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Evaluation of the continued use of an aging variable stability system augmented aircraft for modern flying qualities education

Kevin F. Greene

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To the Graduate Council:

I am submitting herewith a thesis written by Kevin F. Greene entitled "Evaluation of the continued use of an aging variable stability system augmented aircraft for modern flying qualities education." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Fred Stellar, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Kevin Francis Greene entitled "Evaluation of the Continued Use of an Aging Variable Stability System Augmented Aircraft For Modern Flying Qualities Education." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Fred Stellar
Mr. Fred Stellar, Major Professor

We have read this thesis
and recommend its acceptance:

Ralph D. Kimberlin

RV Miller

Accepted for the council:

Interim Vice Provost and
Dean of The Graduate School

EVALUATION OF THE CONTINUED USE OF AN AGING VARIABLE STABILITY SYSTEM AUGMENTED AIRCRAFT FOR MODERN FLYING QUALITIES EDUCATION

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Kevin F. Greene
August 2001

DEDICATION

To my wife Elizabeth and son Benjamin,

who have endured in my absence while pursuing this endeavor.

Any feelings of relief or accomplishment pale in comparison to the happiness and peace I feel knowing they are part of my life.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to a number of individuals who made this effort possible.

Special appreciation goes to Mr. Bob Miller, who spent extensive personal time helping to refresh my knowledge of aircraft stability and control and dynamics theory. Additionally, for his generous support and personal dedication during the development of the SIMULINK model.

Barb Chamberlin's extreme personal effort and endless search of archives for supporting documents was instrumental to the completion of this thesis.

Thanks also to Betsy Harbin for her continued assistance throughout my enrollment in the Aviation Systems curriculum.

ABSTRACT

The University of Tennessee Space Institute (UTSI) obtained two fly-by-wire variable stability aircraft from Princeton University in 1991. These modified Navion aircraft contain several modifications to accommodate a response-feedback type of Variable Stability System (VSS). The aircraft were used extensively while owned and operated by Princeton for research projects for the United States Navy and Federal Aviation Administration. In recent years, externally funded research opportunities have been limited and UTSI has utilized the aircraft in support of the University graduate school curriculum.

The purpose of this thesis is to evaluate the continued use of these aging variable stability system augmented aircraft for a modern, flying quality curriculum.

In order to determine the capabilities of the Navion Variable Stability aircraft as an in-flight simulator and teaching tool, the longitudinal equations of motion and on board Variable Stability System were modeled in the United States Naval Test Pilot School simulation laboratory using Matrix Laboratory (MATLAB) and SIMULINK modeling tools. Characteristic responses of the short period mode of motion were plotted while varying several modeled, in-flight programmable potentiometer settings. Root locus plots were then created to determine the envelope of possible responses for in-flight demonstrations. The flaps and throttle channels were modeled but were not exercised for this evaluation.

Analysis of the root locus plot revealed that the Navion is capable of demonstrating a wide range of longitudinal short period characteristics, including unstable conditions.

Though this was a limited study, focusing on only the longitudinal short period modes of motion, the aging Navion VSS aircraft shows excellent potential to perform as an in-flight laboratory and demonstration platform in a modern flying qualities curriculum. Additionally, research and development agencies continue to utilize variable stability aircraft for flight control system development. This aircraft possesses great potential for utilization in the professional aerospace industry and should be maintained for use in both educational and research flight activities.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

α	alpha, angle of attack
$\dot{\alpha}$	alpha dot, change of α with respect to time
$\bar{c}$	mean aerodynamic chord
$C_{()}$	non-dimensional coefficient, with respect to the subscripted parameter
Δ	delta, change of parameter that follows
δ_e	change in elevator position
δ_{flp}	change in flap position
δ_T	change in throttle position
Deg, deg	degrees
$\frac{d}{dt}$	1st derivative with respect to time
$\frac{d^2}{dt^2}$	2nd derivative with trespect to time
FT	feet
g	acceleration due to gravity, 32.2 ft/sec^2
Hz	hertz, cycles per second
I_X	longitudinal axis moment of inertia
I_Y	lateral axis moment of inertia
I_Z	directional axis moment of inertia
m	mass

$M_{()}$	pitching moment
η	control vector
n	load factor
n/α	change in load factor per change in angle of attack
ρ	rho, density slug/ft^3
q	pitch rate
Q	dynamic pressure, $\frac{1}{2}\rho V^2$
rad	radians
sec	seconds
S	wing area
θ	theta, pitch attitude
θ_{dot}	theta dot, pitch attitude change with respect to time
u	forward velocity component
V	velocity, knots true airspeed
w	vertical component of velocity
$\dot{w}$	vertical velocity change with respect to time
ω_{sp}	short period frequency (rad/sec)
$X_{()}$	longitudinal force
ζ	damping ratio
$Z_{()}$	normal force

Definitions

CAP	control anticipation parameter
KTAS	knots true airspeed
MATLAB	Matrix Laboratory, Computer math modeling software
NACA	National Advisory Committee on Aerospace
SIMULINK	control system design software
TPS	Test Pilot School
USNTPS	United States Naval Test Pilot School
UTSI	University of Tennessee Space Institute
VSS	variable stability system

Chapter I

INTRODUCTION

The University of Tennessee obtained two fly-by-wire variable stability aircraft from Princeton University in 1991. These aircraft contain several modifications to accommodate a response-feedback type of Variable Stability System (VSS). One of these aircraft, registration N55UT is the focus of this evaluation and incorporates six-degree of freedom variable control. The VSS aircraft were used extensively while owned and operated by Princeton for research projects for the United States Navy and Federal Aviation Administration. In recent years, externally funded research opportunities have been limited and UTSI has utilized them in support of the University graduate school curriculum. They have provided an excellent platform for performance, stability and control and flight test instruction.

The purpose of this evaluation is to investigate the continued use of this aging variable stability system augmented aircraft for a modern, flying quality curriculum. The Navion's Longitudinal variable stability flight control system was modeled using the MATLAB control system modeling software. Root locus plots were made to determine the range of longitudinal short period frequency and damping values achievable while varying the cockpit adjustable gain potentiometers. These gain potentiometers control longitudinal static stability and pitch damping characteristics when the aircraft is operated from the evaluation pilot's position.

Chapter II

BACKGROUND

FLYING QUALITIES

The flying qualities of an airplane are related to the stability and control characteristics and can be defined as those stability and control characteristics that are important in forming the pilot's impression of the airplane. The pilot forms subjective opinions about the ease or difficulty of controlling the airplane in steady and maneuvering flight. In addition to the longitudinal dynamics, the pilot's impression of the airplane is also influenced by the feel of the airplane that is provided to the pilot by the stick force and stick force gradients. The Department of Defense and Federal Aviation Administration have made a list of specifications with regard to airplane flying qualities. These requirements are used by the procuring and regulatory agencies to determine whether an airplane is acceptable for certification. The purpose of these requirements is to ensure that the airplane has flying qualities which do not place any limitation on the vehicle's flight safety or restrict the ability of the airplane to perform its intended mission. (16)

In specifying flying quality criteria, it is necessary to recognize differences in classes of airplanes, in types of maneuvers required in some phase of flight and in possible failure states of airplane systems. Aircraft are classified according to size as shown in Table 2-1.

Table 2-1 Aircraft Classifications (16)

Airplane Class	Definition
I	Small, light airplanes, such as light utility, primary trainer, and light observation aircraft.
II	Medium-weight, low-to-medium maneuverability airplanes, such as heavy utility, light or medium transport/cargo/tanker, reconnaissance, tactical bomber.
III	Large, heavy, low-to-medium maneuverability airplanes, such as heavy transport/cargo/tanker, heavy bomber.
IV	High maneuverability airplanes, such as fighter/interceptor, attack, tactical reconnaissance.

Table 2-2 Flight Phase Categories (16)

Category	Definition
A	Non-terminal flight phases that require rapid maneuvering, precision tracking, or precise flight-path control. Included are: air-to-air combat, ground attack, weapon delivery, terrain following, in-flight refueling.
B	Non-terminal flight phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight path control may be required. Included are: climb, cruise, loiter, descent.
C	Terminal phases, normally accomplished using gradual maneuvers and usually require accurate flight path control. Included are: take-off, catapult launch, approach, wave-off, go around and landing.

Flight phases are divided into three categories as shown in Table 2-2. Category A refers exclusively with military aircraft. Most of the flight phases listed in categories B and C are applicable to either military or commercial aircraft. Flying qualities are specified in terms of three levels, defined as follows: (16)

Level 1	Flying qualities clearly adequate for the mission flight phase.
Level 2	Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.
Level 3	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A phases can be terminated safely, and Category B and C flight phases can be completed.

Handling Qualities Ratings

When evaluating aircraft handling qualities, two key factors must be considered, performance and workload. Performance is the precision of aircraft control attained by the pilot. Workload is the amount of effort and attention, both physical and mental, the pilot must provide to attain that level of performance. Pilot compensation is the measure of increased workload a pilot must supply to maintain a level of performance due to less favorable or deficient handling characteristics. The total workload is the sum of workload due to compensation and workload due to task. The Cooper-Harper rating scale (Figure 2-1) requires the pilot to answer a series of questions in order to assign a Handling Quality Rating.

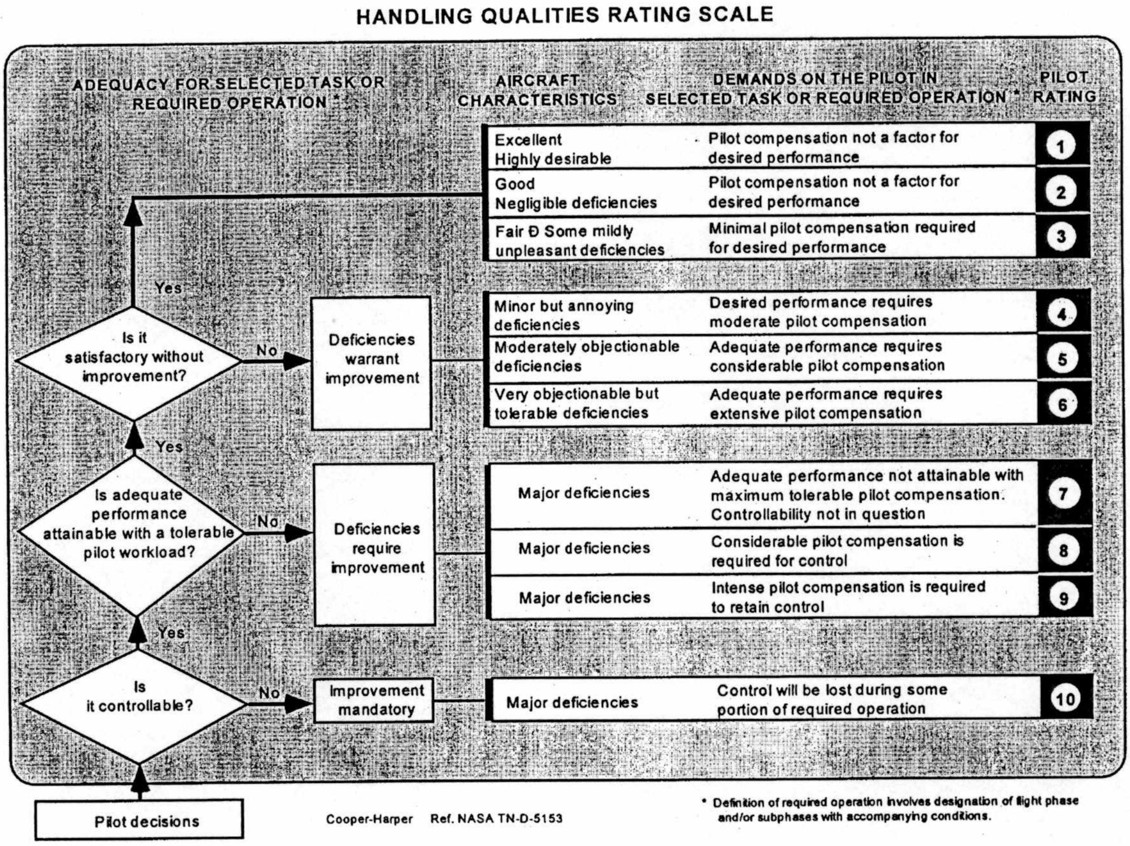

Figure 2-1 Cooper Harper Rating Scale (5)

These questions guide the pilot through the handling quality assessment. (5)

1) Is the aircraft controllable?

