Dryden Lectureship in Research

Flying Qualities from Early Airplanes to the Space Shuttle

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This paper discusses the historical development of the study of flying qualities and the evolution of flying qualities requirements. Subjects considered include the scope of flying qualities, early historical development of flying qualities, research on flying qualities requirements, human response characteristics, command control systems, gust response and its relation to flying qualities, prediction of flying qualities, discussion of the Space Shuttle and of some recent airplanes, and format of the flying qualities requirements.

Introduction

I BECAME acquainted with Dr. Dryden's work earlier in my career than most people because I wrote a bachelor's thesis on boundary layers. In the process of studying for this project, I read the NACA technical reports on the subject written by Dr. Dryden. I was greatly impressed not only by the quality and completeness of his experimental work but also by his ability to use electronic equipment such as vacuum tube amplifiers, which were then in an early stage of development, to make detailed flow measurements of the turbulence in boundary layers. The impressive scientific work conducted by Dr. Dryden was one of the factors that influenced me to choose a career in aeronautical research with NACA.

On starting work with NACA at Langley Field in July 1940, I was assigned to the Flight Research Division. The next few years, during the period of World War II, proved to be an exciting time. I was working under Dr. Robert R. Gilruth, who had undertaken the task of studying requirements for the flying qualities of airplanes. During that time, a new military airplane was produced practically every month, and many of these airplanes were assigned to Langley for study and improvement of their flying qualities. Development of flying qualities of airplanes, however, had been in progress since the earliest days of aviation, and it is necessary to go to an earlier stage in history to obtain the complete background of these developments.

Scope of Flying Qualities

First, let us define what we mean by flying qualities. A definition that I wrote many years ago and that still seems to be applicable is: *Flying qualities are defined as the stability and control characteristics that have an important bearing on the safety of flight and on the pilots' impressions of the ease of flying an airplane in steady flight and in maneuvers.* The safety of flight aspect is very important. Much of our basic information on flying qualities comes from knowledge learned as a result of airplane accidents or incidents of loss of control. In recent years, there has been a tendency to broaden the definition of flying qualities to include the capability of the aircraft to perform its assigned operations. The scope of flying-qualities research is therefore related to the continual development of aircraft capabilities and to the operational requirements for each particular airplane.

The study of flying qualities is closely related to the following disciplines: dynamic stability and control, feedback control theory, human response analysis, and aeroelasticity. These subjects themselves are closely related to each other inasmuch as they involve many of the same mathematical developments.

Early Historical Development of Flying Qualities

Because the subject of flying qualities involves the human pilot and his interactions with the airplane, the history of flying qualities really began with the Wright Brothers' first flight in 1903. Even before then, however, several of the early aeronautical pioneers had developed knowledge that would contribute to the study of flying qualities. Figure 1 illustrates the development of stable, powered, model airplanes and some work on stability theory prior to the Wright Brothers' flight. Alphonse Pénaud[1] in 1873 invented the rubber-powered model airplane and developed stable configurations capable of successful flight. In 1877, E. J. Routh[2] published his celebrated criterion for the stability of dynamic systems, which made possible the study of airplane stability. F. W. Lanchester[3] in 1893 demonstrated a rubber-powered model of considerably greater wing loading than those of Pénaud and also worked out the theory of the long-period longitudinal motion of airplanes. Finally, from 1897-1903, S. P. Langley[4] built and successfully flew steam-powered and gasoline-powered model airplanes that were intended as scale models of his proposed man-carrying airplane. In this period, dynamic stability was the all-important criterion for the successful flight of these models. With the advent of manned flight, however, dynamic stability became a somewhat academic subject, and flying qualities assumed a major role in the development of manned flight.

The period between the Wright Brothers' flight in 1903 and the pre-World War II era of 1935 is shown in Fig. 2. During their first flights at Kitty Hawk,[5] the Wright Brothers were hampered by an overbalanced longitudinal control surface. The overbalanced canard surface caused what we would call today a pilot-induced oscillation, with the airplane darting up and down and with the flights ending when the airplane hit the ground at the bottom of an oscillation cycle. (It is interesting that both Wilbur and Orville made considerably longer flights on their second attempt than on their first attempt, a fact that already should tell us something about the adaptive nature of the human pilot.) During the next few years, however, they corrected this problem and developed a high degree of skill in flying their airplanes, despite the fact that these machines were inherently unstable both longitudinally and laterally and had relatively unnatural arrangements of controllers. It is interesting that Wilbur and Orville learned to use different arrange-

Presented as Paper 88-0751 at the AIAA 26th Aerospace Sciences Meeting, Reno, NV, Jan. 11-14, 1988; received Feb. 22, 1988; revision received July 11, 1988.

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ments of controllers.[6] By 1909, Louis Bleriot developed the configuration that became representative of most subsequent airplanes; i.e., a tractor airplane with the propeller directly attached to the motor and with controls in a stick and rudder pedal arrangement, which has been universally adopted in later years. With the rapid development of airplanes during World War I, many designers, through a trial and error procedure, developed configurations that had very good flying qualities. For example, the Fokker D-VII developed by Anthony Fokker[7] had an excellent ability to perform aerobatic maneuvers, as well as to remain controllable in stalled conditions and to recover from spins.† Airplanes based on this design were used as crop dusters in this country for many years, and aerobatic biplanes today still have very similar configurations. Some other developments related to flying qualities are also illustrated in Fig. 2. The classical dynamic stability theory of airplanes was worked out by Bryan in 1904 and later presented in a textbook entitled *Stability in Aviation* published in 1911.[8] This theory starts with the complete six-degree-of-freedom equations of the airplane, separates them into the longitudinal and lateral groups, and introduces the concept of stability derivatives. This theory is practically identical to the theory taught in colleges today. The only major improvement in the theory was presented by Cowley and Glauert[9] around 1921. They introduced the effect of lag of downwash in the longitudinal equations. Later, Glauert[10] expressed the equations in nondimensional form. Another important event that foreshadowed later developments was the invention of gyroscopic stabilizers or autopilots for airplanes. A gyroscopic stabilization system was installed and demonstrated in 1913 in a Curtiss pusher by Elmer Sperry.[11] This device proved to be ahead of its time but was revived during the 1930's with the development of autopilots for transport airplanes. Wiley Post used a Sperry autopilot to enable him to make a solo around-the-world flight in 1933. By the end of the period shown in Fig. 2, around 1935, piston-engine airplanes had reached an advanced stage in their development. Light airplanes looked very similar to those flying today, efficient transports such as the DC-3 had been developed, and racing airplanes like the Schneider Cup Racers foreshadowed the fighters of World War II. All this was accomplished without any formal handling-qualities requirements.

