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ADVANCED CONTROL TECHNOLOGY AND
AIRWORTHINESS FLYING QUALITIES REQUIREMENTS

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INTRODUCTION

Advanced control technology poses a difficult task for the authorities faced with specifying airworthiness flying qualities requirements--and for the manufacturers who must comply with and anticipate these requirements. Requirements for advanced civil transports employing this technology must be carefully framed, such that public safety is ensured and technological advances in civil aviation are not discouraged. It is no secret that excessively complex and overstringent requirements discourage innovation, while clear and flexible requirements (for example, those that give credit for reliability in systems) encourage development and advances in technology.

The specification of flying qualities requirements involves consideration of the complete pilot-airframe-systems loop, the task, and the environment. Figure 1 suggests the complexity of this job; many of these advanced civil configurations tend to be large and flexible and dependent on complex control systems for enhancement of stability, control effectiveness, and control feel characteristics over enlarged flight envelopes, and for numerous automatic control modes. The result is a greatly increased emphasis on failure effects that degrade flying qualities. Key questions being faced include: How good must the flying qualities be in the failure condition? Which failures and combinations must be demonstrated? And how must they be demonstrated?

French and British authorities, in preparing for Concorde SST certification, authored a new form of flying qualities requirements that rely heavily on probabilistic analyses (TSS Part 3, ref. 1). In TSS 3, the required standard of flying qualities varies according to the likelihood of the flight condition occurring, and thus considers the wide range of flight phases, system failure effects, and atmospheric environment. Although it is being applied to Concorde by European authorities and some features of the method have been utilized in U.S. military specifications, the TSS 3 approach has met with mixed reactions among the U.S. civil aviation community because of concerns over the practical implementation of the method.

Since 1969, an ongoing NASA/FAA research program has used the Ames Flight Simulator for Advanced Aircraft (FSAA) in the development of certification criteria for supersonic cruise aircraft. NASA, FAA, industry representatives, and British and French airworthiness authorities are participating in this program. The question of proper accountability of failures has arisen on numerous occasions. These experiences have brought to a focus the

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need to review the present treatment of failure cases in the requirements and to examine some of the questions associated with implementation of the TSS 3 type of concept.

This paper, which reports on the findings to date from a continuing study of the subject, comprises the following: a review of the treatment of failure cases in various flying qualities requirements; a description of methods used and relevant lessons learned from recent Autoland certification programs as an example of applied probability procedures; a discussion of uncertainties about the TSS approach; and finally (because these procedures indicate an increasing reliance on simulation methods), a description of three recent experiences with marginal configurations that demonstrate the potential significance of elements sometimes omitted from simulation tests.

CURRENT TREATMENT OF FAILURE CASES IN VARIOUS FLYING QUALITIES REQUIREMENTS

Aircraft flying qualities requirements deal primarily with controllability, stability, and handling characteristics. Civil and military requirements were reviewed for the manner in which failure cases were covered, the amount of flying qualities degradation allowed, the conditions under which failures were to be assessed (for example, introduction of atmospheric effects), and methods for demonstrating compliance. (As used throughout this paper, the term "failure" includes malfunctioning as well as failure to function; degraded system performance below specified tolerances represents a failure to function properly.) Documents reviewed included Federal Aviation Regulations applicable to transport category airplanes (FAR 25, ref. 2), Tentative Airworthiness Standards for Supersonic Transports (TASST, ref. 3), industry recommendations (AIA committee report, ref. 4 and SAE Aerospace Recommended Practice 842B, ref. 5), Franco-British Concorde TSS Standards (TSS, ref. 1), and U.S. military specification (MIL-F-8785B, as described in ref. 6).

Federal Aviation Regulations - FAR 25 and TASST

For orientation, an outline of FAR 25 is shown in figure 2. Flying qualities requirements are contained in "Subpart B - Flight," which is further broken down into topic headings. Although flying qualities are closely interrelated with many performance requirements (many of which involve engine failure conditions), this discussion is primarily concerned with those items indicated by an arrow, and the related paragraphs in "Subpart D - Design and Construction" and "Subpart F - Equipment."

Failure Cases in FAR 25- Philosophy towards treatment of failures has undergone significant change in recent years. For years, about the only multiple failure cases were two-engine-inoperative control requirements and a requirement that the airplane be controllable with all engines inoperative. Only single control system failures were considered. In April 1970,

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Amendment 25-23 incorporated a number of changes into FAR 25 dealing with system failures and introducing the consideration of multiple failures. Stability augmentation systems and automatic systems were dealt with specifically. Some of the new requirements came from the tentative SST requirements and were recognized to be generally applicable and needed because of the increasing dependence on more complex systems of the new generation of subsonic transports. The example shown in figure 3 illustrates the present treatment of control system failures. As indicated, FAR 25.671 requires the capability of continued safe flight and landing after any single control system failure or after any combination of failures not shown to be extremely improbable.

Current FAA interpretation of the terms "probable," "improbable," and "extremely improbable" is shown in the sketch below.

FREQUENCY OF OCCURRENCE PER FLIGHT HOUR
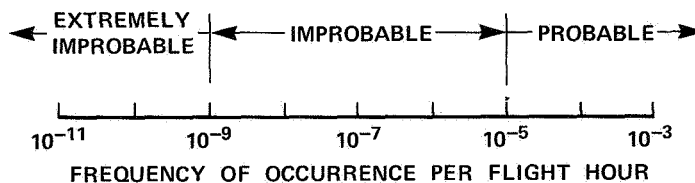
Failure cases in the other aircraft systems must also be analyzed under "Subpart F - Equipment." In addition to requiring the capability of continued safe flight and landing after any failure condition not extremely improbable, FAR 25.1309 requires that the systems and associated components be designed so that

> "the occurrence of any other failure conditions which
> would result in injury to the occupants, or reduce the
> capability of the airplane or the ability of the crew
> to cope with adverse operating conditions is improbable."

In addition, nearly all requirement sets contain catchall paragraphs which are in general terms, but provide evaluation pilots basis for rejection of unsatisfactory situations not covered specifically. An example of this is FAR 25.143 which states

> "(a) The airplane must be safely controllable and
> maneuverable during - (1) takeoff; (2) climb; (3) level
> flight; (4) descent; and (5) landing. (b) It must be
> possible to make a smooth transition from one flight
> condition to any other without exceptional piloting
> skill, alertness, or strength and without danger of
> exceeding the limit-load factor under any probable
> operating conditions (including the sudden failure of
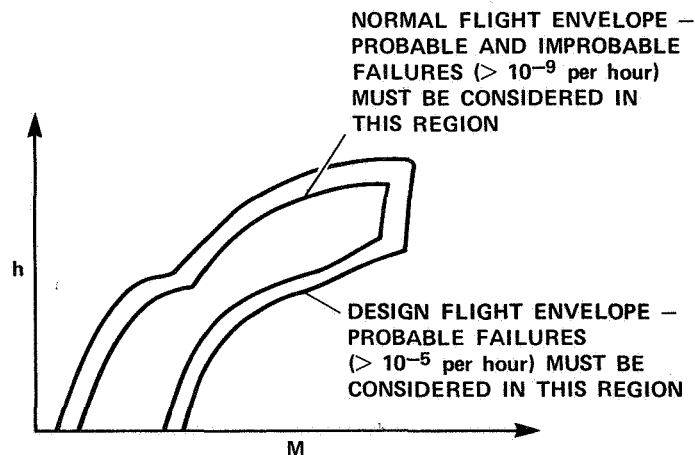> any engine)."

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The phrase "under any probable operating conditions" is certainly subject to interpretation as including failure cases.

