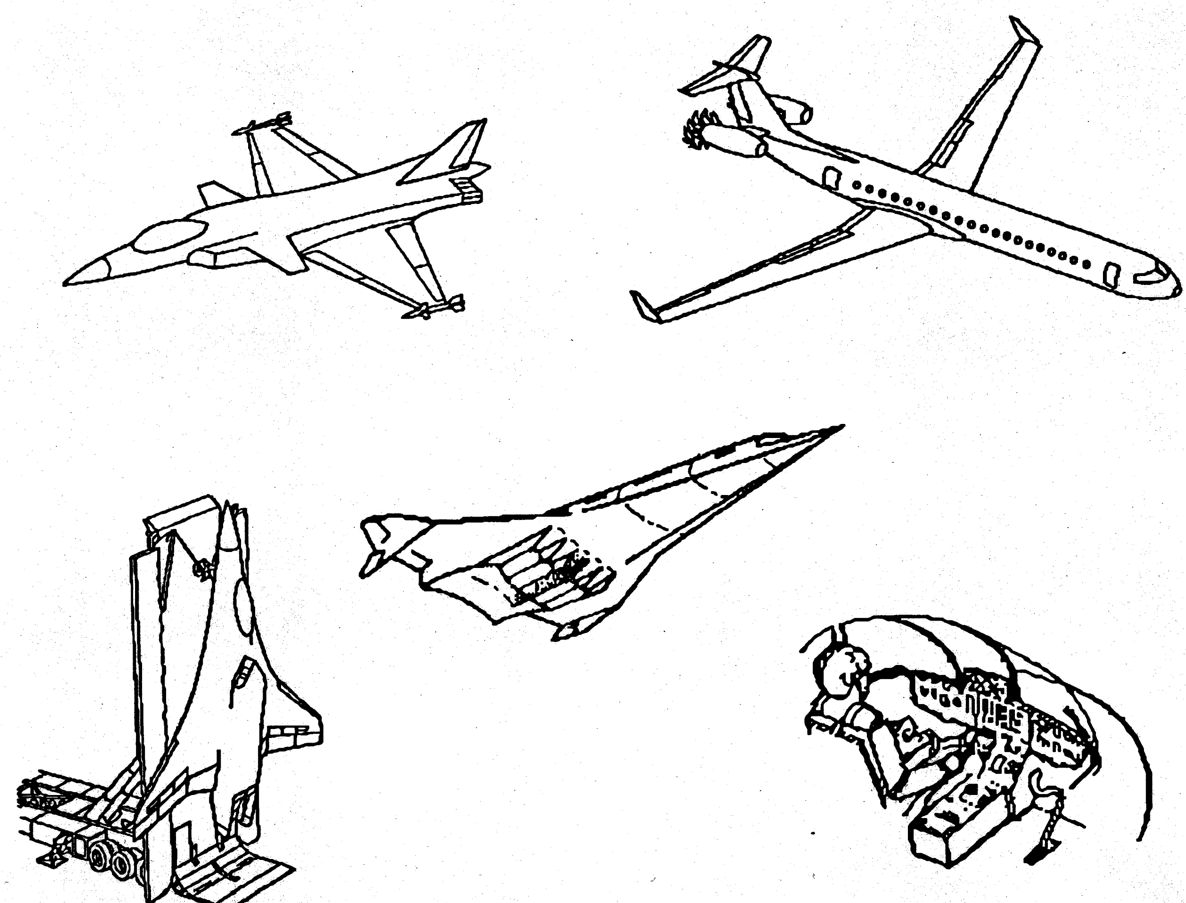
FLYING QUALITIES RESEARCH CHALLENGES

Summary from the
1986 Workshop On Flying Qualities
Research Challenges
Sponsored by NASA & DoD



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Edited by
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FLYING QUALITIES RESEARCH CHALLENGES

EXECUTIVE SUMMARY

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Government-sponsored research of aircraft flying qualities has waned over the past few years at a time when the complexities and challenges are growing at an alarming rate. In order to arrest and to reverse this trend, government research managers of the Air Force, Navy, Army and NASA have formed an ad hoc committee with participation from the aerospace community to develop a strategy. The strategy involves the following:

(1) **Defining the challenges and opportunities.** Hold a workshop, form teams by aircraft class and generate a document summarizing the problems, challenges, opportunities, needs and future trends.

(2) **Develop a technical plan.** Government managers and assigned class leaders will develop a plan to address the challenges and needs previously defined. The plan will be coordinated between agencies and services and with the help of the entire aerospace community.

(3) **Agency or service program plans.** Once a technical plan has been developed and prioritized, individual program plans for each service or agency will be developed within each individual political and resource climate. Coordination and cooperation will be used to insure more effective research as each part will be explained in terms of an overall national plan.

This document is the conclusion of step (1) above and will be used to help generate national technical plans and program plans.

Each class of aircraft (e.g., transport, combat/high-performance, VSTOL, rotorcraft and aerospacecraft) have sections that describe recurring problems and resulting challenges that are consistent throughout that class. An obvious trend is that many of the same problems plague each class. A summary of some of the major challenges and opportunities that seem to be important for all or most classes is given below:

Predictive Measures Versus "Fly and Fix" Methods. With the extreme cost of testing and iterating, more than ever there is a need to be able to predict and obtain good flying qualities early in the design process and certainly before first flight.

Trend Toward Integration. Aircraft systems and components are becoming increasingly integrated. Systems are becoming so interactive and interrelated that even small changes in one component or design parameter may have far reaching repercussions throughout the design. While this drives the cost of experimentally tuning skyward, it also provides opportunities for significant additional synergistic benefits if integration is done properly early in the design process.

Need to Link Flying Qualities to Overall Design Process. The degree of integration results in the need of proper flying qualities design from the outset. A major goal of future research will provide methodologies to permit the design of favorable flying qualities to positively and directly impact the design process. Goals are to cut time and cost of simulation, to minimize after-the-fact fixes and to provide maximum opportunity for design synergism.

Opportunity to Provide Optimum Flying Qualities Instead of Merely Acceptable. The application of modern design tools and advanced computer techniques to the control system should enable the designer to optimize flying qualities early in the design process. Current practice is to provide at least minimum characteristics as established by a design criteria. The flexibility could be used to enhance flying qualities further and increase mission performance and productivity from the pilot's perspective even more.

Importance of Flight Simulation. All groups noted that the entire discipline is more or less at the mercy of the quality of the available simulations. Research is needed to help ascertain levels of appropriate fidelity as a function of vehicle class and mission task. Improvements in this area are needed not only to indicate and improve validation levels to satisfy research missions, but provide guidelines for day-to-day operations, performance verification and certification activities of the aerospace community.

Task-Oriented Flying Qualities Criteria and Design Guidelines. The current trend of aircraft with higher degrees of augmentation and automatic stabilization for all classes has indicated the need to break the mission into phases and tasks. Control systems are evolving which are very much task oriented and specific. Design guidelines and flying qualities criteria are needed which relate to these tasks.

Guidelines Needed for Degree of Automation. All aerospace vehicle classes are going toward greater degrees of automation for various functions, including for roles classically reserved for pilots. Guidelines are needed to help designers optimize the integration of automation into the cockpits of future aircraft.

The aerospace community is strongly committed to trying to rekindle the focus and energy needed to enable a strong program in flying qualities research. The challenges and needs have never been greater and the opportunities for significant system enhancement are tremendous. This document is the first step in trying to organize a nationally coordinated plan and research activity which will result in benefits to the community much greater than the sum of the individual parts.

INTRODUCTION

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Flying Qualities is the study of the dynamic characteristics of a total aircraft system with respect to the pilot. Designing and building an aircraft with acceptable dynamic characteristics so as to be accurately controlled by the pilot has been a key challenge for all aircraft dating back to the Wright brothers and even before. All piloted aircraft are compromised for the pilot to effectively and safely carry out its intended mission. Flying qualities requirements play a pivotal role in integrating these design factors to produce a successful aircraft. The government aircraft research organizations and laboratories have long recognized the need for research in helping to design aircraft with excellent flying qualities. However, support for generic flying qualities research has waned in recent times. This is particularly disturbing since the needs for new approaches and new databases have risen dramatically over the same period.

A number of potential contributing issues toward the reduction in sponsored flying qualities research have been identified. The very fact that generic flying qualities research has been sponsored for over 70 years gives the impression that the field is stagnant or at the very least sufficiently mature to permit scarce research funds to be invested in other vital areas. There exists a belief that flying qualities problems are primarily configuration dependent, so that each problem will have to be solved on a case-by-case basis regardless of the generic research that has previously been performed. In an age of computational tools that improve on the number of decimal places of easy-to-understand predictive performance metrics (e.g., drag, thrust, etc.), it is hard to understand empirical, quasi-analytic, (seemingly ad hoc) methods that are only relatively successful in predicting something as difficult to quantify as pilot preferences. Furthermore, with growing emphasis on automation and other deterministic schemes, some view the role of the pilot as diminishing. Although all of these examples have a degree of surface validity they are patently false. For reasons we will state herein, it is our belief that generic flying qualities research programs that span the needs of each class are vitally necessary. However, these comments, observations and remarks provide valuable insights. If fact, these comments illustrate weaknesses that the flying qualities community has wrought upon itself.

The first and most obvious general comment after surveying the attitudes of key program managers, directors and administrators is that flying qualities research may not be fully understood or appreciated. The fundamental, driving research challenges have not been generally recognized within the community of flying qualities researchers, nor by outsiders looking into the field. Because there is not an accepted set of research challenges for flying qualities research, in general, there is not now a national mandate, agenda or even plan to which individual line managers can point to help justify expenditures or resources. If there is no well delineated set of plans, it is hard to perceive how a piece of generic research will fit into the national needs.

Many of these issues have been raised at recent professional meetings and workshops. At the 1986 AIAA Atmospheric Flight Mechanics Conference, a panel of experts led a group discussion which identified the need for a national coordinating committee of government research managers with potential purview over sponsoring or managing flying qualities research. A consensus was reached that a workshop was needed to clearly specify the key challenges and issues that flying qualities research should address.

NASA's Langley Research Center agreed to host the workshop during Thanksgiving week of 1986 with only 2 months notice. It was decided that the workshop attendance would be limited to about 50 through specific invitations in order to allow maximum information exchange. Each organization was contacted and asked to supply a representative. Individuals from NASA, Air Force, Navy and Army helped to organize and plan the various sessions. The final agenda of speakers and activities is included as Appendix A to this document. There were 60 attendees representing 13 commercial companies, 12 government research facilities/organizations, and 4 consulting companies or universities. A list of represented organizations includes the following:

<u>Industry/Airframers</u>

Bell Helicopter-Textron
Boeing-Commercial
Boeing-Military
Boeing-Vertol
Douglas Aircraft
General Dynamics
Grumman Aerospace
Lockheed-Georgia
McDonnell Douglas Helicopters
McDonnell Douglas-Aeronautics
Northop
Rockwell
Sikorsky Helicopter

<u>Government</u>

AFWAL
Air Force Test Pilot School
Army--ARC
Army--EFA
FAA--LaRC Liaison Office
NASA--Ames Research Center
NASA--Dryden Flight Research Facility
NASA--Headquarters
NASA--Langley Research Center
Naval Air Development Center
Naval Air System Command
Naval Test Pilot School

University/Consultants
Calspan Corporation
PRC-Kentron Corporation
Purdue University
Systems Technology, Inc.

The participation is considered to be outstanding especially given the limited warning and the awkward timing (during Thanksgiving vacation week). A list of participants and pictures from the workshop are included as Appendix B to this report.

The stated themes for the workshop included the following: (a) enumerate fundamental challenges that flying qualities research will have to address over the next decade or two to be responsive to the aerospace community's needs; (b) determine if there is a justifiable need for generic flying qualities research; (c) describe the issues for nonspecialists and senior program managers; and (d) identify current and future needs for flying qualities research. Having made progress in these areas, it was hoped that a nationally coordinated plan among the major sponsors of flying qualities research could be developed.

The invitation to workshop organizers, speakers and participants identified a number of key questions that might be used to begin preliminary discussions. These questions included the following:

1) Is flying qualities really a mature discipline?

2) Are there benefits from doing generic flying qualities research?

3) Can flying qualities be adequately addressed in the design stage?

4) Is there an impact to U.S. aeronautical technology if the U.S. does not continue to sponsor flying qualities research?

5) Is project-specific flying qualities research sufficient for ensuring adequate flying qualities criteria, design guidelines and methodologies?

6) Is there something like computational flying qualities which might be easily understood and pursued as a national goal?

The workshop approach, as outlined in Appendix A, was to have a series of invited presentations, two working group meetings, followed by working group summary reports. The invited presentations were divided into five vehicle class-specific groups and one generic group. The five class-specific groups included: Transport, High-Performance/Combat, VSTOL, Rotorcraft and Aerospacecraft. After the presentations, participants, speakers and group leaders divided into working groups to discuss the issues and prepare summary reports. The next day each group was requested to present for discussion at least three charts summarizing the groups' findings. These charts are included as Appendix C.

Citing many specific problems which could be grouped into several broad categories, participants came to agree strongly that continued general research in flying qualities is indeed vitally needed to assure success of already projected aeronautical and aerospace vehicles.

As an outcome of the workshop it was decided that the major deliverable would be this document clearly describing the fundamental challenges and issues that flying qualities research will need to address over the next 10-20 years. The goal is that this document can be used by multiple groups and agencies for advocating the need for their participation in a national effort to improve the state of the art in flying qualities specifications, design criteria/guidelines and prediction.

The following sections represent invited papers pulled together by session chairmen and other invited individuals to try and make a clear story illustrating the need for flying qualities research. Each section is intended as a consensus position describing the inclinations and attitudes of the widest possible spectrum of participants. When minority positions are laid out clearly, they have also been included for completeness.

This document is the principal product of the workshop. It is a good attempt at addressing the critical issues considered at the workshop. This document clearly states the problem, the need and the challenges of performing flying qualities research. This document is intended as an effective means for leading into a national effort for planning and coordinating related flying qualities research activities throughout the nation.

WORKSHOP SESSION SUMMARIES

FLYING QUALITIES FOR TRANSPORT AIRCRAFT

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SUMMARY

The technology associated with flight control, cockpit information displays, and computation has advanced to a stage where it is now possible to tailor the airplane responses to commands and disturbances--and to present the pilot with information in a variety of formats. This hardware capability has progressed to the point where it should be possible to provide good flying qualities in all flight phases.

The large flying qualities database that has been developed over the years is comprehensively summarized in the present Military Specifications. However, this database cannot be directly applied to the new flight control system design methods. The origin of the problem stems from the application of the new technologies, the high levels of stability and control augmentation contemplated, and the use of modern multivariable synthesis methods to design flight control systems. That is, today's flying qualities criteria and flight control system design guidelines are, for the most part, not applicable to highly augmented vehicles. The failure to obtain good flying qualities on some recently developed vehicles, prior to first flight, suggests that the criteria imposed by the government and/or used by the designers were not valid or were improperly interpreted. Therefore, a serious and critical situation has developed; i.e., the flying qualities and controls engineer has been provided the capability, within limits, to tailor the airplane response to whatever is desired. However, the definition of what the desired response should be for specific mission tasks is not available.

There is an urgent need for new research data, new experimental and analytical tools, validated design criteria, and guidance to industry for application of existing and new criteria so as to achieve good flying qualities for future aircraft, including all flight phases, prior to first flight. It must be determined what the proper set of flying qualities requirements are so that the costly "fly-and-fix" syndrome can be avoided.

There are four major domains which still dominate the design of an aircraft: aerodynamics, structures, propulsion, and flight control. The future of flight control technology seems to be in the direction of integration with many of the other control functions of the aircraft. This integration is required by the payoff that is achievable from the increased coordination of

the various aircraft control functions, and the automation of many piloting tasks. In order to realize the advances required for next generation flight control systems, it is clear that high priority future research should be conducted in this area and the elements to be considered should include: (1) task-oriented flying qualities criteria for highly augmented aircraft; (2) control power/rate determination factors; (3) definition/measurement of controller noise sources (flexible modes, sensor noise, time delays, etc.); (4) data for design of cockpit information displays (as a function of pilot task and flight control system characteristics); (5) description of what to "design to"/"test for" with respect to severe atmospheric phenomena; and (6) guidelines for design of unconventional cockpit manipulators (sidesticks, etc.).

A. SIGNIFICANT CHARACTERISTICS

Reduced/Negative Static Stability

By applying the relaxed static stability (RSS) concept and utilizing an active control stability augmentation system, an airplane can be designed with (1) reduced aerodynamic trim drag because of a farther aft c.g. balance and/or (2) reduced aerodynamic parasite drag and lower structural weight because of a smaller horizontal tail surface. Also, the RSS concept will have an even larger payoff for new transport designs having high-aspect-ratio wings and supercritical airfoils that result in substantially increased levels of trim drag at "conventional static margins."

Considerable research has been performed on the design of high-aspect-ratio wings with supercritical airfoil sections which result in significantly improved cruise lift-to-drag (L/D) ratio. Results of this research show that these supercritical wings would provide about 13 percent improvement in cruise L/D at conventional static margins; however, a potential 17 percent improvement would be available with the elimination of trim drag. This is illustrated in figure 1.

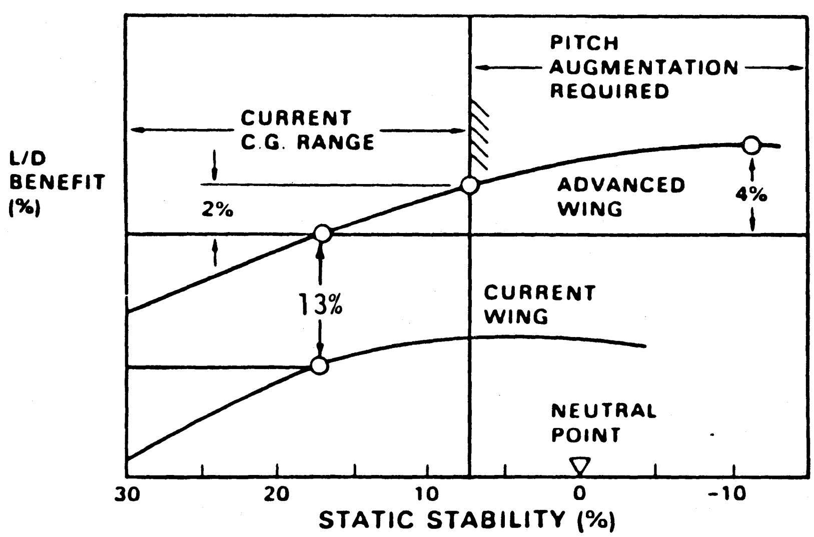


Figure 1.- Reduced/Negative Static Margin (L/D Benefits Versus c.g. Positive)

In order to eliminate this trim drag, thus achieving "optimum" performance, transport aircraft of the future will have to operate 10 to 15 percent statically unstable. This will require a full-time, high-authority stability and control augmentation system.

Superaugmented/Fly-by-Wire Flight Control System

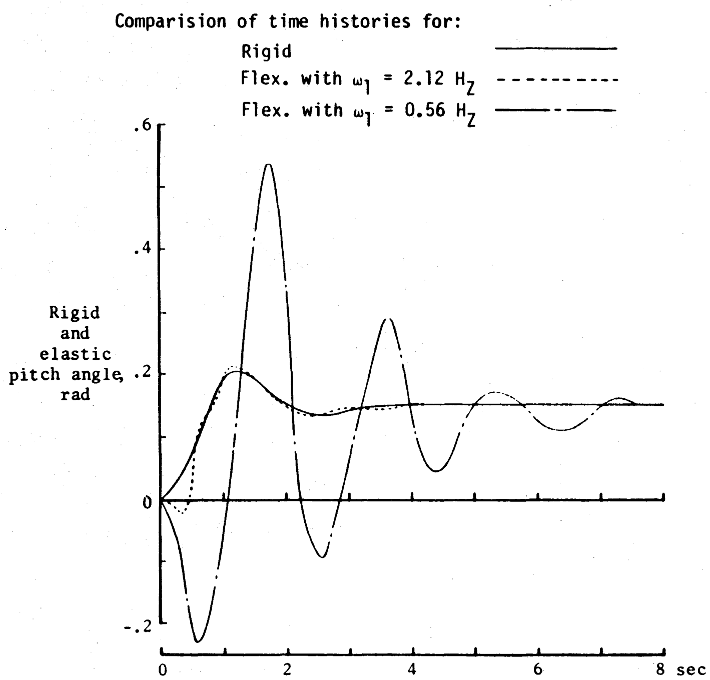
The use of full control authority, implicit in fly-by-wire, and digital computation in a command and stability augmentation system allows the controls engineer to significantly alter the way an airplane responds to the pilot's controls. The response can be of higher order than conventional responses, decoupled in the response of selected variables to pilot input, and the unaugmented airplane response can be masked by the characteristics imposed by the control system. The advantages of command augmentation systems are significant. The response can be task tailored; that is, different responses can be selected depending on the particular piloting and airplane task at hand. Command augmentation systems can be readily synthesized with modern multivariable optimal control techniques.

Increased Structural Flexibility

As a result of more efficient structure, and thus the lowering of structural mode frequencies, the problem of providing satisfactory flying and ride qualities has been compounded. This means stronger interactions between the dynamics of the airframe, the aeroelastic structural modes, and the control system for aircraft of the future. Usually, the attitude dynamics and flying qualities of an aircraft are defined in terms of rigid-body modal characteristics. (For example, the frequency and damping of the short period and phugoid modes are used for flying qualities specifications of the longitudinal dynamics of aircraft). This is possible, not because the aircraft are actually rigid, but because they are "rigid enough" so that structural effects can be ignored. In reality, aircraft are not rigid. The term "relatively rigid" only refers to aircraft in which the vibrational frequencies of the aeroelastic modes are large compared to the frequencies of the rigid-body modes. As the frequencies of the aeroelastic modes become lower, these elastic modes begin to significantly affect the dynamics of the aircraft (Fig. 2). These structural modes pose special problems--not only with describing the flexible dynamics but also in synthesizing control system designs to achieve desired dynamics.

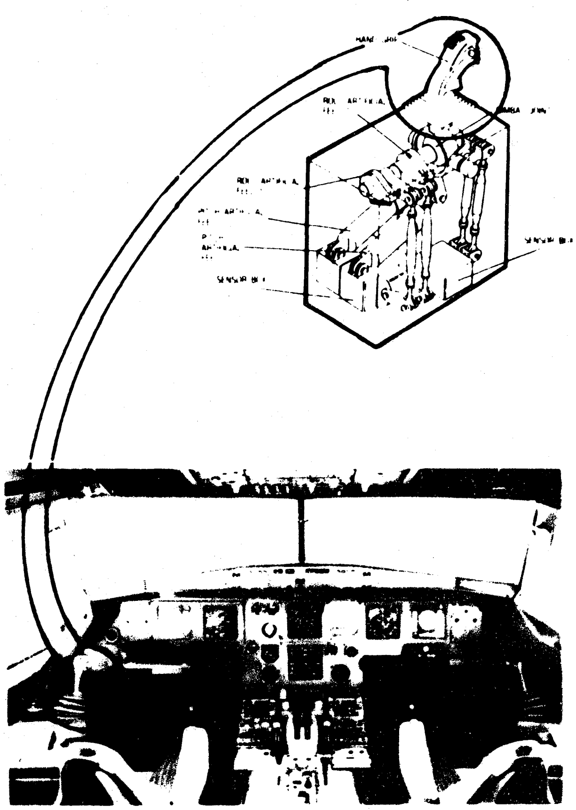
Unconventional Cockpit Controllers

Future transport aircraft will have unconventional cockpit controllers/manipulators (e.g. ministicks or sidesticks). It is believed that for aircraft having fly-by-wire control systems there is no need for large, central control columns and the provision of sidestick controllers mounted on the lateral consoles will "open-up" the pilot's view of the front panel. The sidestick controller design for the Airbus A-320 fly-by-wire subsonic transport is indicated in figure 3.



Lowest Frequency Wing-Body Structural Mode	
Aircraft	Frequency, (H_z)
C-131	3.15
B-1	2.52
L-1011	>2.0
C-5A	1.75
Boeing SCR design	0.98

Figure 2.- Increased Structural Flexibility



- o GENERAL CHARACTERISTICS
  - o NEUTRAL POSITION: 20° FWD AND 12° INWD
  - o MAX. DEVIATION ANGLE ±12° PITCH AND ±20° ROLL
  - o SIDE-STICK INCLUDES:
    - \- A DATUM ADJUST SWITCH TO VARY THE SELECTED HEADING AND VERTICAL SPEED
    - \- A RADIO COMMUNICATION AND INTERPHONE TRIGGER
    - \- AN AUTOPILOT DISCONNECT PUSHBUTTON
- o INSTALLATION
  - o SIDE-STICKS I STALLED ON FWD LATERAL CONSOLES
  - o ADJUSTABLE ARMREST FACILITATES THE SIDE-STICK CONTROL ON EACH STATION

Figure 3.- Unconventional Cockpit Controllers--A320 Side-Stick Controller

The A-320 pilot and copilot sidestick controllers are not mechanically linked together (i.e., movement of one controller will not cause movement of the other controller). This implementation has caused concern as to how simultaneous inputs from both controllers should be treated and as to how one pilot can completely override another pilot in the case of pilot incapacitation or pilot error.

Gust/Load Alleviation

Gust alleviation may well be a requirement for airplanes of the future:

- Commercial aircraft--for passenger comfort and limiting of structural fatigue

- Military aircraft--when low-altitude, high-speed flight is required, simply because the pilot would no longer be able to tolerate the cockpit accelerations

The performance of a gust alleviation system is limited by a number of factors:

- Maximum control surface deflection, which is permitted for the gust compensation

- Maximum control surface deflection rates

- Inertial properties and position of the sensors

- Accuracy of calculation of the gust signal

- Influence of signal filtering

- Backlash, friction, saturation, and other nonlinearities of the actuators

- Effect on "rigid-body" modes

While the gust alleviation function can affect flying qualities, no quantitative bounds have been developed.