The entire period shown in Fig. 2, from the Wright Brothers to 1935, is characterized by a lack of understanding of the relation between stability theory and flying qualities. Stability theory, although highly developed, was not used by designers, primarily because of mathematical complications and computational problems. Even if the theory had been used, however, the results would have probably appeared confusing. The reason for this lack of applicability of stability theory is that, for airplanes of this period, only the long-period modes became unstable. Later studies have shown, however, that these modes have no effect on the pilot in visual flight or in up-and-away instrument flight. At the wing loadings and altitudes used in this period, short-period modes were almost always well damped. Only the lateral-directional mode, the Dutch Roll, might become unstable on an airplane with high dihedral, but pilots since the Wright Brothers had known that large dihedral results in excessive disturbances due to rough air and therefore was never used.

†Anthony Fokker, an excellent test pilot, had found that his newly constructed biplane, and D-VII, about to be entered in a competition, was lacking in directional stability. On the night before the contest, he and two welders secretly added another bay to the fuselage and enlarged the fin. Without an opportunity to test the plane he sauntered over to one of the squadron chiefs and said, "You'll notice a special feature in my ship, Lieutenant, its quickness on turns. Let the others in on it, so they can show it off to the best advantage." Then he left, having put them on guard without their realizing it. With that little tip, they demonstrated the plane as well or better than he could have done himself.[7]

Around 1935, some research organizations were starting to recognize the discrepancies between the predictions of dynamic stability theory and the characteristics of actual airplanes. It was easy to state in regulations that the airplane should be stable both laterally and longitudinally, but what was meant by such a statement? As pointed out by O. C. Koppen,[12] a CAA bulletin stated that the test for lateral stability is as follows: "With the rudder held in neutral, the airplane is rolled about its longitudinal axis to a fairly pronounced angle and the control stick immediately released. A sideslip will result and, if the airplane recovers from the tilted position to an attitude of flight which is level laterally, it is laterally stable." Koppen points out that pilots are going to be very disappointed if they expect to find among airplanes certified as airworthy by the CAA many that are laterally stable according to this definition. As early as 1937, Soulé had published a report[13] in which the dynamic longitudinal motion of several airplanes was measured and found to have no correlation with the pilot's opinion of the airplanes.

Research on Flying-Qualities Requirements

The first effort in this country to write a set of requirements for satisfactory flying qualities was in conjunction with the development of the Douglas DC-4 Airplane. In 1935, Edward P. Warner, working as a consultant to the Douglas Corporation, after discussions with airline pilots, engineers of the aircraft industry, and research men, prepared the requirements entitled "Suggested Requirements for Flying Qualities of Large Multi-Engined Airplanes."[14] Mr. Warner, being a member of the main committee of NACA, also requested that a flight study be made to determine the flying qualities of an airplane along the lines of the suggested requirements. This study was conducted on a Stinson SR-8E airplane. The report, entitled "Preliminary Investigation of the Flying Qualities of Air-

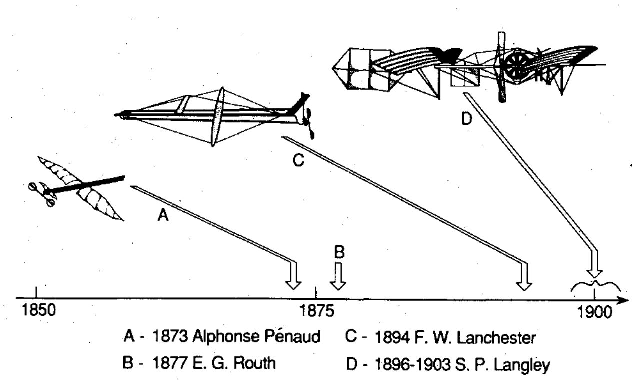


Fig. 1 Early developments related to flying qualities.

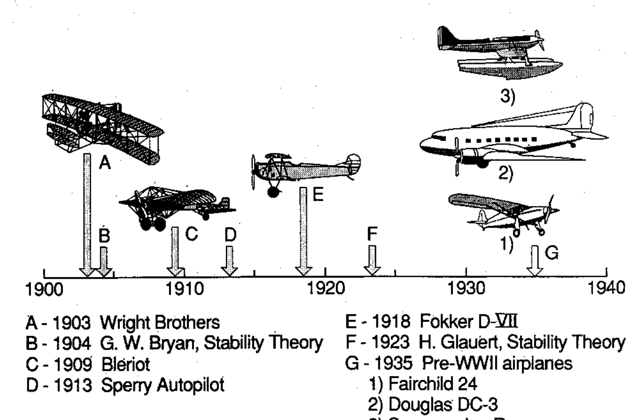


Fig. 2 Flying qualities developments from the Wright Brothers to 1935.

planes," was published in 1940 by H. A. Soulé.[15] It was realized that tests of a large variety of airplanes using improved instrumentation would be required to obtain more generally applicable flying-qualities requirements. This work was continued under the direction of Robert R. Gilruth, with Melvin N. Gough as the chief test pilot. The technique for Gilruth's study of flying qualities was as follows. An airplane was fitted with recording instruments to record all relevant quantities such as control positions and forces, angular velocities, linear accelerations, airspeed, altitude, etc. Then a program of specified flight conditions and manuevers was flown by skilled test pilots. After the flight, the data was transcribed from the flight records and plotted to show the relevant information, and the results were correlated with pilot opinion. The need to manually evaluate and plot each curve or data point helped to insure that unexpected results would not be overlooked. Finally, reports were published on the individual studies. In 1943, Gilruth published the report, "Requirements for Satisfactory Flying Qualities of Airplanes."[16] This investigation was based on tests of 16 different airplanes of all types ranging from light airplanes to the largest airplane flying at that time, the Boeing XB15. This report formed the basis of subsequent military specifications for stability and control characteristics of airplanes.[17,18] During that period, I taught a course to NACA employees entitled "Appreciation and Prediction of Flying Qualities." The notes from this course were later published.[19] The object of this course was to show how the required flying qualities could be related to design characteristics of an airplane. Reports were also published showing how the handling qualities of an airplane could be predicted from wind-tunnel tests.[20,21] Similar developments occurred in England, and, after the war, it was discovered that the Germans also had formulated requirements for satisfactory flying qualities that were very similar to those developed by Gilruth.[22]