Failure Cases in TASST- In TASST (ref. 3), the FAA presented tentative airworthiness standards for study, trial application, and comment during the detail design and prototype phase of supersonic transport development. A number of changes were proposed in this document other than those already discussed, including requirements to cover automatic and manual trim system malfunctions, additional two-engine-inoperative controllability and maneuverability requirements, and extended "flutter, deformation and fail-safe criteria" to consider combinations of failures not shown to be extremely improbable. In the "Stability" section, it was recognized that areas of flight (for example, supersonic cruise) may exist with operational requirements such that the use of reliable automatic flight control systems could be accepted in lieu of the demonstration of classic static stability, provided the loss of automatic flight control would not result in unsafe handling characteristics.

The "Structures" section of TASST is closely related to flying qualities. Paragraph 25.301(e) states that

"For supersonic aircraft, loads must be determined
within the design flight envelope considering the ef-
fects of stability augmentation and automatic flight con-
trol systems, including probable failures and changes in
systems characteristics which can be expected in service.
All malfunctions and failures of these systems must be
considered under FAR 25.671 and FAR 25.1309 within the
normal flight envelope except those shown to be extremely
improbable."

Careful consideration of the complete pilot-aircraft-systems loop and the environment appear very important in satisfying this requirement. Also note that this introduces the assessment of failure effects outside the normal flight envelope (see sketch). The application of flight simulation techniques would appear to be essential for this task.

NORMAL FLIGHT ENVELOPE —
PROBABLE AND IMPROBABLE
FAILURES ($> 10^{-9}$ per hour)
MUST BE CONSIDERED IN
THIS REGION

DESIGN FLIGHT ENVELOPE —
PROBABLE FAILURES
($> 10^{-5}$ per hour) MUST BE
CONSIDERED IN THIS REGION

Turbulence and Flexibility Effects- In the introductory discussions to
both the "Controllability and Maneuverability" and the "Stability" sections
of TASST, it was recognized that the effects of turbulence on the pilot en-
vironment should be evaluated. In addition, it was pointed out that the
structural flexibility and stability characteristics of supersonic trans-
ports will undoubtedly aggravate the pilot environment problem. Flight ex-
perience with the XB-70 and F-12 series aircraft lends considerable weight to
these statements--as have some piloted simulator experiences with large
flexible configurations to be described later. It is very likely that many
of the advanced transport designs will exhibit greater flexibility than cur-
rent subsonic transports and, as will be shown, the effects on handling
characteristics in failure-mode operations can be very significant.

Industry Recommendations

AIA Study Group Proposals- In 1970, a special project group represent-
ing the Aircraft Industries Association (AIA) published the results (ref. 4)
of a study to guide the modernization of the Federal Air Regulations. In
reference 4, proposed "modernized" requirements are presented as a set of
safety standards generally applicable to all transport aircraft types.
These standards describe basic characteristics of the aircraft system that
must be achieved to ensure safe operation. In addition, means for showing
partial or complete compliance with the individual standards are included.
Two fundamental requirements formed the foundation for all the standards
proposed:

> "1. The aircraft must respond to commands of the con-
> trolling intelligence in a consistent manner and
> with the precision appropriate to the task.
> 2. Probable subsystem failures must not result in
> conditions likely to be catastrophic due to human
> inability to cope with them."

These modernized standards specify three modes of operation (manual,
command, automatic), conveying clearly that the controlling intelligence is
not always considered to be the human pilot. They state further that if man
is the controlling intelligence, he should be considered a subsystem of the
total aircraft system. In this way, the standard dealing with operation
following failures accounts for failures of human origin in addition to other
subsystem failures. This standard states,

> "Operation following probable failure of any subsystem
> that affects flight safety shall not unduly restrict
> flight operation after corrective action is taken.
> The degree of restriction permitted shall be inversely
> related to the probability of failure."

It then presents requirements related to the ability to take corrective
action, either by the crew or by automatic means. The acceptable means of
compliance deal more specifically with the failures, and include paragraphs

that parallel FAR 25.671(c) and 25.672(c) (fig. 3).

SAE Design Criteria- Recommended design criteria for handling qualities of civil transport aircraft (SAE ARP 842B, ref. 5) differ in character from the safety requirements described previously. These criteria represent advisory design information as defined by the SAE and were originally modeled after the format of the military specifications of the early sixties. These criteria appear to have avoided the use of probability terminology and include consideration of single and dual control system failures.

> "... Following the [single] most critical failure in
> the [power or boost] flight control system, the planned
> flight may be completed without a significant degrada-
> tion of flying qualities. ... Following the second
> most critical flight control system failure, it shall
> be possible to complete the flight, after takeoff, to
> a suitable airport from the V_2 transition to enroute
> climb to cruise to a safe landing with the most critical
> engine inoperative at the most critical phase of flight."

They further state that failure of any artificial stability system or powered-actuated trim system should not result in an unsafe flight condition. Some of the quantitative criteria (for example, lateral control) are redefined for the failure cases to accept degraded capability.

The significance of aeroelastic effects is recognized in paragraph 2.1.7 of ARP 842B which states

> "Since it can be expected that aeroelastic effects
> will play an important role in supersonic transport
> design, it should be clear that all requirements for
> flying qualities are applicable to the elastic air-
> frame."

Franco-British TSS 3

General Description and Objectives- A new approach to flying qualities requirements was developed by the French and British airworthiness authorities in preparation for the certification of supersonic transports, Concorde in particular. First published in 1969 as TSS 5 and since changed to TSS 3 (ref. 1), these requirements are currently being applied to Concorde. Their most significant feature is the extensive use of probabilities and systems analysis methods in defining the minimum acceptable flying qualities for a given flight situation, considering the flight phase, aircraft configuration, failure state, and environment. The severity of the requirement is directly related to the probability of occurrence of the flight situation. This concept has since been utilized in the British Provisional Airworthiness Requirements for Civil Powered-Lift Aircraft (ref. 7) and in modified form in the current U.S. military specification MIL-F-8785B.

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This approach provides the following significant advantages:

1. a more systematic and complete coverage of all likely flight conditions, whereas past methods have tended to be limited to anticipated critical regions

2. consideration of atmospheric environment effects in a more complete manner

3. a running assessment of the relative risk level throughout the design and development phases for a new aircraft, which provides insight for design modifications

4. a method for defining those cases that can be eliminated from demonstration because of the low probability of occurrence.

The TSS standards are intended to provide the same safety levels for supersonic transports as for subsonic airplanes introduced into service at the same time. These objectives include the following: "For all airworthiness causes the total probability of Catastrophic Effects should be Extremely Remote [$<10^{-7}$ per hour of flight], and the total probability of Hazardous Effects should be remote [$<10^{-5}$] or Extremely Remote." (See table 1 for definition of terms.) Akin to FAR 25, these objectives state that "No single Failure or combination of failures not considered Extremely Improbable shall result in a Catastrophic Effect." They further require that "Remote Failures shall not result in Hazardous Effects" and that "Recurrent Failures shall result only in Minor Effects."

The TSS 3 requirements are categorized into three groups, corresponding to the accident causes attributed to flying qualities: (1) handling – a workload consideration, (2) maneuverability, and (3) involuntary exceedance of airplane limits caused by disturbances due to failures or atmospheric conditions. Various specific criteria are included which, depending on the probability of occurrence of a given "state" (categorized as frequent, occasional, exceptional, and non-exceptional), must be satisfied. There are also a number of requirements, based on judgment and experience, which require demonstration regardless of the estimated probability of occurrence.