Reconfigurable Flight Control System

Reconfigurable/fault-tolerant flight control systems enable performance of a mission with system failures. Since new transport aircraft will rely on their advanced flight control system for safe flight, the control system designer must make the system "fail-safe." That is, the airplane should remain controllable even with multiple failures in the control system. Recent work in this area has focused on failure detection and the subsequent restructure of control laws to take advantage of all operative controls. For example, a stabilator failure would result in the need for additional pitch control--and this pitch control could come from a combination of elevator, ailerons, flaps, and engine thrust.

B. FUNDAMENTAL ISSUES

Criteria for Highly Augmented Aircraft

A serious and critical problem appears to be developing in the design of flight control systems for transport aircraft. The origin of the problem stems from the application of the new technologies, the high levels of stability and command augmentation contemplated, and the use of modern multivariable synthesis methods to design command augmentation systems.

The large flying qualities database that has been developed over the years is comprehensively summarized in the present Military Specifications. However, this database cannot be directly applied to the new flight control system design methods. That is, today's flying qualities criteria are, for the most part, not applicable to highly augmented vehicles.

We have provided the controls engineer with the capability, within limits, to tailor the airplane response to whatever is desired; but, we have failed to provide him with a definition of what the desired response should be for specific mission tasks.

Environmental Effects/Control

The effects, and ultimately the control, of microbursts, wind shears, and/or turbulence are not presently understood to the extent that the controls engineer can design a cure-all control system. Today's transport airplanes still experience crashes or near crashes due to these atmospheric phenomena. Significant data gathering has taken place over the years, but there is still a need for better descriptions of what to "design to"/"test for" with respect to atmospheric phenomena.

Unconventional Cockpit Controllers

For fly-by-wire flight control systems, it does not make sense to "clutter-up" the cockpit with conventional column/wheel controllers. Therefore, use of unconventional controllers/manipulators are coming to the fore. Some of the major issues are:

- When are "new" cockpit controllers required/appropriate?

- What are the weighting factors for determining benefits of "new" controllers?

- What are the optimum design and location of new/separate controllers?

Reduced/Negative Static Stability

It has been shown beneficial to fly jet transports with the cater-of-gravity far aft of the neutral point in order to minimize the trim drag and thereby realize appreciable benefits in fuel savings. It has also been demonstrated that the current state of the art in flight control system design can provide acceptable flying qualities for all flight conditions even with extreme negative static stability margins (-35% chord for the X-29). However, there presently exist essentially no quantitative flying qualities criteria that consider inherently unstable aircraft; for example, criteria relative to pitch-up, stability, available control authority, requirements for maneuver stability, or angle-of-attack limiting in the neighborhood of stall.

Fully Integrated Systems (Flight Control System/Avionics/Propulsion)

There is a growing concern over the balance between the volume of cockpit data that is becoming available and its potential use. On new systems the amount of information that potentially could be displayed may be more than pilots can use--such as up to a half-dozen different descent possibilities for flight crews from which to select. Greater emphasis should be placed on evaluating how much information is needed and ensuring that it is standardized. Integrated cockpits, in which all major systems are coordinated from inception of design, would provide greater efficiency in control and coordination of information displayed.

Aircraft control systems such as thrust and performance management may have very sophisticated systems to perform those functions, but individual units may not always communicate with each other. We have to start thinking in terms of cockpit integration in which the various systems are integrated in their design so that they will work either correspondingly or cooperating with each other or will work through a common system integrator to do the job.

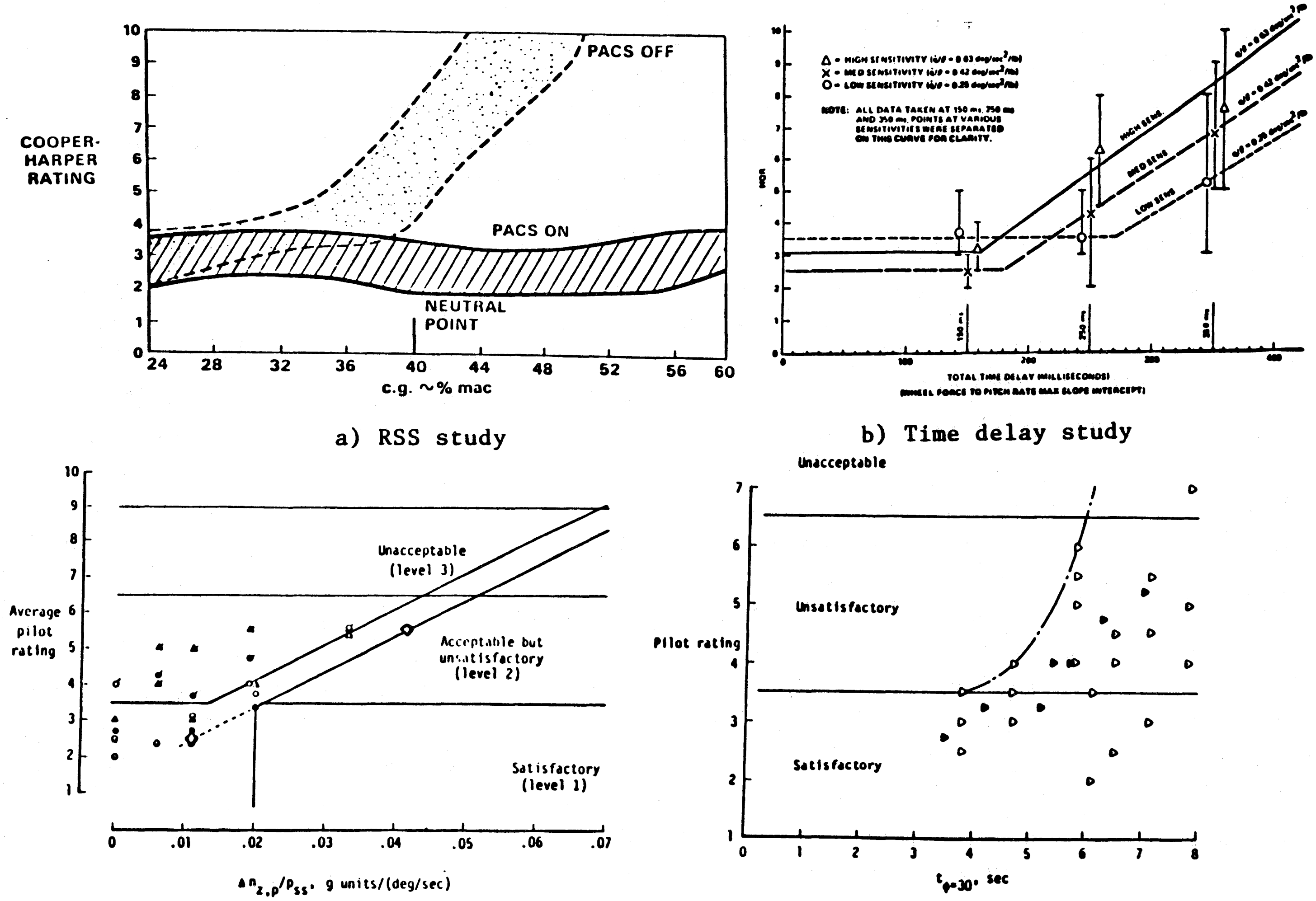
C. HISTORICAL BACKGROUND

Development of Guidelines

The capability of providing acceptable flying qualities for statically unstable aircraft was demonstrated utilizing a 6 degree-of-freedom ground-based simulator. The flying qualities degrade rapidly as the airplane c.g. moves aft of the static neutral point. However, satisfactory flying qualities were obtained on the simulator with up to 20 percent negative static margin by using a pitch active control system (PACS) (Fig. 4a).

Guidelines for allowable time delays in transport aircraft were developed utilizing the total in-flight simulator (TIFS). Also the importance of control sensitivity on allowable time delay was highlighted. The results obtained were significantly different from the conservative guidelines of the present Military Specifications (Fig. 4b).

Guidelines for the design of twin-body transports were obtained utilizing ground-based and in-flight simulators. One such guideline was the maximum fuselage separation at which pilots would not find objectionable accelerations during maneuvering (Fig. 4c). Also, new roll-control power requirements were developed for large transport aircraft (Fig. 4d).



a) RSS study

b) Time delay study

c) Twin-body study

d) Roll control power study

Figure 4.- Sample Accomplishments--Demonstration of Feasibility and Development of Guidelines

Open-Loop Flying Qualities Prediction Techniques

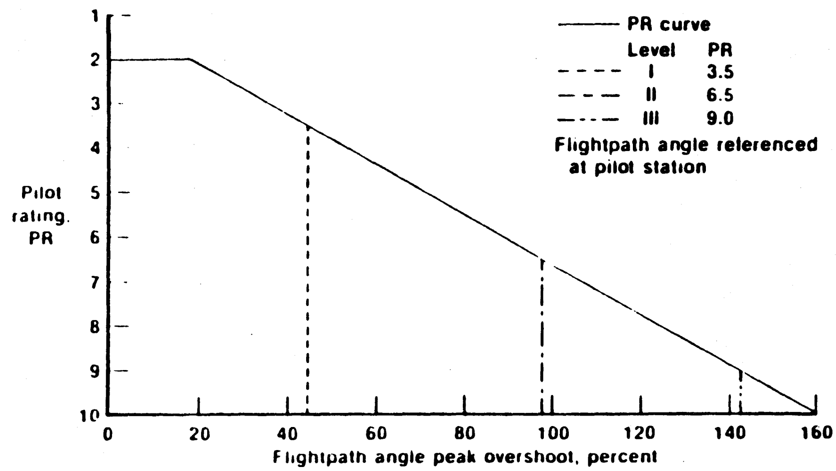
Open-loop techniques usually predict pilot opinion of the aircraft's flying qualities based on aircraft response to a step-control input or on the calculated modal characteristics. One example of an open-loop prediction technique is the recently developed time-domain criterion for the flared landing task (Fig. 5a). This technique predicts pilot rating of the longitudinal flight characteristics of an airplane during the flared landing task based on angle of attack and normal acceleration response to a step impulse, the effective time delay in the pitch-rate response, and the pitch control sensitivity. Although this "prediction technique" has not been applied to any new aircraft, it correlates well with previous flight test experience for a wide variety of aircraft.

Another recently developed open-loop technique is the "flight path overshoot" criterion. It predicts longitudinal flying qualities based on the airplane flight path response to a step impulse (Fig. 5b).

Comparison of prediction techniques applied to TIFS landing program	
Predictive Method	Percentage of Configurations Accurately Predicted by Level
Low order equivalent systems	38 %
Pitch attitude bandwidth	70 %
Altitude rate bandwidth (closed loop method)	63 %
Neal-Smith criterion (closed loop method)	73 %
* Time domain technique	100 %

a) Time domain technique*

$$\text{Pilot Rating} = 1.7\dot{\alpha}' - 1.44N'_{z_p} + 0.55T'_{\alpha} + TD' + \dot{q}' + 2.0$$

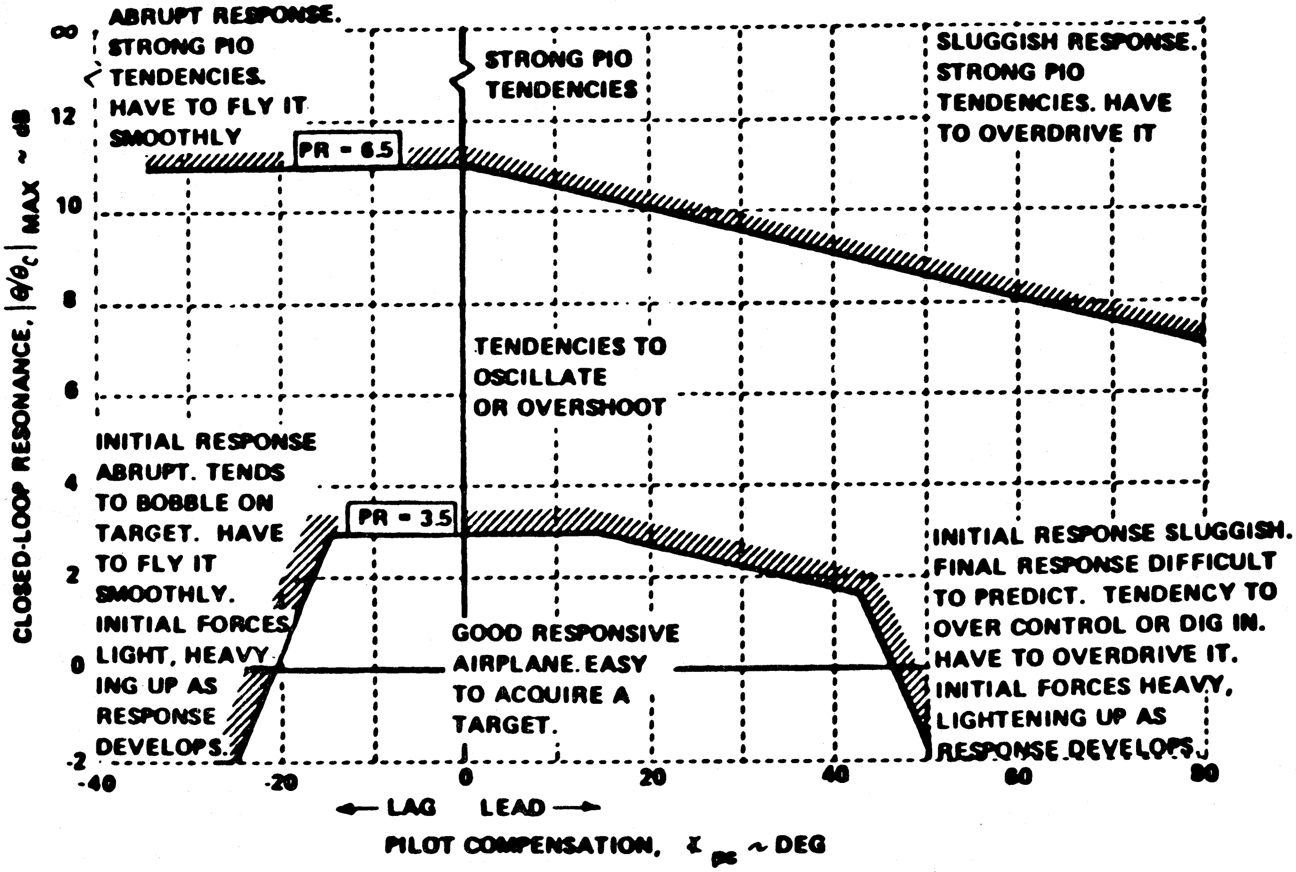


b) Flight path overshoot technique

Figure 5.- Sample Accomplishments--Open-Loop Flying Qualities Prediction Techniques

Closed-Loop Flying Qualities Prediction Techniques

Closed-loop prediction techniques are based on pilot models plus the aircraft--thus the term closed loop. A simple pilot model consists of a lead-lag filter, a time delay, and a gain. Pilot opinion ratings may be predicted/estimated using a correlation developed by Neal and Smith. This correlation is based on the closed-loop frequency response of the pilot and airplane. Pilot-induced oscillation (PIO) tendencies are revealed by the presence of a resonance peak in the frequency response. The required pilot compensation in the form of lead or lag, an indication of pilot required workload, also affects the predicted pilot rating (Fig. 6).



Neal-Smith Criterion

Figure 6.- Sample Accomplishments--Closed-Loop Flying Qualities Prediction Techniques

Current State of the Art

Flying qualities criteria have not kept pace with control system developments such as:

- High-order transfer functions/dynamics
- Time delays
- Decoupled responses
- Direct force control capability
- Nonlinear control laws
- Elastic dynamics
- Superaugmentation

Current flying qualities specifications are generally restricted to conventional/stable aircraft and address vehicle modal characteristics, but not desired response. Also, present-day digital flight control systems have the capability to "optimize" aircraft dynamics, but there is a lack of usable/validated criteria.

D. RESEARCH NEEDS

Flying Qualities Criteria and Flight Control System Design Guidelines for Superaugmented Aircraft

Superaugmented aircraft are an important subclass of "actively controlled," highly-augmented aircraft. Current high-priority problems with superaugmented aircraft flight control systems and flying qualities characteristics are:

- The increased sensitivity of the control system design to flexible vehicle, actuator, and other high frequency controller dynamics as stability-limiting features in the closed-loop flight control/aircraft system.

- Increased sensitivity (when compared to conventional aircraft) of the aircraft control power and control system design to flexible vehicle, pilot remnant and vibration feedthrough, sensor noise, and environmental and mission-task-dependent disturbances and commands. All of these have marked effects on the erosion of the conditional stability margins.

- While the type of effective vehicle dynamics which can be provided in a superaugmented control system, at least in the linear range of operation, are exceptionally broad in possibilities, the effective aircraft characteristics for superaugmented aircraft have yet to be thoroughly examined.

From this list of problems, it is clear that high priority future research should be conducted in this area including: (1) mission tasks (commercial and military); (2) control power/rate determination factors; (3) definition/ measurement of controller noise sources (flexible modes, sensor noise, time delays, etc.); and (4) conventional/unconventional cockpit manipulators and displays.

Design Guidelines for Digital "Back-Up" Flight Control System

A major issue that has to be decided upon is the philosophy concerning failures in flight-critical control systems. The primary requirements for the design of a digital back-up flight control system are:

- Low complexity

- Smooth switch-over from fly-by-wire operational to fly-by-wire back-up (and vice versa)

- "Satisfactory" stability and handling characteristics (NOTE: Satisfactory as used here means the pilot must be able to fly home and safely land the aircraft)

Criteria for transports with relaxed static stability (RSS) need to be developed for degraded flying qualities after system failure. For example, it has been shown that pilots can handle much more rapid divergences due to RSS than the commonly accepted time-to-double amplitude of 6 seconds if there is adequate pitch damping. However, these results are for fighter aircraft and derived from ground-based simulators. Significant additional investigations for transport airplanes, supported by flight tests, are needed. Also, criteria are needed relative to pitch-up, stability, available control authority, and the need for angle-of-attack limiting in the neighborhood of stall.

Flight Control System/Display Design Guidelines for Flight in Severe Atmospheric Conditions

Today's transport airplanes still experience crashes and near crashes due to atmospheric phenomena. The effects, and ultimately the control, of wind shear, microburst, and/or turbulence are not presently understood to the extent that the controls engineer can design a cure-all flight control system. Therefore, work must be undertaken to:

- Better understand the effect of these atmospheric phenomena on aircraft controllability

- Develop control laws that will assist the pilot in maintaining control of the aircraft when these conditions are encountered

- Determine proper information required by the pilot and how this information should be presented to him

Decoupled Control

There are many instances in which a pilot would like to have his existing control/controllers decoupled and, in fact, he could perform certain tasks more effectively and/or safely if he had decoupled control. For example, the pilot would like to be able to change flight path without changing pitch attitude or airspeed; or he might like to change the aircraft heading without having to bank the aircraft.

Direct force control would be required to perform such decoupled control tasks. If these controls (such as thrust, lift, and sideforce generators) are made active, they could also be used to augment the dynamics of the aircraft requiring further research.

E. FUTURE TRENDS AND CHALLENGES

During recent years, the technology associated with flight control, information display, and computation has advanced to a stage where it is now possible to tailor responses to commands and disturbances and to present the pilot with information in a variety of formats. This hardware capability has progressed to the point where it should be possible to provide good flying qualities in all flight phases. In many recent cases, however, (F-16, F-17, F-18, Jaguar, Space Shuttle) the flying qualities have been closer to Level 3 (unacceptable) than to Level 1 (satisfactory), even with the flight control system functioning as designed--that is, not failed. These failures to obtain good flying qualities suggest that the flying qualities criteria imposed by the government and/or used by the designers were not valid or were improperly interpreted.

There is an urgent need for new research data, new experimental and analytical tools, validated design criteria, and guidance to industry for application of the criteria so as to achieve good flying qualities for future aircraft--including all aircraft classes and flight phases.

There are four major domains which still dominate the design of an aircraft: aerodynamics; structures; propulsion; and flight control. The future of flight controls technology seems to be in the direction of integration with many of the other control functions of the aircraft. This integration is required by the payoff that is believed achievable from the increased coordination of the various aircraft control functions and the automation of many piloting tasks. In order to realize the advances required for next generation flight control systems, many of the concerns that were brought out during the November 1986 Flying Qualities Workshop, and summarized in this paper for transport aircraft, must be addressed so that sound "technical positions" can replace "opinion" whenever possible.

The tasks of designing safe and cost effective active control systems for future aircraft provide some of the most interesting and worthwhile technical challenges to our industry.

FLYING QUALITIES

FOR HIGH-PERFORMANCE AND COMBAT AIRCRAFT

Frank L. George
AFWAL/FIGC

SUMMARY

Mission and pilot task requirements naturally divide aircraft into classes as defined in the military flying qualities requirements documents. This influence is very strong in defining criteria for combat aircraft. The missions of combat-class aircraft require both aggressive maneuvering and precise attitude and flight path control at a large variety of flight conditions. The maneuvers involve large angular rates, accelerations and load factors, as well as large angle-of-attack excursions and significant sideslip. Such maneuvers are sometimes described as highly agile maneuvers and super-maneuvers.

In the context of combat mission requirements, the pilot's control tasks include equally wide variations such as gross-target acquisition and fine target tracking, often intermixed in a multi-task environment. Predictability and pilot confidence are important flying qualities considerations for these maneuvers. Techniques to maintain controlled flight without limiting the range of maneuvers are essential design considerations. Other tasks require good flight path stability and response to controls at low speed (for example, accomplishment of a precision landing). Dynamics resulting from asymmetry and other unusual configurations can arise from a number of situations, both normal and abnormal. Examples of such circumstances are maneuver conditions, external stores, intentional configurations such as the oblique wing, or battle damage and failures. In most of these situations the pilot is expected to complete the mission or task effectively. The combination of high performance aerodynamic configurations and fully powered stability and command augmentation can easily lead to conflicts in designing for these diverse dynamic requirements. The aircraft design process currently is perceived as driven by performance considerations. Flying qualities are viewed as part of the control design and their evaluation relies heavily on simulation.

It is essential to relate task/dynamics-oriented flying qualities criteria to mission requirements. This is a generic need which is also critical to successful integration of flying qualities into the design process. The criteria must also be presented in a format that facilitates their use and interpretation in conjunction with modern design methods.

Other research challenges which must be addressed include:

- The need for a mechanism to collect, analyze and share data from ongoing flying qualities research. It would also be useful to have an independent review capability for planned research to assure that it is useful and pertinent (e.g., not duplicative, applies to realistic pilot roles and tasks).

- The need for analysis methods and criteria for large maneuvers and coupled conditions (i.e., not linear, small perturbation).

- The need for imporvement of the effectiveness of simulation; development of standards for validating flying qualities simulations and definition of methods to correlate different simulations (or to compensate for simulator differences from each other or from flight tests).

A. FUNDAMENTAL CHARACTERISTICS OF AIRCRAFT CLASS

Flying qualities for high performance and combat aircraft mean safe and predictable aircraft responses to commands and disturbances over a very large dynamic range. To say it another way, this class of aircraft performs missions that require both aggressive maneuvering and precise attitude and load factor control at a large variety of flight conditions. The maneuvers involve high angular rates and accelerations, as well as large angle-of-attack excursions and significant sideslip. These maneuvers are sometimes described as highly agile maneuvers or supermaneuvers.

In combat missions, the pilot's control tasks include target acquisition and fine tracking often intermixed in a multi-task environment. Predictability and pilot confidence are important flying qualities considerations. Techniques to maintain controlled flight without limiting maneuvers are essential design considerations. Other tasks require good flight path stability and response to controls at low speed (for example, accompolishment of a precision landing). The combination of high performance aerodynamic configurations and fully powered stability and command augmentation can easily lead to conflicts in designing for these diverse dynamic requirements.

Combat aircraft also experience unusual configuration changes (such as asymmetry) resulting from maneuver conditions, external stores, intentional configurations such as the oblique wing aircraft, or battle damage and failures. In most of these situations, the pilot is expected to either complete the mission or task effectively or return to a landing area.

The space shuttle aircraft and future hypervelocity aircraft also are in the category of high performance aircraft by virtue of their very large flight envelopes. At hypersonic speeds, even small maneuvers can produce large aerodynamic and thermal loads and propulsion air inlets may be quite sensitive to attitude changes. These considerations lead to very precise control requirements. Operating at very high speeds and altitudes also introduces some special problems such as height control, flight through atmospheric density shears, and potential visual or motion cue problems.

Summary of Fundamental Characteristics

Airplane:

- Large dynamic operating envelope; speed, altitude, load factor.

- Multiple operating configurations:

  * Air combat
  * Air-to-surface weapon delivery
  * Reconnaissance
  * Aerial refueling
  * Precision landing

Tasks:

- Large, rapid maneuvers

- Precise path control

- Precise attitude control

- High workload

- Mixed manual/automatic control

B. FUNDAMENTAL ISSUES

Flying qualities design criteria are needed that illustrate the relationship to, and the impact of basic design decisions on, the ability to achieve the airplane dynamic characteristics needed to satisfy required mission tasks. The criteria must be consistent and traceable from preliminary design through simulation to flight test. Figure 1 illustrates the ideal situation where design criteria, based on the overall system requirements, guides the design process. The aircraft design process is currently perceived by many people to be driven by performance considerations. Flying qualities are viewed as part of the control design, yet they directly impact mission performance capability. The best, or optimum, total aircraft design for a given mission capability should reflect a balance among aerodynamic performance, control requirements and effective aircraft response characteristics. Design criteria are needed that can confidently predict flying qualities early in the preliminary design process. Thus, they must be consistent with analytical modeling and computer-aided design methods used for aircraft and control system definition. The criteria must also accommodate simulation as a major element of the design process.