2) Is adequate performance attainable with tolerable pilot workload?

3) Is it satisfactory without improvement?

In order to define "adequate" and "desirable", reference to a specific task must be made. This task must be well defined and mission oriented. Handling Qualities Ratings are subjective, thus will vary from pilot to pilot depending on background and experience. It is imperative that the flight test engineer be precise in designing tasks in an attempt to minimize variance between pilots.

IN FLIGHT SIMULATORS

For over fifty years, variable stability aircraft have been utilized for research, flight control system development and handling quality evaluation, including determination of design criteria. Additionally, these valuable tools have proven extremely beneficial to augmenting academic instruction in the areas of aircraft stability and control, dynamics and flight control system design considerations. The purpose of using variable stability aircraft in training is to provide a flying laboratory in which the student can relate engineering parameters of aircraft dynamics and stability and control to their resultant effect on the handling qualities of the aircraft. The unique capability of this type of aircraft is used to illustrate systematic changes to stability derivatives of the aircraft while the student experiences the final effect of each parameter change during performance of mission tasks in the aircraft. This "one experience is worth a thousand words" flying laboratory has proven invaluable for the teaching and understanding of the complex subject of aircraft dynamics and its influence on aircraft handling qualities. (15) Another enhancing feature is that potentially hazardous flight characteristics may be demonstrated in a controlled environment. The complex topic of control systems and their effect on aircraft handling qualities is a major benefit of this type of flying laboratory.

Utilizing in-flight simulators to supplement ground simulator training is important in that in-flight simulators provide a greater level of fidelity than ground-based simulators, thereby increasing the experience and understanding. The advantage of in-flight simulators are centered on the following: (11)

- Visual displays
- Cockpit accelerations
- Task realism
- Pilot stress levels

The visual displays provided to the evaluator are completely accurate because they are in the real world environment. Limitations to field-of-view are actual limitations of cockpit design rather than some visual display limitation. Visual cues in a ground-based simulator often do not contain the detail or field-of-view that pilots perceive in the real world. As the aircraft gets close to the ground during landing tasks, pilots cue increasingly on height and ground texture. In addition, the subtle peripheral vision cues available in the aircraft provide much more information to the pilot in the flare. (18)

The actual airborne environment provides cockpit accelerations that are experienced in an in-flight simulator. Moving-based ground simulators provide acceleration cues to the pilot by slowly washing out the steady state motions and attitudes. (11) The roll axis is especially sensitive to the non-realistic acceleration cues provided in ground-based simulators. Several new aircraft programs have evolved from the ground simulator design phase with an excessive roll sensitivity. This seems to be primarily due to acceptance, and even desirability, of extreme angular accelerations in simulators with no, or limited motion cues. The pilot perceives the roll response mainly through the roll attitude that he sees. This simulator response is two integrations removed from the roll acceleration that he easily picks up with accurate angular accelerations in the actual flight environment. (18) The ground simulator cockpit cues are typically misleading and lead to inaccurate flying qualities assessments. Aircraft evaluation tasks such as formation flying, tracking and landing that are conducted in ground-based simulators present difficulties because it is difficult to replicate the high fidelity visual, motion, wind and ground effect cues.

Finally, realistic stress levels can be created in an in-flight simulator. Realism means more than just accurate visual and motion cues. It also requires that the pilot address the task with the same level of concentration and aggressiveness that he would in an airborne environment. This is especially critical in precision, high gain tasks. (11) Research efforts to develop an in-flight physiological measure of workload measured heart rate, eye blink and evoked potentials during F-4 air-to-ground training missions and performance of a standard laboratory tracking task. Heart rate and eye blink were higher in the air than on the ground. In-flight heart rate increased 20-50% from baseline heart rate during in-flight tracking tasks, whereas the ground based increase was only 10%. In other tests, heart rate and variability were recorded from eight A-7 pilots during a bird strike and a near midair collision while airborne as compared to two simulated crashes. Heart rate increased 50% above baseline for both in-flight emergencies. (9)

VARIABLE STABILITY SYSTEMS (VSS)

A Variable Stability System modifies the aircraft basic control system through the use of electro-hydraulic servos, a computer and sensors. This system permits the evaluator to be exposed to a wide range of flying qualities in realistic mission related airborne tasks. VSS aircraft can effectively demonstrate flight test techniques as well as simulate the dynamics of different aircraft. (15)

The evaluation pilot's controls are separate from the aircraft's conventional flight control system, in that the control surfaces are driven by VSS servos. In addition to the evaluation pilot control inputs, sensed quantities such as angle of attack, sideslip, roll rate, or pitch rate, are all functions of the control surface movement. The sensed inputs to the control surfaces alter the characteristic response of the aircraft. Numerous combinations of aircraft motions can be attained by adjusting the gain of these sensed inputs. The evaluation pilot is not aware of the control surface motion employed to change the response characteristics of the aircraft, but feels that he is controlling an aircraft that has the response characteristics, which the VSS system is providing. (15)

This type of VSS, where sensed parameters are used to alter inputs to the control surfaces, is called “response-feedback”. The primary features of a response-feedback system are illustrated in the pilot-in-the-loop diagram shown in Figure 2-2.

The VSS consists of sensors that measure various aircraft states along with pilot control inputs. An analog computer transforms and combines these signals into control surface commands. The control surfaces are then positioned by parallel servos, and the safety pilot’s (primary pilot station) controls move with all VSS system inputs. (15) This feature allows the instructor pilot to monitor VSS inputs and intervene in the event of system degradations or uncomfortable extreme aircraft motions. These qualities make the in-flight VSS aircraft an excellent piece of laboratory equipment for teaching stability and control and handling qualities. This concept of using the VSS aircraft as a teaching tool is not new. Beginning in 1960 with the United States Naval Test Pilot School, VSS aircraft have been utilized extensively by various test pilot schools around the world. The variable stability program supplements academic training in stability and control and instruction in flight test techniques. The VSS aircraft is ideal for teaching given its numerous capabilities.

Separating variables and examining them individually or in combinations can dissect the complex motions of aircraft. This is useful in showing how the academic theory, developed in the classroom, actually does describe the motion of an aircraft. For emphasis, or to demonstrate variables that may have only small contributions to the complex aircraft motion, certain parameters can be exaggerated. For example, to

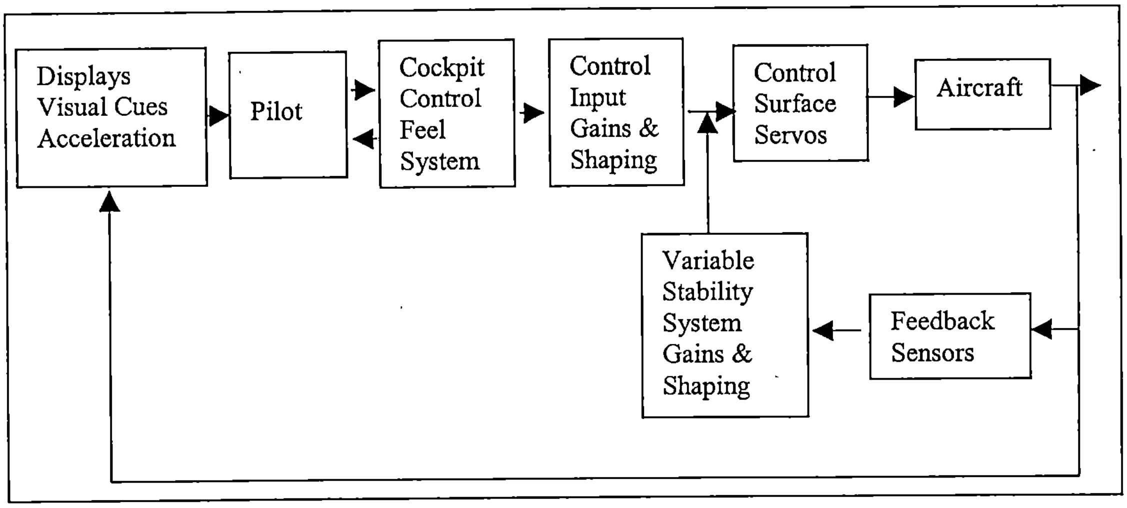

Figure 2-2 Response Feedback Variable Stability System (15)

demonstrate the effects of adverse yaw, the instructor can set an extreme amount of adverse yaw into the system so the student can clearly see its effect. Most aircraft commonly flown today have "reasonably acceptable" flying qualities. The VSS permits demonstration of very poor flying characteristics, possibly even unstable motion, thus providing emphasis on particular design criteria that should be avoided. Stability characteristics representing boundaries in specifications can be examined, and the consequences of exceeding these boundaries can be explored.

In-flight simulators provide an accurate representation of the entire dynamic system illustrated in figure 2-3. The elements include the aircraft and its flight control system, pilot stress, visual motion and aural cues, and external disturbances. A fundamental element of the dynamic system is the pilot who must perform defined tasks.

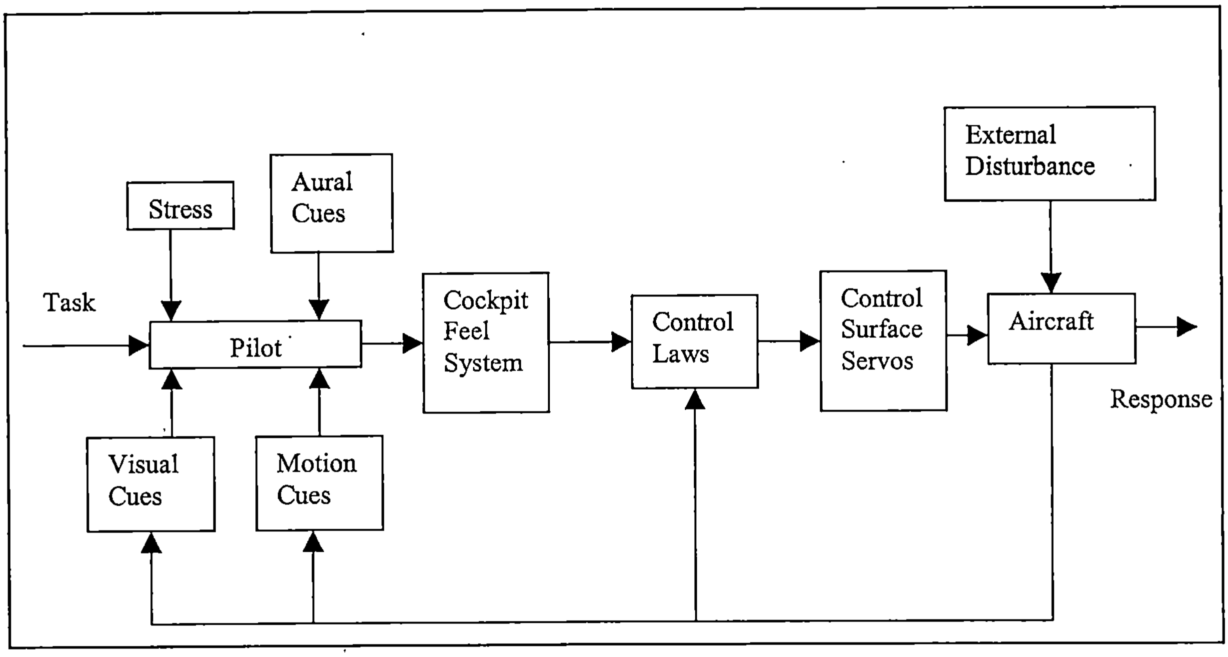

Figure 2-3 The Pilot-Vehicle Dynamic System (6)

