nil)
 -->
 (write (crlf) Did pitch rate overshoot zero to take a positive)
 (write (crlf) value and flight path angle also achieve a positive)
 (write (crlf) value at the end of the simulation?)
 (modify 3 ^ pitch-overcompensated (accept)))
 ;
(p Query::Pitch-down:Did-pitch-rate-recover?
 (Mode query)
 (Elevator-off-nominal-deflection ^ value { <v> > 0. })
 (Sim-results ^ pitch-compensated yes ^ aircraft-stabilized no
         ^ pitch-overcompensated no
         ^ dive-recovered:pitch-rate nil)
 -->
 (write (crlf) After it initially crossed zero did pitch rate)
 (write (crlf) remain greater than its first minimum?)
 (bind <t> (accept))
 (modify 3 ^ pitch-compensated <t> ^ dive-recovered:pitch-rate <t>))
 ;
(p Query::Pitch-down::Did-flight-path-angle-recover?
 (Mode query)
```

```
(Elevator-off-nominal-deflection ^ value {<v> > 0.})
(Sim-results ^ pitch-compensated yes ^ aircraft-stabilized no
        ^ dive-recovered:pitch-rate yes
        ^ dive-recovered:gamma nil)
-->
(write (crlf) Did flight path angle remain positive in the initial)
(write (crlf) stall recovery-or-if it was negative at some point)
(write (crlf) did it later cross from negative to positive?)
(bind <t> (accept))
(modify 3 ^ pitch-compensated <t>
        ^ dive-recovered:gamma <t>))

;
(p Query::Pitch-up:Did-the-aircraft-not-loop?
(Mode query)
(Elevator-off-nominal-deflection ^ value {<v> < 0.})
(Sim-results ^ aircraft-stabilized no
        ^ did-not-loop nil)
-->
(write (crlf) Did pitch angle remain below 111. deg.-and-if it did)
(write (crlf) so but crossed 30. deg. did it decrease and recross)
(write (crlf) this level later?)
(bind <t> (accept))
(modify 3 ^ pitch-compensated <t> ^ did-not-loop <t>))
;
(p Query::Good-stall-recovery?:pitch-rate-minimized
(Mode query)
(Sim-results ^ stall-recovered:pitch-rate-min nil
        ^ stall-recovered:alpha yes)
(Recovery-control ^ apply-time-2 nil)
-->
(write (crlf) Did angle of attack remain below 25. deg.-or-)
(write (crlf) If angle of attack ever exceeded this level did)
(write (crlf) pitch rate reach a minimum before the end of the)
(write (crlf) simulation and within 5. seconds after angle of)
(write (crlf) attack last decreased through 25. deg.?)
(bind <t> (accept))
(modify 2 ^ stall-recovered:pitch-rate-min <t>
        ^ pitch-compensated <t>))
;
(p Query::Good-stall-recovery?:pitch-rate
(Mode query)
(Sim-results ^ stall-recovered:pitch-rate nil
        ^ stall-recovered:pitch-rate-min yes)
(Recovery-control ^ apply-time-2 nil)
-->
(write (crlf) Did pitch rate cross back from negative to positive)
(write (crlf) if angle-of-attack remained below 25. deg. or after)
(write (crlf) angle-of-attack last decreased through 25. deg.?)
(modify 2 ^ stall-recovered:pitch-rate (accept)))
;
(p Query::Good-stall-recovery?:alpha
(Mode query)
(Sim-results ^ did-not-loop yes ^ stall-recovered:alpha nil)
-->
```

```
(write (crlf) Did angle of attack remain below 25. deg. originally)
(write (crlf) -or-if it did cross this level did it always later)
(write (crlf) decrease through it at least before rising above it)
(write (crlf) again?)
(modify 2 ^ stall-recovered:alpha (accept)))
;
(p Query::Good-stall-recovery?:flight-path-angle
(Mode query)
(Sim-results ^ stall-recovered:pitch-rate yes
         ^ stall-recovered:alpha yes
         ^ stall-recovered:gamma nil)
-->
(write (crlf) Did flight path angle remain positive in the initial)
(write (crlf) stall recovery-or-if it was negative at some point)
(write (crlf) did it later cross from negative to positive?)
(modify 2 ^ stall-recovered:gamma (accept)))
;
(p Query::Final-descent?
(Mode query)
(Sim-results ^ aircraft-stabilized yes ^ descent nil)
-->
(write (crlf) Was the aircraft settling into an apparent descent?)
(modify 2 ^ descent (accept)))
;
(p Success
(Mode query)
(Sim-results ^ aircraft-stabilized yes ^ descent no)
-->
(write (crlf) A successful recovery strategy has been found.)
(modify 1 ^ value end))
;
(p Return-to-simulation:1
(Mode query)
(Sim-results ^ pitch-compensated no)
-->
(modify 1 ^ value sim-advise))
;
(p Return-to-simulation:2
(Mode query)
(Sim-results ^ pitch-overcompensated yes)
-->
(modify 1 ^ value sim-advise))
;
(p Return-to-simulation:3
(Mode query)
(Sim-results ^ pitch-compensated yes ^ aircraft-stabilized no
         ^ stall-recovered:gamma yes)
-->
(modify 1 ^ value sim-advise))
;
(p Return-to-simulation:4
(Mode query)
(Sim-results ^ descent yes)
-->
```

```
  (modify 1 ^ value sim-advise))
;
(p Return-to-simulation:5.
 (Mode query)
 (Sim-results ^ stall-recovered:pitch-rate yes
          ^ stall-recovered:gamma no)
-->
 (modify 1 ^ value sim-advise))
;
(p Return-to-simulation:6
 (Mode query)
 (Sim-results ^ stall-recovered:pitch-rate no)
-(Sim-results ^ stall-recovered:alpha nil)
-->
 (modify 1 ^ value sim-advise))
;
(p Return-to-simulation:7
 (Mode query)
 (Sim-results ^ stall-recovered:pitch-rate yes
          ^ stall-recovered:alpha no)
-->
 (modify 1 ^ value sim-advise))
;
(p Return-to-simulation:8
 (Mode query)
 (Sim-results ^ stall-recovered:alpha no)
-->
 (modify 1 ^ value sim-advise))

;
```

```
;**********************************************************************
; Working Memory Initialization
;**********************************************************************
;
(make Mode start)
(make Failure-case-description ^ elevator-jammed-at 13.55
^ elevator-i 2.45 ^ aileron-i 0. ^ flap-i 50. ^ tlever-i 37.78
^ elevtab-i -2.285 ^ landing-gear-i down)
(make Tlever-master nil)
(make Recovery-control nil)
(make Recovery-control-2 nil)
(make Recovery-control-save nil)
(make Scratchpad nil)
(make Sim-results nil)
;
;**********************************************************************
; End
;**********************************************************************
;
```