It has already been stated that the dynamic longitudinal and lateral motions were found to have little correlation with the pilots' opinions of the airplanes. A number of other characteristics, however, were found to be of importance in connection with both pilot opinion and flight safety. These characteristics, included in the quantitative requirements presented by Gilruth, may be summarized by considering the main headings of Gilruth's report. Under the requirements for longitudinal stability and control are the following subjects: characteristics of uncontrolled longitudinal motion, characteristics of elevator control in steady flight, characteristics of elevator control in accelerated flight, characteristics of elevator control in landing, characteristics of elevator control in takeoff, limits of trim change due to power and flaps, and characteristics of longitudinal trimming device. Under the requirements for lateral stability and control are: characteristics of uncontrolled lateral and directional motion, aileron-control characteristics, yaw due to ailerons, limits of rolling moment due to sideslip, rudder-control characteristics, yawing moment due to sideslip, and characteristics of rudder and aileron trimming devices. Finally, requirements for stalling characteristics are included.

The only requirements that involve the airplane dynamic stability are those concerned with the characteristics of the uncontrolled longitudinal and lateral motion. Among the airplanes tested at that time, however, the only unsatisfactory characteristics encountered were problems that could not have been predicted by the simple classical stability theory. In the case of longitudinal motion, unsatisfactory damping of the short-period oscillation was sometimes encountered, involving coupling between the elevator deflection and the airplane motion. In the case of lateral motion, a common problem was "snaking," involving continuous limit-cycle oscillations caused by unfavorable combinations of rudder floating tendency and control-system friction.

Many of the other requirements involve control forces and deflections in specified flight conditions or maneuvers. These quantitative requirements provided a straightforward means of measuring flying qualities in flight tests, as well as giving the designer a basis for predicting the flying qualities of a new configuration. Of particular importance were the requirements for variations of control force and deflection in accelerated flight, frequently referred to as "force per *g*" and "control deflection per *g*." Most previous attempts to correlate measured and predicted stability characteristics had involved straight flight. Pointing out the importance of characteristics in maneuvers was one of Gilruth's most important contributions to the understanding of flying qualities.

The early NACA requirements were stated to be minimum requirements for satisfactory flying qualities. They were felt to be obtainable without any compromise in the performance characteristics of an airplane, and the provision of even more desirable characteristics was encouraged. When the military handling-qualities specifications were written, the requirements started to be related not only to the minimum qualities required for safe flight but to the operational requirements of military airplanes. For example, such specifications as rate of roll were increased beyond the minimum values required for safe flight and ease of control.

During and following the war years, tests of flying qualities of airplanes continued at Langley and at the Ames Research Center, until by 1948 over 60 airplanes of all types had been tested. A typical early report[23] shows the scope of these tests. Gilruth even condensed these results to one-page summaries of the flying qualities of each airplane, which were included in the complete reports. New information was obtained from almost every additional airplane that was studied. In addition, the rapidly expanding performance capabilities of airplanes during this period introduced many new problems as well as new analysis techniques and new control-system design features. A well-publicized problem of this period was the appearance of compressibility effects during high-speed dives of fighter planes. Research conducted on this problem resulted in the use of sweep, thinner airfoils, and the developement of devices such as Mach trim compensators found in modern transport airplanes.

Many of the most important requirements for flying qualities are concerned with characteristics of the control forces. In the days of manual control systems, the control-force characteristics were almost entirely determined by the aerodynamic hinge-moment characteristics of the control surfaces. As a result, a great deal of research was done on control-surface hinge moments and on means of aerodynamically balancing the controls. With the introduction of power controls around 1943, this picture changed rapidly. The control characteristics could then be provided by a feel device more or less independently of the hinge-moment characteristics of the control surfaces. Many new problems were involved with these devices, however, both because of certain undesirable or nonlinear force characteristics introduced by the hydraulic control systems and because of the unusual feel characteristics associated with some feel devices.[24] Also during this period, stability augmentation had its beginnings in the form of yaw dampers to improve the damping of the Dutch-roll oscillations. The need for changing requirements with developments in airplane design is well illustrated by the experience with yaw dampers. Pilots having for the first time experienced a really well-damped Dutch-roll oscillation immediately felt that improved damping should be specified in the requirements.

While such developments as feel devices and stability augmentation introduced additional handling-qualities problems, they also reduced the need for such careful attention to flying-qualities requirements in the design stage. Feel devices could be readily adjusted to vary the control force characteristics after the airplane was built, and damping of the Dutch-roll oscillation could be provided as desired by proper setting of the yaw damper. At the same time, the subject of the dynamic stability of airplanes and the associated analysis techniques assumed new importance, both because airplanes were flying at higher altitudes where short-period modes were more likely to become unstable and because the interaction of the airframe modes with automatic control systems could lead to unexpected stability problems. Among the developments in stability theory that proved useful for such analyses was the use of operational methods, introduced to the aeronautical community by R. T. Jones[25] and popularized with the teaching of the more understandable Laplace Transform method.[26] Another useful technique borrowed from the electrical engineering community was the frequency response method.[27]

A notable result of the introduction of the frequency response analysis technique was its use in the dynamic stability testing of airplanes, pioneered by W. F. Milliken of the Cornell Aeronautical Laboratories.[28] Such methods could be used to measure in flight the transfer functions or the stability derivatives of an airplane. This capability proved to be of great value as airplanes penetrated the transonic range, for which wind-tunnel techniques to measure the stability derivatives were not available. In addition, with the perfection of electronic control equipment, the variable-stability airplane was pioneered by the Cornell Aeronautical Laboratories (now Arvin-Calspan).[29] The variable-stability airplane provided a tool by which a large variety of control characteristics could be studied in a systematic manner rather than relying on tests of a wide variety of different airplanes to cover a range of characteristics. Currently, a Convair 440 (the TIFS airplane, for Total In-Flight Simulator) is the most advanced airplane of this type (Fig. 3). A new airplane based on the F-16 fighter (called VISTA, for Variable Stability In-Flight Simulator Test Aircraft) is currently in the planning stage (Fig. 4). Around 1950, versatile ground simulators became available and furnished still another technique for studying particular problems involving flying qualities. Further discussion of these devices is given subsequently in the section "Prediction of Flying Qualities."