The in-flight simulator is an invaluable tool to study the pilot-vehicle interaction in a real flight environment with complete motion and perfect visual cues while varying the vehicle dynamics through computer simulation. (6)

ACADEMIC INSTITUTION REVIEW

A review of academic institutions that provide education in the field of Aeronautical and Aerospace Engineering (Aero-Engineering) as well as aircraft design, flight test and handling qualities, has been conducted for this investigation. The objectives of the study were to review typical academic courses provided to students in pursuit of degrees in aero-engineering and how universities utilize aircraft as in-flight laboratories. Both undergraduate and graduate university programs were reviewed. Four major universities were reviewed in this study, selected based on their reputation and their utilization of aircraft in support of academic classes. They are, Embry Riddle Aeronautical University, Texas A&M, Kansas University and Parks College. The governing document for the Accreditation Board for Engineering and Technology, Inc. (ABET) was reviewed in order to provide insight into how universities develop their curriculum. Additionally, a member of the Industry Standards Board that provides professional guidance to Kansas University's Aeronautical Engineering Department was consulted to evaluate how industry cooperates with universities in the development of the curriculum. The mission of ABET is to serve the public through the promotion and advancement of engineering, technology and applied science education. Specifically, ABET accredit engineering, technology and applied science programs and assist in development and advancement of education in engineering, technology and applied science. (7) Although ABET deals exclusively with undergraduate programs, their guidelines and criteria present a model from which graduate level degree programs may also benefit.

University Curriculum Review

This curriculum review revealed that the following areas are studied:

-Development and solution of general equations of motion
-Aerodynamic derivatives
-Derivative analysis
-Transfer functions
-Static and Dynamic stability and control
-Automatic stability and control
-Automatic flight controls, including feedback control system analysis
-Aircraft design considerations

Although a rather broad base of topics is typically provided, there is limited offering of dedicated engineering flight-test courses. Engineering flight-testing is a complex field involving electronics, structures, performance, aeronautics, stability and control, instrumentation and design. A competent flight-test engineer must be well versed and able to effectively work with engineers from all of these disciplines. In most present day flight test departments, it is unheard of for an engineer to be involved in all aspects of testing, from design through instrumentation, mission flying, data reduction and report writing. (14) A course that provides students with this experience would better prepare them for this demanding field.

Aircraft Utilization in Degree Programs

Of the four universities reviewed, all utilize aircraft in varying degrees to augment the academic curriculum. In all cases, the aircraft used are production aircraft with different levels of instrumentation. Consequently, airborne laboratory utilization is restricted to evaluating the production aircraft's performance, systems and flying qualities. One university attempts to vary characteristics of the aircraft by physically moving ballast forward and aft to simulate center of gravity changes. This is done to support an exercise in determining the stick fixed neutral point and maneuvering point. None of the universities reviewed have the capability to conduct in-depth airborne evaluations or analysis of various aircraft characteristics, as they are limited in available flight assets.

Student Feedback

Graduates of Kansas University complete an "Exit Survey" conducted by the University's Industry Advisory Board. For three consecutive years, surveys revealed that students found "hands-on" experience the most beneficial, where they are motivated by putting theory into practice. Additionally, students of Parks College invariably label the engineering flight-test course "the most valuable technical elective", and recommend that this course be required of every Aerospace Engineering student. (14)

Critiques provided by students from five graduate classes of the United States Naval and Air Force Test Pilot Schools revealed the following comments regarding the value of the variable stability flights that are an integral part of the curriculum.

> Engineer: "Discussions in class are no replacement for this type of flying."
>
> Engineer: "This is the best way to understand flying qualities."
>
> Pilot: "It is very insightful to see the academics come to life."
>
> Engineer: "I learned more in this flight than one week of academics."
>
> Engineer: "Nothing else in TPS comes close."
>
> Engineer: "An exceptional hands-on experience. The pinnacle of flying qualities."
>
> Pilot: "...explained so much that had until then been just academic instruction."
>
> Engineer: "An incredible program. Without these sorties, the entire flying qualities phase is math, smoke and mirrors."

> Navigator: “You have to get to Naval Post Graduate School. I spent two years there…with lots of controls courses, but I had no real world idea what the results meant.”

Finally, eleven critiques were reviewed of a course offered at UTSI titled, “Advance Flight Control”. All eleven cited that the flight experience in the variable stability aircraft was the most beneficial. Specific comments included:

> “It is good to know what stability and control means to flying qualities.”
>
> “…being able to change parameters in a controlled manner – it put theory into the real world.”
>
> “Theory is great, but when you actually go out and fly to simulate theory it gets reinforced many times over.”

METHODS OF LEARNING

Memory may be thought of as the store of information. Humans possess two different storage systems, working memory and long-term memory. Working memory is used to hold new information until given a more permanent status in memory, that is, encoded into long-term memory. Encoding is the process of putting information into memory. Learning or training describes the transfer of information from working memory to long-term memory. Learning describes how the information transfer occurs, whereas training refers to explicit, intentional techniques used by teachers to maximize learning efficiency. Many principles, strategies and considerations can be employed to enhance training. Elaborative rehearsal describes the process of providing a greater focus on the meaning of material, thereby relating the elements of the material to each other and to information stored in long-term memory. Elaborative rehearsal can result from an active learning situation. (20)

The more memorable the experience, the more likely it is remembered. There are four levels of learning including rote memory, understanding, application and correlation. These levels are hierarchical, and all knowledge learned from previous levels of learning is prerequisite. This process is known as the building block concept of learning. The lowest level of learning is rote. This is a memorization process without the understanding or ability to apply what has been learned. The next level is an understanding of the material. The application level is the achievement of the skill to apply what has been learned to attain proper performance. Finally, the last level of learning is the ability to associate and correlate learned items with other things you have previously learned or encountered. (13)

Chapter III

NAVION VSS AIRCRAFT

DESCRIPTION OF AIRCRAFT

General Description

The aircraft referred to in this thesis was a highly modified Navion aircraft, registration Number N55UT, which was manufactured by Ryan Aeronautical Company, San Diego, California. (Figure 3-1) The Navion aircraft is a low wing, four place, dual, conventional-controlled, utility category aircraft, powered by a single air-cooled engine. The fuselage is an all-metal, one-piece, semi-monocoque structure, conventional empennage with a full cantilever-type horizontal stabilizer with attaching elevators and detachable tips, and a single vertical stabilizer and rudder. The aircraft is equipped with a sliding canopy, hydraulically operated flaps and retractable landing gear. (3) A complete description of the unmodified aircraft can be found in reference 3. Aircraft specifications are listed in table 3-1.

Aircraft Modifications

Numerous modifications have been made to the original design by Princeton University to facilitate in-flight research including studies done by the United States Navy and NASA. The engine is a Teledyne-Continental IO 520 B engine, designed to produce 285 horsepower that drives a three-bladed, constant speed McCauley propeller. External modifications include the incorporation of two vertical all-moving control

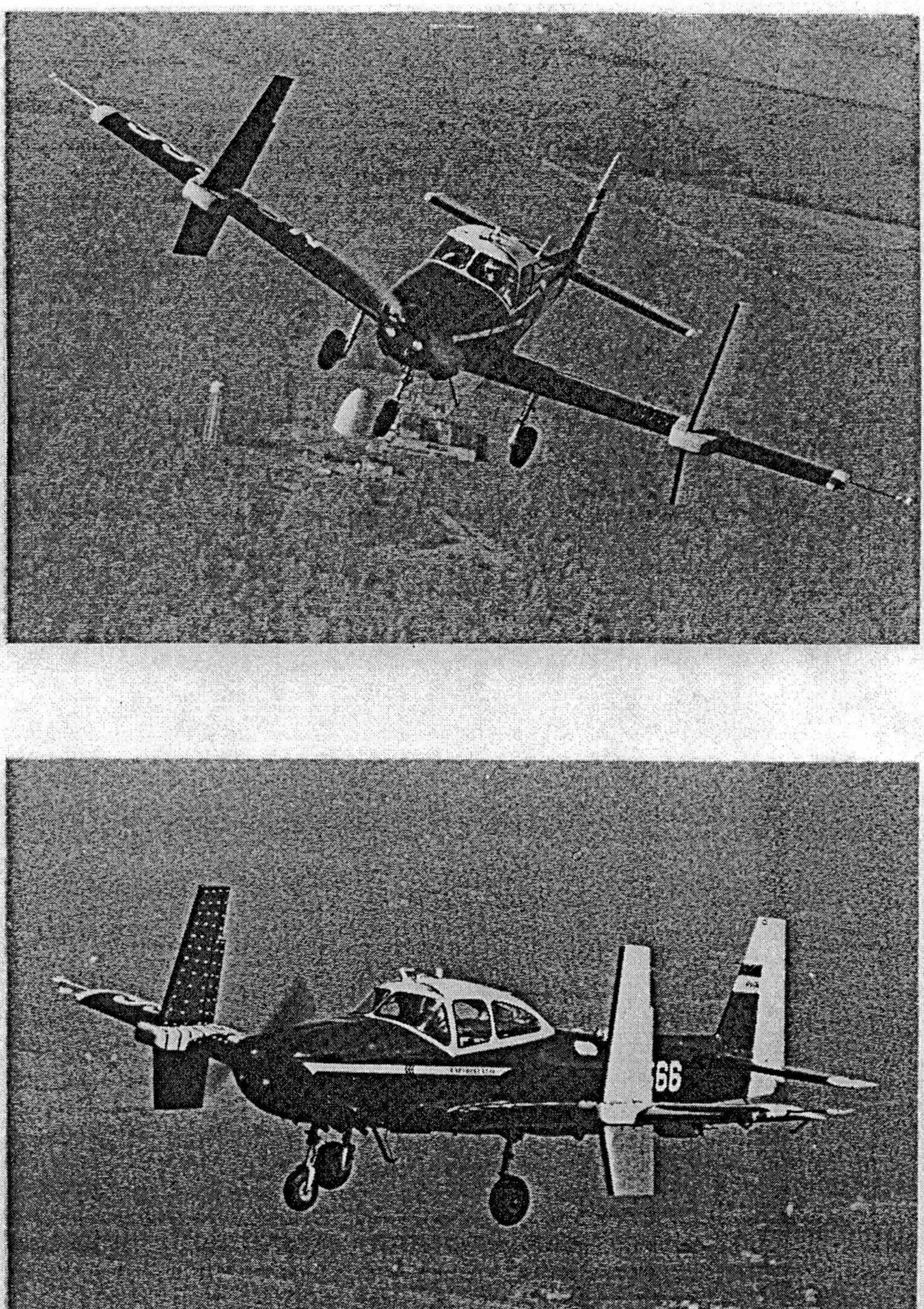

Figure 3-1 Navion Aircraft (10)