One fundamental issue arises from the perception that aircraft performance and control technology have outstripped our understanding of how to combine these elements to achieve appropriate flying qualities. Further, the traditional approach to defining flying qualities criteria has begun with some limited analysis, followed by generating an experimental database and,

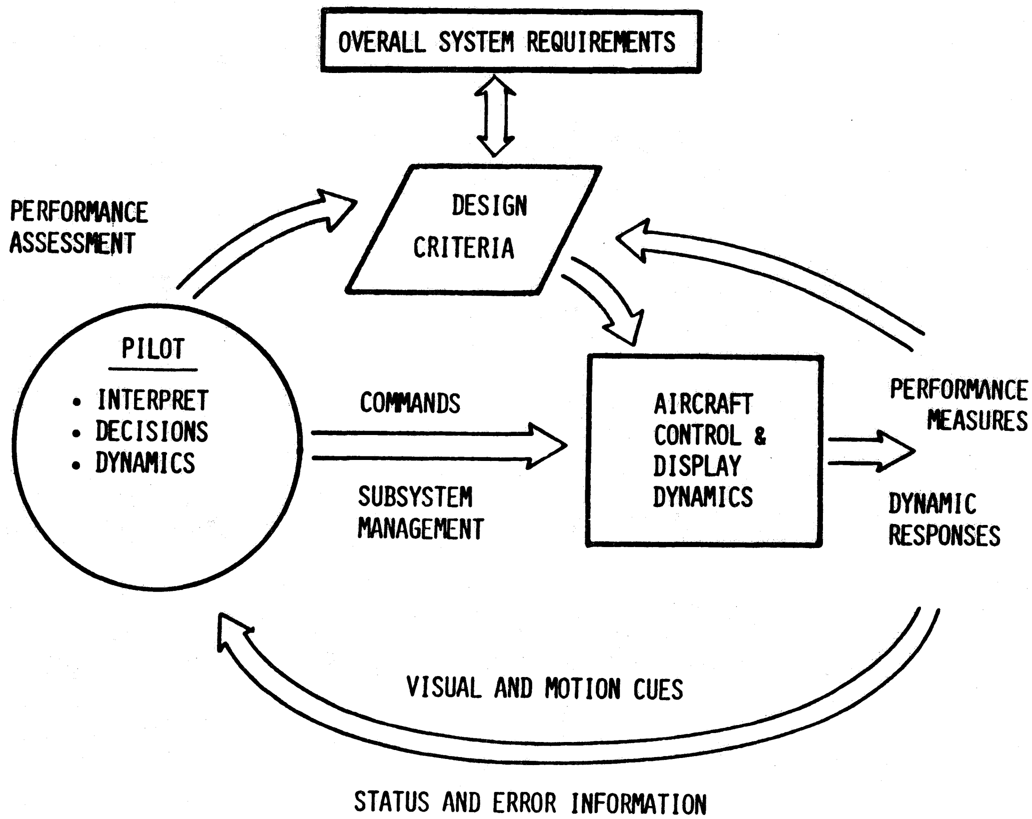


Figure 1.- Dynamic Integration of Criteria in Design Process

finally, criteria definition by correlating the database. This approach is practical as long as a reasonable number of dominant properties can be identified. With multiple control surfaces, multiple control system modes (including some automated ones), the potential for decoupled responses, and so on, it becomes impractical to generate an experimental database for all the possibilities. Given the task and mission performance requirements one alternative is to develop and validate an analytical pilot-in-the-loop theory to describe essential flying qualities. This approach must also link the flying qualities requirements to aircraft and control system design parameters and to manual control and display system requirements.

Summary of Fundamental Issues

Flying qualities are driven by task requirements that often conflict, e.g. accurate, predictable control for both large, rapid maneuvers and precision tracking.

Aircraft performance, control and flying qualities requirements may conflict.

The pilot is subjected to high workload in a multiple task environment.

Criteria must apply for a large range of dynamic modes and configurations.

C. HISTORICAL BACKGROUND

High performance and combat aircraft are perceived by some people to be the most challenging class with respect to flying qualities as well as overall design. Consequently, considerable attention has been given to flying qualities issues for this class of aircraft. For example, the main thrust of pilot-aircraft dynamic modeling research has dealt with precision tracking tasks, representative of aerial gunfighting and precision weapon delivery. Pilot-aircraft dynamic analysis methods have developed along both classical servo-control and optimal, multivariable control lines. As currently used, both approaches assume the pilot acts predominantly as a linear, continuous controller, with full attention on a single well-defined task or, at most, with attention divided between a primary tracking task and an intermittent secondary- or side-task.

Relationships between aerodynamics and aircraft response modes are very well defined for linear dynamic ranges and considerable attention has been given to the high angle-of-attack, stall and post-stall flight regimes. Very well defined criteria exist for the linearized or small-perturbation flight regions. Some quasi-linear and qualitative criteria have been defined for the higher angle-of-attack and nonlinear flight regions.

The military flying qualities requirements for high performance and combat aircraft have the largest substantiating database of any aircraft class. However, this database predominantly covers the so-called classical airplane dynamics. Only a limited amount of data explicitly addresses the newer configurations that may be highly stability and control augmented, have multiple control surfaces for each axis, and may exhibit decoupled response modes.

The equivalent systems technique was developed as a means to extrapolate the classical airplane database to cover configurations with higher order dynamics (due to augmentation, etc.). This technique has been successful for the linearized flight maneuver regions and to the extent that it is desirable for the advanced configurations to fly like classical airplanes. However, this technique may not produce the optimum balance among performance, flying qualities dynamics and task or mission capability.

Summary of Historical Background

Accomplishments:

- A large database exists for classical dynamics.

- The equivalent systems method extends data for advanced configurations.

- Considerable attention has been given to high-alpha, stall and post-stall regimes.

State of the art:

- The linear flight regime is well in hand.
- Quasi-linear criteria exist for high-alpha.
- There are some interim criteria for highly augmented configurations.

D. CURRENT CRITICAL ISSUES

In current and future high performance aircraft, flying qualities are heavily influenced by the flight control system. Hence, flying qualities criteria must encompass a wide range of both aircraft and control system configurations. Flying qualities are, in fact, the link that ties together the airframe and control system design. This is true for automatic as well as manual control modes since flying qualities in essence define the dynamic properties necessary to achieve acceptable task performance. One critical issue then is to develop a unified design approach with flying qualities as the integrating factor. That is, we must have a sound analytical flying qualities theory to guide preliminary design.

Simulation is a key part of the total design process. Task-specific flying qualities criteria are needed for simulator evaluation of designs as well as for flight tests. A broad range of tasks, covering both precision control and large maneuvers, is needed to examine all the potential limiting factors and nonlinearities. Furthermore, simulation effects on flying qualities evaluations must be quantified to increase confidence in both the simulator results and the predictions of actual aircraft characteristics.

Summary of Current Critical Issues

Fundamental flying qualities requirements must be integrated into the design process, and be traceable through analytical design, simulation and flight test evaluation.

More specific, quantified criteria are needed for the wide range of maneuvers and operating configurations expected of high performance and combat aircraft.

Pilot-aircraft system flying qualities analysis methods and criteria must be extended to include large maneuver tasks, transition between precision tracking and large maneuvers, and operation in highly automated systems.

E. FUTURE TRENDS AND CHALLENGES

Technology advancements introduce ever greater varieties of aircraft configurations, aerodynamic properties, control and propulsion options, and cockpit displays. Consequently, it is prohibitive to pursue an entirely experimental/empirical approach to define flying qualities criteria. One major challenge, therefore, is to boil down our knowledge of flying qualities to a set of fundamental design principles sensitive to task and configuration variables and compatible with computerized, integrated system design methods currently being proposed and developed.

Flying qualities must remain identifiable and recognized as the engineering discipline that combines aircraft dynamic properties and control considerations to provide desirable stability and motion characteristics. This is a difficult challenge in the rapidly expanding technological environment in which we operate. We must remember that flying qualities is itself a dynamic entity that evolves and expands with the aircraft dynamic envelope, with new control capabilities and with automation technology. Figure 2 shows the current location of flying qualities considerations in the overall system design decision hierarchy. One critical challenge is to develop a flying qualities link between the top-level mission or task capability decisions and system design decisions. To accomplish this, we must first clearly establish the pilot-centered nature of flying qualities. The shaded part of Figure 3 depicts the scope of most current flying qualities criteria. We must work to expand the scope of our thinking and our criteria development to encompass the entire dynamic interface between the human pilot (and multiple human controllers) and the aircraft system. Our efforts must consider both direct, manual control and indirect or intermittent control or automated modes based on assessment of the system's dynamic state.

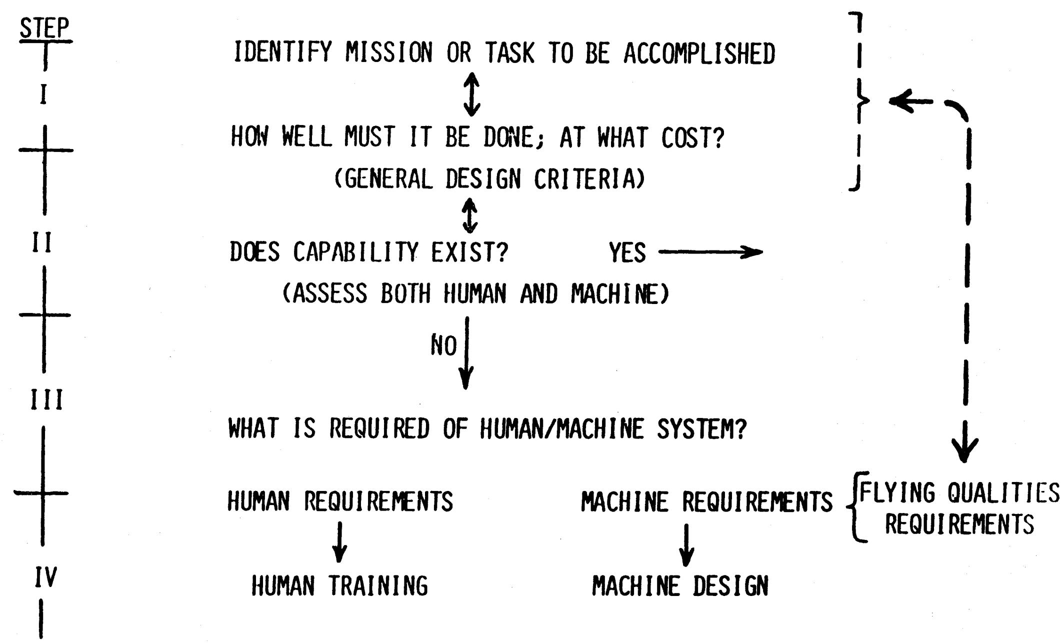


Figure 2.- The System Design Problem - A Decision Hierarchy

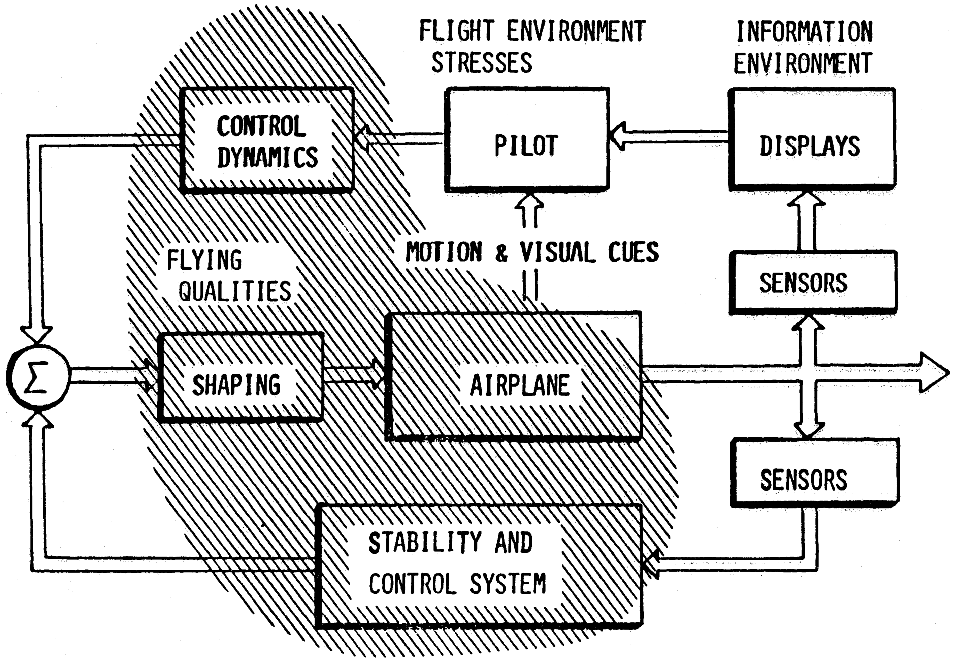


Figure 3.- Pilot-Airplane Flying Qualities Interface

FLYING QUALITIES FOR VSTOL AIRCRAFT

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SUMMARY

VSTOL aircraft offer the provision to change both the direction and the magnitude of the thrust vector to effect the conversion between a vertical takeoff or landing capability and efficient high-speed configuration. Because of the complex interaction of kinematics, aerodynamics, and propulsive forces and moments which occur during this conversion process, the stability, controllability, and maneuverability over the majority of the conversion flight regime are typically inadequate. Therefore, for this class of vehicle, the flying qualities must be included as a fundamental design element. This session of the Flying Qualities Workshop included presentations by both military buyers and contractor designers of VSTOL aircraft. A general conclusion was that the state of the art is not adequate to provide sufficient design or purchasing guidance for the flying qualities of a new VSTOL vehicle. Specific recommendations included the establishment of an "audit trail" flying qualities and mission performance, the quantification of simulation fidelity envelopes, the development of new in-flight simulation vehicles, the analytic definition of mission maneuvers to assist the determination of required control power, and the definition of the interaction among high-order aero, propulsion, and structural dynamics.

A. CURRENT STATUS

The fundamental characteristic of VSTOL aircraft that is distinct from other aircraft classes is, in general, the provision to change the direction of the net thrust vector relative to the vehicle in order to provide a vertical take-off and/or landing capability while reverting to a high speed configuration with efficiencies approaching those of conventional aircraft with fixed thrust vector angle. The VSTOL aircraft flight envelope, therefore, typically involves using aerodynamic lift only at the higher speeds; combining aerodynamic and powered lift over a range of speeds from somewhat above the aerodynamic stall speed to very low velocities; and employing primarily propulsive forces at and near hover. Through the years, the capability to cover this entire flight regime has been implemented by rotating some or all of the engine flows, rotating the engines themselves, rotating the engines and some of the aerodynamic lift surfaces, or installing additional engines that are used only in the powered lift flight regime.

Regardless of the specific means used to effect the conversion from aerodynamic to powered lift or the reverse, the major technological barrier for this class of vehicle is the complex interaction of kinematics, aerodynamics, and propulsive forces and moments which occurs over the majority of flight conditions within the conversion flight envelope, the variation of these interactions with time as the conversion is performed, and the concomitant poor flying qualities and limited control authorities these interactions engender. Unlike conventional aircraft these interactions and the resultant flying qualities are directly linked to the propulsive concept used. Further, VSTOL aircraft typically have unique operational maneuvering requirements in addition to those for conventional aircraft including the need to hover precisely; to move fore, aft, sideways, and vertically for landing; to air taxi; to perform relatively steep descents and climbouts from confined areas; and, of course, to perform the transition from powered lift to aerodynamic lift. Accordingly, the designer, buyer, and pilot are faced with operational use of a vehicle which is expected to perform missions more complex than those for conventional aircraft, and yet which likely will exhibit inadequate levels of stability, controllability, and maneuverability over the majority of the powered-lift flight regime.

The importance of these interactions and the concomitant poor flying qualities has been exhibited repeatedly for this class of aircraft in the development of flight demonstrators. During the past 30 years, on the order of 25 proof-of-concept aircraft have been constructed to examine a wide variety of schemes for effecting the VSTOL capability. The majority of these machines crashed. All of them exhibited fundamentally poor flying qualities. The majority of the designs were deficient to some degree in control power available, particularly in roll, with the control power requirements being dominated by the need to trim out the moments associated with power-induced effects (e.g. ram drag), ground-effect disturbances, and power, flap and speed changes. The need for some degree of stability augmentation to safely carry out even simple operational tasks was apparent for all concepts in low speed and hover, and precision of flight path control in landing approach was less than desired. For many types, VFR operation was marginal and IFR capability impossible without large improvements in stability and damping. Most of the concepts suffered in several ways from ground proximity and propulsion reingestion problems. The significance of all of these effects was not, in general, appreciated at the design stage, and in all cases they led to flying qualities problems that severely restricted the capability of the machine.

The positive influence of this history is the clear recognition that, for this class of vehicle, the flying qualities must be included as a fundamental design element. It is particularly true for VSTOL aircraft that the state of the art in flying qualities criteria has been enabled through a low but continuous level of coupled analytic and experimental research for this class of vehicle, complemented by sporadic but focused proof-of-concept aircraft development. This continuous, if low-level support has, in fact, resulted from recognition of the clear influence of flying qualities on the mission effectiveness of these aircraft. Requirements for VSTOL flying qualities that attempt to define maneuverability and controllability criteria have been developed from the background of this flight experience and a variety of ground-based simulation investigations, and are codified in two documents: AGARD Report 577 and MIL-F-83300. To some extent, the specifications from these documents have been operationally evaluated for recent VSTOL designs (i.e., AV-8A). Significantly, they have also provided design guidance in recent studies for advanced VSTOL configurations thereby demonstrating the direct inclusion of flying qualities concerns at the very front end of the design process. Nonetheless, because of the limited data-base, the specifications lack clear definition for mission elements that are of current interest for VSTOL such as shipboard operation or powered-lift maneuvering.

To summarize, therefore, it may be said that flying qualities considerations dominate mission effectiveness for the VSTOL class of vehicles. Of over 25 proof-of-concept vehicles, only one is currently operational in the free world (the AV-8A and successor AV-8B). The majority of the rest failed, due in large part to flying qualities limitations. Typical of these limitations are insufficient control authority to counteract requirements caused by propulsive and aerodynamic interactions and inadequate levels of stability and damping over significant portions of the powered-lift flight envelope. This experience demonstrates that, for this class of aircraft, flying qualities must be included as a fundamental element in the design process. For VSTOL aircraft, the propulsive concept and systems are inextricably involved in the flying qualities. Flying qualities requirements must directly account for this link of propulsive and aerodynamic forces and moments and, further, must cover the entire range of possible vehicle operating states (hover, conversion or transition, and forward flight). The state of the art in developing such flying qualities requirements has been carried out at low level and has permitted the construction of an operational VSTOL that can currently operate to LPH-class ships in calm seas with 400 ft/1 mile visibility. In addition, the research has supplied sufficient information to provide design guidance for augmentation types and levels that permit accomplishment of some elements of more demanding VSTOL missions and it appears that certain elements of these missions can be realistically examined via ground simulation.

To what extent, then, is the state of the art adequate to provide sufficient design guidance for the flying qualities of a new VSTOL aircraft? This question is of particular importance currently because of new mission requirements that are pointing to the need for a vehicle with short takeoff and vertical landing capability (STOVL) that also has supersonic dash capabilities in the cruise configuration and a joint US/UK program has been initiated to explore the necessary technologies. Based on the existing information, it does not appear possible to design this machine with confidence. Some reasons for this inability involve the need to validate inflight criteria that do exist but are based exclusively on ground simulation results. More generally, many of the reasons involve difficulties that are not entirely unique to the VSTOL world--flying qualities guidance for all classes of vehicles suffers from the same overall lacks.

In general, it is not clear in many cases how to quantify the influence of flying qualities on overall mission effectiveness except in "ex-post facto" situations. One example from the past was the discovery with the X-100 tilt-prop that the entire installed longitudinal control authority was required to maintain trim through a conversion. As a result, only one conversion was ever accomplished. Specific predictive examples do exist. The link between control response characteristics and adverse weather operations for shipboard operations has been established on simulators and partially verified in flight, but such links need to be quantified for all mission elements and flying qualities parameters. In general, it is not possible to define the minimum levels of flying qualities required for new tasks such as shipboard landings nor can "optimum" levels be definitively stated. In general, it is not possible to use ground simulators to examine some elements of the VSTOL mission, particularly hover with minimal augmentation. Further, it is not clear how to quantify the effect of the lack of simulation fidelity in the design process.

For VSTOL aircraft, control authority requirements have not been established for demanding shipboard and land-based operations. Further, means to specify and analytically describe maneuvers associated with VSTOL missions have yet to be found. Hence, the definition of the control authority requirements themselves is difficult and empirical. Because this class of machine links the propulsive system so tightly to the flying qualities, control authority requirements place significant demands on the propulsion system. Yet, it is not clear how to prioritize bleed air or thrust for multi-axis control demands, nor how best to integrate the propulsion and flight controls, nor whether advanced augmentation systems do in fact provide relief from the overall control authority requirements.

B. CRITICAL NEEDS AND FUTURE CHALLENGES

On the basis of the review of the state of the art, several flying qualities research needs and challenges can be identified that, while particularly applicable for VSTOL aircraft, are also generally appropriate for all classes of aircraft. These requirements follow directly from the discussion given above and are summarized below in approximately prioritized order.

First, it is necessary to establish an "audit trail" between flying qualities causes and mission performance effects. This requirement implies a need to analytically define specific mission maneuver requirements in a much more comprehensive fashion. Further, it is necessary to link more closely the flying qualities causes to flight safety. It remains the case that the majority of aircraft accidents involve "pilot error," and yet the degree to which flying qualities deficiencies lead to pilot error is not quantified. As part of the audit trail, it is necessary to reexa ine unconventional responses in an effort to ascertain "optimum" flying qualities and to link the effect of control power demands on installed thrust and, hence, on payload and range. In a general sense, it is necessary to rethink the philosophy of flying qualities specification writing. Part of the problem with the discipline is that the research caters too much to the "spec" writers and not enough to developing a fundamental understanding of pilot-aircraft system performance and capability.

Second, it is necessary to establish "simulation fidelity envelopes" for ground-based simulators. The requirement here is to define mission elements that can be examined successfully on ground simulators, those that cannot, and to quantify the influence of the lack of fidelity. This research implies a closer coupling of human factors/human perceptual modelling with handling qualities pilot models. Extremely important, it also requires in-flight simulation facilities appropriate for the class of vehicle being examined.

In the case of VSTOL, the requirement exists to develop an aircraft with variable stability and control capabilities that can address propulsion/ flight control integration throughout the powered-lift regime.

In a related vein, it is necessary to substantiate design parameters using in-flight simulation when it is clear that these parameters or the appropriate mission elements are outside the fidelity envelope of ground-based simulators. There has been a tendency to eschew this final verification in the past 10 years because of lack of suitable facilities. It is partly for this reason that insufficient information exists to design with confidence the new STOVL aircraft.

For VSTOL aircraft in particular, it is necessary to define control power and control margin requirements for mission effectiveness. As mentioned above, this need implies new definition analytically of the required mission maneuvers. To the extent that this definition cannot be made, careful experimentation and empirical formulation are required. These margins, and whether they must be met for multi-inputs, have a major design impact on the propulsion system for new VSTOL aircraft.

Because the coupling of propulsion system and airframe into the flying qualities for VSTOL aircraft is so tight, it is necessary to define the influences of integrated high-order aero, propulsion, and structural dynamics. Included in the definition must be a quantification of the benefits of the integration and advanced controls on fundamental design aspects such as bleed requirements. Initial ground simulation research in these areas must be carried through to flight validation.

While the need to more explicitly define the flying qualities audit trail implies a need to enlarge the scope of response types and optimum flying qualities investigations, it is of equal importance to define absolute minimum levels of flying qualities. This information forms the basis for basic airframe design decisions appropriate for failed modes and has likewise been overlooked during the past decade.

In a more general sense, there are two additional research challenges that require attention. The first is a definition of the pilot's role when machine decisionmaking (e.g. artificial intelligence) is coupled into the flight control structure. There is no doubt but that this coupling will become prevalent in the future, and it implies hat the f ying qualities roles relative to the mission requirements must be shared between the pilot and the control system. It is not clear what the impact of this coupling implies about the definitions of mission performance requirements in a flying qualities sense, nor how the pilot will interact appropriately with the machine.

Finally, although there is not universal agreement on this issue, it appears to be necessary to develop new flight control system design procedures that are explicitly linked to flying qualities goals. In general, the flight control system designer uses performance goals that are appropriate for the control system, not necessarily the coupled pilot-vehicle system. Some initial research efforts to provide new approaches should be strengthened. Examples include separating response from regulation functions of the control system (e.g., model following) and pilot-in-the-loop procedures such as cooperative control synthesis. Experimental research is required to determine the links between the design requirements and the resulting flying qualities.

To summarize, VSTOL aircraft require many of the breakthroughs in flying qualities definition that are required by other classes of aircraft. In this case, however, obtaining appropriate results is clearly fundamental to the success of the aircraft. An audit trail linking flying qualities causes and mission performance effects must be established. As a result, new efforts to define and describe analytically the mission elements is necessary, and research studies must expand the scope of the investigations to include unconventional control responses and seek optimum flying qualities. Specific goals are the definition of control power and margin requirements and the definition of vehicle-coupled influences of integrated dynamics. In a complementary fashion, however, the audit trail must also be established for the absolute minimum level of flying qualities since this information is mandatory for degraded modes. In order to use ground-based simulators successfully in the design process, the simulation fidelity envelopes must be discovered and defined as a function of mission element and flying qualities parameter. A concomitant requirement is the need for in-flight simulation facilities as tools to substantiate design parameters in those regions outside the ground-based simulation fidelity envelope. More general challenges are the determination of the influence of machine decisionmaking on flying qualities, and the development of flight control system design procedures explicitly linked to flying qualities goals.

FLYING QUALITIES FOR ROTORCRAFT

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SUMMARY

Rotorcraft have several distinctive characteristics that make handling qualities a particular challenge. Many missions involve flight close to the ground in poor weather and at night. The vehicles themselves are difficult to represent mathematically for analysis and simulation. There are complex interactions between axes, and responses to control and disturbances are nonlinear. There are a multiplicity of limits that the pilot has to observe and these limits tend not to be unique. The current helicopter handling qualities specification, MIL-H-8501, was written in 1952 and has long been recognized as obsolete. For the past 10 years, a major effort has been underway to develop a new specification. This is a considerable advance over the old specification, and it is essential that it be adopted and applied. However, there are many handling qualities topics still needing work both for conventional helicopters and current mission tasks as well as for advanced configurations and new mission tasks. To perform this research will require improved fidelity from our ground-based simulators and development of a variable stability helicopter capable of simulating high-performance rotorcraft performing modern demanding missions.