When NACA became NASA in 1958, many of the groups previously involved in flying-qualities research were transferred to the space program. Much of the later work concerned with airplane flying qualities in the country was carried on by System Technology, Inc. (STI) and Arvin-Calspan under Air Force, Navy, and NASA contracts and by the military and NASA flight research groups at the Dryden flight research Center.

Human-Response Characteristics

The development of autopilots and the advancement of analytical techniques to study their effects brought about a gradual realization that better knowledge of the characteristics of the human pilot should allow more accurate predictions of desirable stability and control characteristics. The stability of the controlled airplane was studied by Koppen[30] in 1935 by assuming that the controls were moved in proportion to the angular displacement of the airplane as sensed by the pilot. This method of analysis has the advantage of not increasing the order of the equations of the basic airplane and is useful even today for preliminary stability analyses. This technique showed that when ailerons had high adverse yaw in flight near the stall, the use of ailerons to control the bank angle would result in an unstable oscillatory response. Work along these lines was continued in two MIT doctoral theses by H. K. Weiss[31] and S. N. Lin,[32] in which lag in movement of the controls was taken into account. Lin also used the MIT mechanical differential analyzer to obtain time histories of the response to disturbances. Lin's results provided an early insight into controlled motions of airplanes because similar response calculations with more advanced types of computers were not available for several years after that.

An important advance in the analysis of the effect of the human pilot in controlling a dynamic system was made by A. Tustin, a British electrical engineer.[33] His problem was to improve the tracking of a moving target by an electrically rotated turret in a tank controlled by a human operator. He was able to characterize the human operator's response in terms of a simple control law involving a proportional and lead term and a constant time lag caused by the pilot's sensory and neuromuscular response. In addition, he found that the human pilot response contained a superimposed random motion, which he called the remnant. He was able to use this pilot transfer function to determine modifications for the turret control laws that would greatly reduce the tracking error. He also suggested methods for further analysis of human response characteristics, which have occupied researchers for many years since that time. Work on analysis of pilot's tracking error to determine the pilot's transfer function was continued in this country by J. T. Elkind[34] and E. S. Krendel and G. H. Barnes.[35] Their work was applied to the analysis of airplane handling qualities by many organizations in this country, notably by D. T. McRuer and I. A. Ashkenas of STI. McRuer, in particular, made detailed analyses of the human physiological characteristics to try to explain the results of human response experiments.[36] In addition, he and his co-workers applied these techniques to many practical problems of airplane design, including lateral control, landing approach and flare, pilot-induced oscillations, etc.[37]

While much of the early work was concerned with the response of the human pilot to visual stimuli, some work was conducted to determine the effect of motion cues by using specially built simulators. Early examples of simulators of this type are the yaw chair[38] and the normal-acceleration pitch (NAP) chair used at the NACA Langley Research Center (Fig. 5). Study of human response characteristics soon became an extensive field of research, with many universities and research organizations taking part. An annual conference, known as the Annual Manual, has been held as a forum for this research each year from 1964 to the present, with the exception of 1987.[39,40]

In general, it may be said that the use of human pilot models has been more successful in explaining flying-qualities problems than in predicting them. Such methods apply best when the stimulus to the pilot can be clearly identified, as in the case of a visual tracking task. Such methods have also been used with a fair degree of success in predicting pilot-induced oscillations in which some particular response quantity such as bank angle or normal acceleration takes precedence in the pilot's efforts to control the motion. Other successful applications of this technique have occurred when it can be shown that the

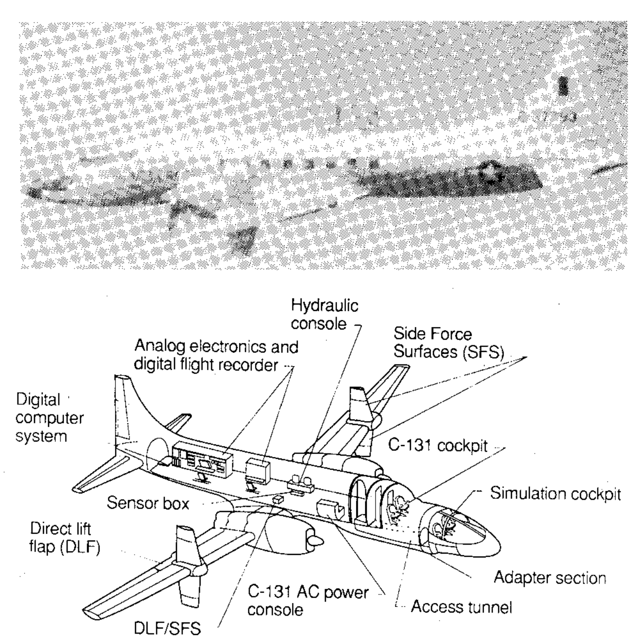


Fig. 3 The TIFS airplane (Total In-Flight Simulator).

normal use of the human pilot model to control one mode of motion results in loss of stability of some other mode. In many cases, however, analyses of human pilot response are made assuming a single input to the pilot. In practice, the human pilot can sense many different quantities and probably has the ability to combine these inputs in determining his control law. For example, a human pilot can sense displacement visually and can sense angular velocities and accelerations as well as linear accelerations through his vestibular mechanisms. In addition, he can sense the accelerations on various parts of his body, the so-called kinesthetic cues. Finally, he can sense control forces and control deflections. The human response analysis will give different results, depending on what combination of sensed quantities is assumed.

Two apparent characteristics of the human pilot sometimes neglected in human response analysis are that he is adaptive and adaptable. By adaptive I mean that he can change his control strategy to satisfy the control task in the same sense as an adaptive control sytem. By adaptable I mean that he becomes accustomed to particular control characteristics and may come to prefer these characteristics, after practice, to some others with which he has not had experience. Examples of the adaptive capabilities of the human pilot were shown by the example mentioned previously of the Wright Brothers' first flights. Similar problems arise in trying to study pilot-induced oscillations. If a pilot encounters a pilot-induced oscillation in flight, he is rarely able to duplicate the experience. He has already learned a new control strategy to avoid the problem and can simply point to a tendency for a pilot-induced oscillation. The adaptable nature of the human pilot also may be illustrated by many examples. In establishing the desired value of stick force per g in maneuvers, fighter pilots invariably choose lower forces than bomber pilots. Another instance in which researchers have reached incorrect conclusions is the failure to appreciate the ability of pilots to adapt to airplanes of different size. In Gilruth's original handling-qualities studies he found, contrary to the expectations of many people, that pilots were satisfied with much lower values of rolling velocity on larger airplanes than on smaller ones. In making tests on variable-stability airplanes in an effort to predict required handling qualities for larger airplanes, erroneous results may be obtained if this adaptable characteristic of the human pilot is not taken into account.