Table 3-1 Aircraft Specifications (8)

Name		Dimension
Wing	Area	180 FT^2
	Span	33.38 FT
	Chord	5.67 FT
	Leading Edge Sweep	3.0 Deg
	Dihedral	7.5 Deg
	Root Incidence	2.0 Deg
	Tip Incidence	-1.0 Deg
	Airfoil:	
	Tip	NACA 6410R
	Root	NACA 4415R
	Aileron:	
	Area	5.4 FT^2
	Deflection	± 20.0 Deg
	Flap:	
	Area	83.6 FT^2
	Deflection	± 30 Deg
	Horizontal Tail:	
	Area	43.0 FT^2
	Incidence	-3.0 Deg
	Airfoil	NACA 0012
	Elevator:	
	Area	14.1 FT^2
	Deflection	± 30 Deg
Vertical Tail	Area	18.1 FT^2
	Airfoil	Modified NACA 0013.2
	Fin Offset	2.0 Deg
	Rudder:	
	Area	11.6 FT^2
	Deflection	left 23, right 17 Deg
Side Force Surface (each)	Area	16.0 FT^2
	Airfoil	NACA 0012
	Deflection	± 30 Deg
Gross Weight	Gross	2609 LB
	Ix	1573.7 SLUG-FT^2
	Iy	2736.0 SLUG-FT^2
	Iz	3673.8 SLUG-FT^2

Figure 3-2 Side Force Generators

surfaces mounted on each wing. (Figure 3-2) These surfaces are modified Schweizer 2-32 sailplane horizontal tail assemblies, which are designed to produce side forces of up to ± ½ g at 105 knots. (4)

Changes to the flap hinges and actuation provide up and down deflection of approximately ± 30 degrees, resulting in increased lift modulation authority and smaller drag changes compared to the original configuration.

The vertical tail incorporates a chord-wise extension and a span-wise 'cap' on the rudder surface, thus increasing the vertical fin surface area. The modification was designed to increase sideslip control and compensate for the forward placement of the side force generators with respect to center of gravity.

The cabin has been modified to incorporate a variable stability system for research and flying qualities evaluations. The two aft seats have been removed to accommodate the analog VSS computer and several aircraft sensors. The co-pilot's station has been modified in order to accommodate an analog fly-by-wire control system for an evaluation pilot. The conventional flight controls have been removed and replaced with a center stick controller for pitch and roll control and separate rudder pedals for sideslip control. Figure 3-3 shows the cockpit configuration. The allowable gross weight has been increased to 3150 pounds. (4)

Conventional Flight Controls

The conventional flight control system consists of rudder pedals, a control yolk for aileron and elevator control, and cables and linkages connected to the control surfaces. Conventional control is available from the left pilot's seat only (safety pilot). The control column, to which the control wheel shafts (through universal joints) are attached, pivots at the base to permit forward and aft movement. Sprockets on the forward end of the control wheel shaft are interconnected by a chain, the ends of which attach to cables routed through pulleys at the top and bottom of the column. The ailerons are controlled by a combination linkage and cable system. Disconnect fittings are located within the control cable guard box on the floor and turnbuckles are located at each bell crank. A balance cable interconnects the bell crank in each wing, and has a turnbuckle located in the right wheel well. The safety pilot's rudder pedals are connected to a torque tube and are hinged at the floor. The rudder control system consists of two cable assemblies,

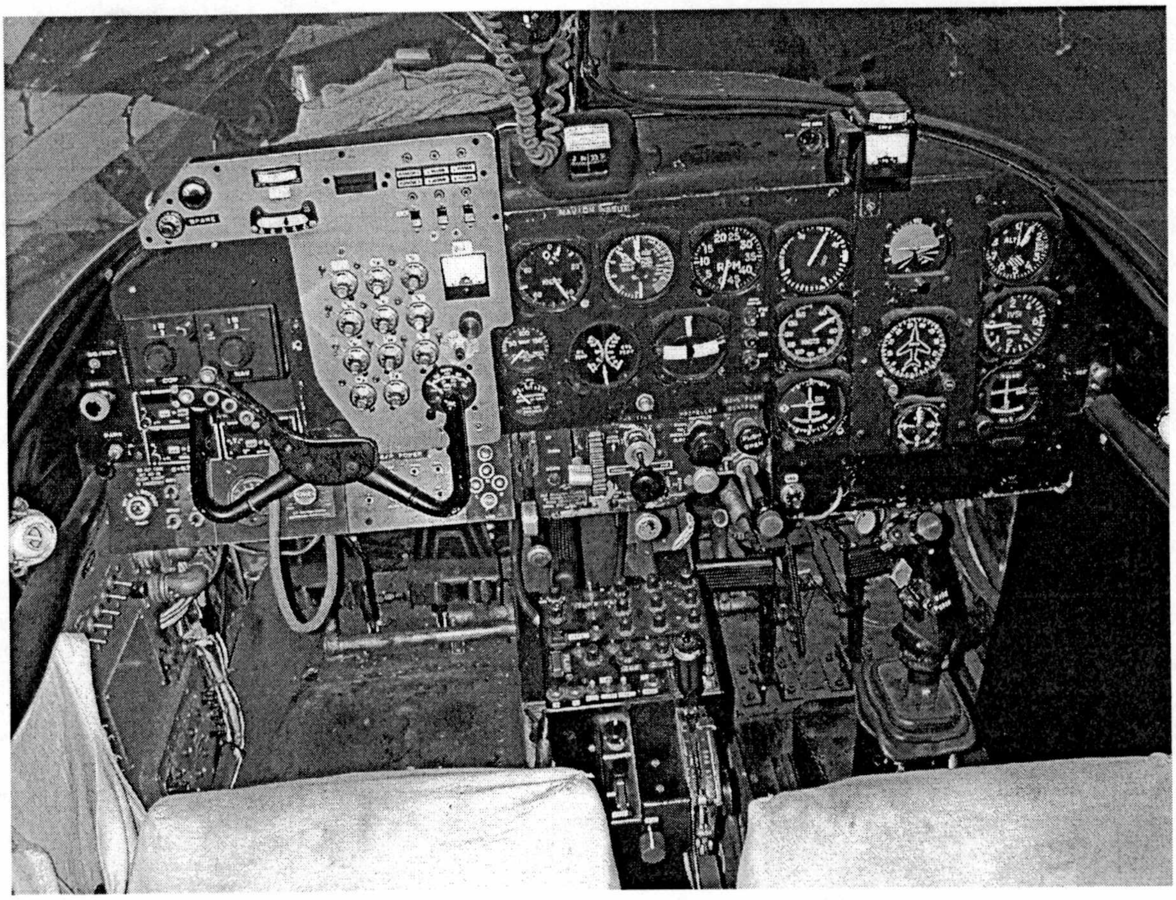

Figure 3-3 Navion Cockpit

connected to rudder pedal torque tube arms, and running aft to the rudder horns. Two rods, extending forward from the pedals to the bell crank for nose wheel steering, serve as a balance cable for the system. The elevator control system consists of two cable assemblies connecting the control column arm with the elevator horn. (4)

Variable Stability System Flight Controls

The co-pilot's station has been equipped with an analog, variable stability, fly-by-wire control system, incorporating power actuated control surfaces that are commanded by electrical signals. The signals come from the various cockpit controllers and motion sensors, which, when appropriately summed, provide a net signal to each servo, and thereby command an aircraft response of a particular character and magnitude. Table 3-2 shows inputs to the respective controller and functions varied. (4)

The servos are hydraulic, supplied by an engine-driven hydraulic pump delivering approximately nine gallons per minute at 1050 pounds per square inch of pressure. Full authority is provided to the conventional elevator, aileron and rudder control surfaces at a maximum rate of about 70 degrees per second by hydraulic servos. The hydraulic servos are modified units originally designed for the B-58 HUSTLER, and incorporate built in solenoids and pilot force-override disengage features. Figure 3-4 shows the left aileron Servo-Actuator. (4)

Table 3-3 displays the maximum control surface authority and hydraulic servo-actuator rate limits, and approximate second order frequency responses. The hydraulic pump capacity is designed to permit two-thirds maximum rate on the side force generator servos and maximum rate on all other servos simultaneously. (4)

Independent control over normal acceleration is exercised through the Navion flap, modified to deflect up and down. Actuation is hydraulic with a maximum available surface rate of 110 degrees per second. At 105 knots, the available authority is sufficient to effect slightly more than ± 1 g. (4)

Thrust control and drag modulation is by hydraulic servo on the engine throttle. The engine RPM is maintained by a constant speed propeller.

Direct side force control is obtained by dual vertical surfaces mounted on nacelles

Table 3-2 System Inputs (2)

	Channel	Input	Function Varied
Moment Controls	Pitch	Stick Displacement	Control Sensitivity
		Thrust Lever	Simulated Thrust Moment
		Thumbwheel	Simulated DLC Moment
		Radar Altitude	Ground Effect Moments
		Airspeed	Speed Stability
		Angle of Attack	Static Stability
		Pitch Attitude	Attitude Hold Sensitivity
		Pitch Rate	Pitch Damping
		Flap Angle	Trim Change for Flap
		Flap Rate	Moment from Flap Rate
		Simulated Turbulence	Turbulence response
	Roll	Stick Displacement	Control Sensitivity
		Sideslip	Dihedral Effect
		Roll Rate	Roll Damping
		Yaw Rate	Roll Due to Yaw Rate
		Pedal Displacement	Roll Due to Rudder
		Simulated Turbulence	Turbulence Response
	Yaw	Pedal Displacement	Control Sensitivity
		Sideslip	Directional Stability
		Yaw Rate	Yaw Damping
		Roll Rate	Yaw Due to Roll Rate
		Stick Displacement	Yaw Due to Aileron
		Simulated Turbulence	Turbulence Response
Force Controls	Normal	Stick Displacement	Lift Due to Control
		Thrust Lever	Lift Due to Thrust
		Radar Altitude	Ground Effect Lift
		Angle of Attack	Lift Change Near Stall
		Simulated Turbulence	Turbulence Response
	Thrust/Drag	Stick Displacement	Control Surface &DLC Drag
		Thrust Lever	Throttle Sensitivity
		Radar Altitude	Ground Effect Drag
		Airspeed	Drag Change With Speed
		Angle of Attack	Drag Change With AOA
		Flap Position	Drag Due to Flap Deflection
	Sideforce	Sideslip	Crosswind Force
		Bank Angle	Sideforce Due to Bank
		Lat Stick Input	Sideforce Due to Aileron
		Rudder Pedal	Sideforce Due to Rudder
		Yaw Rate	Sideforce Due to Yaw Rate
		Thumb Controller	Direct Sideforce Control.
		Simulated Turbulence	Turbulence Response