Theoretical Application- Figures 4 and 5 illustrate theoretical application of the TSS 3 concept. (Reference 9 points out that practical application requires many simplifying assumptions, although little information on these assumptions has been found in the literature.) First, the various possible flight "tasks" and their associated probabilities of occurrence per flight are defined. As shown in figure 4, a task is defined by four primary elements plus the secondary workload: (1) the flight subphase, for example, localizer capture; (2) state of the atmosphere; (3) state of the aircraft, which includes possible failures; and (4) flight technique. Elements 1 and 4 represent lists prepared by the applicant while elements 2 and 3 represent four-dimensional matrices. The probability P_n of a given task per flight is then calculated from estimates of the probabilities of (1) performing a given subphase per flight, (2) encountering a given atmospheric state during the subphase, (3) having a given aircraft state during the subphase, and (4)

using a given flight technique.

Figure 5 represents the author's interpretation of a method described in TSS 3 for showing compliance with the general handling requirement. Pilot evaluation of a given task identifies a class of difficulty C, which is then converted to the probability P_u that a pilot will not be able to accomplish the workload. The probability of a handling incident during a given subphase per flight is determined by summation over the classes of difficulty of the product of P_u and P_n for that subphase. The total probability of a handling incident per flight is computed by summation over all the subphases that make up a flight. For partial compliance, this total probability must then be less than a safety index, which has been defined as an acceptable risk level.

TSS 3 states that the demanded safety level is to be demonstrated by a limited number of flight tests proposed by the applicant. (Justification for tests omitted is also required.) The majority of these are to be conducted in calm air or low turbulence. Compliance with requirements for flight in turbulence are to be demonstrated by a limited number of flight tests, supported by theoretical studies and simulator tests.

From this brief description, it is clear that numerous questions can be raised regarding the practical application of this approach and that considerable simplifications are needed. In the next section, simplifications are described which have been made in the application of a similar procedure in the U.S. military specification. While all the uncertainties are not laid to rest, discussions in the following sections address many of the expressed concerns, and point the way for continuing work.

U.S. Military Specification (MIL-F-8785B)

Similarity with TSS Concept- MIL-F-8785B (presented with background information in ref. 6) serves dual roles as design requirements and as evaluation criteria. At a 1971 AGARD meeting, a paper (ref. 9) was presented comparing the TSS 3 concept and MIL-F-8785B. It concluded that they are basically the same in intents and goals, although one distinction was made: in addition to assuring that there will be no limitations on flight safety due to deficient flying qualities, MIL-F-8785B demands that mission effectiveness will not be compromised. Similarity of the two criteria is not coincidental; discussion following presentation of the AGARD paper acknowledged the significant contributions made by M. Wanner, representing the Service Technique Aeronautique of France and a strong advocate of the TSS 3 concept, during the preparation of MIL-F-8785B.

A number of simplifying assumptions have been made to permit practical application of MIL-F-8785B, including:

    (1)   No probability assessment is made for aircraft mass and mass distribution. A probability of 1 is used for all points in the envelope. Thus, probability of state of the aircraft is dependent

on failure probabilities only.

(2) No attempt is made to estimate the probability of the state of the atmosphere. The required flying qualities are associated with the state of the airplane. (A number of specific flying qualities requirements must be met with specified turbulence conditions, however.)

(3) The probability of being in a given area of the flight envelope has been assumed equal to 1, due to inability to specify this value.

"Levels" of Flying Qualities- Three levels of flying qualities are defined in MIL-F-8785B, as shown in table 2. Cooper-Harper pilot ratings generally associated with the three levels are also shown. Exceptions to these relationships exist, however. For example, level 3 flying qualities for a landing task would correspond to a pilot rating no poorer than 6.5 (requires adequate performance; see fig. 6).

The minimum required flying qualities are defined separately for airplane normal states and airplane failure states. For airplane normal states, level 1 flying qualities are required within the operational flight envelope, and level 2 within the service flight envelope (fig. 7). For airplane failure states, the probability of encountering level 2 flying qualities must be less than 10^{-2} per flight within the operational flight envelope and the probability of encountering level 3 flying qualities must be less than 10^{-4} per flight in the operational flight envelope and less than 10^{-2} in the service flight envelope.

Theoretical Compliance Procedure- Figure 8 illustrates the procedure outlined in MIL-F-8785B for determining theoretical compliance with the failure state requirements. Airplane failure states that have a significant effect on flying qualities are first identified and the corresponding probabilities of encounter per flight are computed, based on the longest flight duration to be encountered during operational missions. The degree of flying qualities degradation associated with each airplane failure state is determined in terms of levels as defined in the specific requirements. The most critical airplane failure states are then determined (assuming the failures are present at whichever point in the flight envelope being considered is most critical in a flying qualities sense), and the total probability of encountering level 2 flying qualities in the operational flight envelope due to equipment failures is computed. Likewise, the probability of encountering level 3 flying qualities in the operational flight envelope is computed. The computed values are then compared with the requirements.

Concept Recommended for Civil Airworthiness Application- Many of the military specifications were originally recommended by Cornell Aeronautical Laboratory, Inc. (now the Calspan Corporation) under contract to the Air Force Flight Dynamics Laboratory. In 1973, Calspan completed a review of the "Flight" subpart of the Yellowbook (Tentative Airworthiness Standards for Powered Lift Transport Category Aircraft) for the FAA. The final report (ref. 11) proposed that the Yellowbook be revised to a new format based on

many of the ideas used in the military specification and in the British Provisional Airworthiness Requirements for Civil Powered-Lift Aircraft (ref. 7).

General Observations

Based on review of the various requirements, several observations can be made. All elements of the aviation community have acknowledged the need for increased attention to failure effects and have made the transition from single failure to multiple failure philosophy. The prediction of system failure probabilities and their effects has become a significant factor in flight certification of aircraft employing stability augmentation, automatic, and powered control systems. For aircraft employing active controls technology to full advantage, the system failures and effects analyses are even more important. This results in a growing need for close integration of the systems and flying qualities disciplines. Present U.S. certification practice appears to treat the systems and flying qualities evaluations somewhat separately, with the effects of failures often defined by analytic means in the systems studies. While this procedure may have served adequately in the past, the foregoing observations suggest that they will, at the very least, require reexamination for future applications.

General recognition is apparent that atmospheric effects (e.g., turbulence) can influence an airplane's handling characteristics significantly and should be considered, although the method of including this is loosely defined. The high cost of flight testing, the large number of cases to be evaluated, the desire to assess in specified atmospheric conditions, and at marginally safe conditions can be expected to increase the reliance on piloted flight simulators for much of this work.

FAILURE CASE ANALYSES IN AUTOLAND CERTIFICATION

Systems safety analysis procedures used in recent Autoland certification programs represent current examples of the application of probability procedures to the certification of total airframe-systems combinations, including consideration of atmospheric effects. Because of the close relationship with the evaluation concepts previously discussed, the procedures used in the Category IIIA automatic landing programs for the McDonnell Douglas DC-10 and the Lockheed L-1011 (refs. 12-14) were reviewed and relevant findings are noted.

Procedures

The procedure described in ref. 13 appears to be generally representative of the programs for both airplanes. The certification process, which represents the final cycle of studies made in the design and development phases, used progressive simulation and testing, as indicated in figure 9,

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in order to minimize the amount of flight testing required. The first step was the use of high-speed repetitive-operation simulation methods to accomplish the millions of landings required for establishment of the low probability results in a reasonable time period. In the second phase, several thousand simulated landings were made using the actual flight hardware computers. The hydraulic control systems hardware ("iron bird") was then added to the simulation in order to pick up effects of any hardware imperfections. Finally, a minimal number of flight test demonstrations (on the order of a hundred) were made to verify the high end of the performance probability curves. Some of the simulated failure effects were verified by inserting failures into the autopilot during actual approaches. Each of these phases was used to verify the results of the preceding phase.