Some references giving the current state of knowledge of human pilot characteristics for various applications are as follows: display design,[41] manipulators,[42] effects of rotary motion,[43] and effects of linear motion.[44] Recent efforts to represent the human by use of optimal control theory are given in Refs. 45–47.

Command Control Systems

As soon as autopilots were installed in airplanes, it was realized that control of the airplane could be accomplished by changing the index or setting the autopilot. This method was used to reduce the workload of formation flying bombers in World War II with the use of the so-called formation stick. Most autopilots, however, were severely limited in control authority for safety reasons. Control through the autopilot, therefore, could be accomplished only in gentle maneuvers. It was not until the development of highly reliable triply or quadruply redundant automatic control systems that control of the airplane through the automatic system became practical. On a high-performance airplane there are also many advantages in the use of command control systems. The weight and complication of the control system can be reduced, and with digital control systems, the designer has freedom to vary control laws after the hardware is installed. Even before the reliability problem was attacked, research studies were made of the problems and capabilities of command control systems.[48,49] Subsequent developments in this field took place under the acronyms CCV (Control Configured Vehicles), ACT (Activity Control Technology), CAS (Command Augmentation Systems), and currently under the title Superaugmentation. As shown in Fig. 6, the use of such systems enabled the exploitation of capabilities such as relaxed static stability, maneuver load allevation, structural mode suppression, and gust load alleviation. The use of digital computers to provide greater freedom in choice of control laws as well as greater reliability through redundancy was explored by NASA[50] using the F-8 Digital Fly-by-Wire Airplane (Fig. 7). Digital control systems are by now widely accepted for high-performance airplanes. These techniques introduced the capability of providing new flying-qualities characteristics, possibly unlike those encount-

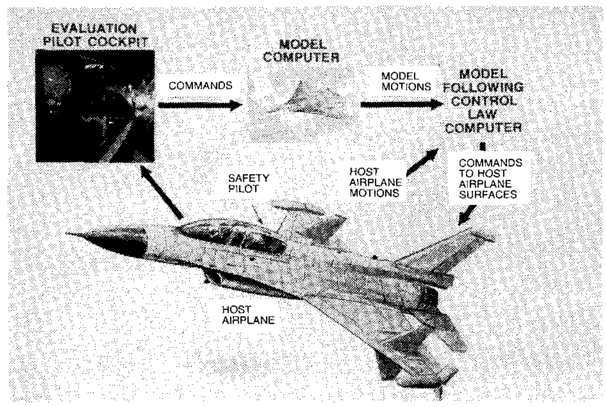
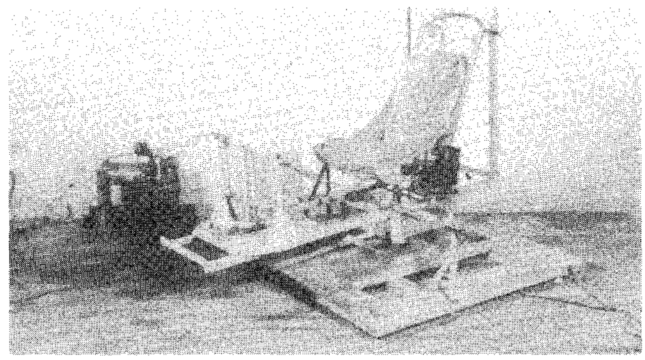
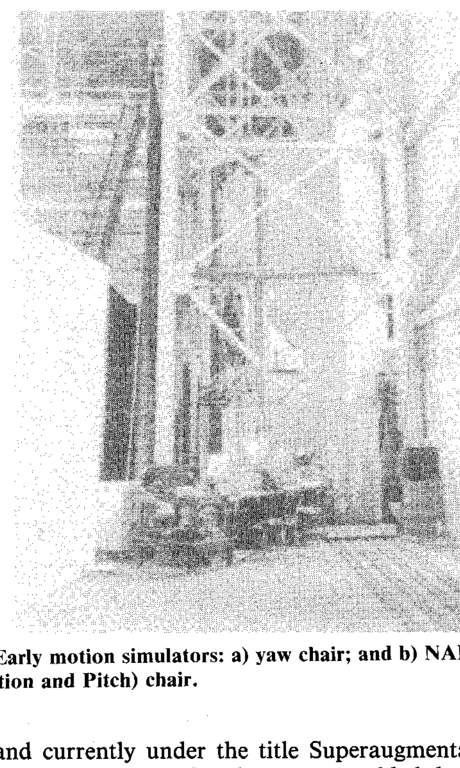


Fig. 4 The proposed VISTA airplane (Variable Stability In-Flight Simulator Test Aircraft).



a)



b)

Fig. 5 Early motion simulators: a) yaw chair; and b) NAP (Normal Acceleration and Pitch) chair.