A. DISTINCTIVE CHARACTERISTICS

Mission Characteristics

Many modern rotorcraft missions involve flight close to the ground or clost to other obstacles such as ships. This demands a continual precision of control that is seen in other aircraft only during takeoff and landing or formation flight. It means that the outside world has to be visible at all times and yet the user wants to operate in poor weather and at night. As a result, vision aids have to be used and since it will be many years before vision aids provide anything close to the fidelity of looking out the window in visual meteorological conditions (VMC) we can expect the visual cues to be degraded and of major concern to handling qualities. Many of these low-altitude, low-speed tasks are performed relative to some ground-fixed reference, and even though a constant wind is a complicating handling qualities factor, local objects, such as buildings, treelines, or hills can disturb the airflow to make the task even more difficult. Another unique mission capability of rotorcraft is their ability to carry slung loads. This introduces many complications to the overall handling qualities task.

Vehicle Characteristics

In addition to the missions performed by rotorcraft, the vehicles themselves have many unique characteristics with implications on handling qualities needs and criteria development. Because of their complex aerodynamics, they are exceedingly difficult to represent mathematically for analysis and simulation. There are complex interactions between the main and tail rotor and there are profound interactions between the flight control system and the propulsion system. When flying at low speed, the low dynamic pressure means that small perturbations in flight direction or wind can have large effects on the rotorcraft forces and moments. The kinematics are more predictable but still highly complex. The overall result is considerable cross coupling between longitudinal and lateral directional axes (pitch-to-roll, collective control to yaw, etc.), which inhibits the traditional separation of longitudinal and lateral motion. Responses to control and disturbances are nonlinear so that response to control is different to the left than to the right, the responses change nonlinearly with size of disturbance, and many of these effects are frequency dependent.

Flight Envelope

Another ramification of these complexities which is important for handling qualities is the multiplicity of limits that the pilot has to observe. A rotorcraft pilot can break his aircraft in many more ways than a fixed-wing pilot. These limits tend not to be unique. For example, normal load factor limit depends on the mix of longitudinal cyclic and collective control used to induce the limit. Many limiting parameters are difficult to sense and few limits are indicated to the pilot. In future rotorcraft, advances in active vibration systems will be capable of masking even rotor vibrations which the pilot has used in the past as an indication of rotor stall. As a result, pilots tend to give known limiting conditions a wide berth so they stay well within the available performance envelope instead of exploiting the rotorcraft's full potential.

Cockpit Environment

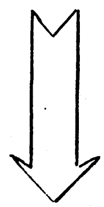
Finally, the critical ingredient for handling qualities, the pilot, is subjected to a unique environment of high noise, high vibration, and extreme temperatures. This quickly causes fatigue and necessitates short mission times. The long-term result is that most old helicopter pilots are hard of hearing and have bad backs.

B. FUNDAMENTAL ISSUES

Need for Criteria

Good handling qualities manifest themselves by allowing the pilot to fully exploit the rotorcraft's inherent performance with acceptable workload when given adequate training. Methods of achieving good flying qualities are indicated on figure 1.

ANALYSIS - APPLICATION OF SPECS
- PILOT-IN-THE-LOOP ANALYSIS



GROUND SIMULATION

FLIGHT EVALUATION
- VARIABLE STABILITY AIRCRAFT
- IN-FLIGHT SIMULATION
- TEST BED
- PROTOTYPE
- OPERATIONAL TEST
- FEEDBACK FROM FIELD

INCREASING COST AND DELAY IN FEEDBACK OF DATA FOR FUTURE APPLICATIONS

Figure 1.- Methods of Achieving Good Handling Qualities

Clearly, the cost of making any changes to correct deficiencies increases as the aircraft moves further into the development cycle, so handling qualities criteria and specifications have high leverage on development cost. They also have leverage because of another consideration: 65 percent of the cost of a new design is committed during the design stage; 20 percent more during development. By the time an aircraft flies, only 15 percent of the final cost can be influenced.

In summary, handling qualities criteria and specifications provide the following capabilities:

1. Department of Defense (DoD) and the manufacturers can make intelligent, informed design tradeoffs during aircraft design and development.

2. When documented and compiled in a flying qualities specification, the data provide a central source in design guidance which will help avoid reinventing the wheel each time an aircraft is developed or modified.

3. DoD agencies can intelligently monitor, guide, or evaluate the manufacturer's research and designs.

One could ask how the lack of handling qualities background has impacted rotorcraft design. Usually its influence is less clear-cut than an error in structural limit, weight overruns, or underestimated drag, since it involves the ability of the pilot to perform his mission tasks. Pilots are very adaptable and mission tasks are usually ill-defined. Thus, the tasks may still be performed even though the pilot is overworked and perhaps only marginally in control. Such situations will show up as reduced mission success in combat environments. In peacetime it will result in high accident rates (pilot "error" is the most common cause of accidents) and thus high training hours to develop and maintain proficiency. More obvious examples are that better handling qualities design capabilities may have avoided the redesign of the Apache empennage from a T-tail to a low-mounted, horizontal stabilizer late in the development program. Better criteria, simulation capabilities, math models of rotor downwash and more rotor-on wind tunnel testing may have avoided potential problems. High-performance, fixed-wing aircraft are replete with handling qualities problems discovered at or after first flight, and fixed-wing handling qualities criteria and specifications are many years ahead of those for rotorcraft.

Status of Existing Specifications

This leads into the second question, do we have to do more handling qualities research? A new rotorcraft specification is being developed to replace MIL-H-8501 (1961). This is a considerable advance over the existing specification. It is essential that this specification be adopted and applied, but its deficiencies must be recognized. Section 4 outlines some of the outstanding research needs but the general concerns are as follows: (1) The missions to be performed by rotorcraft are constantly changing. When MIL-H-8501 was generated (1961) helicopters were underpowered, unstable, and used for sedate maneuvering in clear VMC. When the current Army/NASA research effors to review this specification started (1975) the doctrine of nap-of-the-earth (NOE) flying had evolved, with the concurrent need for high agility and maneuverability close to the ground. This later evolved into NOE at night and in poor weather thus bringing in more handling qualities considerations. The latest evolving rotorcraft mission is the need to perform air-to-air combat (1986). This again raises agility and maneuverability levels and is clearly dominated by handling qualities considerations. Even where missions have not evolved much, for example shipboard recovery, the criteria are still not adequate and the Navy still cannot operate in all the desired sea states and visual conditions.

In summary, helicopter flying qualities knowledge is emerging from the dark ages and has a long way to go before it can be declared a mature discipline.

Research Sponsorship

Based on the clear need to do more handling qualities research, the third issue is, should it be sponsored and performed by government agencies? Past experience has shown that handling qualities criteria will not evolve as a by-product from the design process. The designer is too busy and the manufacturers are usually in a highly competitive situation. Any new design represents just one possible design solution for a given set of requirements.

The trade-off studies conducted in developing a design can be based on proprietary data which are not available to other manufacturers, nor would the results of these studies be timely. If the U.S. government does not continue to sponsor flying qualities research, it would impact the cost and quality of future aircraft. Research would not be shared with the industry at large and, therefore, manufacturers would have to duplicate research in solving problems and be protective of results.

Research Tools

One of the primary reasons that the database for rotorcraft handling qualities is so sparse is because the tools for performing helicopter handling qualities research are so poor. Despite considerable investment in simulation facilities by NASA and the Army, the fidelity of current ground-based simulators in the region of low speed and hover is inadequate for developing specific handling qualities boundaries. It is suspected that the visual systems are to blame for deficiencies during small amplitude maneuvering and that the motion systems are the major contributors for aggressive tasks. Unfortunately, though several efforts have been made to come to grips with this problem, these studies have so far been unsuccessful and currently there is no focused research effort to determine the basic requirements for an acceptable simulation of the low-speed and forward-flight regime. This work badly needs to be performed. In addition, a modern variable stability rotorcraft is needed to provide anchor points for trends defined in ground-based simulation. At NASA-Ames, aside from the CH-47 (which is not agile enough, and may have to be returned to the Army next year), there is no inflight rotorcraft simulator available in the U.S for basic research. Because of this deficiency the efforts to revise MIL-H-8501 have relied heavily on the Canadian National Research Council to develop supporting data with their variable stability Bell 205. However, the Bell 205 is also limited by its performance and agility capability which impose restrictions on evaluating advanced rotor concepts.

Advances in developing these simulation tools will also benefit the designer. All four principal helicopter manufacturers have, or are developing, extensive helicopter simulator facilities as part of their LHX predesign efforts. They will be faced with the same problems of simulation validation as exist in the government. They need improvements in simulator fidelity to be able to use them as credible design tools. Training simulators suffer from similar problems. Both Black Hawk and Apache training simulators are known to have deficiencies which can induce incorrect training.

In summary, there is a continuing need for rotorcraft handling qualities work. Not only are the design criteria deficient and lacking substantiation, but the primary tools for such work need considerable development. A major effort by government research organizations is needed to attack these problems.

C. HISTORICAL BACKGROUND

Handling Qualities Specification Development

The current helicopter handling qualities specification, MIL-H-8501, was written in 1952 with a minor revision in 1961. It has long been recognized as obsolete. It is still being used for testing by the flight test establishment and yet it is ignored for mission suitability assessment. A new specification is essential. In 1982 the U.S. Army started an effort to develop a new specification. Responsibility for specifications rests with the Aviation Systems Command (AVSCOM) Directorate of Engineering, but the effort to generate the new specification is being led by the Aeroflightdynamics Directorate of ARTA with help from NASA-Ames under the Army/NASA joint agreement. The work is monitored by a Technical Review Committee having representation from the Army, the Navy, the Air Force, and the FAA. Manufacturers have been involved at every step of the way. A version oriented at LHX was developed and adopted by AVSCOM as an Airworthiness Design Standard (ADS-33) in December 1985. This was distributed with a LHX draft Request for Proposals in 1986. Since that time, efforts have been made to expand the coverage to other types of helicopters so that it can become a credible generic specification. After one more review, it is planned to submit the product for tri-service coordination in preparation for adoption as a new MIL SPEC. The proponents of this proposed specification recognize that there are many topics with inadequate coverage, but overall it is a significant improvement and should be adopted. Work to improve the coverage should then continue.

The history of helicopter development reflects the deficient handling qualities design techniques and design criteria. There has been heavy reliance on fixing problems discovered during flight testing (e.g., Apache T-tail was modified to a low-mounted horizontal stabilizer). Many flight test fixes are in the category of cut-and-try. Solutions were usually found, but generally the problems were not sufficiently understood so that the solutions could be extrapolated to new designs.

In contrast to the fixed-wing industry, the helicopter manufacturers have made little or no use of simulators. The desire for single-pilot capability with LHX, and the focus of the Advanced Rotorcraft Technology Integration (ARTI) program has produced a recognition of the need and utility of flight simulators and resulted in a major development effort of simulator facilities by all four major manufacturers. Clearly, they now recognize the importance of handling qualities; and they now need help in developing the tools and the criteria for performing design trade-offs.

D. RESEARCH NEEDS

Tools

In adopting the new rotorcraft handling qualities specification, it must be recognized that many topics have not been addressed. Of those that have been addressed, some rely on data that were generated on ground-based simulators and many lack flight data for validation. This is important because of the current inability to perform credible ground-based simulation of rotorcraft, especially at low speed and hover with degraded response types. There will always be a need to generate flight test data for validation and verification, but the magnitude of the task (Fig. 2) is so large that full use must be made of ground-based simulators to do the broad parameter investigations.

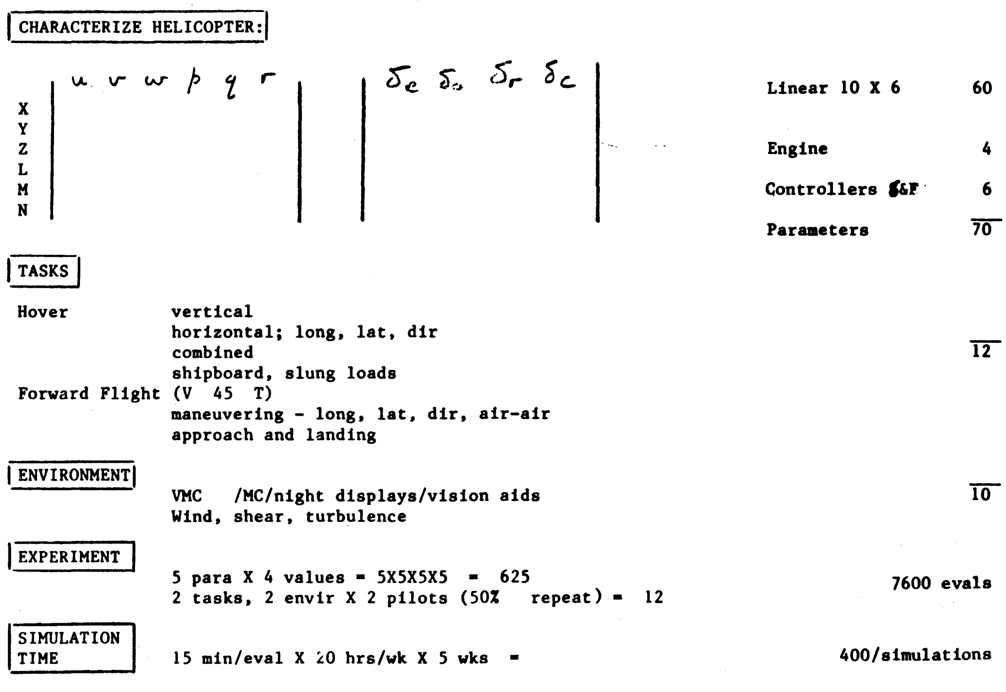


Figure 2.- Scope of Rotorcraft Handling Qualities Problem

A clear high-priority need, then, is to improve the capabilities for performing ground-based simulation. Such simulators can be used not only for flying qualities research but are also needed to support design development and to help solve problems from the field. Simulation upgrades can be divided into two aspects: engineering fidelity, the primary ingredient of which is the mathematical model representing the helicopter; and perceptual fidelity, the primary contributors being the visual and motion cues which are added to the engineering fidelity aspects. Methods have to be developed for systematically assessing simulation fidelity and for identifying and improving deficient aspects. Ingredients in engineering fidelity improvements would be improved interactional aerodynamic prediction methods and low-altitude atmospheric disturbance models. No matter how much effort and success is achieved with ground simulators, for the foreseeable future there will be a need for flight verification. Some flight verification can be obtained by comparison with existing aircraft, but for more comprehensive checks there is a need for an inflight simulator, or variable helicopter so that parameters can be varied systematically over a range of interests and used to verify a range of tasks and configurations as they evolve and are explored on the ground simulator. As discussed earlier, the U.S. does not currently have such a machine, and a major effort should be launched to develop one. Some of its features should be as indicated in figure 3. Figure 4 lists these primary tools for research.

RESEARCH CAPABILITY	FLIGHT SAFETY	PRODUCTIVITY
HIGH EXCESS POWER	TWO ENGINES	PRODUCTION VEHICLE
LARGE MANEUVER ENVELOPE		
HIGH ATTAINABLE CONTROL BANDWIDTH	LARGE HINGE OFFSET	TIMELY SPARES SUPPORT
ADEQUATE PAYLOAD AND CARGO COMPARTMENT VOLUME	TWO PILOTS/SYSTEM OPERATOR	LOW MAINTENANCE MAN-HOURS PER FLIGHT HOUR
		TWO PILOTS/SYSTEM OPERATOR

Figure 3.- Rotorcraft-Aircrew Systems Concepts Airborne Laboratory (RASCAL)--Primary Capabilities

- VARIABLE STABILITY HELICOPTER
- SIMULATION VALIDATION ASSESSMENT AND FIDELITY IMPROVEMENT
- MATH MODEL FIDELITY IMPROVEMENT
- LOW ALTITUDE ATMOSPHERIC DISTURBANCE MODELS

Figure 4.- Rotorcraft Research Needs--Near-Term Goals

Topics

Some of the topics that need more work are listed in figure 5. Some of these topics have not been addressed at all in the revised specification (for example, slung loads, response to upsets as distinguished from response to control, multi-code control blending, nonlinear control characteristics and digital implementation of high-gain stability and control augmentation systems). Some of the topics that have been addressed, but for which criteria cannot yet be formulated, are side-stick controllers, cross-coupling, and thrust response dynamics and margins. Some of the topics needing more work are broad-based and pervade the whole specification (for example, the effects of visual cue degradation, mission task element definition and quantification of performance benefits). Another class of topics needing work is oriented at specific missions such as air-to-air combat (these include the uses of thrust vectoring and maneuver enhancement by limiting and cueing). Some longer term goals are shown in figure 6.

- SLUNG LOADS -- INCLUDING TWIN LIFT
- THRUST VECTORING POSSIBILITIES AND POTENTIAL
- VISUAL CUE DEGRADATION EFFECTS AND QUANTIFICATION
- RESPONSE TO COMMAND VERSUS STABILIZATION OF UPSETS
- DIGITAL IMPLEMENTATION OF HIGH GAIN SCAS
- SINGLE PILOT SCAS
- GUIDANCE FOR FAILURE WARNING AND TRANSIENTS
- CROSS COUPLING
- SIDE STICK CONTROLLERS
- MANEUVER ENVELOPE ENHANCEMENT BY LIMITING AND CUEING
- THRUST RESPONSE DYNAMICS AND MARGINS
- CONTROL MODE BLENDING
- NONLINEAR CONTROL BLENDING
- MISSION TASK ELEMENT DEFINITION AND PERFORMANCE BENEFITS
- AIR-AIR COMBAT VEHICLE VERSUS WEAPONS

Figure 5.- Rotorcraft Research Needs--Near-Term Handling Qualities Topics

- AUTO SHIPBOARD LANDING (0.0)
- AUTO NOE
- AUTO FORMATION FLYING
- TWIN/TRIPLE LIFT
- 0,0 TACTICAL LANDING (L,1)
- CAREFREE MANEUVERING
- FLIGHT CONTROL--PROPULSION--FIRE CONTROL INTEGRATION

Figure 6.- Rotorcraft Research Needs--Future Trends and Challenges

This incomplete situation reflects the dynamic character of rotorcraft technology. As the vehicle capabilities evolve, the missions that the user would like them to do also evolve. The work done on rotorcraft handling qualities in the last 12 years is a major contribution, but increased resources will be required if we are ever to catch up with the increasing challenges.

FLYING QUALITIES FOR AEROSPACECRAFT

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SUMMARY

Aerospacecraft are characterized by a vast flight envelope, complex propulsio systems, unconventional long period modes of motion, limited forward visibility, high leverage weight/performance tradeoffs and a need for power off landing capabilities. They will require manual as well as highly automatic control modes and must provide much greater operational flexibility than current vehicles. Since they are both aircraft and spacecraft, they inherit the strengths and weaknesses of flying qualities technology as applied to bot classes of vehicles. In the advanced aircraft field, many deficiencies are known to exist in current flight control design criteria. Knowledge in the hypersonic and spacecaft regime is very limited. Current critical research needs include determining vehicle modes of motion and their sensitivity to propulsion system parameters and atmospheric disturbances, visibility require ments, task analyses, precision required to remain within thermal and propulsion system constraints, and criteria development. Future challenges will be automation, orbital operations, and vehicle integration.

A. CHARACTERISTICS OF AEROSPACECRAFT

Vast Flight Envelope

The flight envelope of aerospacecraft is the largest possible (Fig. 1), encompassing the regimes of a hypersonic aircraft as well as spacecraft. This class of vehicle will include the capability of taking off horizontally, accelerating to orbit, reentering and decelerating to a horizontal landing as well as the current shuttle-type capability with vertical launch and unpowered entry and landing. Consequently, a large variety of configurations and propulsion systems is possible (Fig. 1a). Vehicles using airbreathing propulsion must be capable of a large range of dynamic pressures. Thus, in addition to capabilities as a hypersonic aircraft they must be capable of spacecraft functions such as orbit, rendezvous, docking and reentry. In this regard they are similar to the Shuttle; however, because of their large dynamic pressure range, single stage-to-orbit capability from a horizontal takeoff and horizontal landing capability, they are truly unique.

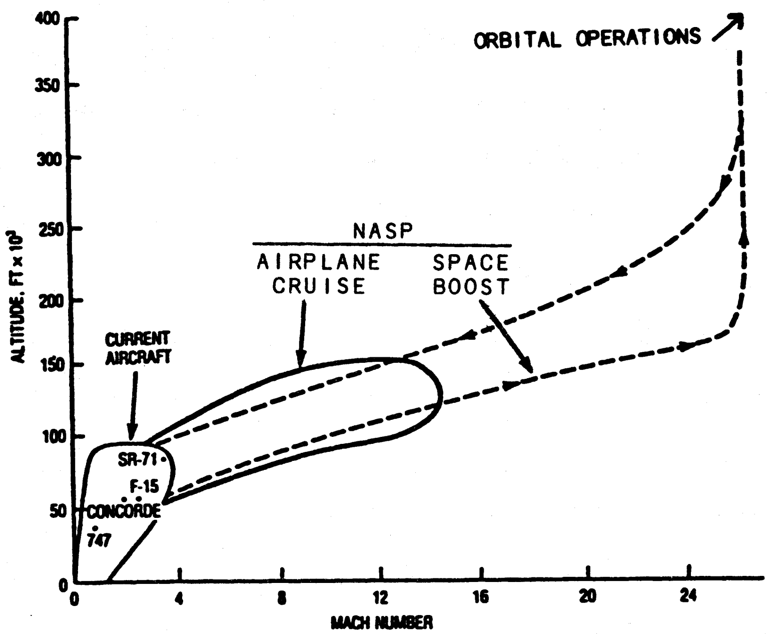

Figure 1.- Aerospacecraft Flight Envelope

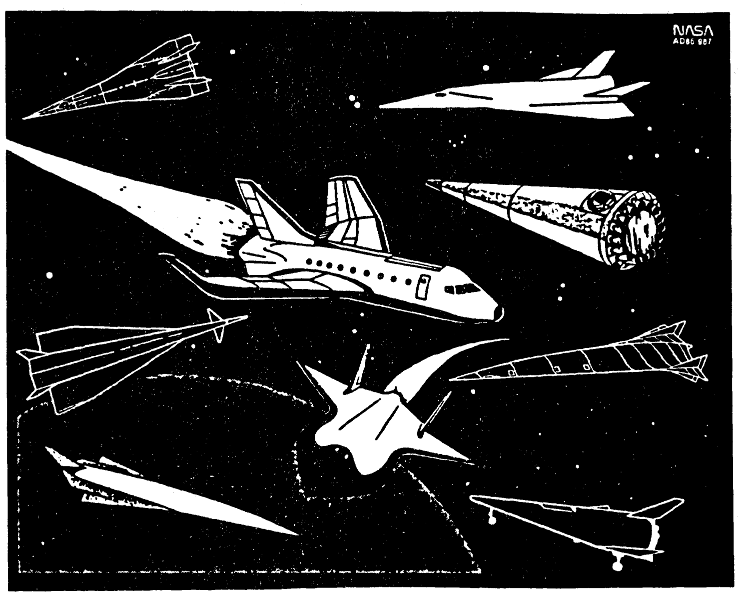

Figure 1(a).- Aerospacecraft Configurations and Propulsion Systems

In addition, all aerospacecraft have a micro-g environment; that is, they experience significant periods of time at less than 1g. A large percentage of astronauts have experienced motion sickness during zero g. After being in orbit for a while they adjust and the sickness goes away. However, aerospacecraft missions may be at low g long enough to induce motion sickness but may reenter before the crew has time to adjust to the low g levels. There is also an indication that the micro-g environment changes the perception of acceleration cues which can have a significant effect on handling qualities.

Complex Propulsion System

The demands of a hypersonic cruise and single stage to orbit require a very complex propulsion system (Fig. 2) consisting of variable and perhaps hybrid cycles. In addition, this propulsion system will be characterized by an equally complex inlet and nozzle system that is highly integrated into the vehicle shape. This propulsion system can be expected to have strong interaction with the vehicle motions and controllability.

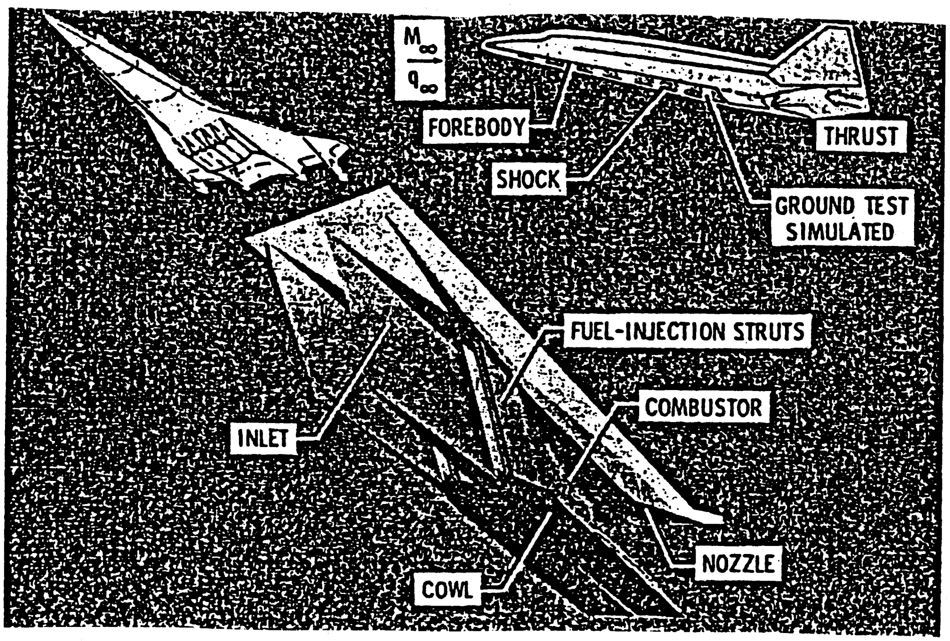

Figure 2.- Complex Aerospacecraft Propulsion System

Long Period Modes of Motion

Because of its high speed, aerospacecraft have very high kinetic energy levels. This has a strong effect on the vehicle long period modes of motion, increasing their sensitivity to atmospheric disturbances and propulsion system effects. In addition, the high energy levels cause the vehicle long period modes of motion to have a very large ratio of altitude changes to velocity changes, greatly complicating trajectory control and autopilot behavior (Fig. 3).