Environmental conditions for these simulations included turbulence and wind shear, with levels specified in FAA Advisory Circular 20-57A. In the DC-10 program, key performance characteristics of the sensors, analog computer, and mechanical controls were varied between simulation runs within the normally expected ranges using a Monte Carlo sampling routine (ref. 12).

Not evident in the procedure just described is the reliability and safety analysis, a considerable task consisting of an integrated combination of several kinds of analyses and computer simulation techniques. This extensive process is described in detail in ref. 12. Suffice to say that it involved identifying all possible single and multiple faults in the system and their effects, eliminating all single faults that were hazardous, and establishing that no multiple fault in the system having a probability of occurrence greater than 10^{-9} per landing was hazardous.

Relevant Findings

Integrated Programs Necessary- Ordinary numerical reliability analyses were recognized at the outset to be inadequate for fully assessing Autoland system reliability and safety. Because of the basic system complexity, the airborne-ground systems interfaces, and the numerous pilot-aircraft interfaces, integrated programs of laboratory testing, computer analyses, and simulation were found necessary.

Design Guidance Provided- Certification considerations began with the design phase. As the system design evolved, the reliability and safety analyses provided continued assessment of compliance and identified areas requiring design modification. Consideration of failure effects significantly influenced the design of many other aircraft systems, for example, electrical supply.

Multiple Failure Analysis Found Manageable- The multiple failure analysis appeared at first to be an almost impossible task, requiring the combination of all possible failures in all possible sequences and analyzing the result. This task became manageable by first defining what was hazardous and then working backward to find all combinations of faults that could produce the event.

Definition of Atmospheric Disturbances Needed- Atmospheric disturbance effects can become primary design factors. In some flight tests, for example, a condition not anticipated to be critical—a quartering tailwind—was found to be serious. Other flight test experience has indicated that present specified wind shear values may be inadequate. The potential significance of such disturbances makes accurate definition of the atmosphere essential.

Broad-based Engineering Judgment Necessary- A fundamental merit and a hazard of the probability approach are revealed in this quotation from ref. 13:

"The probability approach to analysis seems, from experience, to have great merit in that the necessity to calculate very low probability numbers forces on the analyst a discipline that makes him study the system in greater detail. The danger in the approach is that the analyst may place too much emphasis on the techniques he has developed, and lose sight of the many assumptions implied in these techniques. In short, there is a danger of placing implicit belief on the accuracy of a calculated number. This danger can be avoided by the use of highly skilled engineers who are capable of understanding system and aircraft operation as well as the detailed working of the circuits to be analyzed."

Concluding Observations

Although the Autoland systems safety analysis procedures described herein appeared extremely cumbersome at the outset, in actual practice they became manageable—while providing significant payoffs in terms of design guidance and improved safety. It should also be noted, however, that while the effort involved in an Autoland certification program is undoubtedly large, the effort appears small when compared to the total effort required in rigorously applying the procedures of TSS 3 to an advanced transport aircraft over its entire flight envelope. The number of cases to be considered for Autoland is limited: the Autoland process is concerned primarily with the final few minutes of flight, and the controlling intelligence can be mathematically modeled more readily than can the human pilot.

UNCERTAINTIES REGARDING THE TSS APPROACH

While the potential advantages of the TSS 3 type of approach have been shown to be very significant (partially verified by the Autoland experience), numerous questions and uncertainties have been raised regarding its practical implementation. These can be grouped under the following headings: (1) reliance on probability methods and reliability prediction, (2) size of the evaluation matrix, (3) use of the pilot rating scale, (4) definition of the

atmospheric environment, and (5) use of simulation methods. In the following discussion, each of these has been addressed in order to provide some insight into these topics, to dispel some fears, and to indicate where further work is needed.

Reliance on Probability Methods and Reliability Prediction- Concern has been expressed with regard to the ability to define some of the required probabilities, such as the flight subphase, pilot technique, and atmospheric environment. Conservative engineering estimates of the first two should be possible with careful study. Definition of the probability of a given atmospheric environment appropriate to a given subphase requires more research (to be discussed later).

In reliability and safety analyses, there is always the danger of "blind faith" in the calculated number. As pointed out in TSS 3 and in refs. 8 and 15, these methods are used as an aid, not as the sole criterion; it is essential that they be combined with good engineering judgment and experience. The practical limitations of a given method must be taken into account and experience with other aircraft in service must be factored into the total assessment. For example, the present safety assessment of redundant systems goes far beyond the failure analysis by considering possible effects of errors by the crew and maintenance personnel, as well as the effects of events outside the aircraft which could affect more than one channel at a time. Redundant systems are checked for common faults to ensure, for example, that both electrical systems are not routed through a common wiring bundle or under galleys and toilets, or that lines from both hydraulic systems are not supported by a common bracket.

A common question asks how probability values of the order of 10^{-7} per flight hour can be estimated with confidence. Reference 16 points out that this is exactly the reason for the philosophy that no single failure can create a catastrophic flight condition. The period of proof-testing required to prove this failure rate would be impractical. However, the individual failure rates of interest in multiple-failure analyses, of the order of 10^{-3}, can usually be estimated with reasonable confidence. It is also intended that critical system failure records be kept on new aircraft entering service over the initial period of operation to verify the reliability estimates.

Evaluation Matrix- The matrix of conditions requiring evaluation under the procedure described in TSS appears awesome. However, considerable simplification appears possible and merits continued study. Also, in practice, the number of failures to be investigated normally turns out to be a manageable number (ref. 8). The fault analysis usually shows a limited number of ways a system can malfunction following a variety of single and multiple faults. Many can be discarded because the result is not serious or the probability of occurrence is clearly satisfactory.

Use of the Pilot Rating Scale- Concern has been expressed over making a pilot rating scale a part of legal regulation, to be used in determining the minimum safety level of an airplane. Questions faced whenever the pilot

rating scale is used become especially significant when it is the minimum safe boundary being defined. Typical questions are: What pilots are to do the rating, how many, how to extrapolate from the flight test situation to the operational one, etc. These questions and others are worthy of careful study and resolution. Considerable worthwhile discussion on many of these issues is contained in ref. 10. Many of the questions raised, however, are not unique to the TSS procedure, but are equally applicable to the present evaluation process where the subjective opinions of the airworthiness pilots are key factors in defining the acceptability of a given airplane.

Definition of the Atmospheric Environment- Definition of the significant elements of the atmospheric environment and associated probabilities is an area receiving considerable attention in the U.S. and in Europe, and justifiably so. The influences of atmospheric disturbances become especially troublesome as flying qualities are degraded and the workload approaches the saturation point.

Many of the turbulence models currently being used in simulation studies have been tailored to match power spectra measurements. Other concepts are being studied. For example, recent work in the U.K., stimulated by Autoland experience, is investigating the use of discrete gust patterns (ref. 17), and work is continuing in this country under NASA sponsorship at the University of Washington and elsewhere to develop "non-Gaussian" models. Also, an investigation devoted to verification or improvement of present methods for modeling aircraft response to turbulence appears worthwhile.

Simulation Methods- The preceding discussions leave little doubt that the use of simulation methods will play an increasingly key role in the design, development, and certification of advanced transport aircraft. The application of simulators to the certification demonstration process must not be approached naively, but with appreciation for the limitations of these methods and for the degree of fidelity (math model, pilot station layout, visual display, motion, etc.) required for specific tasks. Representation of the appropriate workload level, for example, is an important factor in evaluating minimum safe handling qualities.

For a safety assessment as defined in TSS 3, development of this simulation capability early in the design phase, with progressive updating of the airplane model and the pilot/pilot station interface, appears essential. Acquisition of data for improvement of simulation fidelity must be factored into layout of early flight tests. Accurate representation of failure annunciators and warning devices must be incorporated as they are defined, as they are important elements in the evaluation of a proposed system's acceptability.