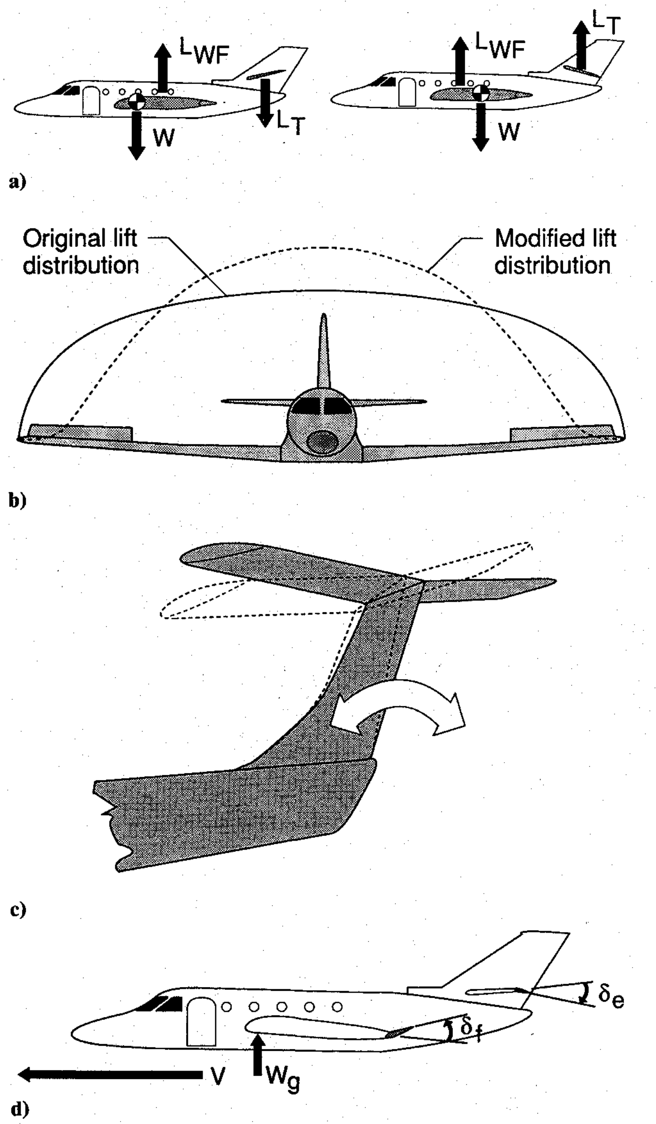


Fig. 6 Capabilities of active control systems: a) relaxed static stability; b) maneuver load alleviation; c) structural mode suppression; and d) gust load alleviation.

ered with conventional control systems. These developments opened up new problems and whole new fields for research.

It should perhaps be mentioned that a well-designed conventional manual control system on a typical small subsonic airplane has many desirable features, some of which are so expected that they are taken for granted and not even mentioned in flying-qualities requirements. To list a few of these characteristics, it may be mentioned that the aerodynamic hinge moments increase with the dynamic pressure, thereby maintaining a constant stick force per *g* and helping to prevent the pilot from overloading the airplane in flight at high speed. The control forces appear approximately in phase with the control deflection, thereby providing the pilot with anticipation of the magnitude of the maneuver that will follow. Aerodynamic damping moments on the control surfaces suppress control oscillations. With a stable airplane, the variations of stick position and force with airspeed give the pilot warning of speed changes from the trim condition and give him appreciation of approach to the stall. Control friction prevents the pilot from putting in unintentional small stick motions that might result in inadvertent disturbances to the flight path. Furthermore, this friction occurs separately in various controls so that the pilot can move one control without disturbing the others. The pilot retains the ability to move the controls when the airplane is either on the ground or in flight beyond the stall, and he can

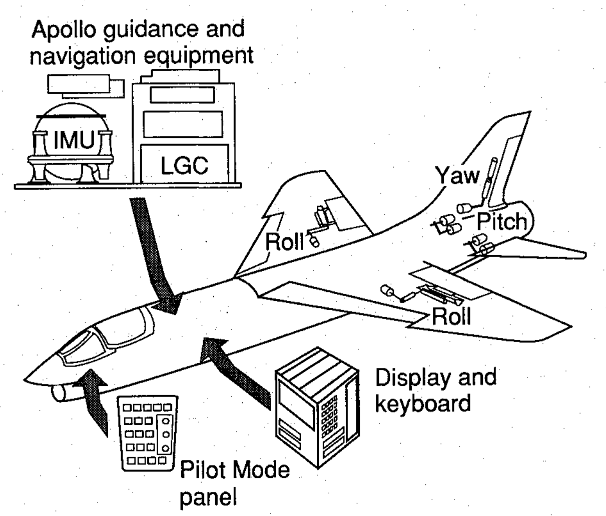


Fig. 7 NASA F-8 Digital Fly-by-Wire Airplane.

use the most effective control techniques to recover from stall and spins. All of these features are taken for granted with manual control systems, but some of them may disappear when command control systems are used. For example, if a so-called force stick is used for the control input (i.e., a control stick that responds to force inputs), the problem of inadvertent pilot control about other axes is frequently encountered and must be considered in the design of the electronic control systems. With command of such quantities as normal acceleration, the response may be too quick, requiring the use of prefilters to slow down the response and avoid the tendency for pilot-induced oscillations. In controls that command airplane response quantities such as normal acceleration or pitching velocity, any control input may cause the control surface to go to full deflection when the airplane is on the ground, because feedback of the measured quantity is lost. The response of the control system beyond the stall may not be correct for stall or spin recovery. Frequently these control systems are designed so that the control stick remains centered when the airplane returns to a trim condition following a disturbance. Such systems lose any inherent stall warning through the control motion and force. All these problems can be overcome by suitable design of the automatic control system, but they need to be considered during the design stage. Many problems were encountered with early versions of these control systems because of neglect of some of these factors. Digital control systems have, in the past, introduced problems of lag in the control response due to inadequate sampling rates or cycle time. These problems should be less prevalent in the future because of the constantly increasing capabilities of digital computers.

A major advantage of command control systems is the ease with which limiting can be incorporated. With manual control systems, the pilot always has the capability to stall the airplane or exceed its structural limits. Therefore, many of the flying-qualities requirements for airplanes of this type have to do with providing adequate warning to the pilot so he will avoid these difficulties. With a command control system, it is simply necessary to limit the magnitude of the command to values below those that would lead to a dangerous condition. This capability may be particularly desirable on airplanes such as transports that are not intended for flight beyond normal limits. On the other hand, on fighter airplanes, the active control systems may be used in another way to improve the controllability at high angles of attack in the stalled region.