Unpowered, low-L/D vehicles, such as the Space Shuttle Orbiter, inherently have stable long period modes. However, airbreathing propulsion systems can strongly destabilize these modes in regions where thrust is increasing with velocity. Figure 4 shows the trend of phugoid damping for a rocket-powered vehicle and a simple airbreather. YF-12 data representing a complex airbreather are shown for comparison, illustrating the strong influence of the propulsion system.

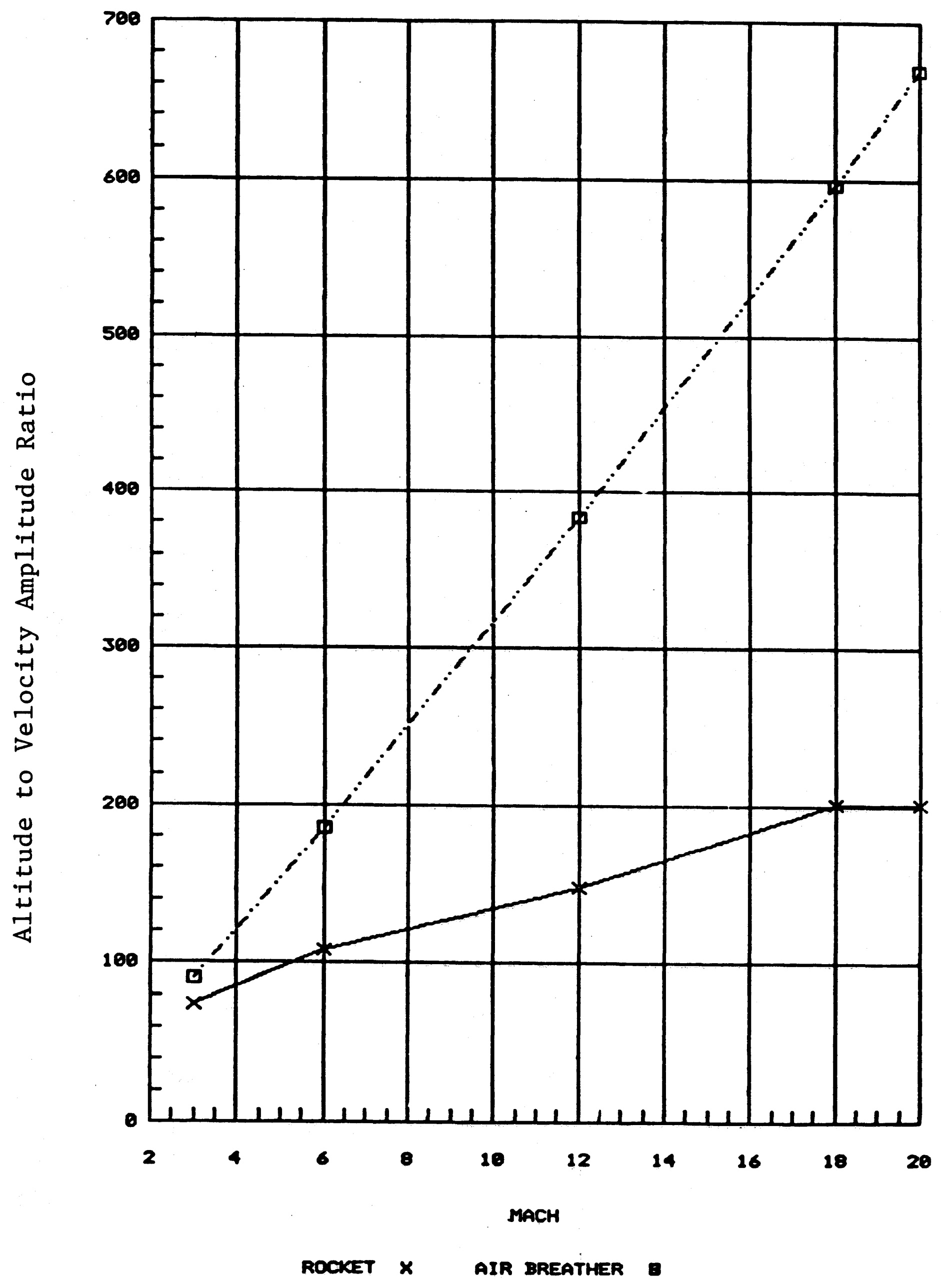

Figure 3.- Altitude to Velocity Amplitude Ratio - Phugoid Mode

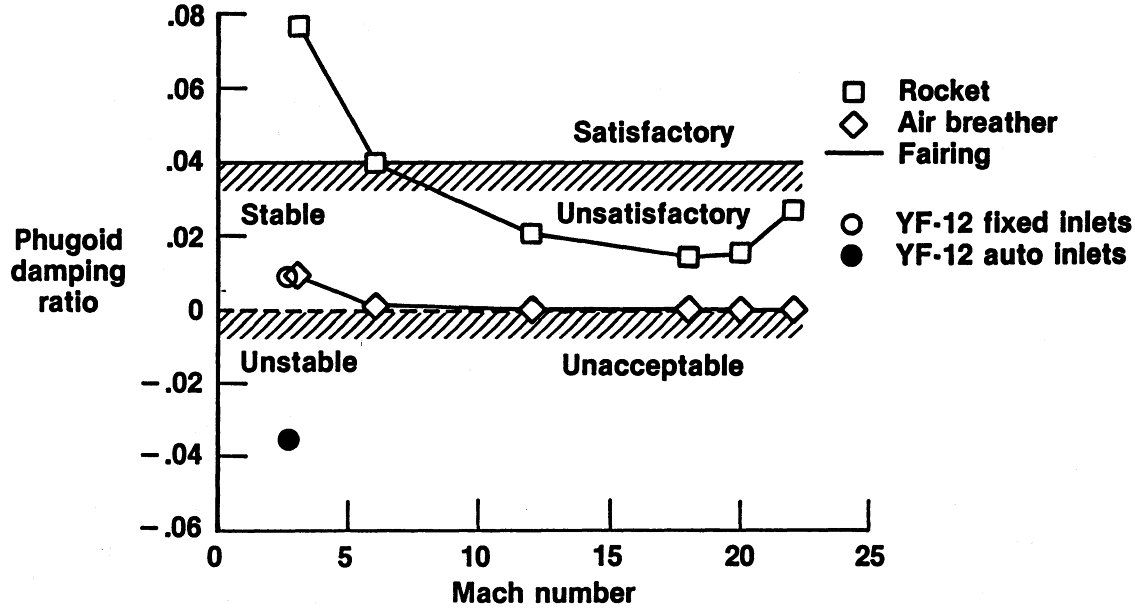

Figure 4.- Generic Hypersonic Cruise Vehicle, Dynamic Pressure = 500 lb/ft^2

No Direct Forward Visibility

In order to achieve the low drag levels required for hypersonic flight, some aerospacecraft have extremely high fineness ratios. As a result, it is virtually impossible to provide direct forward visibility without prohibitive drag or weight penalties. This means that these vehicles must utilize some form of remote or indirect vision. This is particularly critical for landing.

High Leverage Weight/Performance Tradeoffs

Aerospacecraft have an inherently low payload to takeoff gross weight (TOGW) ratio due to the tremendous fuel quantities required for their vast flight envelope. Consequently, a small percentage change in TOGW means a large percentage change in payload. Small changes in empty weight can mean significant changes in vehicle capabilities because of the large increase in fuel to get the increased weight into orbit; or, it might mean the vehicle will not get into orbit at all.

Power-Off Landing Capability

Because of the criticality of weight for orbital capability, the vehicle must have the option of power-off landings so that all fuel can be used to maximize mission performance when necessary. The large, heavy, low-L/D characteristics of aerospacecraft make the unpowered landing task even more difficult, particularly in adverse weather. Characteristics of these landings may include:

- High touchdown speeds
- Steep glide slope
- One landing opportunity
- No-go-around capability
- Energy management in adverse winds
- PIO sensitivity
- Unmanned missions

B. FUNDAMENTAL ISSUES

Manual vs. Automatic Control

Although sophisticated flight controls will be required to stabilize and augment the vehicle, it is felt that none of the aerospacecraft tasks will require automatic control and that the pilot can manually fly the vehicle throughout the flight envelope using state-of-the-art control and display systems. This is not to say, however, that this is the optimum arrangement, only that it is possible. This means that the role of the pilot is a fundamental issue in aerospacecraft and much thought will be required to determine the best use of the pilot. If the pilot's capabilities are used as a backup to automatic systems, the complexity of the systems required for redundancy management may be substantially reduced. However, this will introduce additional constraints on flying qualities to allow manual takeover of a degraded vehicle.

Spacecraft Interface

An interesting question is the vehicle "interface" between atmospheric and space flight. Should the flight controls for aerodynamic and space flight be designed by the same team or broken up into two groups, one with spacecraft background and one with aircraft background?

Experimental vs. Operational Vehicle

Another fundamental issue is whether the aero-space plane is an operational or experimental vehicle. In an experimental vehicle, large uncertainties are expected and a conservative approach using the pilot as a backup for simple but highly reliable design approaches might be best. In an operational vehicle, with a better database in hand, more emphasis might be placed on sophisticated automatic flight systems optimized for best performance.

Another aspect of operational capability is the ability to handle off-nominal and/or degraded situations such as bad weather. Crosswinds, wind shear, poor visibility, short runways, etc., are particularly critical for the terminal area energy management and landing phase. Shuttle operations have not been able to attain such capability, in large part due to marginal flying qualities. This can significantly impact the cost of operation.

C. Historical Background

Since it is both aircraft and spacecraft, the aero-space plane inherits all the strengths and weaknesses of flying qualities knowledge of both aircraft and spacecraft. In the conventional aircraft field, a large body of data and experience exists and significant strides have been made in understanding the effects of time delays, control sensitivity, artificial feel, command augmentation systems, and flight path overshoot. However, definitive design criteria for these factors have yet to be adopted. In addition, it has been well established that design requirements are very sensitive to task definition. So, it is not known how applicable present criteria are for aerospacecraft tasks.

The body of knowledge for spacecraft flying qualities is very sparse compared to conventional aircraft. X-15 and Shuttle experience has contributed some knowledge on the aircraft/spacecraft interface.

The XB-70 and YF-12 programs have provided valuable insight to the influence of airframe-propulsion interactions on a high-speed vehicle. However, these effects are expected to be significantly more pronounced on an aerospacecraft.

D. CURRENT CRITICAL RESEARCH NEEDS

On the basis of this review, several critical research needs have been determined. These needs are summarized below:

Determine basic vehicle modes of motion and their sensitivity to propulsion system parameters and atmospheric disturbances.

Determine the basic landing characteristics of aerospacecraft, powered and unpowered, during adverse weather and runway conditions, considering visibility requirements and possible unstable airframe, longitudinally and laterally.

Conduct piloted simulations to determine meaningful tasks for aerospacecraft.

Determine flight path precision required to remain within thermal and propulsion system constraints.

Develop criteria for:

* flight path control in landing
* flight path control in hypersonic flight
* phugoid and height mode stability
* allowable propulsive forces, moments and coupling
* response to atmospheric disturbances

E. FUTURE TRENDS AND CHALLENGES

Automation

It is anticipated that the current research needs will be primarily directed toward a research vehicle (X-30) where the emphasis will be on manual control, simplicity, and robustness. For the future, lessons learned from the X-30 will be directed at providing a more sophisticated optimized high performance vehicle. To achieve either form, the tradeoffs between manual and automatic control will have to be studied. The role of the pilot in an automated vehicle will have to be determined. The influence of the micro-g environment on the pilot's abilities will have to be considered.

Orbital operations

Criteria for orbital operations, such as rendezvous, docking, reentry, orbital plane change, and skip, need to be established. In addition, criteria are needed for the interface between aerodynamic and spaceflight where reaction controls and aerodynamic control are equally effective.

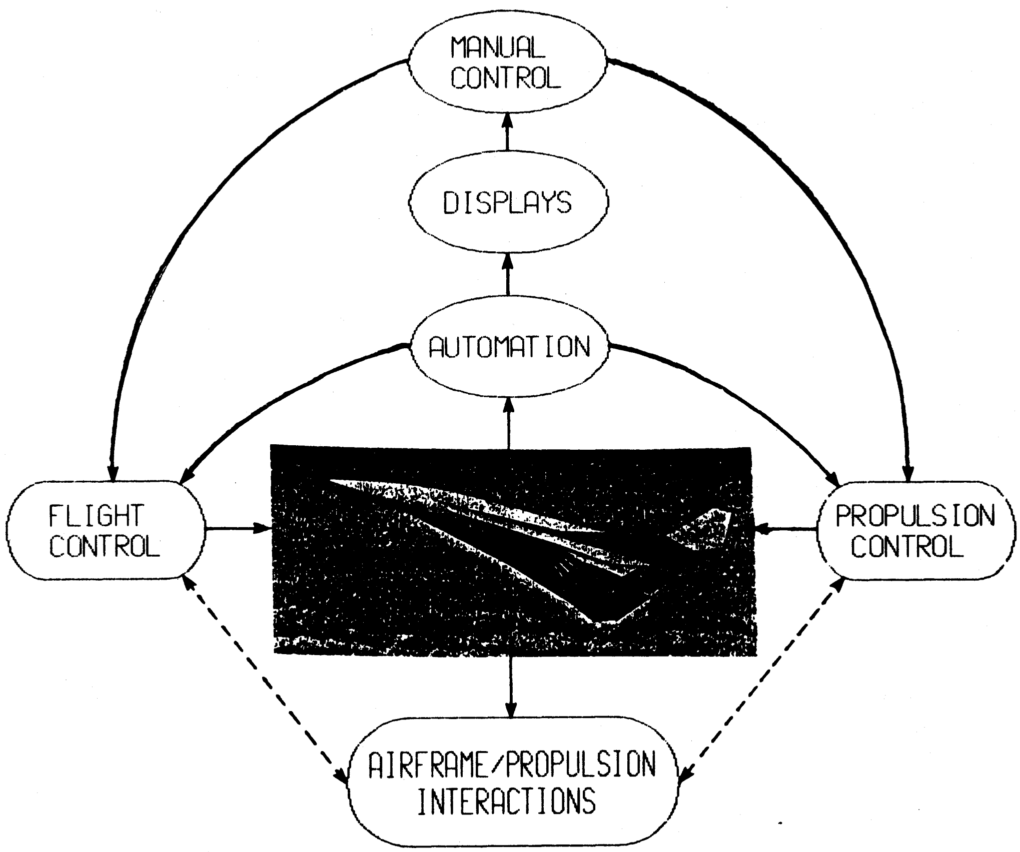

Figure 5.- The Integration Challenge

Integration

To achieve high levels of performance and safety, the vehicle will have to be integrated (Fig. 5) to a degree never before achieved. The airframe, propulsion system, flight controls, and pilot displays must be harmonized in order to control unfavorable interactions and utilize favorable ones. The pilot must be able to take over gracefully in case of system failures and have information at hand to make intelligent decisions.

RELATED RESEARCH OVERVIEWS

IMPORTANCE OF GENERIC FLYING QUALITIES RESEARCH

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This section addresses the need for generic, as differentiated from configuration-specific, research in flying qualities. NASA, the military services, and industry continue to perform advanced development projects and research related to specific mechanizations of aircraft systems. The question is whether or not such work provides a sufficient knowledge base for the design of aircraft to meet envisioned new operational and performance requirements.

Several viewpoints can be taken. The adequacy of today's aircraft is the result of a combination of the following: advances through flying qualities research (as exemplified by MIL-F-8785B and C, and MIL-STD-1797, the pertinent US Military Specification) applied to evolving techniques of flight control system design; extensive use of vehicle-specific piloted simulation in the development of all new military and commercial aircraft; and after-the-fact operational limitations or fixes of flying qualities deficiencies discovered during developmental flight testing and initial operation (a necessity more often than not). Extensive simulation is costly, and downstream modification is even more so. As performance demands increase, so does the cost of meeting flying qualities requirements in development time, dollars, range, payload, observability, etc. New mission requirements (for example, National Aerospace Plane and shipboard basing of VSTOL aircraft) have no database for flying qualities design. Data gaps exist even for conventional aircraft. While vehicle-specific technology programs such as the AFTI-F-16 Automated Maneuvering Attack System show significant improvements in operational capability, these aircraft remain nonoptimized, point designs which give minimal guidance for future design. Cost constraints inevitably limit the scope of both the design and the flight evaluation. Furthermore, detailed assimilation of even that capability by the rest of the aircraft design community is not widespread.

Generic research is the foundation of current flying qualities criteria, developed largely in the U.S. and used worldwide. However, developments in multi-input, multi-output optimal control design methods and digital technology have outpaced flying qualities expertise. Application is limited by the insufficiency of criteria to use with advanced control techniques (and, it must be added, by some lack of appreciation for the applicability of present flying qualities criteria to them). While the present database applies to quite an extent, in some important cases the criteria have been found inadequate or nonexistent for new tasks or new control concepts. For example, large command inputs with high-gain feedback can saturate the control system, causing the aircraft response characteristics to vary with the command magnitude. The tolerable amount of this in various tasks is an unanswered question. Designers need generic criteria, based on more than what worked in a given specific case.

A flight control system can augment stability and control characteristics of the basic airframe only as much as available control power and rate allow. Thus, flying qualities criteria remain crucial to design tradeoffs. With an escalating performance price to be paid for flight control power and rate capability, reasonably precise criteria are needed even in the conceptual and preliminary design stages. A rather small error could put the design far off optimum and be very costly to correct down the line. But for current design needs, available criteria relating to flying qualities are not adequate. Such criteria must be of a parametric nature, which implies that generic research is needed. An example is the sparsity and ambiguity of available data on use of blending direct lift with pitch control for approach and landing.

Active control technology, including integration of flight control with other subsystems, is seen as necessary to get the increases in operational capability required of new aircraft (i.e., semiautomatic fire control, structural load relief, flutter suppression, maneuver enhancement, ride control, etc.). In both normal and failure situations, these applications all either directly or potentially impact flying qualities, but only a very few vehicle-specific implementations are available to guide the designer. It is a long and costly process, therefore, to incorporate this necessary technology in a new aircraft. The timing thus works against optimization, since knowledge will not be adequate before the design freeze. While display details, engine dynamics, etc., generally have unique features, nevertheless design-usable, task-oriented methods and criteria could greatly speed and strengthen the design process. Vehicle programs such as the X-29 can only investigate the characteristics of the particular aircraft. Even small changes to digital flight control systems have proven costly in time and effort. Analysis and criteria, however, are inherently of a generic nature.

Extensive development and validation are needed if even the analytical approach is to be accepted as a way of stating design requirements. Yet pilot-vehicle capability is certainly the end product. Pilot-vehicle analysis may furnish the only way to give requirements the generality needed to encompass the wide variety of tasks and design realizations. Generic research of several types is needed. Basic tools need enhancement: pilot models for multi-input, multi-output tasks; workload assessment and measurement, for the entire pilot task and environment as well as for flying the aircraft. The cues a pilot needs/uses in particular tasks need better identification, and the dynamic pilot/automation/display interface has so far only been touched lightly. Simulator limitations produce discrepancies with flight results. For example, the YF-16 "unofficial first flight" would not have been a near disaster had the simulator provided correct control gains. But the characteristics of most ground-based simulators are poorly documented. Calibration of simulator flying qualities vs. flight and improved simulation capability for such critical tasks as hover and nap-of-the-earth rotary-wing operation are necessary for both research and aircraft development. Task-tailored flying qualities offer the prospect of improved operational capability, but the task-specific database is grossly inadequate. Another unanswered question is the blending of these tailored control laws: how far can pilots reliably and safely adapt to multiple control modes? Present flying qualities criteria for the stall/spin/departure area are largely qualitative and of limited help to a designer, especially when designing for extended maneuver capability. The other sections of this paper list more specific flying qualities problems of a generic nature.

In questioning aircraft manufacturers or government project offices on the need for continuing generic flying qualities research, one finds a conflict of interest--"our product is the best, and we certainly know how to design it"-- so admitting a need for further research can be difficult. Similarly, some flying qualities requirements which have been accepted despite the inadequacy or lack of a database may become design drivers for certain configurations. Heavy reliance on simulation, supplemented by adjustments during flight tests, are commonly relied upon to produce good flying qualities. For example, even experimental and technology demonstrator aircraft development (the X-29 is a case in point) typically involve multiple simulations at various facilities, endless comparisons and much work to explain or rationalize differences. While (with some notable exceptions) that approach has worked, it provides little or no early design tradeoff capability and is costly in time and funds. Recent history, furthermore, abounds with examples of unexpected setbacks because of the limitations of the simulator as a design tool.

A perhaps inherently generic factor that must be addressed is to provide feasible, valid, cost-effective means of verifying compliance with new flying qualities criteria from conceptual and preliminary design through simulation and flight test.

The all-too-prevalent concept that "the flight control system can do it all" begs two fundamental considerations:

- Specifically, what to do, and what not to do, for adequate flying qualities

- Practical limitations such as flight control system stability limits, control saturation and structural interactions

Solving these problems through trial and error in aircraft design is a long, costly, grossly suboptimal way to go. Generic research requires some funding up front, but its cost will soon be recovered in downstream savings, enhanced mission effectiveness or even prevention of failure.

THE NEED FOR AN IMPROVED THEORETICAL UNDERPINNING FOR FLYING QUALITIES

David K. Schmidt, Professor
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In the flight dynamics literature, problems such as the following are noted with existing vehicles and are also anticipated with future systems:

1. Differences are cited in the time delay allowable for acceptable man-machine performance in various tasks.

2. New technology, such as artificial intelligence (AI), will present significant man-machine problems.

3. Though they represent the latest in flight control technology, vehicles such as the Shuttle, YF-16, and F-18 have suboptimal dynamics from a flying qualities perspective.

4. The trade-off between controls and display is not well understood, nor is there an accepted design procedure for active displays.

5. Our ground-based simulators have insufficient fidelity, yet they are still used in design.

6. We do not know what the most appropriate vehicle responses are in any task more complex than simple precision pitch-attitude control.

The burning question is, "Why?"

The reason lies in the fact that we do not fundamentally understand the basic man-machine system in general and the dynamic interactions in particular. For example, what responses are being primarily controlled in the various tasks, and what loops are the human closing to affect his control action? As noted in the recent Wright Brothers Lecture by Harper and Cooper, the variables the pilot is sensing and acting on are not understood, and furthermore, these "loop closures" are different in different portions of the tasks. This is the situation that exists today with the "traditional" tasks of continuous vehicle control. Understanding the dynamic interaction of man and machine becomes even more imperative with the introduction of AI in the cockpit and the human's task changing to intermittent control, supervisory decision making, and continuous control after a system failure.

To respond to these challenges and to be able to actually utilize our technology to optimize man-machine performance, we must aggressively pursue research addressing the more basic issues of quantitatively defining the tasks and key dynamics, along with identifying human strengths and limitations in these tasks, so as to optimally design the machine. In other words, we must address the fundamental questions in man-machine dynamics. In doing so, not only can we draw from the extensive systems theories, but operations research tools (such as queuing theory) are available to model the man-machine system in new tasks (such as supervisory decisionmaking). Efficiency is enhanced by keeping the focus on developing fundamental understanding since wheels will not be reinvented in the design of specific systems, the design process will require fewer expensive iterations late in the design cycle, and experimental investigations can be more crisply defined. Therefore, the quality and quantity of the results per unit cost will be enhanced.

PILOTED SIMULATION FOR HANDLING QUALITIES RESEARCH STATUS AND POTENTIAL

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A. BACKGROUND

Since a great deal of handling qualities data is obtained from ground-based and in-flight simulation, the question of the validity of existing and future simulation facilities was raised numerous times during the workshop. In this article, we explore the current status of ground-based and in-flight simulators available for handling qualities testing and propose an approach to resolve limiting deficiencies.

The use of simulators for handling qualities research can be divided into three categories:

1. Development of criteria for handling qualities specifications.

2. Prediction of flight characteristics of new aircraft in an environment which allows test pilots to experience unexplored regions of the flight envelope prior to testing the actual hardware.

3. Design and evaluation of control laws and displays in a controlled environment.

Each of these categories is accomplished using both ground-based and in-flight (variable stability) simulation. Ground-based simulators provide a highly controlled environment but suffer from less than perfect visual and motion cueing. Ideally, a first-cut result is obtained in the ground-based environment and subsequently refined with a variable-stability experiment. Unfortunately, in practice, funding limitations usually do not allow the luxury of in-flight simulation, and, when it is available, the high cost of in-flight simulation often results in less than adequate time for familiarization and repeat runs to the point where the data is of questionable validity. In addition, in-flight simulation has specific shortcomings which must be resolved, even if adequate time can be allocated to the experiments.

B. CURRENT STATUS - GROUND-BASED SIMULATION

Visual Systems

The most commonly used visual systems consist of the camera-model system (cms), and computer-generated imagery (cgi). Essentially all modern simulators employ the cgi approach because of its flexibility and capability for producing a sharper image. The primary limitations of the cgi are time delay and inability to create sufficient microtexture (fine-grained texture).

While time delay is acknowledged to be a significant problem in achieving adequate simulation fidelity, there has been little fundamental research into how much can be allowed before the results are compromised. Current piloted simulations run with time delays as high as 220ms, whereas a value between 80 and 100ms is considered as acceptable (although there is little data to support this "rule of thumb").

The availability of microtexture as a fundamental cue for precision control has been inferred from several experiments and seems intuitively correct. Such experiments have been considered low priority (read low budget) and frequently are simply observations from tests with other objectives. As a result, the assertion that microtexture is a primary cue is not based on data that can stand the test of close scrutiny, or be used to quantify how much fine-grained texture is enough. Since microtexture is very expensive in terms of cgi database allocation, a requirement for more of it must be well supported. There are some new visual systems that provide small regions of increased microtexture, based on the pilot's eye-point-of-regard, but no formal comparisons have been made to determine if they improve fidelity.