RELATED SIMULATION EXPERIENCES

The preceding discussions lead to the conclusion that the final acceptance of many aircraft failure states may be based largely on simulator evaluations (and engineering judgment). Three recent simulation experiences have empha-

sized factors which, with more stable configurations, might have been considered of secondary importance, but became critical components requiring accurate representation in the simulation of marginal configurations. The first emphasizes the significance of turbulence effects, the second indicates the importance of motion cues in critical tasks, and the third demonstrates control limitations that can be imposed by structural mode effects.

Turbulence Effects

In 1972, parallel studies were conducted on two simulators to investigate the SAS-failed approach and landing of delta-wing transports (refs. 18 and 19). Three research test pilots performed ground-based evaluations on the NASA/Ames six-degree-of-freedom Flight Simulator for Advanced Aircraft (FSAA), followed by flight evaluations on the USAF/Calspan Total In-Flight Simulator (TIFS), both shown in figure 10. In a matrix of twenty test configurations, seventeen were unstable longitudinally. The primary task was an ILS approach under IFR conditions, breakout to VFR conditions at 91-m (300-ft) altitude, visual approach and landing. A series of approaches with added tasks included crosswind approach, glide-slope error correction, localizer error correction, and moderate (0.91 m/sec or 3.0 ft/sec rms) turbulence. Of these, the turbulence task proved to be the most critical, although the turbulence intensity used was not uncommon (probability of encountering turbulence of 0.91 m/sec or greater is on the order of 0.1 to 0.3).

Pilot rating data from both investigations is shown versus a divergence parameter, time to double amplitude of angle of attack T_{2_α}, in figure 11. Pilot ratings from the FSAA study are shown by the shaded band, with the scatter primarily attributable to interpilot variation. Values of T_{2_α} of 6 sec and greater were found to be acceptable for the emergency case. As T_{2_α} decreased (divergence rate increased) below this level, pilot ratings show that handling characteristics deteriorated rapidly.

Initial examination of the TIFS pilot rating data showed considerable scatter due to the varying turbulence intensities encountered during the flights. In analyzing the data, Calspan used measurements of the actual turbulence environment to compensate the pilot rating data for each configuration. These results are shown in figure 11 for gust intensities of 0.46 m/sec (1.5 ft/sec) and 0.91 m/sec (3.0 ft/sec). Although the difference between the two levels of turbulence intensity appears small, the differences in subjective evaluation were significant.

Motion Effects

An investigation was conducted at Ames recently to identify the role of cockpit vertical acceleration cues in the landing task (ref. 20). A piloted simulator having very large amplitude vertical motion (24 meters total travel) was utilized in a test series in which the fidelity ("washout") of the vertical acceleration reproduction was deliberately varied over a wide range, representing simulators with varying amounts of available vertical travel. The external

visual scene was provided by a black and white uncollimated TV monitor. The airplane simulation represented a large sweptwing business jet transport. Three levels of static longitudinal stability were simulated, corresponding to 15 percent static margin, neutral, and 5 percent unstable static margin.

The results indicated that vertical motion cues were utilized in the landing task and were particularly important in the simulation of aircraft with marginal longitudinal handling qualities. Figure 12 shows a measure of landing performance, altitude rate at touchdown, plotted against the motion washout filter natural frequency ω_m. The corresponding vertical travel requirements are shown along the top scale. The data indicate that the effect of motion was relatively inconsequential for landing of the stable configuration with good flying qualities, although an oscillatory tendency was observed without motion. However, with the configurations having marginal longitudinal handling qualities, significant degradation was apparent in achievable performance as the motion was constrained (and thereby distorted). At values of ω_m of 1.0 and above, divergent flight path oscillations were common and touchdowns were essentially uncontrolled in many landings.

Structural Mode Effects

In another simulation program in which a very large flexible aircraft was represented complete with structural modes, a very significant degradation in flying qualities resulted from the pilot station motions caused by fuselage bending. Evaluations of the completely unaugmented airplane without motion and body bending resulted in pilot ratings of 5.0 - 5.5 (fig. 6). With motion and body bending, the structural modes were easily excited and the pilots were unable to use the sharp pulse inputs (in pitch) normally used for control of an unstable airplane. This prevented the use of effective control techniques and yielded a pilot rating of 9.

Recommendations

These examples have illustrated the fact that careful attention must be devoted to defining the simulation requirements for a given task. A high degree of sophistication is often required in evaluations of marginal cases if confidence is to be placed in the results. Practical design and evaluation procedures will very likely, by necessity, rely on simplified simulations (very limited motion, no structural mode representation, etc.) for the bulk of the work. It is emphasized that verification testing of critical cases should be planned in simulation facilities which provide a high fidelity of the total task presentation.

CONCLUDING REMARKS

Advanced transport aircraft designs have become increasingly dependent on complex flight control systems in order to improve their flight characteristics.

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In this report, various civil and military flying qualities requirements have been reviewed with regard to their treatment of failure cases and consideration of atmospheric environment effects. There appears to be common acceptance of the philosophy that no single failure should create an unsafe flight condition, nor should any combination of failures that are not extremely improbable. Although consideration of atmospheric environment effects in handling assessments is required, the method for doing this is often ill-defined.

There is an increasing need for an orderly procedure for combining the systems analyses (reliability and fault analyses) with the flying qualities evaluation process, taking the likely atmospheric states into account. Such a procedure can aid in the achievement of design economies and a level of safety equivalent to that of current transports; this is a challenging task since the contribution of system failures to catastrophic effects is at present a very small proportion of the total. Review of the probability-based procedures described in the Anglo-French TSS 3 shows that additional development effort is needed to simplify implementation. Simplified procedures described in the U.S. military specification and lessons learned from recent Autoland programs appear useful for continuing studies devoted to this purpose.

In order to minimize flight testing and to enable evaluation in specified atmospheric conditions and hazardous failure cases, simulation techniques will be used extensively in such procedures. Some recent simulation experiences emphasize that turbulence effects significantly influence the pilot evaluations of marginal configurations, and that evaluation of such conditions sometimes requires more accurate representations of the pilot/aircraft interface (pilot station motions, etc.) than are provided in many current engineering simulations.

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Table 1. Definition of probability terms (ref. 8)

Failures	Effects	
	Type	Definition
Recurrent failures	Minor effects	Can readily be counteracted by crew and may involve: (a) small increase in work load. (b) moderate degradation in performance or handling. (c) slight modifications to the permissible flight envelope.
Remote failures	Major effects	May produce: (a) significant increase in crew work load. (b) significant degradation in performance or handling characteristics. (c) significant modification of the permissible flight envelope. but will not remove the capability to continue a safe flight and landing without demanding more than usual skill on the part of the flight crew.
Extremely remote failures	Hazardous effects	These effects may be more than major providing that the overall risk of catastrophe is extremely improbable, taking into account likely crew action.
Extremely improbable failures	Catastrophic effects	Resulting in fatalities.

Recurrent. (Frequency of occurrence up to about 10^{-5} per hour of flight.) Expected to occur from time to time in the life of an airplane.

Remote. (Of the order of 10^{-5} to 10^{-7} per hour of flight.) May happen a few times during the total operational life of a type of aircraft. For example, a remote failure includes failure of two engines in one flight.

Extremely Remote. (Not expected to occur more often than 10^{-7} per hour of flight.) Unlikely to occur during the total operational life of all aircraft of a type, but nevertheless has to be considered as being possible.

Extremely Improbable. So extremely remote that it can be stated with confidence that it should not occur.