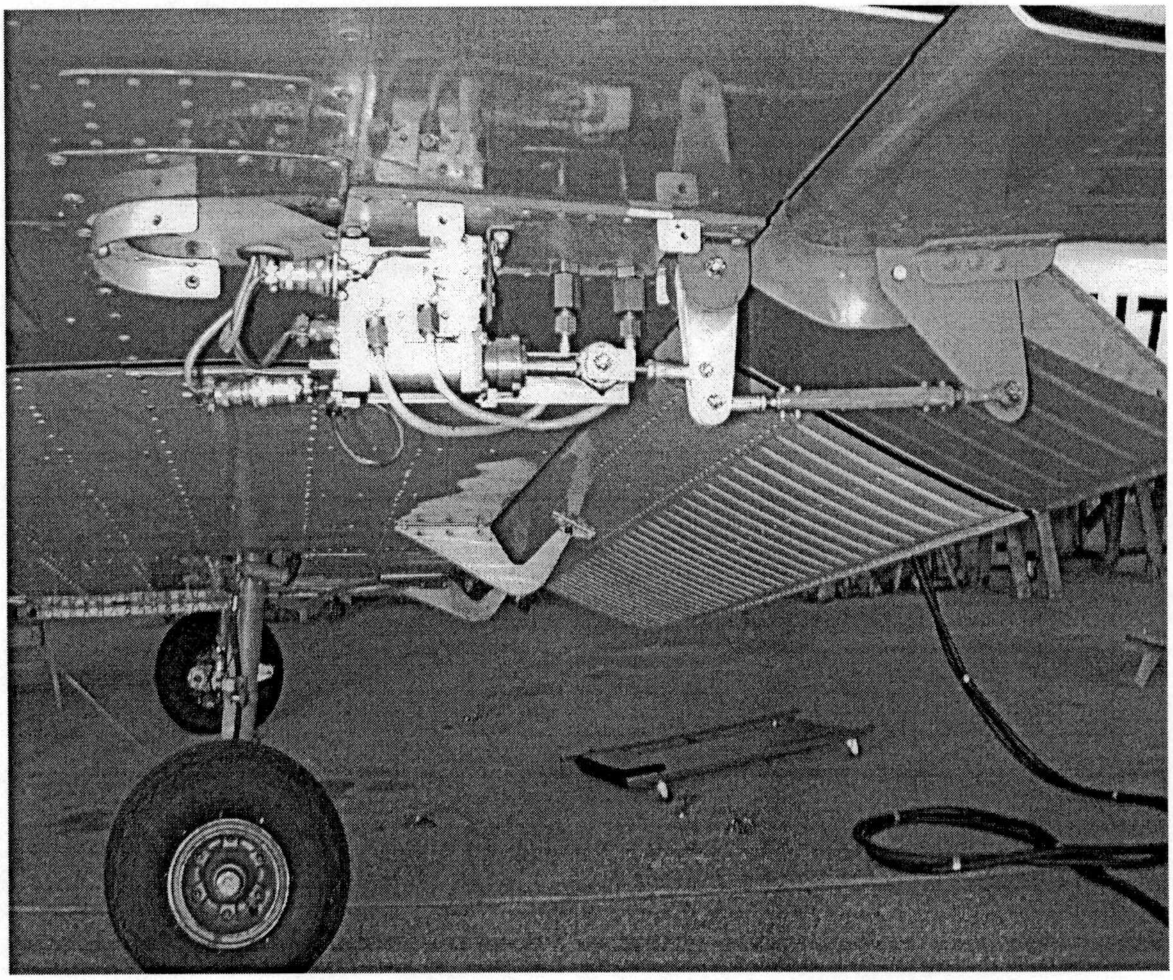

Figure 3-4 Left Aileron Servo-Actuator

Table 3-3 Servo Response (2)

Controller	Displacement (deg)	Rate (deg/sec)	Bandwidth Hz	Max Effect
Elevator	+20 / -30	70	5, 10	9.9 rad/sec
Ailerons	+/- 20	70	5, 10	9.2 rad/sec
Rudder	+/- 20	70	5, 10	4.2 rad/sec
Engine	-	-	0.6 (1)	0.005g
Sideforce	+/- 35	60	2,3	0.5g(2)
Flaps	+/- 30	110	2,3	1.1g

Notes: (1) Limited by engine to 1st order time constant of 0.25 sec
(2) Measured at 105 KIAS

on each wing. The location was chosen based on NASA wind tunnel studies, which indicated a minimum cross-coupling effect. The rolling moment induced by deflection is designed to be near zero. The surfaces are interconnected by a cable system, which permits either surface drive actuator, located in the nacelle fairing, to drive both surfaces. Hinging and aerodynamic anti-servo type tabs provide control surface float to a 'faired' position in the event of hydraulic power loss. Range of actuation is ± 35 degrees. In addition to direct side force control, the surfaces provide the means to simulate crosswinds. At 105 knots, the available authority is sufficient to effect a side force of approximately ± 0.5 g. (4)

Gain Potentiometers (POTS)

All of the control surfaces that provide for six degree of freedom control are driven by electronic signals to the servo-actuators. The signal is a sum of several feeder signals.

Feeder signals may include cockpit control position, control surface position and aircraft parameters. Many of the signals are fed through manually adjustable gain potentiometers (POTS) en-route to the summing junction of the servo drive. These POTS provide an analog electronic means for programming linear control laws by providing variable amounts of coupling between the control surfaces and aircraft parameters. (17) Reference 17 lists the scaling and calibration data for determining commanded values, reported to be linear throughout the range of possible adjustments. Several of the potentiometers are configured with a toggle switch that allows changing the sign of the commanded coupled parameters, allowing both increases as well as decreases in gain settings. For example, the pot setting labeled Mα is a ten position rotary POT with a sign changer toggle. This allows for the POT to be adjusted between values of –10 to +10.

Safety Features

The left pilot's location is configured for the function of safety pilot. The safety pilot's controls are mechanically connected to flight controls through the conventional system. This allows the safety pilot to continually follow the movements of the basic airplane controls, monitor the systems and flight path, and be ready to disengage or override the evaluation pilot in case of a malfunction or unsafe condition. For disengaging, a disconnect switch on the control yolk is the primary cutout. The main electrical and hydraulic controls provide the secondary means of deactivating the system. Manual override of the hydraulic servo-actuators is possible for all controls except the flap. The force required for override is set through an adjustable poppet valve on each servo, typically set for 40 pounds. Warning of a system failure is provided by warning lights. (4)

The elevator, aileron and side force systems incorporate redundant control channels. Substantial errors between the commanded and actual control position are detected and a switchover to a second servo is made automatically. The evaluation pilot retains control during this process, but all inputs to the switched channel, except those from the safety pilot's control column, are eliminated, reducing the possibility that a defective transducer or signal path is causing the problem. Redundant sensors for the control input signal are incorporated but the other transducers are not duplicated. The fact that a channel has switched to the secondary servo is communicated to the safety pilot by a warning light, allowing him to disconnect the system and assume control. Redundancy was also incorporated in the side force channel. In the case of a detected error in a channel, the surfaces drive to the safety pilot command point. No redundancy is provided for the rudder, throttle or flap channels. Flaps are designed to rapidly trail aerodynamically to a 10 degree down position in the event of a failure in the flap transducer. (4)

An "abort mode" is incorporated into the system, automatically transferring control to the safety pilot when activated. By depressing the disengage thumb switch, the flap travels at maximum rate to a 20 degree down position and power is automatically advanced to a climb setting. The system is designed to recover from a 70 knot, six-degree approach, with a simulated up-flap failure in less than 10 feet of altitude loss. (4)

Chapter IV

ANALYSIS OF LONGITUDINAL MODES OF MOTION

DEVELOPMENT OF COMPUTER MODEL

In order to determine the capabilities of the Navion Variable Stability aircraft as an in-flight simulator and teaching tool, the longitudinal equations of motion and on-board Variable Stability System were modeled in the USNTPS simulation laboratory using Matrix Laboratory (MATLAB) and SIMULINK modeling tools. Characteristic responses of the short period mode of motion were plotted while varying several modeled, in-flight programmable potentiometer settings. Root locus plots were then created to determine the envelope of possible short period responses for in-flight demonstrations.

Software Review

Matrix Laboratory (MATLAB)

MATLAB is a popular tool of practicing engineers and scientists. It provides a technical computing environment for interactive computation, data analysis, and graphical visualization, affording more creativity through its visualization and computational capabilities. Quickly able to generate Bode, Nyquist and Nichols plots, root locus plots, pole-zero plots and plots of transient responses, MATLAB allows the control system design engineer to focus on the information in all of the graphical displays without the tedious task of creating plots by hand. MATLAB version 5.3 was used in the development of this model. (12)

SIMULINK

SIMULINK is a software package for use with MATLAB. It is an interactive environment for modeling, simulating and prototyping dynamic systems, including discrete, analog and mixed signal systems. SIMULINK provides the means to model a system rapidly without the requirement of writing extensive code. SIMULINK block diagrams provide a highly interactive environment for non-linear simulation. Providing immediate access to the mathematical, graphical and programmable capabilities of MATLAB, data can be analyzed and parameters optimized directly from SIMULINK. (19)

Equations of Motion

Equally important to exhibiting positive static stability, aircraft should also be dynamically stable, whether by means of its natural modes of motion or through flight control system design. The degree of dynamic stability and those factors affecting the stability, are important in assessing an aircraft's flying qualities. (16) Equations of motion for an aircraft are developed in order to evaluate the factors that affect these dynamic motions.

Applying Newton's laws, and making several initial assumptions, equations of motion for small disturbances can be derived for an aircraft. Assumptions must also be made in order to linearize the equations so that they may be solved. The following assumptions apply to the development of the equations:

1) The earth is fixed in space.
2) The aircraft is a rigid body.
3) The aircraft is disturbed from an equilibrium flight condition of wings level and constant altitude.
4) The longitudinal (X-body) axis is aligned with the relative wind at time zero.
5) Small angle approximations are applied.
6) The product of small variables can be neglected.
7) The aircraft is configured with an elevator-type tail surface.

Omitting the tedious development, and applying these assumptions, the longitudinal equations of motion are presented without proof. (16)

$$\left(\frac{d}{dt}-X_u\right)\Delta u - X_w\Delta w + (g\cos\theta_0)\Delta\theta = X_{\delta e}\Delta\delta_e + X_{\delta T}\Delta\delta_T$$

$$-Z_u\Delta u + \left((1-Z_{\dot{w}})\frac{d}{dt}-Z_w\right)\Delta w - \left((u_0+Z_q)\frac{d}{dt}-g\sin\theta_0\right)\Delta\theta = Z_{\delta e}\Delta\delta_e + Z_{\delta T}\Delta\delta_T$$

$$-M_u\Delta u - \left(M_{\dot{w}}\frac{d}{dt}+M_w\right)\Delta w + \left(\frac{d^2}{dt^2}-M_q\frac{d}{dt}\right)\Delta\theta = M_{\delta e}\Delta\delta_e + M_{\delta T}\Delta\delta_T$$

Since this investigation is limited to the longitudinal axis, the lateral / directional equations are not included. The equations presented are simple, ordinary, linear differential equations with constant coefficients. The coefficients are made up of the aerodynamic stability derivatives, mass, and inertia characteristics of the airplane. When the equations are written as a system of first order differential equations, they are referred to as state-space, represented by: (16)

$$\dot{x} = Ax + B\eta$$

where x is the state vector, η is the control vector and the matrices A and B contain the aircraft's dimensional stability and control derivatives respectively. Due to their very small contribution to aircraft response, Z_q and $Z_{\dot{w}}$ are neglected. Rewriting the equations in the state-space form and neglecting these terms, yields: (16)

$$\begin{bmatrix} \Delta\dot{u} \\ \Delta\dot{w} \\ \Delta\dot{q} \\ \Delta\dot{\theta} \end{bmatrix} = \begin{bmatrix} X_u & X_w & 0 & -g \\ Z_u & Z_w & u_0 & 0 \\ M_u + M_{\dot{w}}Z_u & M_w + M_{\dot{w}}Z_w & M_q + M_{\dot{w}}u_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \Delta u \\ \Delta w \\ \Delta q \\ \Delta\theta \end{bmatrix}$$

$$+ \begin{bmatrix} X_{\delta e} & X_{\delta T} \\ Z_{\delta e} & Z_{\delta T} \\ M_{\delta e} + M_{\dot{w}}Z_{\delta T} & M_{\delta T} + M_{\dot{w}}Z_{\delta T} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \Delta\delta_e \\ \Delta\delta_T \\ \Delta\delta_{flp} \end{bmatrix}$$

The state vector, x, control vector, η, and matrices A and B are given by: (16)

$$x=\begin{bmatrix}\Delta u\\ \Delta w\\ \Delta q\\ \Delta\theta\end{bmatrix} \qquad A=\begin{bmatrix} X_u & X_w & 0 & -g\\ Z_u & Z_w & u_0 & 0\\ M_u+M_{\dot{w}}Z_u & M_w+M_{\dot{w}}Z_w & M_q+M_{\dot{w}}u_0 & 0\\ 0 & 0 & 1 & 0\end{bmatrix}$$

$$\eta=\begin{bmatrix}\Delta\delta_e\\ \Delta\delta_T\\ \Delta\delta_{flp}\end{bmatrix} \qquad B=\begin{bmatrix} X_\delta & X_{\delta T} & X_{flp}\\ Z_\delta & Z_{\delta T} & Z_{flp}\\ M_\delta+M_{\dot{w}}Z_\delta & M_{\delta T}+M_{\dot{w}}Z_{\delta T} & M_{\delta flp}+M_{\dot{w}}Z_{\delta flp}\\ 0 & 0 & 0\end{bmatrix}$$

In order to more accurately reflect the Navion VSS configuration, variables have been added in the control matrix B for flaps so that they may be modeled as controls rather than part of the configuration.