Motion Systems

The motion systems on ground-based simulators are inherently limited and require washouts to continuously recenter the linkage. Ideally, these washouts are below the human operator's detection threshold, although this is not always the case when aggressive tasks are simulated. As a result, there are frequent (but always undocumented) pilot comments related to a lack of consonance between the visual and motion systems, even to the point of inducing motion sickness in experienced test pilots.

Impact of Current Simulator Deficiencies on Results

Current simulators are essentially an exact replication for tasks involving flight in instrument meteorological conditions (IMC), or nonprecision visual tasks. They tend to be less valid for precision tasks with respect to outside cues (e.g., landing, hovering, and air refueling) or when aggressive maneuvering is involved. For example, the results of simulations to determine acceptable handling characteristics for precision STOL and CTOL landings have resulted in questionable data. In one STOL simulation using a variable stability aircraft, comparisons of the same configurations with flight test results showed that the touchdown sink rates were significantly higher in the simulator and that the pilot ratings differed considerably. For that reason, only in-flight simulation results were considered as supporting data for the landing criteria in the proposed MIL-Standard and Handbook (replacement for Mil-F-8785C).

Ground-based simulation results for aggressive maneuvering tasks are questionable because of erroneous motion cues and limited field of view in the visual systems.

Piloted simulation results for tasks involving low-speed and hover (helicopters and VSTOL) have been at significant odds with results obtained from flight tests using a variable-stability helicopter and operational experience with the AV-8B Harrier VSTOL. Specifically, the predicted stabilization requirements necessary to accomplish precision hovering tasks tend to be overly severe in the ground-based simulator. For example, the results of several ground-based simulations indicated a requirement for attitude-command-attitude-hold, whereas the in-flight results indicate a simple rate response is not only adequate but desirable. This deficiency has been overcome on some simulations by presenting flight director-type information on a head-up-display (HUD), relegating the cgi to the role of status information (i.e. the pilot does not close loops on it). Unfortunately, little can be learned about the required handling qualities from such an experiment.

C. CURRENT STATUS OF IN-FLIGHT SIMULATION

Fixed Wing

The state of the art of in-flight simulation for fixed-wing aircraft is reasonably well developed. Most of the problems in this area are associated with the high cost of in-flight simulation and the lack of variable stability aircraft with adequate performance envelopes.

Most in-flight simulations are either too ambitious or are under funded. This results in a lack of adequate familiarization time with each new configuration, including time to determine the best control sensitivities. Note that erroneous control sensitivities can completely mask the dynamics, resulting in excessive intra- and inter-pilot rating scatter. The number of repetitions allowed is usually very small. For some flared landing experiments this has reduced the total exposure time to less than 30 sec. There are currently no accepted guidelines which set standards for the number of required repetitions, or for time required to obtain valid subjective pilot rating data. The development of such guidelines is not a trivial exercise and would require a focused effort with appropriate funding.

Current in-flight simulators have limited flight envelopes (e.g., variable stability T-33, TIFS, and Lear) and are of limited use for obtaining data for aggressive maneuvering or STOL landings. The primary use of two of the three existing fixed-wing variable stability aircraft is for training at the Test Pilot Schools, with research being accomplished as TPS projects or on a noninterference basis.

D. RESEARCH REQUIREMENTS

Ground-Based

The actual capability of ground-based simulators is a hotly contested issue and there is significant resistance to investigating and documenting simulator validity. While some work has been done in this area, it suffers from lack of focus, minimal funding, and general disagreement where simulation validity is concerned. Very little data related to simulation validity is in a form which is referenceable.

The hardware sophistication for ground-based simulation is improving rapidly, especially in the areas of computing power and computer generated imagery (cgi). While great sums of money are being invested in new hardware, there has been little effort invested in establishing quantitative requirements. Such requirements are needed to establish specific goals and direction for future hardware development and to assess the value of new developments currently being advertised. The following specific requirements need to be established for fixed-wing and rotary-wing ground-based simulators:

Maximum allowable values of time delay for specific tasks

Minimum acceptable field of view for specific tasks

Minimum microtexture (probably in terms of spatial frequency and depth of modulation) for specific tasks

Specific motion system requirements for selected maneuvers and various levels of aggressiveness

The work necessary to establish these requirements is not trivial and will require a strong commitment from the highest levels of management at NASA. Research programs required to accomplish the above-noted objectives are outlined below.

Time Delay. Systematic variations in time delay need to be evaluated for the most critical tasks (which must be determined). Such variations must be accomplished using a simplified visual scene and the fastest possible computer so that sufficiently small values can be achieved. The simulated aircraft and feel system must be idealized and should place the minimum possible computing requirements on the mainframe computer. Separate requirements should be established for rotary and fixed-wing aircraft. Of course, the most advanced cgi obtainable should be employed.

Texture. A determination of the necessary microtexture will require a combination of simulation and flight testing. Possible approaches to be explored are:

1. Simulation--Utilizing the largest cgi database available, create a small area with the maximum possible microtexture. Systematically vary the depth-of-modulation, spatial frequency, and field-of-view for the most critical tasks (to be determined).

2. Flight Test--Vary the depth of modulation, spatial frequency (these two make up what is normally referred to as the modulation transfer function (MTF)), and field of view in a flight test environment. Systematically vary the MTF by means of specially designed lenses to be worn by the pilot. The feasibility of this approach has been investigated for rotary-wing hover tasks and found to show great promise. Compare the results of the simulation and flight tests for constant MTF and field of view.

3. Motion Effects--Systematically vary the motion system variables, and aggressiveness of the tasks found to be most critical. Note that the most critical tasks are typically those requiring aggressive piloting technique. This is, however, not always the case. For example, a simulator with large lateral travel (e.g. the NASA Ames FSAA) can produce significant miscues for a simple coordinated turn. Utilize different simulators to investigate the effect of travel in each axis (for example, the NASA Ames VMS for the vertical axis and the NASA Ames FSAA for the lateral axis). Determine the amount of miscue required to affect the piloted evaluations and/or to induce motion sickness.

The above factors are not independent, a fact which may require iterative testing. For example, the addition of significant microtexture will probably result in a requirement for less time delay.

At least five pilot subjects should be utilized for all of these experiments and sufficient training time and repetitions must be allowed so that these issues are guaranteed not to be a factor in the evaluations. This will require that this project have substantial priority.

Recognizing that some research has been conducted in each of the above areas in the past (albeit fragmented and poorly documented), the first phase of the program should consist of gathering and assessing all existing published and unpublished data and developing a program plan. This phase should include systematic evaluations of the latest state-of-the-art simulations in the free world. These examinations should consist of quantitative measurements of the visual system time delay, field of view, MTF, and motion system characteristics, as well as qualitative piloted evaluations for specific tasks.

In-Flight Simulators

The in-flight simulators available for handling qualities research in the U.S. are badly outdated and/or are excessively limited in terms of their flight envelope. For example, development of requirements for the revision to the rotary wing specification (MIL-H-8501A) necessitated extensive use of the Canadian NRC variable stability helicopter which, while limited, is probably the most useful facility available. Many of the requirements in the latest upgrade to the fixed-wing handling qualities specification (MIl Standard and Handbook) are poorly substantiated due to a lack of data representative of modern fly-by-wire aircraft.

Unlike ground-based simulators, the technology for in-flight simulation is well developed. The primary obstacle to development of the required fixed and rotary wing variable stability aircraft is that the need for such facilities has not been established at levels of NASA and DOD management that can make a difference.

E. SUMMARY

Simulation validity is an emotional issue and strong support from top management will be required to substantially improve the current situation. Current ground-based simulators are valuable for estimating trends in most, but not all, cases. Variable-stability, in-flight simulation is required to obtain specification quality data and flight control system design guidance. Current in-flight simulators have excessively limited flight envelopes. This minimizes their usefulness for developing handling qualities requirements for modern fixed and rotary wing aircraft.

FLYING QUALITIES TESTING METHODOLOGY

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A. BACKGROUND

The flying qualities of an aerospace vehicle are an expression of the "goodness" or quality of the interaction between the pilot (human controller) and the vehicle (controlled element) in the context of performing particular tasks in a specific environment with that vehicle (Fig. 1).

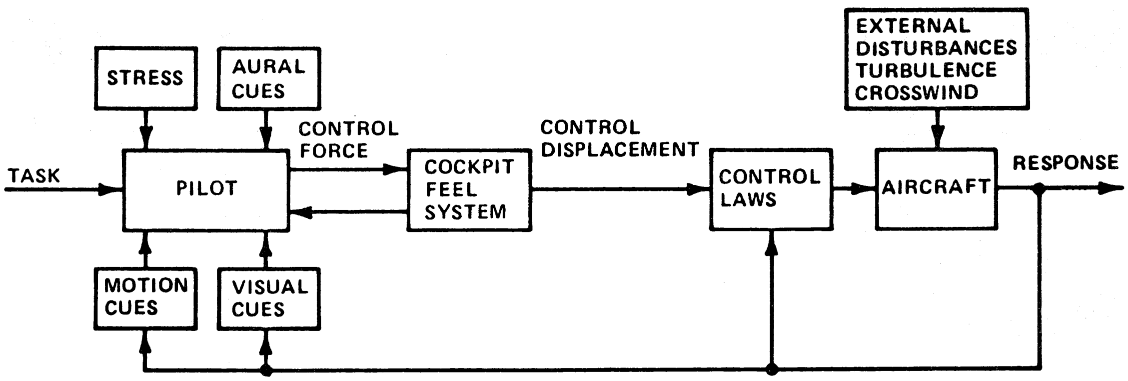


Figure 1.- Pilot-Vehicle Dynamic System

The qualities are rated by the pilot, who is the flying qualities evaluator, for their degree of goodness relative to two criteria, namely closed-loop performance and pilot workload. Such assessments by the pilot are embodied in qualitative comments which discuss the specific nature of the piloting issues or factors which lead to the assessment and are summarized in numerical pilot ratings using the Cooper-Harper rating scale (Fig. 2). There is also continuing effort aimed at developing alternate, more objective metrics for flying qualities than pilot assessment although, to date, the latter is still the most effective. Flying qualities information is utilized by designers and flight test groups to assess success of a total vehicle system design relative to pertinent customer specifications, to grade the merits of competing design options, to determine the need for design refinements, and to provide a database to guide future designs. Development of a database to support flying qualities design requirements, in particular, depends on the data being of a sufficiently generic nature to maximize their applicability to a variety of airplane-flight control configurations. However, design guidance may still be limited for many specific aircraft designs and, hence, flying qualities testing must also be performed during the design development.

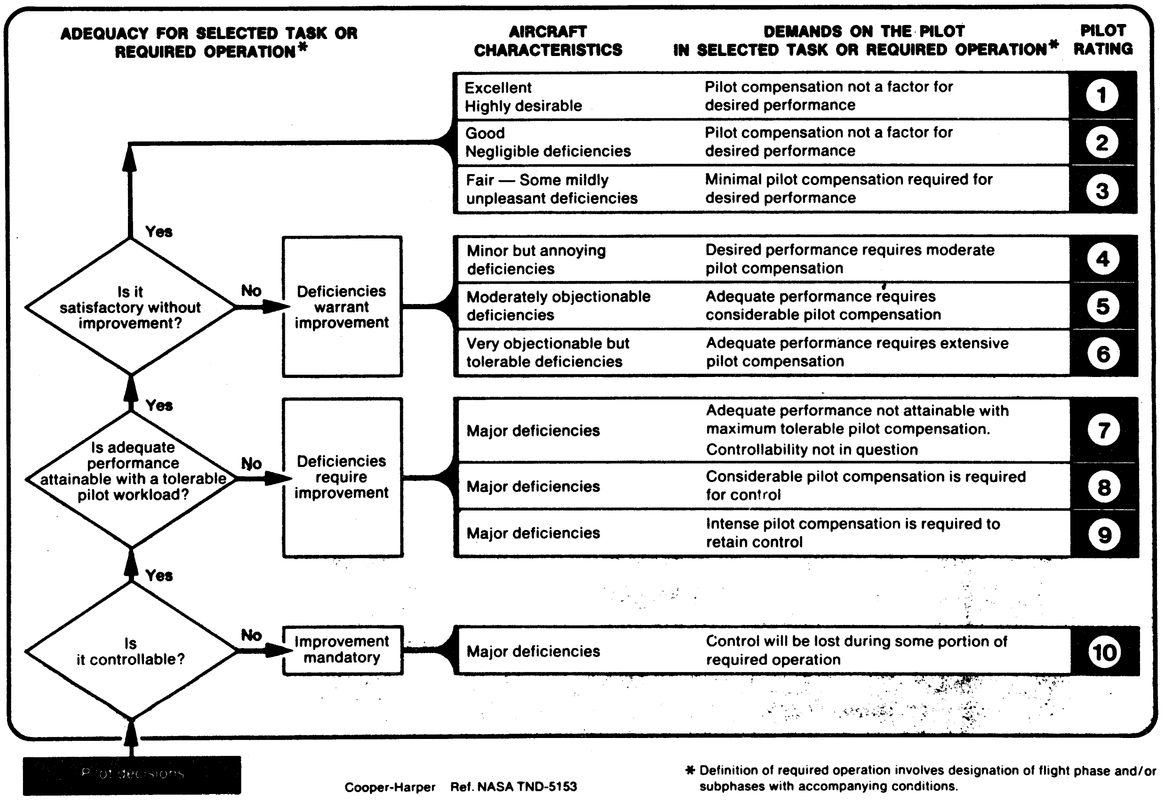


Figure 2.- Handling Qualities Rating Scale

Over the years of flying qualities research and development, a process has evolved which makes complementary use of various flying qualities assessment tools to impact designs in a timely fashion. One tool is analytic but empirical in nature in that it requires matching the subject design to an existing vast database resident in MIL-Specs and other documents to try to predict flying qualities. Another analytic tool is the application of a variety of closed-loop criteria that make use of pilot compensation models and stipulated loop closures appropriate for given piloting tasks to assess closed-loop performance for varying levels of compensation and required pilot-vehicle bandwidth. The predicted flying qualities are generated by reference to previous correlations with in-flight experiments. The ground-based simulator is a commonly utilized pilot-in-the-loop tool which presents a cockpit environment, an artificial visual scene and either motion base or a fixed base as the cueing platform relative to which the pilot performs his flying qualities assessment. The artificiality of the visual and motion cues may significantly affect the piloting cue environment and, hence, the pilot's control strategy and his flying qualities assessment. Finally, the tool with the highest level of fidelity is the in-flight simulator where the cueing environment consists of the real-world visuals, full-scale real and sustained motion and the feasibility of uncompromised piloting tasks.

Although these tools for generating flying qualities data yield significant differences in fidelity, they can and should be used in a complementary fashion either progressively or intermingled in the course of planning and executing a flying qualities experiment (Fig. 3). One must be cautious in how and when the tools are used, mindful of their advantages and limitations. Often, the decision on their use in a given experiment is based on perhaps shortsighted economic considerations or ease of access rather than on technical merit. Yet, the credibility of the flying qualities results may strongly depend on the fidelity of the tool utilized for the assessment.

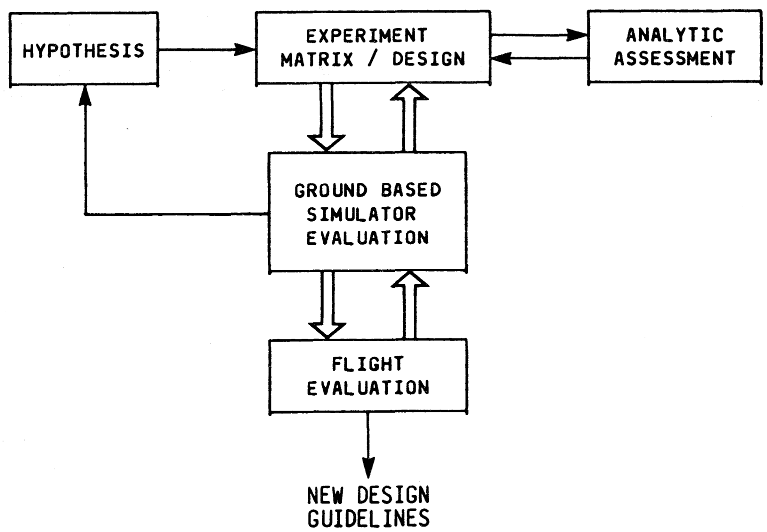


Figure 3.- Flying Qualities Data Used in Planning and Executing a Flying Qualities Experiment

A recent project conducted by Calspan for the U.S. Air Force will be utilized to illustrate a flying qualities research methodology. The investigation was sponsored by the USAF Human Resources Laboratory, the Simulation SPO, USAF AMRL, and USAF AFWAL. It made use of ground-based and in-flight simulation tools for pilot-in-the-loop assessment, not in the build-up or progressive sense but rather in the intermingled fashion, since the comparative results were in themselves an objective of the study. For both the ground-based and in-flight scenarios, the USAF/AFWAL variable stability NT-33A was utilized (Fig. 4).

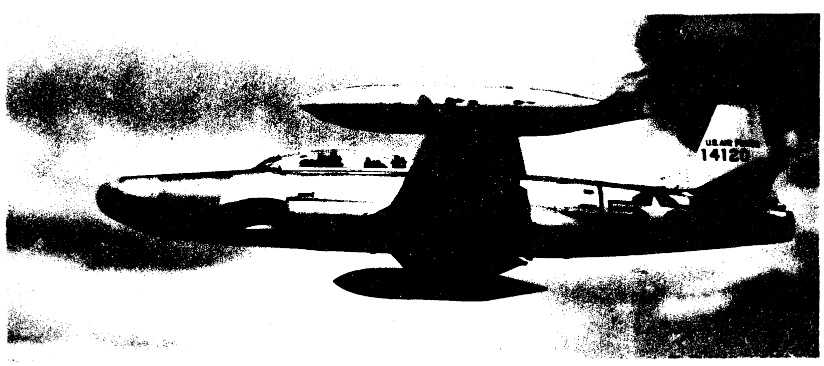


Figure 4.- USAF/AFWAL Variable Stability NT-33A

B. HYPOTHESIS OF THE STUDY

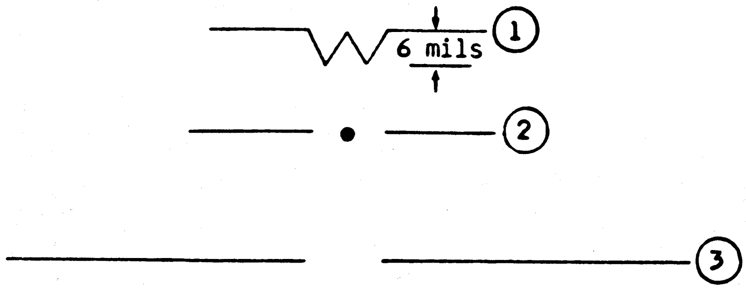
Based on past data and experience, it has been apparent that the effects of time delays in a ground simulator's cueing environment on the perceived flying qualities are a function of the nature of the piloting task performed in the ground simulator and the aircraft dynamics simulated. Therefore, the time delay effects should be closely related to the specific aircraft simulated. The study objective was to develop guidelines for the simulator manufacturers as to the amount of time delay that is permissible in ground simulators without affecting the flying qualities perceived by the pilot and, in particular, for minimum effect on the pilot's control strategy in a given task.

C. TEST MATRIX

Baseline aircraft dynamics representing four different classes of aircraft and piloting tasks were selected and varying levels of time delays were added to these dynamics specifically to the command paths of the pitch and roll axes. Analytic flying qualities prediction criteria were applied to the baseline characteristics (no added delay) to ensure an adequate degree of goodness for tasks appropriate to the respective class of aircraft simulated. A preliminary set of added delays to be tested were chosen based on past experience. These choices were then refined in the calibration phase of the program both in the ground-based and in the in-flight simulation modes. The magnitudes of delay tested were selected to span expected flying qualities thresholds.

D. EVALUATION TASK SCENARIO

Since a flying qualities assessment is totally dependent on the assigned piloting task, considerable effort was expended to define this experiment element to yield the desired form of results. The task environment was the up-and-away flight condition for all four "generic" aircraft. The piloting tasks chosen to yield representative maneuvering of these simulated aircraft were generated on the head-up display (HUD) of the NT-33A (Fig. 5). For each aircraft/time delay configuration, the pilot was required to track, in pitch and roll, a command bar on the HUD programmed with a coordinated sequence of steps and ramps and a separate sequence composed of sum of sinusoids (for pilot modeling analysis). Another task was to regulate the simulated aircraft to level flight as it was continuously upset in pitch and roll. The amplitudes and rates associated with the tasks were matched to the class of aircraft being simulated. Finally, the evaluation pilot performed these tasks under simulated instrument meteorological conditions by using a blue-amber vision restricting system permitting him to view only HUD, both in the ground-based and in-flight tests. Thus, the sole significant cue difference between these two environments was the lack of motion cues in the ground-based evaluations (Fig. 6).



1) "Extended-Wings" Waterline (fixed pipper reference)

2) Command Bar for Tracking Tasks

3) Horizon Line

Figure 5.- HUD Format

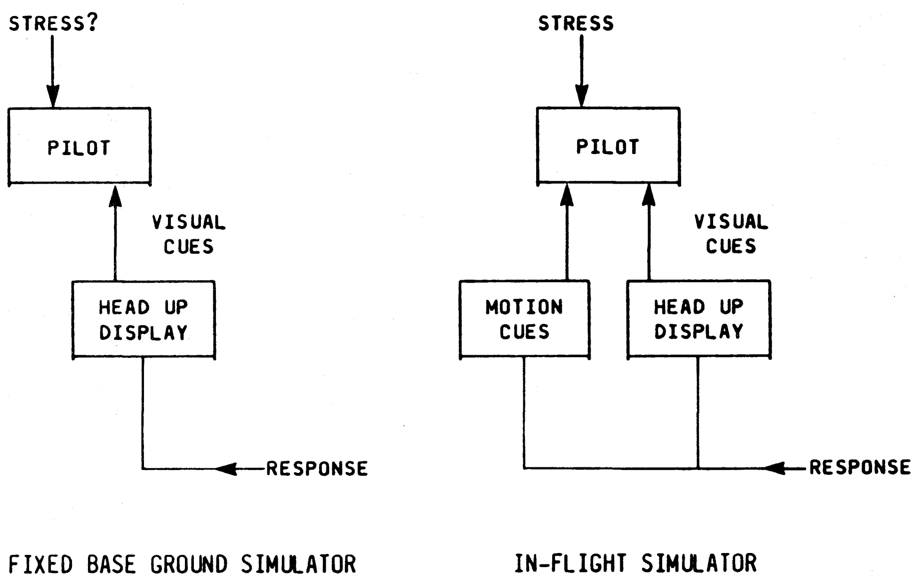


Figure 6.- Experiment Cue Environments

E. CONDUCT OF THE EXPERIMENT

Three experiment test pilots were utilized. Each "flew" a complete series of fixed-base/ground-based evaluations of the generic aircraft--time delay combinations as well as a series of in-flight evaluations all in the NT-33A. When logistically practical, ground-based and in-flight evaluations were chronologically intermingled. For each configuration, the pilot gave detailed comments on salient features of his assessment and then summarized this assessment by assigning a pilot rating based on pilot workload/compensation and closed-loop performance in the assigned tasks. The Cooper-Harper rating scale was used.

F. PRELIMINARY RESULTS

Figures 7 and 8 show some representative results in the form of pilot ratings versus added time delay for two ends of the spectrum of generic aircraft tested; a highly maneuverable fighter and a heavy transport from both fixed-base ground simulator and in-flight eva uations. One should remember that the significant difference between ground-based and in-flight cases was motion cueing. There were, of course, less tangible psychological differences. For brevity, only the pilot rating data will be considered. Some general observations can be made from the pilots' comments. At any given added time delay condition motion cueing appears to have a stronger effect on pilot rating for a maneuverable fighter-type aircraft than for the heavy transport category. In fact, for the fighter case, the motion cues appear to "help" the pilot in his task performance leading to better average ratings. In the transport case, motion cue effects are clearly weaker. The transport case exhibits thresholds of added time delay before flying qualities degrade; the thresholds are somewhat lower without motion cues, but the rates of degradation after the threshold are about the same. On the other hand, with the fighter case, degradation from added time delay begins at much lower levels of delay both with and without motion cues. In summary, pilot rating is significantly more sensitive to added delays in the fighter scenario than in the transport case, a result which supports the contention of the study's hypothesis. An equally important outcome is the effect of motion cues on pilot rating, potentially on pilot control strategies and, hence, on the fidelity of fixed-base ground simulator versus the in-flight environment as tools for generating valid flying qualities data.