Table 2.- Flying qualities levels from MIL-F-8785B

Level	Description	Corresponding pilot rating (in general)
1	Flying qualities clearly adequate for the mission flight phase	1 - 3.5
2	Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists	3.5 - 6.5
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 flight phases can be terminated safely, and Category B and C flight phases can be completed.	6.5 - 9+
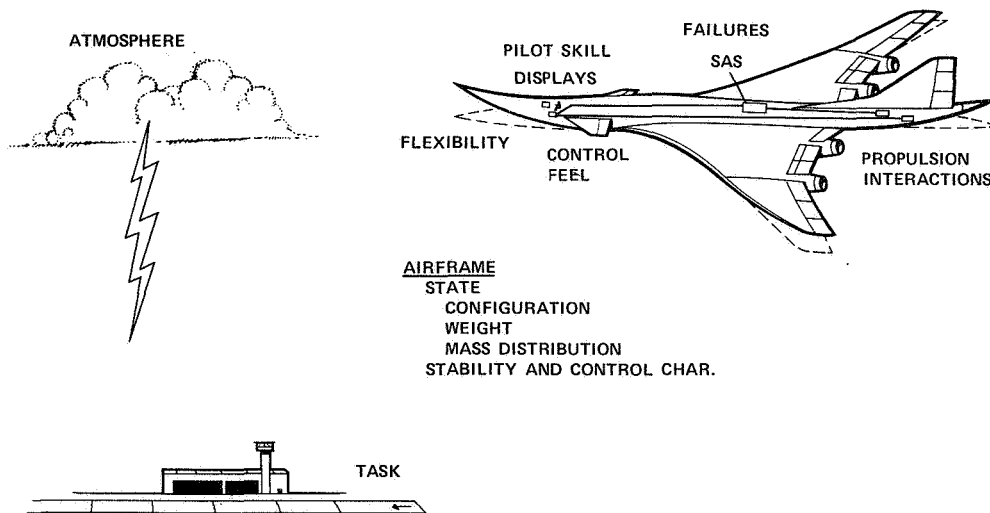
Figure 1.- Factors influencing flying qualities

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FAR 25 AIRWORTHINESS STANDARDS: TRANSPORT CATEGORY AIRPLANES (ref. 2)

SUBPARTS

A.   GENERAL

B.   FLIGHT

      GENERAL

      PERFORMANCE: RECIP. ENGINE POWERED AIRPLANES

      PERFORMANCE: TURBINE ENGINE POWERED AIRPLANES

      CONTROLLABILITY AND MANEUVERABILITY   ⬅

      TRIM   ⬅

      STABILITY   ⬅

      STALLS   ⬅

      GROUND AND WATER HANDLING CHARACTERISTICS   ⬅

      MISCELLANEOUS FLIGHT REQUIREMENTS   ⬅

C.   STRUCTURE

D.   DESIGN AND CONSTRUCTION   ⬅ ···

E.   POWERPLANT

F.   EQUIPMENT   ⬅ ···

G.   OPERATING LIMITATIONS AND INFORMATION

Figure 2.-   FAR 25 outline identifying sections of interest.

SUBPART B   FLIGHT

> 25.181 DYNAMIC LONGITUDINAL, DIRECTIONAL, AND LATERAL STABILITY.
>   ANY SHORT PERIOD OSCILLATION OCCURRING BETWEEN STALLING SPEED AND MAXIMUM ALLOWABLE SPEED APPROPRIATE TO THE CONFIGURATION . . . MUST BE HEAVILY DAMPED WITH PRIMARY CONTROLS (1) FREE AND (2) IN A FIXED POSITION.

SUBPART B   FLIGHT

> 25.21(e)
>   IF COMPLIANCE WITH THE FLIGHT CHARACTERISTICS REQUIREMENTS IS DEPENDENT UPON A STABILITY AUGMENTATION SYSTEM OR UPON ANY OTHER AUTOMATIC OR POWER-OPERATED SYSTEM, COMPLIANCE MUST BE SHOWN WITH PARAGRAPHS 25.671 AND 25.672.

SUBPART D   DESIGN AND CONSTRUCTION

> 25.671 CONTROL SYSTEMS – GENERAL
>
> (c) THE AIRPLANE MUST BE SHOWN BY ANALYSIS, TESTS, OR BOTH TO BE CAPABLE OF CONTINUED SAFE FLIGHT AND LANDING AFTER ANY OF THE FOLLOWING FAILURES OR JAMMING IN THE FLIGHT CONTROL SYSTEM AND SURFACES . . . , 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.
>   (2) ANY COMBINATION OF FAILURES NOT SHOWN TO BE EXTREMELY IMPROBABLE, EXCLUDING JAMMING
>   (3) ANY JAM IN A CONTROL POSITION NORMALLY ENCOUNTERED . . . UNLESS THE JAM IS SHOWN TO BE EXTREMELY IMPROBABLE OR CAN BE ALLEVIATED . . .
>
> 25.672 STABILITY AUGMENTATION AND AUTOMATIC AND POWER-OPERATED SYSTEMS
>
> (b) THE DESIGN . . . MUST PERMIT INITIAL COUNTERACTION OF FAILURES OF THE TYPE SPECIFIED IN PARAGRAPH 25.671(c) WITHOUT REQUIRING EXCEPTIONAL PILOT SKILL OR STRENGTH, BY EITHER DEACTIVATION OF THE SYSTEM, OR A FAILED PORTION THEREOF, OR BY OVERRIDING THE FAILURE BY MOVEMENT OF THE FLIGHT CONTROLS IN THE NORMAL SENSE.
>
> (c) IT MUST BE SHOWN THAT AFTER ANY SINGLE FAILURE . . .
>   (1) THE AIRPLANE IS SAFELY CONTROLLABLE WHEN THE FAILURE OR MALFUNCTION OCCURS AT ANY SPEED OR ALTITUDE WITHIN THE APPROVED OPERATING LIMITATIONS THAT ARE CRITICAL FOR THE TYPE OF FAILURE BEING CONSIDERED;
>   (2) THE CONTROLLABILITY AND MANEUVERABILITY REQUIRE-MENTS OF THIS PART ARE MET WITHIN A PRACTICAL OPERATIONAL FLIGHT ENVELOPE . . . DESCRIBED IN THE AIRPLANE FLIGHT MANUAL; AND
>   (3) THE TRIM, STABILITY, AND STALL CHARACTERISTICS ARE NOT IMPAIRED BELOW A LEVEL NEEDED TO PERMIT CONTINUED SAFE FLIGHT AND LANDING.

Figure 3.-   Example of control system failure treatment in FAR 25.

1. FLIGHT SUBPHASE
ELEMENTARY OBJECTIVE
WITH TOLERANCES
(e.g. LOCALIZER CAPTURE)

2. STATE OF THE
ATMOSPHERE
• TURBULENCE
INTENSITY
• TEMPERATURE
GRADIENT
• VISIBILITY
• MEAN WIND
ON GROUND

3. STATE OF THE
AIRCRAFT
• MASS
• MASS DISTRIBUTION
• SELECTED
CONFIGURATION
• FAILURES

4. FLIGHT
TECHNIQUE
CHOICES AVAILABLE
TO PURSUE SUBPHASE
OBJECTIVE

PLUS SECONDARY WORK
(CHECKLIST, RADIO TRAFFIC, NAVIGATION)

CONSTITUTE A TASK

PROBABILITY (TASK) =

PROB (SUBPHASE PER FLIGHT) x
PROB (ATMOSPHERIC STATE DURING SUBPHASE) x
PROB (AIRCRAFT STATE DURING SUBPHASE) x
PROB (GIVEN CHOICE OF FLIGHT TECHNIQUE)

Figure 4.-   Elements defining the "task" in TSS 3 (refs. 1 & 16).