The values of the derivatives listed in these equations were determined through a number of means. Significant research has found several references where the Navion aircraft stability derivatives have been estimated using several methods, including full-scale wind tunnel and in-flight testing. No one source provided all of the non-dimensional derivatives required for the model, therefore several approximations and assumptions were necessary. Most of the previous studies focused on aircraft Registration Number N66UT. Reference 8 (Fernand, 1978) investigated the primary stability derivatives of aircraft N55UT exclusively. Aircraft specific data, flight conditions, and when available, stability derivatives, were used from this source to formulate the model. Derivatives determined for aircraft N66UT are used when N55UT information was not available. Additionally, reference 16 (Nelson,1989) values were used, adjusted to be consistent with this investigation's modeled flight conditions.

Finally, when required, parameters were estimated when their contribution to the longitudinal short period modes of motion were assumed to be insignificant. Flight conditions used in determining these derivatives are listed in Table 4-1. Tables 4-2 and 4-3 list the non-dimensional and dimensional derivatives respectively for the model, and the formulas used in determining them.

DETERMINATION OF VSS LONGITUDINAL ENVELOPE

Using the determined stability derivatives and aircraft parameters, the longitudinal axis was modeled using SIMULINK. (Figure A-1) In order to accommodate future evaluations, the flaps and throttle channels were modeled but are not exercised for this study. Short period frequency and damping were evaluated throughout the range of POT settings, Mα and Mθ(dot) (Mq). Table 4-4 displays the two POTS varied in this study and their calibration and scaling information as determined from reference 1.

Aircraft Short Period Demonstration Capabilities

An 8-degree longitudinal pitch stick doublet was programmed as the commanded input, chosen to enable aircraft mode excitation with minimum excursion from trimmed airspeed. Figure A-2 is a root locus plot, representing the envelope of values of

Table 4-1 Flight Conditions for Computer Model

Parameter	Value
Airspeed	105 KTAS (177.45 feet per second)
Altitude	3500 FT Mean Sea Level
Density	.00214283 slug/ft^3
Flap Position	10 deg Down

Table 4-2 Non-Dimensional Derivatives (8)(16)

Derivative	Value	Derivative	Value
C_{Du} , C_{Lu}	0	$C_{Z\delta e}$	-.2867
C_{D0}	.05	$C_{M\alpha}$	-.6107
$C_{D\alpha}$	.33	$C_{M\dot{\alpha}}$	-4.36
C_{L0}	.41	C_{Mq}	-7.867
$C_{L\alpha}$	4.44	$C_{M\delta e}$	-.8207
$C_{Z\alpha}$	-5.623	$C_{Z\alpha}$	-5.623
C_{Zq} , C_{Mu}	0		

Table 4-3 Dimensional Derivatives

Derivative	Conversion	Value	Derivative	Conversion	Value
X_u	$\frac{-(C_{Du}+2C_{D0})QS}{mu_0}$	-0.04	$Z_{\delta e}$	$\frac{-C_{z\delta e}QS}{m}$	21.49
X_w	$\frac{-(C_{D\alpha}-C_{L0})QS}{mu_0}$	0.03	M_u	$C_{Mu}\frac{QS\bar{c}}{u_0 I_Y}$	0
Z_u	$\frac{-(C_{Lu}+2C_{L0})QS}{mu_0}$	-0.36	M_w	$C_{M\alpha}\frac{QS\bar{c}}{u_0 I_Y}$	-0.04
Z_w	$\frac{-(C_{L\alpha}+C_{D0})QS}{mu_0}$	-1.9	$M_{\dot{w}}$	$C_{M\dot{\alpha}}\left(\frac{\bar{c}}{2u_0}\right)\left(\frac{QS\bar{c}}{u_0 I_Y}\right)$	-0.00494
$Z_{\dot{w}}$	$\frac{-C_{Z\dot{\alpha}}\frac{\bar{c}}{2u_0}QS}{mu_0}$	0	M_α	$u_0 M_w$	-7.10
Z_α	$u_0 Z_w$	-336.54	$M_{\dot{\alpha}}$	$u_0 M_{\dot{w}}$	-0.088
$Z_{\dot{\alpha}}$	$u_0 Z_{\dot{w}}$	0	M_q	$\frac{C_{Mq}\frac{\bar{c}}{2u_0}(QS\bar{c})}{I_Y}$	-1.58
Z_q	$\frac{-C_{Zq}\frac{\bar{c}}{2u_0}QS}{m}$	0	$M_{\delta e}$	$\frac{C_{M\delta e}(QS\bar{c})}{I_Y}$	-10.32

Table 4-4 Potentiometer Definitions (1)

Potentiometer	Definition	Units	Min Value (1)	Max Value
Mα	Deg -δe / deg α	Deg / deg	-.93	.93
$M\theta_{(dot)}$ (Mq)	Deg -δe / deg/sec nose up	Deg / deg	-14.8	14.8

Note: (1) With polarity toggle switched to minus position.

frequency and damping that can be demonstrated. Analysis of the root locus plot reveals that the Navion is capable of demonstrating a wide range of longitudinal short period characteristics, including unstable conditions. The "+" symbol represents points where the combination of POT settings resulted in a mismatch between commanded and actual elevator position by more than ½ degree. This represents conditions of either saturation or rate limiting. Superimposed on the plot is the envelope of frequency and damping values that represent MIL-STD-1797A recommended values for Category C, Level 1 handling qualities. These values were derived from the MIL-STD-1797A Control Anticipation Parameter (CAP) criteria. (Figure A-3) The Control Anticipation Parameter is defined as:

$$\text{CAP}= \frac{\omega^2{}_{sp}}{n/\alpha}$$

As evidenced in Figure A-2, capabilities exist to demonstrate a range of flying qualities both within and outside of this envelope. Figures A-4 through A-7 are provided as examples of SIMULINK time histories to convey the physical response of the aircraft at several combinations of M_α and $M_{\theta dot}$ POT settings. Figure A-7 represents values which plot on the unstable portion of the S-plane as indicated by the divergent response. Noted also is the separation of commanded verse actual elevator position at approximately 6.75 seconds, which represents the point at which the elevator reaches maximum deflection.

Chapter V

FLIGHT CONTROL SYSTEM COURSE DEVELOPMENT

The VSS Navion, owned by the University of Tennessee Space Institute, is an invaluable tool for aircraft modes of motion and handling quality flight-testing instruction. As such, maximum utilization within an academic curriculum should be considered. The following is a proposal for a course that utilizes the Navion as an in-flight simulator/laboratory/test platform. This course was developed considering the capabilities of the VSS aircraft and the results of simulation developed during this evaluation. It was developed based on knowledge of education requirements gained while assigned as a flight instructor at the United States Naval Test Pilot School. The course may be presented as either a senior-level graduate course or industry short course, following the same outline, differing only in audience and entry-level prerequisites. Course length is designed for approximately 40 hours of classroom academic instruction, which includes two or three flights, depending on the experience of the students.

COURSE TITLE

Introduction to Flight Control System Design and Flying Qualities Flight Testing.

PURPOSE

To provide exposure to flying qualities testing of modern flight control systems including academics, simulation, flight demonstration, flight test, data reduction and specification compliance.

OVERVIEW

This course is designed to familiarize students with the concepts of aircraft handling qualities, flight control system design and flight test, through the study of dynamic modes of motion, the parameters that effect these modes, aircraft design characteristics and modern flight control systems. Utilizing the Variable Stability Navion aircraft, various aircraft modes of motion are demonstrated to supplement the academic theory. Culmination of the course is an iterative design project of a flight control configuration where the students will determine optimum gains required for an in flight task.

SPECIFIC OBJECTIVES

1) Thorough understanding of the various aircraft dynamic modes of motion and parameters that affect these motions.

2) Understanding of the complex subject of aircraft and control system characteristics and their effect on aircraft handling qualities.

3) Appreciation for the benefits and limitations of advanced flight control systems.

4) Exposure to flying qualities flight-testing, data reduction and handling qualities ratings and specification compliance.

5) Familiarization with frequency domain specification criteria and its application in light of mission, flight phase and task.

PREREQUISITES

Acceptance to this course would require previous courses in aerodynamics and college level mathematics including differential equations, Laplace Transforms and second order system analysis. Additionally, familiarity with the computer control system modeling sofware MATLAB and SIMULINK is recommended.

COURSE CURRICULUM OVERVIEW

The following is a recommendation of course topics and class hours:

1) First and Second Order Systems (2 hours)
2) Dynamic Systems Analysis (2 hours)
    - Laplace Transforms, Transfer Functions
    - Root Locus, Frequency Response
3) Aircraft Statics and Dynamics (12 hours)
    - Static and Dynamic Stability
    - Aircraft Dynamic Modes of Motion
    - Equations of Motion
    - Longitudinal Aircraft Stability and Control
    - Lateral Directional Stability and Control

4) Aircraft Control Systems (4 hours)

  - Compensation
  - Response Types; α, g, q, attitude Command Systems

5) Handling Quality Ratings; Cooper Harper (2 hours)

6) Longitudinal Flight Test Techniques (2 hours)

7) Specifications (FAA Part 23 / Military Specifications)(2 hours)

8) MATLAB / SIMULINK review (2 hours)

9) Flight Briefings (2 hours)

10) Flights (2 x 1.5 hours) (3 hours)

11) Flight Debrief / Data Analysis (4 hours)

11) Design Exercise Brief (1 hour)

12) LAB / DESIGN TIME (2 hours)

DESIGN EXERCISE

A flight control system design project would conclude the course. In order to bound the scope, only the longitudinal axis is explored. Provided to the students would be the MATLAB model, Figure A-1. Students will determine the best combination of $M\alpha$ and $M_\theta$dot gains and forward path gain $M_{\delta e}$ (POT settings) that provide the best response to simulated inputs. When satisfied, these POT settings are set in the aircraft where they have the opportunity to evaluate a task (landing), after an in-flight evaluation. Students are able to fine tune their POT settings to improve task performance while airborne.