Gust Response and Its Relation to Flying Qualities

The ability of an airplane to fly smoothly through turbulence would certainly appear to be an essential feature of its flying qualities. Very little attention has been paid to this problem, however, either in the formulation of requirements or in the design of control systems to reduce the response to turbulence. The lateral-directional response has, admittedly, been a subject of study in the formulation of requirements for the characteristics of the Dutch-roll oscillation and in the design of autopilots to reduce the rolling and yawing motion. In the case of the longitudinal response, however, the problem of reducing the normal acceleration due to turbulence has been neglected. Use of the elevator control to reduce the response of normal acceleration is generally ineffective, and use of flaps on the wing capable of deflection in both the upward and downward directions is an essential part of a gust-alleviation system. Since very few airplanes are equipped with such control surfaces, no requirements for gust alleviation were included either in Gilruth's original requirements or in more recent military specifications. Several research projects have demonstrated what can be accomplished along these lines. Rene Hirsh in France has successfully demonstrated the effectiveness of aeromechanical gust-alleviation systems in light airplanes. A Beech B-18 airplane (Navy designation C-45) was fitted with a gust-alleviation system by the NACA in 1955.[51] More recently a research project was conducted in Germany on the Dornier Do-28 TNT airplane.[52] These airplanes are shown in Fig. 8. Both these studies showed that worthwhile reduction in disturbance due to turbulence could be obtained. The practical application of these methods, like the widespread use of command control systems, requires the use of highly reliable, redundant, automatic control systems because high authority controls capable of generating forces sufficient to damage the airplane structure are required. On an airplane with such a control system, it should be possible to design a gust-alleviation system with very little penalty in weight or additional complication. Unfortunately, the types of airplanes that have the greatest need for gust alleviation are the light airplanes or commuter transports that operate at low attitudes. Usually the expense involved in the development of such systems is prohibitive for airplanes of this type. Nevertheless, as more experience is obtained with such systems on high-performance military airplanes, it is hoped that use of these systems will find wider acceptance.

Prediction of Flying Qualities

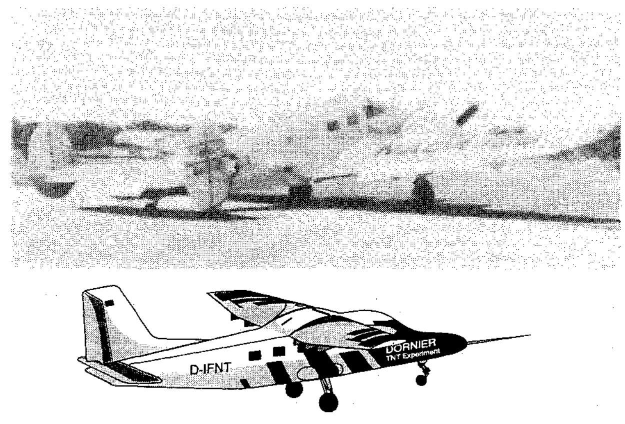
One of the most important objectives of flying-qualities research is the ability to predict flying qualities of new airplanes while they are still in the design stage. Many airplanes, of course, still have manual control systems. Gilruth's requirements, and the requirements formulated for military airplanes of the World War II era, were based on a wide range of designs of this type and should be expected to be useful in predicting the flying qualities of the latest general aviation and commuter airplanes.

All of the requirements for advanced airplanes incorporating stability augmentation and command control systems cannot be expected to be based on previous experience with the same types of problems because, as pointed out previously, these systems may introduce entirely new types of response controls. Two widely used methods are available to predict the handling qualities of airplanes of these types. First, the attempt is made to predict the handling qualities based on a mathematical analysis of closed-loop control of the human-pilot airplane combination. Numerous techniques of this type have been proposed, most of which have been validated over some range of parameters either by simulation studies or by tests in variable stability airplanes. The amount of literature in this field is formidable[53] and might be quite discouraging to a new engineer attempting to work in this area. The question may arise as to what method would be most applicable to the particular configuration under consideration. The methods most likely to prove successful are those based on aircraft of the same size or configuration as those used in developing the method, or, if these conditions are not met, criteria and techniques should be based on nondimensional parameters that would be expected to apply over a wide range of conditions. Several notable failures in the prediction of flying qualities have occurred because of the application of requirements based on dimensional parameters to airplanes of size or speed range widely different from those used in validating the requirement.

Simulation methods provide a very desirable technique to be used in conjunction with analytical studies. Simulators have the advantage that they can theoretically include all the nonlinear characteristics of the actual control system and can provide an actual human pilot with cues that attempt to simulate those encountered in flight. The widespread use of simulators to design satisfactory control systems may make the reliance on written handling-qualities specifications less important than before. Many examples exist in which very satisfactory control systems were developed through use of simulation techniques. Such simulators, however, are not without their pitfalls.

Early simulators, such as the yaw chair referred to previously, were restricted to a very limited range of problem areas, but they had the advantage that the motion of the simulator very faithfully reproduced the desired airplane transfer functions and did not introduce lags or other artifacts in the stimuli provided the pilot. More complex simulators, such as those shown in Fig. 9, provide visual displays as well as angular and linear motion cues, but these quantities may be subject to lags and nonlinear response characteristics that make such devices misleading for highly accurate research studies or even for development tests. An example of the type of problem encountered was a general aviation simulator at Langley that used a limited motion base and a visual TV display of a runway. It was found that experienced test pilots had great difficulty in making successful simulated landings, whereas members of a troop of explorer scouts who were being shown the simulator were able to land successfully on the first attempt. When such an experience is encountered, it is apparent that something must be wrong with the simulation. In this case, it was found that the lag in the motion shown by the visual display was greater than the lag shown on the cockpit instruments. Such problems have, of course, been the subject of much study in the development of satisfactory simulators. These subjects are discussed in an Agard Symposium[54] and in a series of proceedings of AIAA conferences held every two years.[55]

Another factor sometimes overlooked in the use of simulation techniques is the great sensitivity of the sensory apparatus of the human, which requires the simulator to produce cues with equal precision. For example, a human can sense an oscillation of normal acceleration of two thousandths of a g. Angular motions detected by sighting through a gunsight are also very small. With a good quality manual control system, a pilot



a)

b)

Fig. 8 Airplanes equipped with experimental gust-alleviation systems: a) Beech B-18 (military designation C-45); and b) Dornier Do-28 TNT.