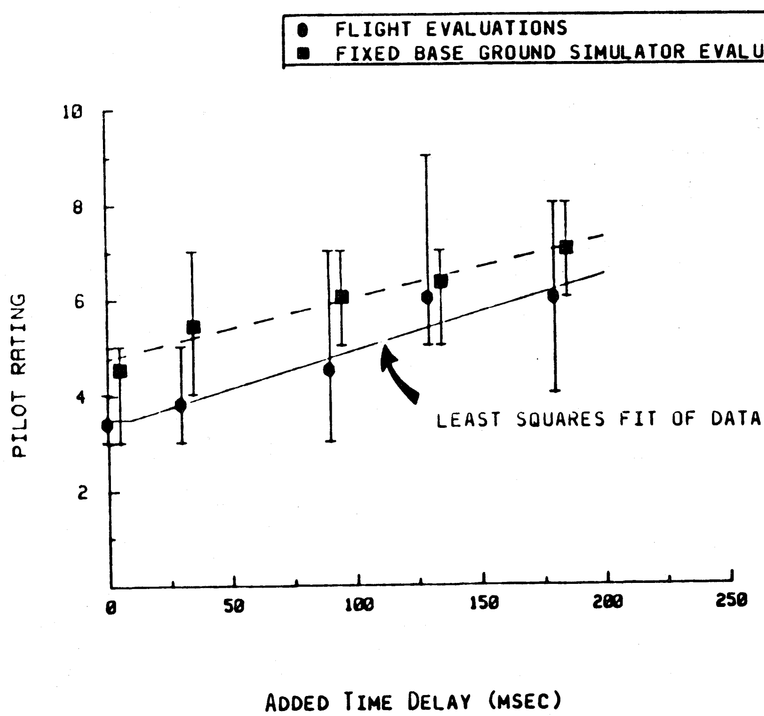


Figure 7.- Effect of Time Delay on Generic Fighter Flying Qualities (Averaged Piloted Rating Plus Rating Ranges)

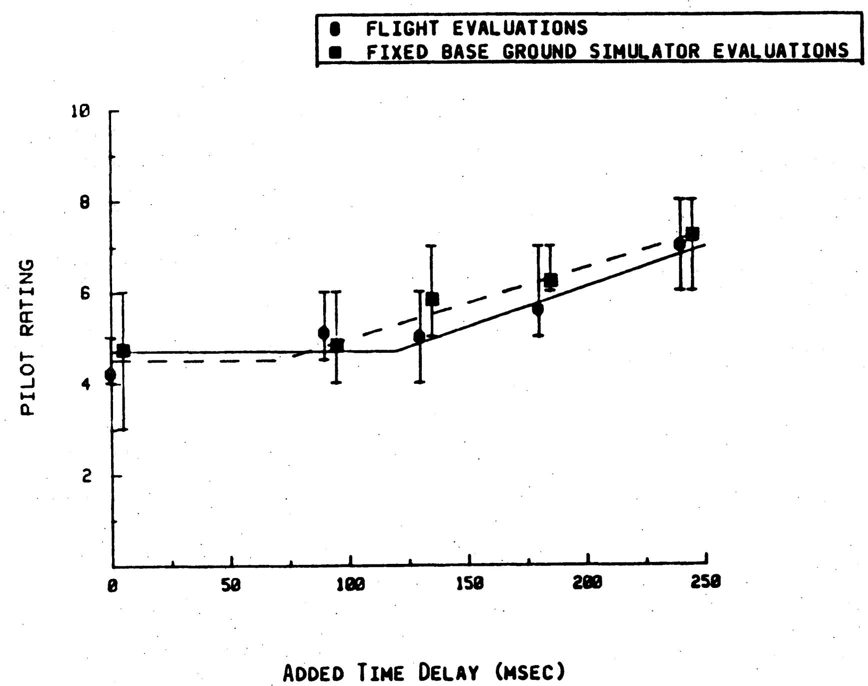


Figure 8.- Effect of Time Delay On Generic Heavy Transport Flying Qualities (Averaged Pilot Ratings Plus Rating Ranges)

This capsule view of a recent flying qualities research project was presented to highlight features of the flying qualities testing methodology as well as shed some insights into some of the tools of that methodology.

CONCLUSIONS

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The overwhelming view is that the cost of "man-rating" aeronautical systems is going to continue to be a prime driver in aircraft design for the foreseeable future. Although flying qualities may not be an economic figure of merit, they are a design constraint. Aircraft will have to have at least acceptable flying qualities before any mission objectives can be considered, and better flying qualities can significantly improve the mission effectiveness. Some configurations and total classes of aircraft will be feasible only if appropriate flying qualities can be defined and achieved. In most other cases, mission performance, safety and reliability are totally dependent upon the pilot's capability to precisely control the vehicle.

There have been many recent examples in virtually all classes of aircraft, where flying qualities related issues have resulted in enormous cost overruns, program delays and even project cancellations. Unfortunately, by the nature of the need to solve problems when behind schedule, the lessons learned have not been successfully applied to next generation aircraft. In addition, specific solutions and results generally are not directly applicable to the next configuration without thorough understanding of the fundamental issues. Projects, flight demonstrations and full-scale development programs inherently do not tend to answer these questions. As a result, all government procuring agencies, airframe manufacturers and consultants in attendance at the workshop agreed that there is a need for flying qualities research programs.

The workshop participants addressed some of the key questions posed by the call to the meeting. An attempt at providing consensus answers follows:

(1) Is flying qualities really a mature discipline? No. The 70 year history of successful flying qualities research belies the belief that flying qualities prediction, evaluation criteria and design guidelines are mature. In fact, in recent times a number of new challenges have come to the forefront and have invalidated many of the past lessons. For example, aircraft are so highly augmented that they no longer fly like conventional aircraft. They are said to have responses which are controls dominated. Designers can generally make them have any response the pilot wants, except that of a conventional aircraft (due to system lags and other limitations). The extent to which the present criteria and guidelines apply is questionable. Additionally, the degree of automation has risen without appropriate guidance on how to integrate the pilot and automatic systems together.

(2) Are there benefits from doing generic research? Yes. Sections of this report have been written on this very question. The distinction is made, however, that what is really needed is class generic flying qualities research. This is an attempt to develop criteria, design guidelines and predictive methods for a given class of aircraft (e.g., rotorcraft or high-performance/combat). Solving problems for a specific configuration typically only generates one datapoint when literally hundreds are needed to develop useful criteria. Generic research experiments tend to develop a database which allows the results to be applied to new configurations with a minimum of extrapolation. The goal is to be able to minimize flying qualities issues and problems after the configuration has been designed and has entered flight test.

3) Can flying qualities be adequately addressed in the design stage? Potentially, yes. In fact, with the major compromises that have been made in recent configurations for low-speed and maneuvering flying qualities, it must. The problem is that flying qualities come from a complex combination of aircraft flight dynamics and controls system design. Furthermore, the heart of flying qualities is pilot preference, which is not an easy function to estimate, predict or consistently reproduce. This makes the problem very nonlinear and stochastic. Fortunately, it is believed that systematic guidelines can be developed to minimize the risk and improve the probability of acceptable flying qualities through careful development of evaluation criteria and predictive methods.

4) Is there an impact to U.S. aeronautical technology if the U.S. does not continue to sponsor flying qualities research? Yes. At a time of escalating unit costs and increased competition from abroad, the U.S. cannot afford to leave unaddressed one of the prime contributors to cost overruns and development delays--unpredicted flying qualities problems. For certain configurations and classes of aircraft, the performance numbers are so similar that deciding votes may well come from the chief test pilots as they choose the plane that "flies the best." Flying qualities significantly impacts how the pilot views the aircraft and how overworked he is achieving its intended mission. The rapid change to highly augmented aircraft has left the current flying qualities database old and antiquated. Sets of new criteria, design guidelines and predictive measures are desperately needed to insure the preeminence of U.S. aircraft technology.

5) Is project-specific flying qualities research sufficient for ensuring adequate flying qualities criteria, design guidelines and methodologies? No. As mentioned above, specific projects typically generate one data point. The goal of these projects is to satisfy a customer or regulating authority as soon as possible, rather than to understand a phenomenon or to generalize the results. Such fundamental understanding and study is needed if a particular solution is to contribute to a database which can be used to generate criteria and design guidelines.

6) Is there something like computational flying qualities which might be easily understood and pursued as a national goal? Perhaps. Predictive methods for flying qualities would enable flying qualities goals to be included earlier in the design process. However, the variable and

stochastic nature of pilot preferences is a difficult concept to integrate with the deterministic approach that design currently takes.

To accurately represent pilot preferences with analytical/computer models will require a great deal of cross-fertilization among human factors, flight dynamics, control design, and flight research. However, it was considered risky by the majority of the workshop participants to expect near-term results applicable to aircraft and control system design. This is an area in which more basic research is needed.

During the symposium each group was asked to summarize their findings. A format of three viewgraphs was suggested and included: 1) fundamental characteristics of the specific class; 2) current state of the art in flying qualities; and, 3) flying qualities research challenges. The actual charts used at the symposium are included as Appendix C. Based upon the workshop discussions, each group was asked to submit a chapter for this document which included the following sections: 1) fundamental characteristics of the specific class; 2) fundamental flying qualities issues; 3) historical background including sample accomplishments and current state of the art; 4) current critical research needs; and, 5) future trends and challenges.

A number of general and recurring issues evolved out of the different group summaries. Some of these consensus issues are briefly discussed below.

Distinction of Class Generic Versus Basic Generic -- Generic research is needed in each class so that new configurations can learn from the lessons of previous ones. If researchers do not take time to understand the fundamental issues, solutions to one problem probably will not be applicable to another.

Need for Usable Task-Oriented Criteria -- Flying qualities criteria of the past were very general and applicable to conventionally flying aircraft over wide envelopes. However, with the advent of highly augmented, controls dominated configurations, the design of systems for specific tasks is required. A major thrust for the future of control systems design is task-tailored controls. Hence, usable task-related criteria are needed.

Opportunity to Provide Optimum Flying Qualities Instead of Merely Acceptable -- The application of modern design tools and advanced computer techniques to the control system should enable the designer to optimize flying qualities early in the design process. Current practice is to provide at least minimum characteristics as established by a design criteria. The flexibility could be used to enhance flying qualities further and increase mission performance and productivity from the pilot's perspective even more.

Need to Link Criteria to Mission Objectives for Effective Advocacy -- Most disciplines can visibly point to "counts of drag," "pounds of fuel," "points of L /D," "pounds of structure," or "dollars" as figures-of-merit by which to measure contributions. Unfortunately, the prime figure-of-merit for flying qualities is related to pilot preference, which is hard to quantify or even explain. So a prime goal of this document and future advocacy efforts will be to help explain the impact of flying qualities upon overall configuration figures-of-merit that program managers, chief designers, procuring agents and accountants alike can appreciate. It is a significant challenge, but has been achieved in several chapters of this document.

Trend Toward Integration -- Aircraft systems and components are becoming increasingly integrated. Systems are becoming so interactive and interrelated that even small changes in one component or design parameter may have far reaching repercussions throughout the design. While this drives the cost of experimentally tuning skyward, it also provides opportunities for significant additional synergistic benefits if integration is done properly early in the design process.

Guidelines Needed for Degree of Automation -- Automation of aircraft systems and operations is becoming more and more prevalent. The role of the pilot is being changed to more of a mission commander rather than a full-time, dynamic controller (servo) inside the overall aircraft control system. Some questions are: What is the best allocation of roles between pilot and automatic systems? How active does the pilot need to be to effectively command the mission? To what degree should the pilot be expected to back-up the system in the event of failures? How effective can the pilot be expected to be switching back and forth from roles as an onboard decisionmaker and as a coordinated servo-mechanism, and how can this effectiveness be enhanced? These are complex issues which need to be considered and worked from several different viewpoints.

Simulation Validation is a Big Issue and Concern -- Ground-based, real-time simulation and flight-based simulation are the basic tools that flying qualities researchers use before the configurations and designs are frozen and prototypes are developed. However, a prime concern is the uncertain degree to which results are actually valid. There is a tremendous dearth of data, in all classes of aircraft, to determine which types of simulations are useful and applicable for which types of tests, and what quantitative simulation characteristics are needed for validity. Validity is definitely a function of task, aircraft, purpose of tests and a host of other important parameters. Basic research in simulation validity is emphatically needed.

Need for Analytical Flying Qualities Models and Predictive Methods -- In order for flying qualities to be considered an engineering discipline capable of influencing aircraft design, analytical/computational algorithms are needed for predicting flying qualities. Once an aircraft can be analyzed and the flying qualities predicted while still a concept, it will be possible to optimize the configuration and controls system for performance while achieving adequate flying qualities. Hence, development of fundamental and installed pilot models and analysis techniques are needed.

This document is just one attempt at a continuing effort describe the challenges and issues that need to be addressed by flying qualities research. The next step is to use this report as a starting point to begin a national effort in coordinating and planning research activities for flying qualities. Each individual research task will become more vital, more widely applicable and easier to advocate or defend. However, describing the problems, planning research and coordinating results is not a one-time activity; it is a full-time, continuing endeavor.

APPENDIX A

FINAL WORKSHOP AGENDA

APPENDIX A

1986 WORKSHOP ON FLYING QUALITIES RESEARCH CHALLENGES

NASA Langley Research Center
Hampton, VA
November 24-25, 1986

AGENDA

Monday, November 24

Opening Remarks

7:30 - 8:15 AM -- Registration
8:15 - 8:25 AM -- Welcome

Dr. J.F. Creedon
Director for Flight Systems
NASA LaRC

8:25 - 9:00 AM -- Call to Action

Workshop Organizational Details
Dr. Steve Sliwa, Workshop Chairman
Deputy Chief, Guidance & Control Division
NASA LaRC

Perspective of Flying Qualities Discipline Research
John DiBattista
Program Manager for Aero & Space Controls Research
NASA -- Office of Aeronautical & Space Technology

Perspective of Flying Qualities Project Research
Terry Putnam
Acting Assistant Director for Aeronautics
NASA -- Office of Aeronautical & Space Technology

Sessions of Invited Presentations

9:00 -10:25 AM Transport Aircraft (Chairman, W. D. Grantham, NASA LaRC)

"Transport Aircraft - Introduction"
William D. Grantham, Senior Research Engineer
NASA-LaRC

"Aircraft Design - Blending the Old with the New"
Bob Meyer, Group Engineer
Lockheed-Georgia

"Flying Qualities Research Needs for Transport Aircraft"
Bill Rickard, Section Manager, Stability and Control Technology
Douglas Aircraft

"Flying Qualities Criteria for Transport Aircraft FCS"
John Schuler, Principal Engineer
Boeing Military Aircraft Co.

"Interpretation of Flying Qualities Requirements for FCS Design"
Ed Rynaski, Technical Staff Engineer
Calspan Corporation

"Flying Qualities, Workload, and Pilot Error"
Irving Ashkenas, Vice President and Technical Director
Systems Technology, Inc.

"Effects of Display Information and Unconventional Controllers on Transport Aircraft Flying Qualities"
George Steinmetz, Senior Research Scientist
NASA LaRC

10:25 -10:30 AM BREAK

10:30 -12:00 PM High Performance/Combat (Frank L. George, AFWAL)

"High Performance/Combat - Introduction"
Frank L. George, Flying Qualities Group Leader
AFWAL

"Flying Qualities Issues from the Air Force Systems Engineering Perspective"
John T. Browne, Stability and Control Group Leader,
Aeronautical Systems Division, AFWAL

"Flying Qualities Issues from the Navy's Perspective"
Tom Lawrence
NASC

"Flying Qualities Issues from the Navy's Perspective"
Robert Palmer
NADC

"Flying Qualities Issues from an Industry Consultant's Perspective"
Charles Chalk, Technical Staff Engineer
Calspan Corporation

"Flying Qualities Issues from an Industry Consultant's Perspective"
Irving Ashkenas, Vice President and Technical Director
Systems Technology, Inc.

12:00 - 1:00 PM -- LUNCH

1:00 - 2:25 PM -- V/STOL (Dr. Victor Lebacqz, NASA ARC)

"V/STOL - Introduction"
Dr. Victor Lebacqz
NASA ARC

"V/STOL Flying Qualities from a Purchaser's Point of View"
John W. Clark
NADC

"V/STOL Flying Qualities from a Purchaser's Point of View"
David J. Moorehouse
AFWAL

"V/STOL Flying Qualities from a Designer's Point of View"
Frank J. Shirk
McDonnell Douglas

"V/STOL Flying Qualities from a Designer's Point of View"
Walter Valckenaere
Grumman Corporation

2:25 - 2:30 PM -- BREAK

2:30 - 3:55 PM -- Rotorcraft (David Key, Army--Aeroflightdynamics)

"Status of the Helicopter Handling Qualities Specification Efforts"
David Key, Chief, Aircrew-Aircraft Systems Division
Army--Aeroflightdynamics Directorate (ARC)

"Defficiencies in the Helicopter Handling Qualities Database"
Roger Hoh, Principal Research Engineer
Systems Technology, Inc.

"Sikorsky Perspective on Handling Qualities Research Needs"
Knute Hansen, Handling Qualities Engineer
Sikorsky Aircraft

"Boeing Perspective on Handling Qualities Research Needs"
Ed Hankar, Handling Qualities Engineer
Boeing Vertol

"Bell Helicopter Perspective on Handling Qualities Research Needs"
Tom Wood, Chief, Aerodynamics
Bell Helicopter

"McDonnell Douglas Perspective on Handling Qualities Research Needs"
Ray Prouty, Handling Qualities Engineer
McDonnel Douglas

3:55 - 4:00 PM -- BREAK

4:00 - 5:00 PM -- Aerospacecraft (Donald T. Berry, NASA DFRF)

"Aerospacecraft - Introduction"
Donald T. Berry
NASA DFRF

"XB70, YF12, Shuttle Experiences Pertinent to Aerospacecraft"
Bruce Powers, Group Leader
Flying Qualities Vehicle Techniques Branch
NASA DFRF

"Industry Viewpoint on the Flying Qualities Challenges for Aerospacecraft"
Ken Barnes, Project Engineer, Hypersonic Technology,
General Dynamics - Ft. Worth

5:00- 6:00 PM -- Generic Ideas - Audience Participation (Dr. Steve Sliwa)

"AGARD Summary of Flying Qualities Research Issues"
Jarrell R. Elliott, Head, Analyical Methods Branch
NASA LaRC

"Research Opportunities in Man/Machine Dynamics - A University Perspective"
Dr. David K. Schmidt, Professor
Purdue University

Audience Interaction & Participation
Dr. Steve Sliwa
NASA LaRC

6:00 - 7:00 PM -- DINNER BREAK (Activities Building)

Working Group Sessions to Prepare Summaries

7:00 - 8:00 PM -- Working Group Session #1

8:00 - 9:00 PM -- Working Group Session #2

There will be five tables set up, one for each group (Transport, High-Performance/Combat, V/STOL, Rotorcraft, & Aerospacecraft). Each participant or speaker should join a group of his or her choice for the first session. Ideally, each participant should join another group for the second session. Purpose of these sessions will be to help group leaders generate 3 summary slides to be presented next day covering the focus area and to volunteer for work assignments for the written report due in January.

9:00 PM -- Retire for the Evening

Tuesday, November 25

8:20 - 8:30 AM -- Adminstrative Details (Dr. Steve Sliwa)

Working Group Summary Reports & Discussions

8:30 - 9:00 AM -- Transport Aircraft (Grantham)

9:00 - 10:00 AM -- High-Performance/Combat (George)

9:30 - 10:00 AM -- V/STOL (LeBacqz)

10:00 - 10:30 AM -- Rotorcraft (Key)

10:30 - 11:00 AM -- Aerospacecraft (Berry)

11:00 - 11:30 AM -- Generic Flying Qualities (Sliwa/Elliott)

Conclusion

11:30 - 12:00 PM -- Plans & Remaining Actions (Sliwa)

12:00 PM -- Adjourn

APPENDIX B

PARTICIPANT LIST AND PHOTOGRAPHS

APPENDIX B

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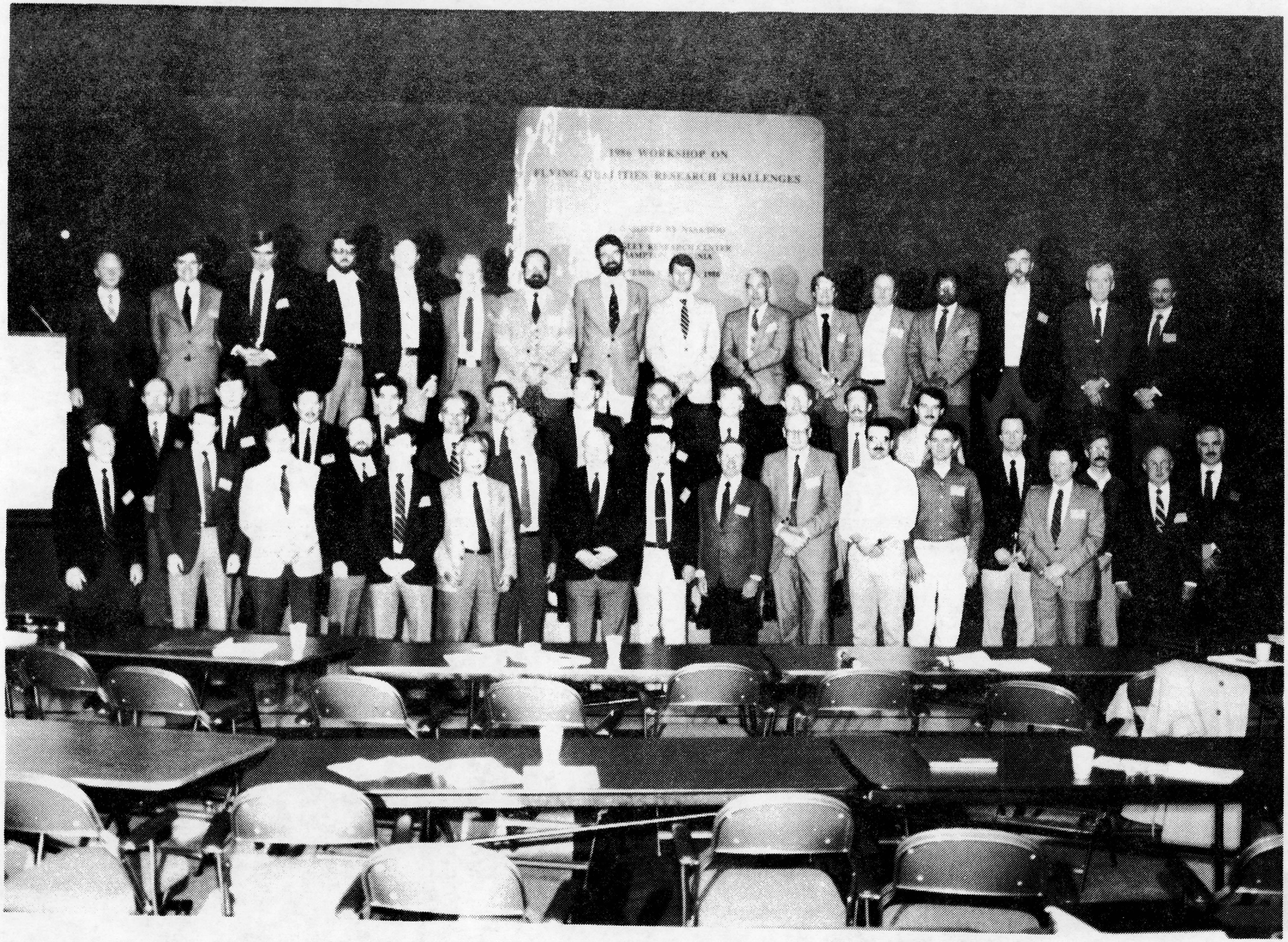

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(left to right): Virginia B. Marks; Frank L. George; William D. Grantham; Steven M. Sliwa; David Key; Donald T. Berry; and Victor Lebacqz

APPENDIX C

WORKSHOP SUMMARY CHARTS

FUTURE TRANSPORT AIRCRAFT CHARACTERISTICS

- REDUCED/NEGATIVE STATIC STABILITY
- SMALLER/ACTIVE CONTROL SURFACES
- DIRECT FORCE CONTROL
- SUPERAUGMENTED/FLY-BY-WIRE FCS
- FULLY INTEGRATED SYSTEMS (FCS/AVIONICS/PROPULSION)
- RECONFIGURABLE FCS
- INCREASES STRUCTURAL FLEXIBILITY
- GUST AND LOAD ALLEVIATION
- SEVERE ATMOSPHERIC CONDITIONS
  - OPTIMAL FCS DESIGN
  - OPTIMAL PILOT PROCEDURES
  - OPTIMAL PILOT DISPLAYS/INFORMATION

FLYING QUALITIES OF TRANSPORT AIRCRAFT

CURRENT STATE-OF-THE-ART

- FLYING QUALITIES CRITERIA HAVE NOT KEPT PACE WITH CONTROL SYSTEM DEVELOPMENTS SUCH AS:
  - HIGHER-ORDER TRANSFER FUNCTIONS
  - TIME DELAYS
  - DECOUPLED RESPONSES
  - DIRECT FORCE CONTROL CAPABILITY
- PRESENT SPECS GENERALLY RESTRICTED TO CONVENTIONAL/STABLE AIRCRAFT
- PRESENT SPECS ADDRESS VEHICLE MODAL CHARACTERISTICS, BUT NOT DESIRED RESPONSE
- DIGITAL FCS HAVE CAPABILITY TO "OPTIMIZE" A/C DYNAMICS--BUT THERE IS A LACK OF USABLE/VALIDATED CRITERIA

TRANSPORT A/C FLYING QUALITIES RESEARCH CHALLENGES

- USABLE, TASK-ORIENTED CRITERIA FOR HIGHLHY AUGMENTED A/C
  - ACTIVE CONTROLS
  - TIME DELAYS
  - FLEXIBLE STRUCTURES
  - CONVENTIONAL/UNCONVENTIONAL MANIPULATORS
- CRITERIA FOR CONTROL POWER AND SURFACE RATE REQUIREMENTS
- DATA FOR DESIGN OF INFO DISPLAYS--AS A FUNCTION OF PILOT TASK AND FCS CHARACTERISTICS
- DESCRIPTION OF WHAT TO "DESIGN TO"/"TEST FOR" WRT SEVERE ATMOSPHERIC PHENOMENA
- GUIDELINES FOR DEGREE OF AUTOMATION

HIGH PERFORMANCE/COMBAT AIRCRAFT FUNDAMENTAL CHARACTERISTICS

- LARGE DYNAMIC MANEUVER ENVELOPE:
  - LARGE ANGLES AND RATES
  - PRECISE ATTITUDE, LOAD FACTOR CONTROL
  - DEPARTURE PREVENTION/CONTROL

- ASYMMETRIC CONDITIONS

- SIMULATION INHERENT PART OF DESIGN

HIGH PERFORMANCE/COMBAT AIRCRAFT RESEARCH CHALLENGES

- INTEGRATE MANEUVER TASK REQUIREMENTS/DYNAMICS
- COORDINATED EFFORT TO COLLECT AND ANALYZE DATA
- NONLINEAR METHODS/CRITERIA
- SIMULATOR ~ VALIDATED/CORRELATION/COMPENSATION