Chapter VI

CONCLUSIONS

The University of Tennessee Space Institute possesses a very valuable and unique capability with the VSS Navion aircraft in-flight simulators. Aside from professional test pilot schools, there is little opportunity for aeronautical engineering students and industry professionals to gain an in-depth understanding of the complex modes of motion of aircraft. In-flight variable stability aircraft, with the ability to separate variables and exaggerate their effects on aircraft modes of motion has proven to be invaluable in the training of engineering students and pilots for many years. They are utilized with resounding success in the professional test pilot schools around the world. The ability to simulate numerous aircraft characteristics in one flight while answering the following questions is a capability which should be exploited to the maximum extent possible.

1) What is the airplane doing?
2) Why is it doing it?
3) Is the motion good or bad?
4) What is this physical explanation?

Though this was a limited study, focusing on only the longitudinal short period modes of motion, the Navion VSS aircraft shows excellent potential to perform as an in-flight laboratory and training platform in a modern flying quality curriculum. Additionally, research and development continues to utilize variable stability aircraft for flight control system development. This aircraft possesses great potential for utilization in the professional aerospace industry.

Chapter VII

RECOMMENDATIONS

This study provides a limited assessment of the capabilities of the Navion VSS aircraft to supplement a flying quality academic curriculum. Considering the limited number of variable stability aircraft, it is highly recommended that the University of Tennessee Space Institute continue to pursue funding and efforts toward maintaining these unique aircraft and expanding their use in educating aerospace engineering professionals.

Several assumptions have been made to develop the simulation model upon which the conclusions were drawn. These assumptions should be verified through a series of aircraft ground and flight tests. Specific recommendations include the follow:

1) Conduct a ground test to verify the calibration and functionality of all the cockpit VSS potentiometers.

2) Conduct experimental flight tests to determine the envelope of effects that the variable flaps have on longitudinal stability derivatives.

3) Incorporate a graduate level course similar to that presented in this paper.

4) Encourage graduate students to continue to focus their thesis research toward the efforts of improving the VSS.

5) Investigate the feasibility of incorporation of a variable feel system.

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APPENDIX

SIMULATION RESULTS

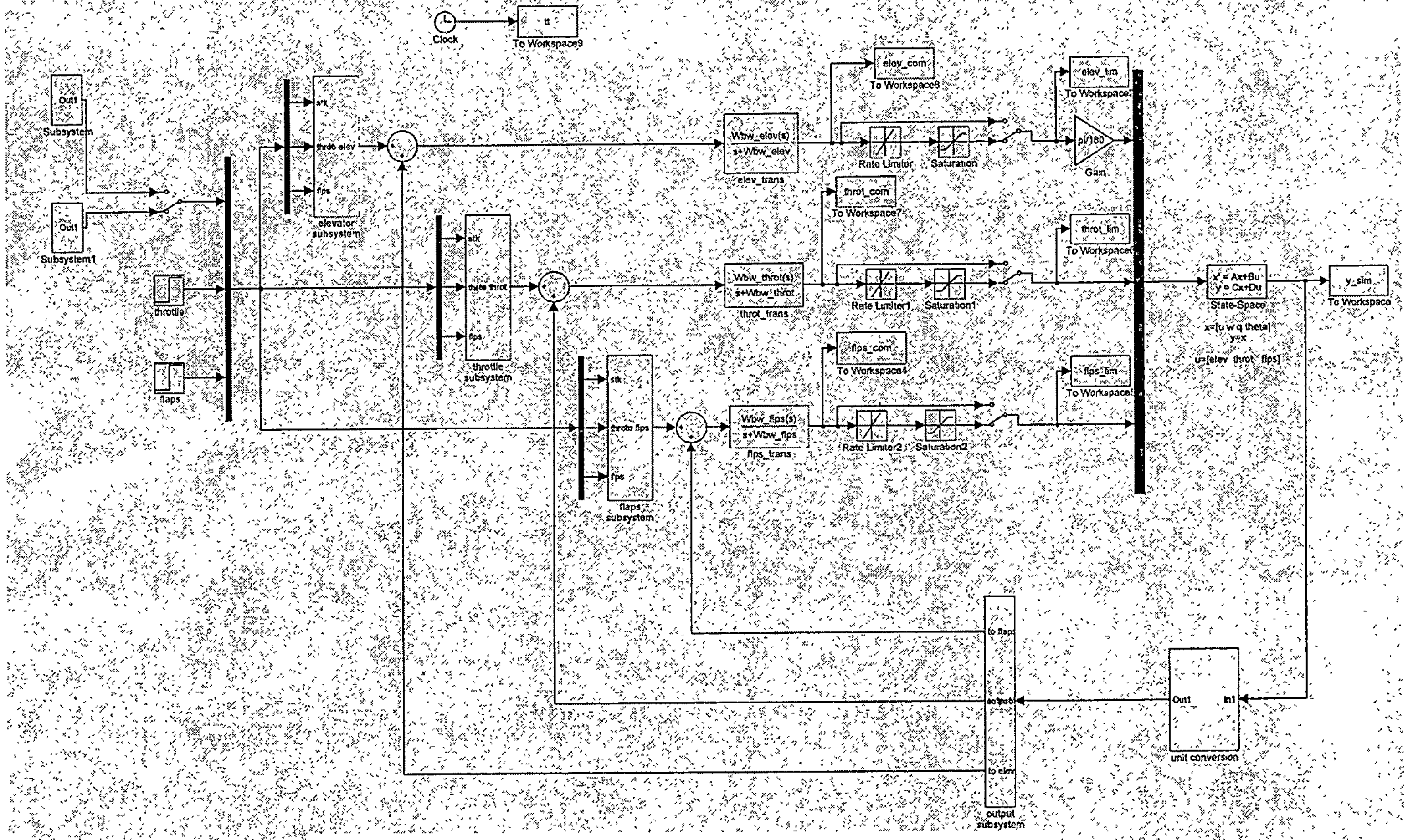


Figure A-1 Navion Longitudinal Axis SIMULINK Model

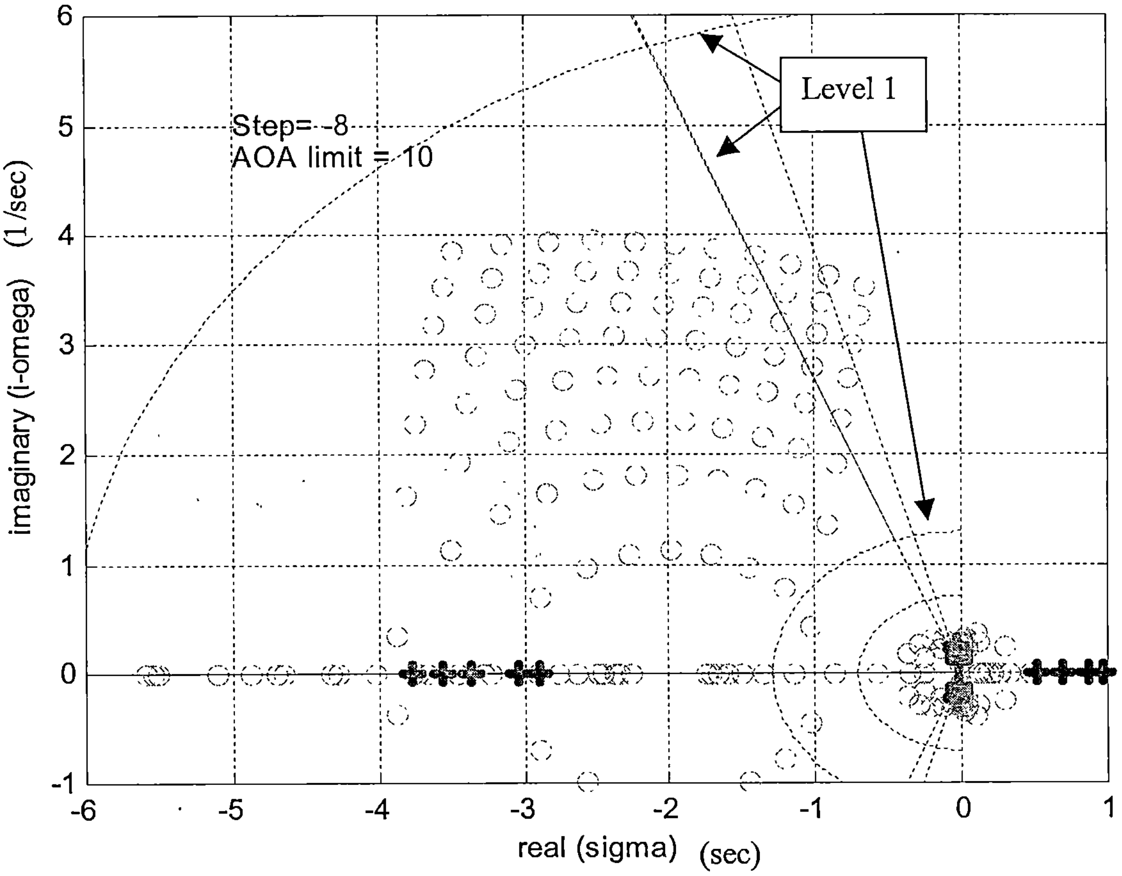
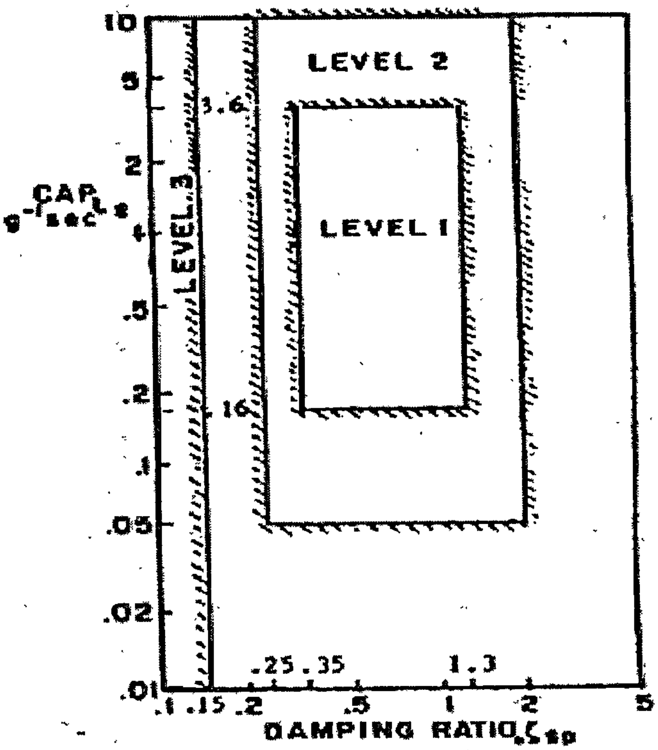