SUBPHASE A
SUBPHASE B
SUBPHASE C

PILOT EVALUATIONS

TASK 1
TASK 2
TASK 3
TASK 4

PILOT OPINION SCALE

PROB (TASK)

SUBPHASE TABLE

DID YOU SUCCEED IN CARRYING OUT THE TASK?	IS THIS WORK LOAD LESS THAN OR EQUAL TO THE MAXIMUM WORK LOAD IN EVERYDAY OPERATION ACCEPTABLE FOR THIS SUB-PHASE	CLASS
		C2*
YES	YES	C3
		C4
	NO	C5
		C6
NO		C7*

c CLASS OF DIFFICULTY

C	C3	C4	C5	C6	C7*
P_u	10^{-11}	10^{-7}	10^{-4}	10^{-2}	10^{-1}

SUBPHASE C: INITIAL CLIMB

TASK	C	P_u	P_n
1	C3	10^{-11}	.90
2	C4	10^{-7}	.06
3	C4	10^{-7}	.01
4	C6	10^{-4}	2×10^{-6}
.	.	.	.
.	.	.	.
.	.	.	.

(EXAMPLE ONLY)

P_u

P_n

PROB (INCIDENT DURING SUBPHASE/FLIGHT) = Σ [$P_u \times P_n$]

CLASSES OF DIFFICULTY

= 10^{-11} (.90) + 10^{-7} (.06 + .01) + 10^{-4} (2×10^{-6} + ...)

PROB (INCIDENT/FLIGHT)   = Σ Σ [$P_u \times P_n$]

SUBPHASES   CLASSES OF DIFFICULTY

$\leqslant$ SAFETY INDEX

Figure 5.-   One possible method described in TSS 3 (ref. 1) for
showing compliance with handling requirement.

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HANDLING QUALITIES RATING SCALE

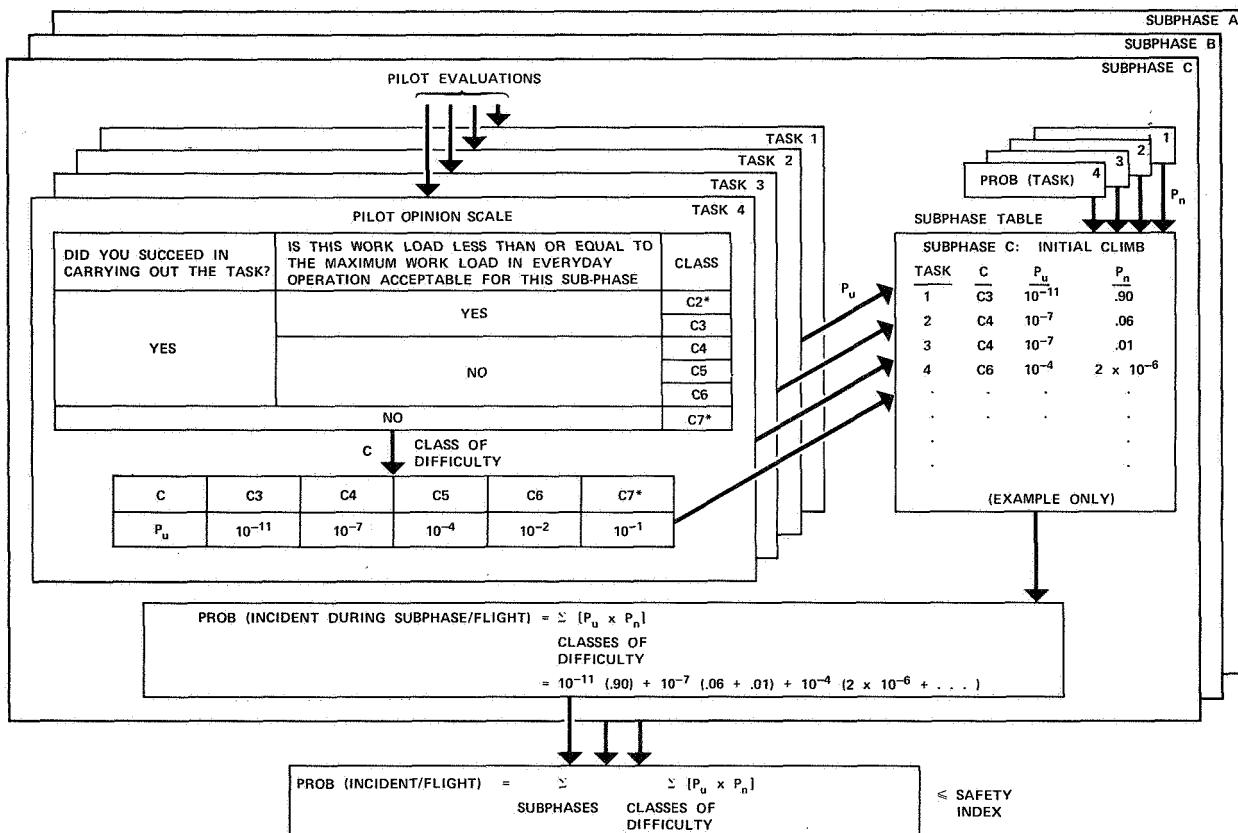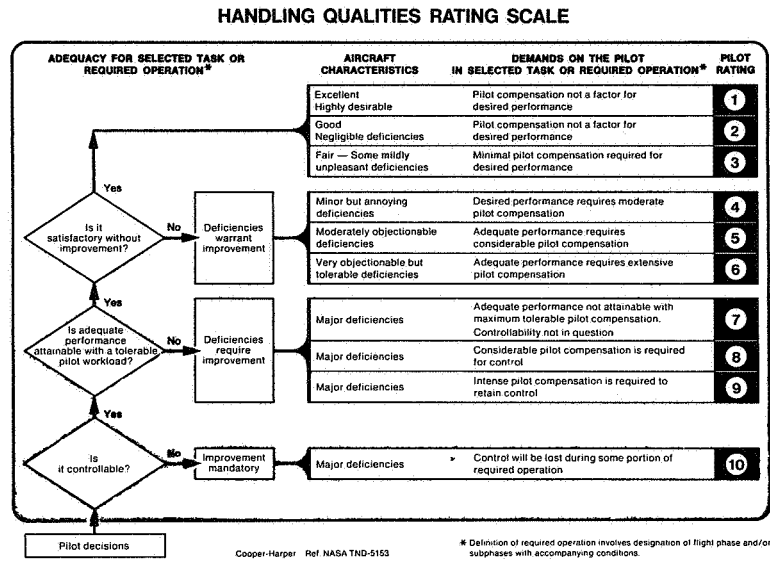| ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION*			AIRCRAFT CHARACTERISTICS	DEMANDS ON THE PILOT IN SELECTED TASK OR REQUIRED OPERATION*	PILOT RATING
			Excellent Highly desirable	Pilot compensation not a factor for desired performance	1
			Good Negligible deficiencies	Pilot compensation not a factor for desired performance	2
			Fair — Some mildly unpleasant deficiencies	Minimal pilot compensation required for desired performance	3
Is it satisfactory without improvement?	No	Deficiencies warrant improvement	Minor but annoying deficiencies	Desired performance requires moderate pilot compensation	4
			Moderately objectionable deficiencies	Adequate performance requires considerable pilot compensation	5
			Very objectionable but tolerable deficiencies	Adequate performance requires extensive pilot compensation	6
Is adequate performance attainable with a tolerable pilot workload?	No	Deficiencies require improvement	Major deficiencies	Adequate performance not attainable with maximum tolerable pilot compensation. Controllability not in question	7
			Major deficiencies	Considerable pilot compensation is required for control	8
			Major deficiencies	Intense pilot compensation is required to retain control	9
Is it controllable?	No	Improvement mandatory	Major deficiencies	Control will be lost during some portion of required operation	10

Yes / Yes / Yes — Pilot decisions

Cooper-Harper Ref. NASA TND-5153

* Definition of required operation involves designation of flight phase and/or subphases with accompanying conditions.