HIGH PERFORMANCE/COMBAT AIRCRAFT
STATE OF THE ART

- HIGH ANGLE METHODS/CRITERIA LIMITED
  - SENSOR/ENGINE LIMITS

- TRACKING CRITERIA OK; GROSS MANEUVER AND BLENDING CRITERIA NEEDED

- ASYMMETRIC CRITIERA/COUPLING CRITERIA NEEDED

- SIMULATION ADEQUACY NOT CLEAR

V/STOL AIRCRAFT

- FLYING QUALITIES CONSIDERATIONS DOMINATE MISSION EFFECTIVENESS
  - 25 PROOF-OF-CONCEPTS, ONLY ONE CURRENTLY OPERATIONAL, MAJORITY OF REST FAILED DUE TO FLYING QUALITIES LIMITATIONS
  - DEMONSTRATE FLYING QUALITIES MUST BE INCLUDED AS FUNDAMENTAL DESIGN ELEMENT

- FLYING QUALITIES ARE CLOSELY LINKED TO PROPULSIVE CONCEPT

- FLYING QUALITIES REQUIREMENTS COVER ENTIRE RANGE OF POSSIBLE VEHICLE OPERATING STATES (HOVER, TRANSITION, FORWARD FLIGHT)

V/STOL AIRCRAFT

STATE OF THE ART

- HAS BEEN ENABLED THROUGH A LOW BUT CONTINUOUS LEVEL OF COUPLED ANALYTIC AND EXPERIMENTAL RESEARCH FOR THIS CLASS OF VEHICLE

- WHAT DO WE KNOW?
  - HAVE BUILT OPERATIONAL V/STOL THAT CAN OPERATE TO LPH SHIPS IN CALM SEAS WITH 400 FT/1 MILE VISIBILITY
  - CAN PRESCRIBE CONTROL AUGMENTATION TYPES AND LEVELS THAT PERMIT ACCOMPLISHMENT OF SOME ELEMENTS OF MORE DEMANDING V/STOL MISSIONS
  - CAN DESIGN FLYING QUALITIES FOR CERTAIN ELEMENTS OF V/STOL MISSION REALISTICALLY IN GROUND SIMULATION

V/STOL AIRCRAFT

STATE OF THE ART (CONTINUED)

- **WHAT DON'T WE KNOW?**

  - CAN NOT QUANTIFY INFLUENCE OF FLYING QUALITIES ON OVERALL MISSION EFFECTIVENESS

  - CAN NOT DEFINE MINIMUM LEVELS OF REQUIRED FLYING QUALITIES, NOR OPTIMUM FLYING QUALITIES

  - CAN NOT USE GROUND SIMULATORS FOR SOME ELEMENTS OF V/STOL MISSION; CAN NOT QUANTIFY EFFECT OF LACK OF FIDELITY

V/STOL AIRCRAFT

FLYING QUALITIES CHALLENGES

- ESTABLISH "AUDIT TRAIL" BETWEEN HANDLING QUALITIES CAUSES AND MISSION PERFORMANCE EFFECTS
  - UNCONVENTIONAL RESPONSES; OPTIMUM FLYING QUALITIES

- ESTABLISH "SIMULATION FIDELITY ENVELOPE" FOR GROUND SIMULATORS
  - HUMAN PERCEPTUAL MODELS
  - IN-FLIGHT SIMULATION FACILITY

- SUBSTANTIATE DESIGN PARAMETERS WITH IN-FLIGHT SIMULATION FOR PARAMETERS OUTSIDE FIDELITY ENVELOPE OF GROUND SIMULATORS

- DEFINE CONTROL POWER AND MARGIN REQUIREMENTS FOR MISSION EFFECTIVENESS

V/STOL AIRCRAFT

FLYING QUALITIES CHALLENGES (CONTINUED)

- DEFINE VEHICLE-COUPLED INFLUENCES OF INTEGRATED HIGH-ORDER AERO, PROPULSION, AND STRUCTURAL DYNAMICS

- DETERMINE ABSOLUTE MINIMUM LEVEL OF FLYING QUALITIES FOR DEGRADED MODES

- DEFINE PILOT ROLE WHEN MACHINE DECISION MAKING IS COUPLED INTO THE CONTROL STRUCTURE

- DEVELOP FCS DESIGN PROCEDURES EXPLICITLY LINKED TO FLYING QUALITIES GOALS*

*NOT UNANIMOUS AGREEMENT

ROTORCRAFT

1. DISTINCTINVE CHARACTERISTICS

VEHICLE: COMPLEX INTERACTIONAL AERODYNAMICS
HIGHLY COUPLED, NONLINEAR, HIGH-ORDER
MULTIPLICITY OF LIMITS

MISSION/TASK: SUSTAINED OPERATIONS CLOSE TO
GROUND EXTREME RANGE OF VISUAL
ENVIRONMENT SLUNG LOADS

PHYSIOLOGICAL: EXTREME NOISE, VIBRATION,
TEMPERATURE

ROTORCRAFT

2. FUNDAMENTAL ISSUES

- LACK OF FLIGHT DATA FOR CRITERIA DEVELOPMENT/VALIDATION

- INABILITY TO DO CREDIBLE NOE SIMULATION (HOVER--L2, L3)

- NEED L3 CRITERIA FOR FLIGHT CRITICAL FAILURES

- NEED BIGGER COMPUTERS FOR REAL-TIME SIMULATIONS

- NEED TO ACCOMMODATE PAST GENERATION HELICOPTERS WITH NEW SPEC

- HOW TO RELATE COST EFFECTIVENESS TO IMPROVED H.Q.

ROTORCRAFT

3. HISTORICAL BACKGROUND

- HEAVY RELIANCE ON FLIGHT TEST FOR PROBLEM SOLVING
- MANUFACTURERS MINIMAL USE OF SIMULATORS
- MINIMUM AUGMENTATION
- OBSOLETE SPEC - TESTED BUT IGNORED IN MISSION ASSESSMENT
- NEW SPEC IN WORKS

ROTORCRAFT

4. CURRENT RESEARCH NEEDS

- SIMULATION VALIDATION
- MATH MODEL FIDELITY IMPROVEMENT
- VARIABLE STABILITY HELICOPTER
- SIDESTICK CONTROLLER DESIGN CRITIERIA
- VISUAL CUE DEGRADATION VS SCAS
- FAILURES, WARNINGS, AND TRANSIENTS
- SINGLE PILOT SCAS
- INTERACTIONAL AERODYNAMICS
- DRY RUN OF NEW SPEC BY FLIGHT TEST COMMUNITY
- MISSION TASK ELEMENT--RESPONSE TYPES
- LOW ALTITUDE ATMOSPHERIC DISTURBANCE MODEL
- MANEUVER ENVELOPE LIMITING AND CUEING
- CROSS COUPLING CRITERIA
- AIR-TO-AIR COMBAT VEHICLE VS WEAPON SYSTEMS
- USE OF THRUST VECTORING

ROTORCRAFT

5. FUTURE TRENDS AND CHALLENGES

- AUTO SHIPBOARD LANDING (0,0)
- AUTO NOE
- AUTO FORMATION FLYING
- TWIN/TRIPLE LIFT
- 0,0 TACTICAL LANDING (L.1)
- CAREFREE MANEUVERING
- FLIGHT CONTROL--PROPULSION--FIRE CONTROL INTEGRATION

AEROSPACECRAFT FUNDAMENTAL CHARACTERISTICS

1) UNIQUE FLIGHT ENVELOPE
    1.1 HORIZONTAL TO TAKEOFF AND LANDING
    1.2 SPACEFLIGHT INTERFACE
    1.3 MICRO G ENVIRONMENT
2) COMPLEX PROPULSION SYSTEM
    2.1 AIRBREATHING/ROCKET
3) HEIGHT MODE OF MOTION
4) NO DIRECT FORWARD VISIBILITY
5) HIGH LEVERAGE WEIGHT/PERFORMANCE TRADEOFFS
6) POWER OFF LANDING CAPABILITY
7) MANUAL CONTROL POSSIBLE THROUGHOUT FLIGHT ENVELOPE

AEROSPACECRAFT

STATE OF THE ART

1) X-15, SHUTTLE EXPERIENCE

2) XB-70, YF-12 EXPERIENCE

3) SCRAMJET RESEARCH

4) HIGH UNCERTAINTY IN AERO, PROPULSION, AND ATMOSPHERIC PARAMETERS

5) TRAJECTORY OPERATIONS PRIMARILY PREPROGRAMMED

AEROSPACECRAFT FLYING QUALITIES CHALLENGES

1) AIRFRAME/PROPULSION INTERACTIONS
   - 1.1 CONTROL OF ENGINE/INLET UNSTART TRANSIENTS
   - 1.2 TRAJECTORY CONTROL REQUIRED TO STAY WITH ENGINE LIMITS
   - 1.3 INFLUENCE ON HEIGHT AND PHUGOID MODES
   - 1.4 CONTROL IN ATMOSPHERIC DISTURBANCES
2) LANDING
   - 2.1 POWERED
   - 2.2 UNPOWERED
3) DISPLAYS
   - 3.1 LANDING
   - 3.2 TRAJECTORY CONTROL
   - 3.3 ORBITAL OPERATIONS
4) AIRFRAME/PROPULSION/FLIGHT/CONTROL/DISPLAY INTEGRATION
5) AUTOMATION
   - 5.1 MANUAL/AUTO TRADEOFFS
   - 5.2 AUTO/MANUAL TRANSITION

GENERIC FLYING QUALITIES
Observations

- "USABLE" TASK-ORIENTED CRITERIA
- SIMULATOR ~ VALIDATED/CORRELATION/COMPENSATION
- LINK CRITERIA TO MISSION OBJECTIVES
- GUIDELINES FOR DEGREE OF AUTOMATION
- MOVE TOWARD COMPUTATIONAL FLYING QUALITIES FOR COMPUTER-AIDED PREDICTION

OBSERVATIONS

- NEED MORE FOCUS ON WHY'S/PAYOFFS
- TASK SPECS REDUCE GENERIC FLAVOR
- TRANSPORT CHALLENGES MAP INTO OTHER CATEGORIES
- RELIABILITY MAY BE F.Q. ISSUE
- BOTH TIME HISTORY AND FREQUENCY DOMAIN CRITERIA HAVE ROLES TO PLAY
- DATA COLLECTION/ANALYSIS NEEDS ORGANIZATION/ QUANTIFICATION
- BETTER HANDLE ON SENSITIVITY OF F.Q. PARAMETERS ON CONFIGURATION PARAMETERS NEEDED

OBSERVATIONS

V/STOL

- HIGH-ORDER COUPLED DYNAMICS (AERO, PROPULSION, CONTROL) IMPORTANT
- SIMULATION FIDELITY IS AN ISSUE
- CONTROL POWER AND MARGIN REQUIREMENTS NEED A TIE TO MISSION

EFFECTIVENESS

- MINIMUM LEVEL OF H.Q. NEEDED FOR DEGRADED MODES
- PILOT ROLE, WHEN COUPLED WITH AUTOMATION MODES, NEED WORK
- MORE BASIC QUANTIFICATION OF PAYOFFS NEEDED

APPENDIX D

ADDITIONAL AEROSPACE COMMUNITY INPUTS

GENERAL DYNAMICS
Fort Worth Division
P. O. Box 748, Fort Worth, Texas 76101

18 November 1986

Dr. Steven M. Sliwa
Deputy Chief
Guidance & Control Division - MS 479
NASA - Langley Research Center
Hampton, Virginia 23665-5225

Dear Sir:

General Dynamics is pleased to have been invited to the Workshop on Flying Qualities Research Challenges. We feel very fortunate to have been in a position to apply many of the handling quality criteria to a number of high performance aircraft during recent years. From these experiences we have found that whereas flying qualities may be considered to be a mature discipline, past research has not resulted in a widely accepted set of requirements that can be used for design and can easily be validated by test. Until that time when reliable and consistent criteria exist, the need for continuing flying qualities research will be with us.

A poll of engineers in the Fort Worth Division whose work involves the flying qualities discipline has resulted in the following list of topics that should be considered in future flying qualities research:

1. Minimize/consolidate requirements
2. Requirements that can be designed to and validated by test
3. More emphasis on time domain criteria
4. More research on acceptable time delays
5. Better criteria for higher order systems
6. Better control power and surface rate criteria
7. Research should result in more task oriented criteria
8. Displays should be considered in future research
9. More effort should be devoted to correlating the results of fixed-base simulators/moving-base simulators/flight test so that the benefits/limitations of simulation can better be understood

10. Criteria relative to V/STOL and hypersonic aircraft are sadly deficient
11. Increased efforts designed to provide guidance in the optimum integration of basic stability and control aerodynamics and flight control system design to provide good flying qualities with minimum impact on aircraft performance, structures, and systems are warranted.

Again, thank you for inviting General Dynamics to participate in your workshop. We are looking forward to discussing these and the many other issues facing the flying qualities community in your workshop.

Sincerely,

Dr. Carl S. Droste
Manager
Flight Control Systems

/nbb

cc: R. G. Bradley
J. E. Walker, III
K. H. Barnes
L. N. Hammett

MCDONNELL AIRCRAFT COMPANY

Box 516, Saint Louis, Missouri 63166 (314) 232-0232

29 December 1986

Dr. Steven M. Sliwa
Deputy Chief Guidance & Control Division
NASA Langley Research Center
Hampton, Virginia

Dear Steve:

1. After returning from the recent Flying Qualities Workshop at NASA Langley, I have documented on the attached enclosure the generic needs for flying qualities research as applicable to High-Performance Combat Aircraft. Several of these items were discussed during the Workshop group sessions, however, many other issues were also voiced by the participants. I will forward a copy to Frank George, AFWAL.

2. Frank Shirk's presentation, "V/STOL Flying Qualities from a Designer's Point of View," adequately covered MCAIR's position regarding generic research for this class vehicle.

3. I hope this information will be beneficial in completing the final report and formulating future research plans.

Eldon H. Anderson

Eldon H. Anderson
Branch Chief - Aerodynamics
Dept 341, Bldg 32/2/MS122

EHA/tla

MCDONNELL DOUGLAS CORPORATION

FLYING QUALITIES RESEARCH NEEDS FOR HIGH-PERFORMANCE/COMBAT AIRCRAFT

1. Generic in-flight research is needed to validate existing criteria and develop new criteria. This benefits the number of flight iterations previously required during full scale development. Potential areas of research include:

- o More exactly defined boundaries are needed in MIL-8785C for precision tracking criteria. Criteria exists in pitch axis, however, limited criteria are available in lateral/directional axis.
- o Control integration and direct force controls need more research.
- o Non-classical responses of highly augmented vehicles and the need to account for pilot location with respect to the instantaneous center of gravity.
- o Equivalent time delay. Need additional supporting data in directional and roll axis.
- o High angle-of-attack flying qualities research is needed to establish minimum requirements for combat maneuvering. Areas of evaluation would include consideration of relaxed roll rates, roll mode time constant, minimum CAP levels.

2. Develop standardized tasks for government and industry. This would include precise description of task and acceptable performance standards.

Specifically, mission related tasks should include:

- o Air-to-Air Tracking (fine tracking and gross acquisition)
- o Air-to-Ground Weapon Delivery
- o Formation Flying
- o In-Flight Refueling

3. Additional research and documentation of differences between ground simulators and flight. Several investigations to date have helped identify where control laws based on piloted fixed or motion base simulation lead to poor flying qualities when implemented in-flight. Additional guidelines which establish the cause of these discrepancies would reduce full scale development time.

4. The possible flying qualities penalties of relaxed static stability are limited. Requirements on control margins, failure modes, and effectiveness limiters are very significant to total operational vehicle acceptance.

5. A need exists for a new in-flight advanced technologies and design criteria demonstrator. Current testbed aircraft exhibit limited flight envelopes. The aircraft should provide high performance and compatibility with existing Navy and Air Force fleet aircraft. Integrated cockpit displays, digital flight control system, and multiplex data transmission and recording capability would provide the required flexibility.

In Reply Refer to
3734-86-JH-151

NORTHROP

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12 December 1986

Dr. Steven M. Sliwa, Deputy Chief
Guidance and Control Division, MS479
NASA Langley Research Center
Hampton, Virginia 23665-5225

Dear Steve:

It was good to see you at the recent Flying Qualities Workshop. We at Northrop appreciated the chance to participate, and I would like to congratulate you on a very well-run meeting.

Jerry Lockenour wrote to you before the meeting, mentioning that we planned to collect our ideas here at Northrop so that I could present them. It turned out that so many of our ideas were echoed by those making the formal presentations that I thought I could best help you achieve your goal of a short meeting by keeping quiet most of the time. For the record, however, I would like to list the items raised by Jerry, Dinesh Joshi, Alex Dobos-Bubno and Tom Dull.

Research needed for gaps in the data base:

- Roll coordination at high angles of attack, especially for larger aircraft.
- Task dependency.
- Ride qualities.
- Control harmony, particularly dynamic.
- Criteria for new controller concepts (e.g., sidesticks, throttles with thrust vectoring/reversing).
- Criteria for outer loop modes like integrated fire/flight control.

Some other comments were:

Is flying qualities a mature discipline? - To some extent yes, because there are many things we know. For example, for an evolutionary aircraft like the F-20 we can (and did) design control laws which work quite well first time. The problems arise for aircraft with new features. These problems can be tackled in a vehicle-specific way, but history has shown far greater cost-effectiveness in an intelligently-interpreted generic data base.

Will computational flying qualities ever be a reality? - It will continue to complement empirical parameter boundaries and manned simulation as a research-oriented parallel path.

Finally, I would like to add some personal comments based on the F-18 flight control system development. The problems in the early development were caused by equivalent time delays. We had already established some empirical guidelines for delays using generic data from Calspan's NT-33, so we knew the reason for the problem and the direction to go to solve it. The investment by the Government to gather and publish the relevant data was negligible compared with its overall investment in the F-18 control system. And I'm sure the same generic data were useful on the Space Shuttle and YF-17 development, to name just two others.

Could the F-18 problem have been solved in a vehicle-specific way? - The answer is yes, because the overall resources of McAir, the Navy, Calspan and STI would all have been thrown into the problem. I would estimate though that the cost of getting a solution for this one aircraft would have been several times the cost of getting a generic solution applicable to all aircraft. It's a matter of cost-effectiveness.

Thank you again for the opportunity to attend the fine workshop, and for allowing me to present Northrop and personal views. Good luck with the funding.

Yours Truly,

John.

John Hodgkinson

FLYING QUALITIES WORKSHOP

NASA LANGLEY RESEARCH CENTER
24 NOVEMBER 1986

POSITION SUMMARY: FLYING QUALITIES, WORKLOAD AND PILOT ERROR

I. L. Ashkenas
Systems Technology, Inc.

The art of "Flying Qualities" has too restrictive a connotation relative to the design implication and practice of the science of Pilot-Vehicle-Integration.

The theoretical treatment of Pilot-Vehicle-Display situations initially attempted to explain and consolidate Flying Qualities results and data. However it has progressed far beyond the treatment of classical vehicle dynamic response parameters which dominated such data, and has kept pace structurally, and in some areas computationally, with modern developments based on maturing computer, flight control, display, and manipulator states of art.

Almost from the beginning, Pilot-Vehicle-Display Theory has been a tool whose application to a variety of problems has yielded enhanced design solutions and appreciation for the factors involved. Extensions to include display sampling and divided attention effects have also emphasized the empirically developed relationships between control workload and pilot rating. And divided attention and increased workload have been identified as contributing causes of pilot error. Errors in judgement and wrong decisions are more difficult to treat but can be included in a generalized structure which admittedly needs a better empirical data base.

Bringing this structural model to more complete fruition and greater acceptance via increased use of computer aids (including expert sytems), and regular non-or semi-intrusive data gathering on routine simulations and in-flight tests, deserves high priority. Just as Computational Fluid Dynamics (CFD) serves a useful and highly desirable design function despite the existence and heavy utilization of very mature wind-tunnels, so will a Computer Aided Manual Control and Display Analysis and Design (CAMCADAD) procedure serve to underpin, correlate, explain and provide design guidance, interpretation and prediction for analogous (still immature) manned simulations.

The hope is, as for CFD, that CAMCADAD computations will eventually prove so reliable and useful that they will at least partially replace ad hoc simulator experiments and serve to lend more meaning and efficiency to those that are still considered necessary.

RESPONSE TO QUESTIONS ASKED BY THE NASA WORKSHOP ON FLYING QUALITIES RESEARCH CHALLENGES

NASA LANGLEY, NOVEMBER 24-25, 1986

E. G. RYNASKI

CALSPAN

IS FLYING QUALITIES A MATURE TECHNOLOGY

LITTLE HAS BEEN DONE SINCE 1970 TO:

1. BUILD UPON THE SOLID FOUNDATION OF MIL-F-8785(C)
2. INTERPRET MIL-F-8785(C) FOR THE FLIGHT CONTROL SYSTEM DESIGNER
3. DESIGN FLIGHT CONTROL SYSTEM USING MIL-F-8785(C) AS A DIRECT DESIGN CRITERIA
4. DEFINE BEST USE OF ADDITIONAL EFFECTORS (CANARD, DIRECT LIST FLAP, THRUST VECTORING, ETC.) FROM A FLYING QUALITIES POINT OF VIEW
5. INTEGRATE COCKPIT CONTROLLERS, DISPLAYS, ETC. INTO A F.Q. FORMAT

AS A RESULT -

CANNOT EVEN DEFINE, FOR INSTANCE, IF AND WHEN A SIMPLE COMPENSATION NETWORK, SUCH AS PROPORTIONAL PLUS INTEGRAL, SHOULD OR SHOULD NOT BE INCLUDED IN THE CONTROL SYSTEM FROM A F.Q. POINT OF VIEW

INSTEAD -

CONTROL THEORY HAS BEEN HONED AND REFINED TO A HIGH MULTI-INPUT, MULTI-OUTPUT DEGREE. WE KNOW HOW TO GET ALMOST WHATEVER WE WANT IN TERMS OF CLOSED-LOOP DYNAMICS, BUT WE DON'T YET KNOW WHAT WE NEED.

ARE THERE BENEFITS FROM DOING GENERIC FLYING QUALITIES RESEARCH?

MOST FLYING QUALITIES, AS IN MIL-F-8785(C), ARE GENERIC. IF ONE AGREES THAT ANY FLYING QUALITIES RESEARCH IS BENEFICIAL, THEN GENERIC FLYING QUALITIES, THE CORE DYNAMICS RESEARCH, IS ESSENTIAL.

SPECIFIC CONTROL SYSTEM, HARDWARE-ORIENTED ITEMS THAT MAY DIFFER FOR EACH AIRPLANE, SUCH AS COCKPIT CONTROLLER CHARACTERISTICS OR FEEL SYSTEM DYNAMICS, MAY BE CONSIDERED VEHICLE SPECIFIC TO BE DETERMINED AS A PEROGATIVE OF THE VEHICLE DEVELOPER.

WHAT WOULD HAPPEN IF THE U.S. DOES NOT CONTINUE TO SPONSOR GENERIC FLYING QUALITIES RESEARCH?

VERY LITTLE. COORDINATION BETWEEN THE EUROPEAN COUNTRIES IS ALMOST NON-EXISTENT. THE U.S. IS ABOUT THE ONLY SOURCE ACCEPTABLE TO MOST OTHERS. EVEN THE SOVIETS USE MIL-F-8785.

CAN FLYING QUALITIES BE ADDRESSED IN THE AIRCRAFT DESIGN STAGE?

YES, CERTAINLY

1. BY USING A FLYING QUALITIES SPECIFICATION AS A CONTROL SYSTEM DYNAMICS CRITIERIA
2. WITH AWARENESS OF LIMITATIONS, BY PROPER USE OF:
   a. GROUND-BASED SIMULATORS
   b. IN-FLIGHT SIMULATORS
3. BY NOT CONTINUALLY REPEATING THE MISTAKES OF THE RECENT PAST
   a. IS IT A MATTER OF INFORMATION DISSEMINATION OR SIMPLY A MATTER OF THE CONTROL SYSTEM DESIGNER WORKING IN A VACUUM
4. WILL THOSE IN THE AUDIENCE WHOSE FUNCTION IT IS TO DESIGN THE CONTROL SYSTEM PLEASE RAISE THEIR HAND?

ARE AIRCRAFT SPECIFIC RESEARCH STUDIES SUFFICIENT TO PUSH THE STATE-OF-THE-ART IN FLYING QUALITIES?

1. TO WHAT EXTENT HAS AIRCRAFT-SPECIFIC RESULTS AFFECTED MIL-F-8785(C)?

2. THE CHRONOLOGICAL DEVELOPMENT OF AIRCRAFT, SUCH AS THE F-16, F-17, F-18, SHUTTLE, AND OTHERS HAS DEMONSTRATED THAT LESSONS ARE NOT LEARNED.

3. ALMOST EVERY AIRFRAME DEVELOPER DESIGNS HIS SYSTEM BASED UPON HIS OWN COMPANY'S PAST EXPERIENCE.

4. EACH AIRCRAFT-SPECIFIC STUDY NORMALLY REPRESENTS ONLY ONE DATA POINT.

5. MIL-F-8785(C) REPRESENTS THE RESULTS OF HUNDREDS OF DATA POINTS. IF AIRCRAFT SPECIFIC RESEARCH STUDIES WERE THE ONLY DATA SOURCE, IT WILL LIKELY TAKE 100 YEARS TO ACCUMULATE THE DATA NEEDED TO ADEQUATELY BUILD UPON THE SPECIFICATION.

WILL COMPUTATIONAL FLYING QUALITIES EVER BE A REALITY?

DEPENDS ON WHAT IS MEANT -

1. CAN AIRCRAFT TIME HISTORIES BE ANALYZED BY COMPUTER, THEN AUTOMATICALLY ASSESSED WITH RESPECT TO 20 OR 30 EXTANT CRITERIA TO YIELD 20 OR 30 OPINIONS OF THE VEHICLE FLYING QUALITIES, THE ANSWER IS -
"YES"

2. WILL A COMPUTER EVER BE SMART ENOUGH TO REPLACE THE EXPERIENCE AND JUDGEMENT NEEDED BY THE FLYING QUALITIES EXPERT TO MAKE THE DECISIONS NECESSARY TO PRODUCE AN AIRPLANE WITH SUPERIOR FLYING QUALITIES, THE ANSWER IS -
"PERHAPS BY THE YEAR 2001"