Figure A-2 Root Locus Plot



c) CATEGORY C FLIGHT PHASES

Figure A-3 Short Period Dynamic Frequency Requirements

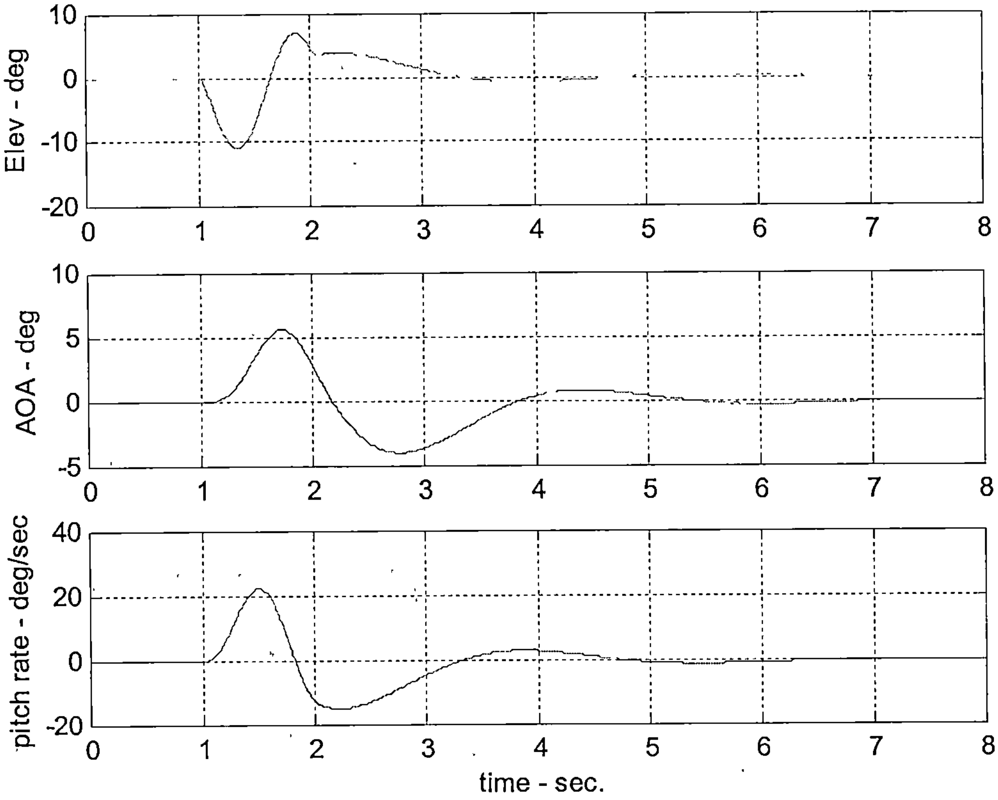


Figure A-4 Time History Response with Mα = 0 and Mθ dot = -10
(Aircraft Potentiometer Settings)

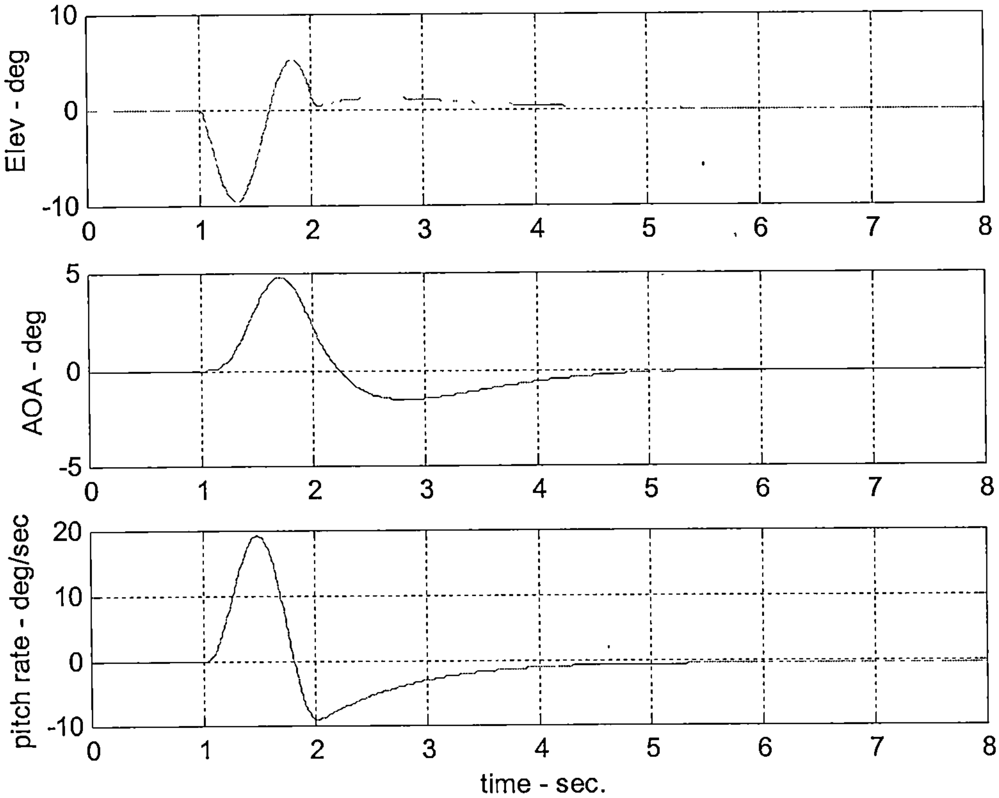


Figure A-5 Time History Response with Mα = -5 and Mθ dot = -5
(Aircraft Potentiometer Settings)

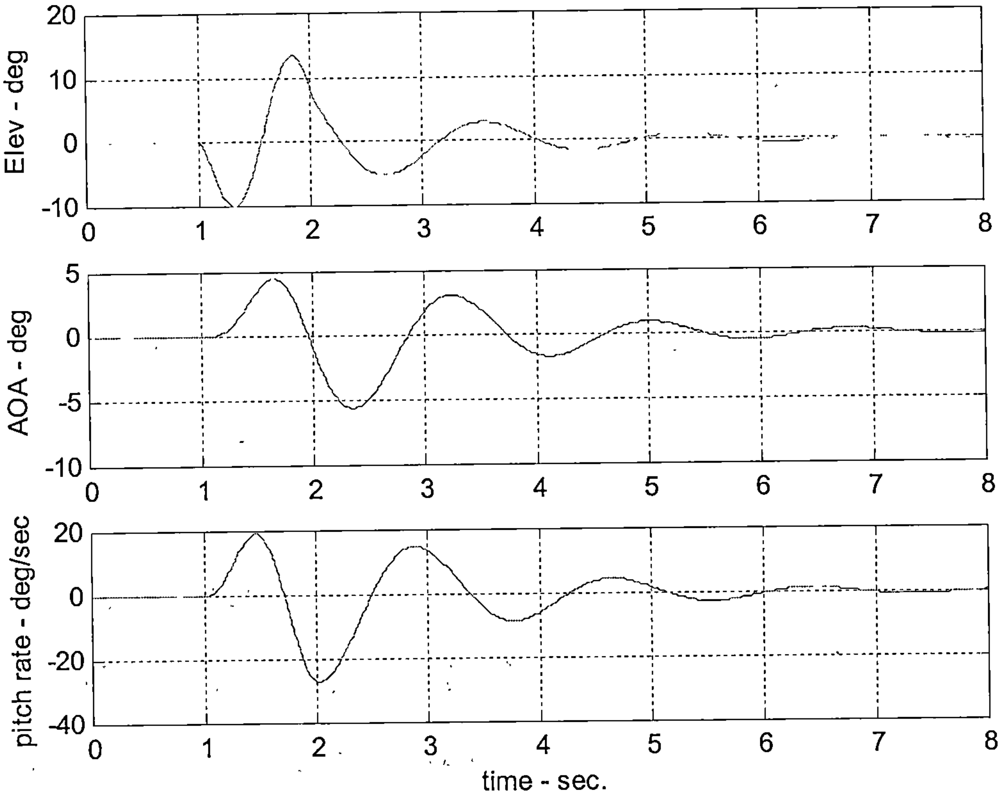
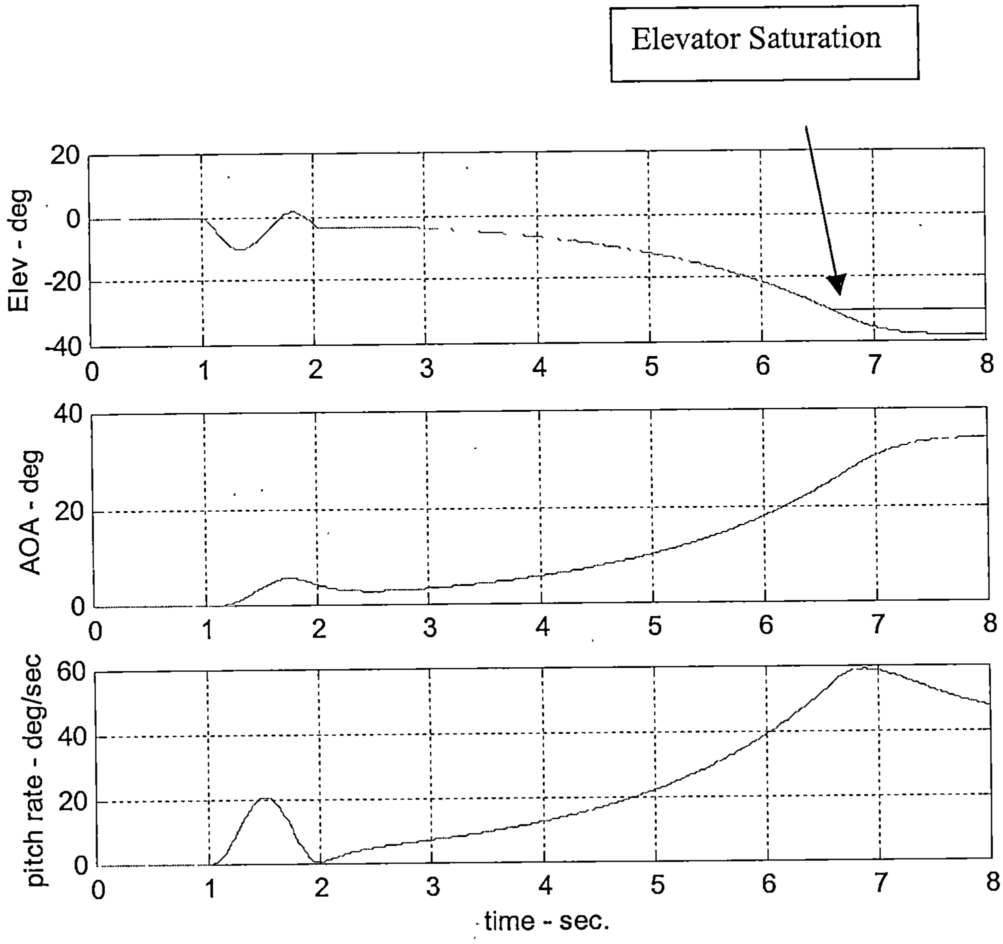


Figure A-6 Time History Response with Mα = 10 and Mθ dot = -10
(Aircraft Potentiometer Settings)



Elevator Saturation

Figure A-7 Time History Response with Mα = -10 and Mθ dot = -5
(Aircraft Potentiometer Settings)

VITA

Kevin Greene was born in Queens, New York on October 26, 1961. He attended Catholic schools in Northport and Smithtown, Long Island, New York. He graduated from Saint Anthony's High School in May 1979. He earned a Bachelor of Science degree in Mechanical Engineering from Loyola Marymount University in Los Angeles, California in May of 1985. Following one year of employment by Northrop Aircraft Corporation in Hawthorn, California he entered the United States Navy and began flight training in February 1986. He has completed three Western Pacific and Arabian Gulf deployments flying A-6E Intruders and F/A-18 Hornets in support of Operations Desert Storm and Southern Watch. He graduated from the United States Naval Test Pilot School in 1993. He attended the University of Tennessee Space Institute and earned a Master of Science degree in Aviation Systems in August 2001. He is currently a flight instructor at the United States Naval Test Pilot School in Patuxent River, Maryland where he resides with his wife Elizabeth and son Benjamin