Figure 6.- Cooper-Harper pilot rating scale (ref. 10).

NORMAL STATES   FAILURE STATES

OPERATIONAL FLIGHT ENVELOPE   LEVEL 1
LEVEL 2
SERVICE FLIGHT ENVELOPE

PROB (LEVEL 2) $< 10^{-2}$ PER FLIGHT
PROB (LEVEL 3) $< 10^{-4}$ PER FLIGHT
PROB (LEVEL 3) $< 10^{-2}$ PER FLIGHT

Figure 7.- MIL-F-8785B minimum flying qualities requirements.

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DURATION OF LONGEST FLIGHT
DURING OPERATIONAL MISSIONS

RELIABILITY AND
FAILURE EFFECTS
ANALYSES

ESTIMATED CORRESPONDING
FAILURE RATES

COMPUTE

AIRPLANE FAILURE
STATES WITH
SIGNIFICANT EFFECT
ON FLYING QUALITIES

PROBABILITY OF ENCOUNTERING
FAILURE STATE PER FLIGHT

ANALYSES AND
SIMULATION
TESTS

COMPUTE

TOTAL PROBABILITY OF
ENCOUNTERING LEVEL 2
IN OPERATIONAL FLIGHT
ENVELOPE

IS TOTAL
PROBABILITY
$< 10^{-2}$
PER FLIGHT?

YES   COMPLIES

NO   DOES NOT
           COMPLY

"LEVEL" OF
FLYING QUALITIES

IF LEVEL 2

DETERMINATION OF MOST
CRITICAL AIRPLANE FAILURE
STATES (ASSUMING FAILURE
PRESENT AT MOST CRITICAL
POINT IN OPERATIONAL
FLIGHT ENVELOPE)

IF LEVEL 3

IS TOTAL
PROBABILITY
$< 10^{-4}$
PER FLIGHT?

YES   COMPLIES

NO   DOES NOT
           COMPLY

IF LEVEL 2   O.K.

DETERMINATION OF MOST
CRITICAL AIRPLANE FAILURE
STATES (ASSUMING FAILURE
PRESENT AT MOST CRITICAL
POINT IN SERVICE FLIGHT
ENVELOPE)

IF LEVEL 3

IS TOTAL
PROBABILITY
$< 10^{-2}$
PER FLIGHT?

YES   COMPLIES

NO   DOES NOT
           COMPLY

Figure 8.-   MIL-F-8785B procedure for determining theoretical compliance
with airplane failure state requirements.

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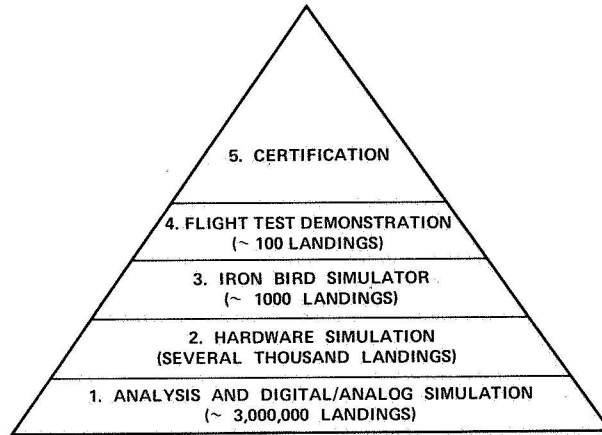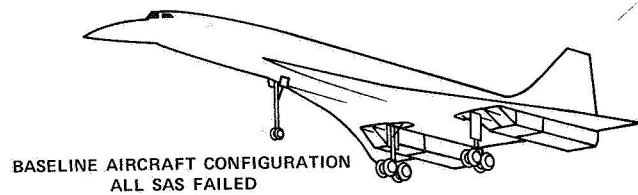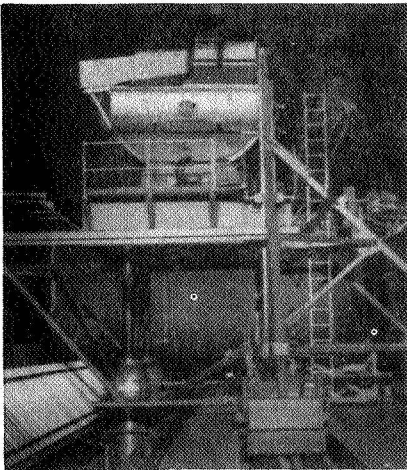Figure 9.- Progressive simulation and testing in Autoland certification (ref. 13).

BASELINE AIRCRAFT CONFIGURATION
ALL SAS FAILED

TOOL — NASA/AMES
FLIGHT SIMULATOR FOR
ADVANCED AIRCRAFT
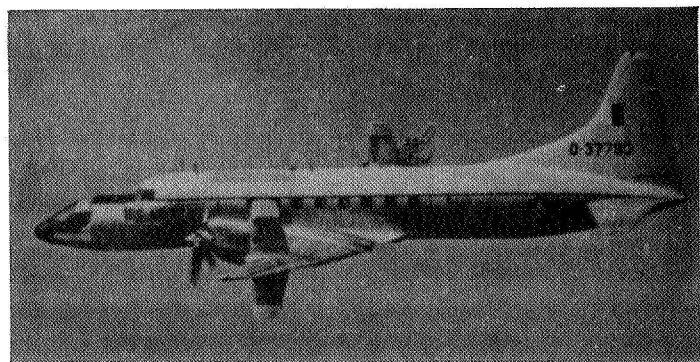
TOOL — USAF/CALSPAN
TOTAL IN FLIGHT
SIMULATOR

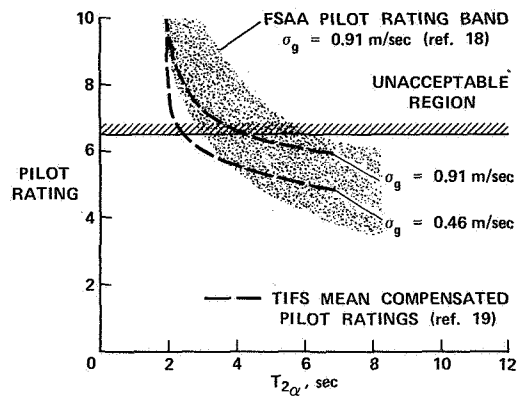Figure 10.- Simulation study of minimum longitudinal stability for SAS-failed landing.

Figure 11.- Pilot rating vs time to double amplitude $T_{2\alpha}$, showing effect of turbulence intensity (σ_g is rms value). Landing task, unaugmented delta-wing transport.
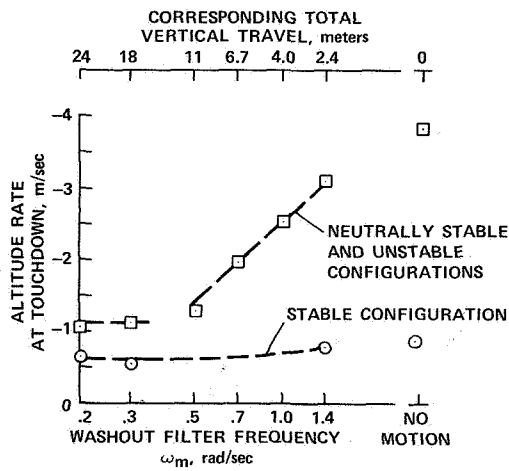

Figure 12.- Vertical motion effects on landing performance (ref. 20).