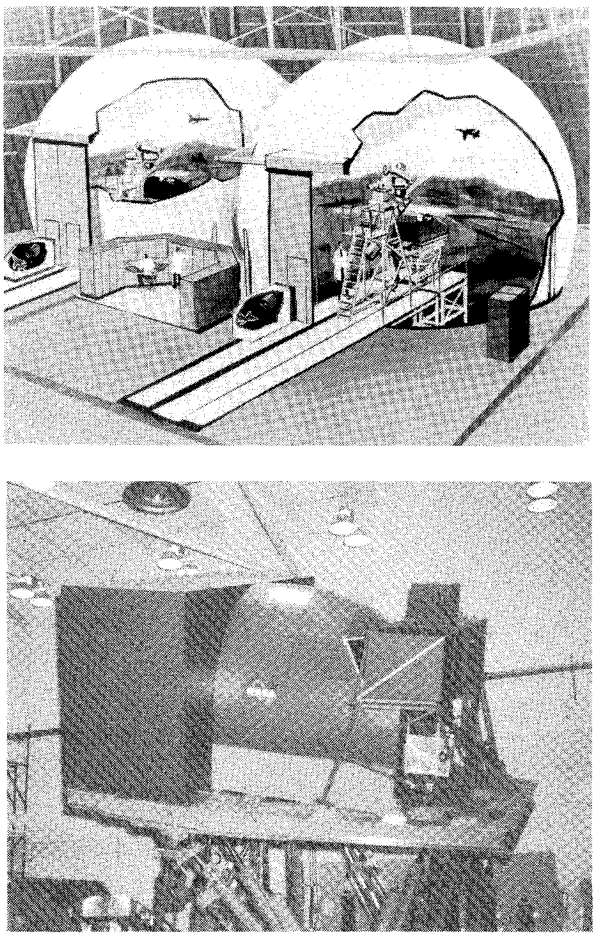


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Fig. 9 Modern simulation facilities: a) DMS (Differential Motion Simulator); and b) VMS (Visual Motion Simulator).

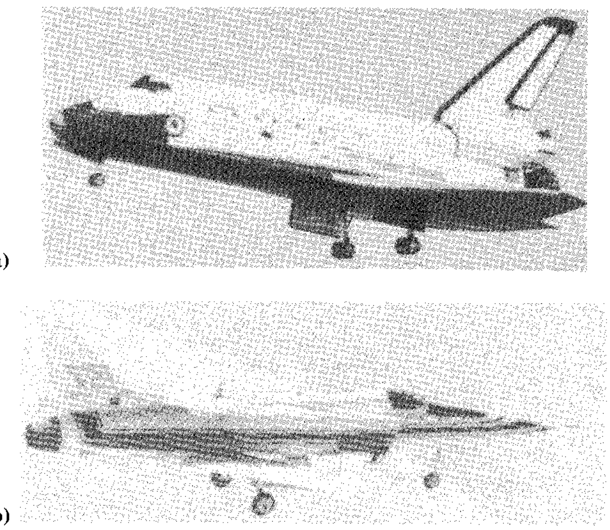

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Fig. 10 Airplanes with digital fly-by-wire control systems: a) Space Shuttle Orbiter; and b) Grumman X-29 airplane.

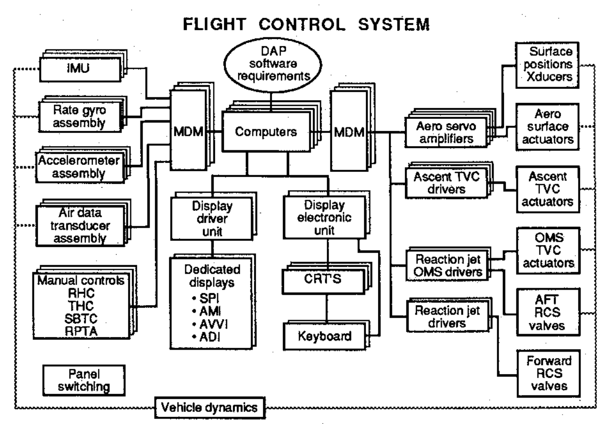

Fig. 11 Components of the Space Shuttle Orbiter control system.

can track a target in maneuvering flight with an accuracy of about two tenths of a degree. Tracking is indeed an important operation for military airplanes and, if the control system does not permit tracking to this degree of accuracy, the handling qualities will be considered deficient. Some general-purpose simulators, however, project the target image to an angular accuracy of only about half a degree. Obviously, an order-of-magnitude better accuracy would be required to study the effect of a control system on the tracking ability of a pilot-airplane combination.

Finally, experience with modern airplanes and the solutions of problems encountered in their development must be kept in mind in predicting flying qualities of new configurations. A discussion of experience in the application of theory to problems of this type is given in Ref. 56.

Discussion of Space Shuttle and Some Recent Airplanes

The title of this paper is "Flying Qualities from Early Airplanes to the Space Shuttle." Inasmuch as the Space Shuttle is mentioned in the title, some comments on its flying qualities appear to be in order. The Space Shuttle, or more correctly, the Space Shuttle Orbiter, is an example of a digital fly-by-wire airplane. Such an airplane has no mechanical connection between the control stick and the control surfaces. A picture of the Shuttle Orbiter is shown in Fig. 10. The Shuttle control system was designed in the early 1970's and might not represent the latest thinking in control-system design. A more recent example of a digital fly-by-wire control system is that in the Grumman X-29, also shown in Fig. 10.

Although the Orbiter was developed so long ago, the design of the control system has proved to be a model for later applications involving these systems.[57] A digital control system was made necessary by the wide variety of tasks and flight conditions to be handled by the Shuttle, including launch, on-orbit phases, entry, and landing. A diagram of the Shuttle control system is shown in Fig. 11. This figure shows mainly the various components in the system and their degree of redundancy. Though it would be desirable to show the functions of these various components in block-diagram form, the complication of the system is such that this amount of material could not be shown in a single figure. Such a block diagram has been prepared, but it must be viewed as a wall chart that covers the whole side of a room. Some unusual features of the system may, however, be mentioned. First, during the entry phase of the flight, the control system must rely completely on data from the inertial navigation system because no air data system is available in the hypersonic speed range. The angle of attack during entry is so high that the vertical tail and rudder have no effectiveness and, as a result, yaw jets are used in conjunction with the elevons to provide lateral control. Also, during this phase of flight, the elevons provide more adverse yaw than rolling moments. As a result, the elevons are used in a reverse direction to yaw the vehicle in order for the dihedral effect to supply the desired rolling moments. Later in the entry, the elevon motion for lateral control is reversed so that the elevons assume their normal function of rolling the airplane.

The Shuttle Orbiter is designed so that the astronauts can take control at any point in the flight. Their function would be to maneuver the vehicle in accordance with cockpit displays in order to follow the computed entry trajectory. In practice, however, the entry is performed under automatic control until the orbiter reaches an altitude of 40,000 ft. At this point, the astronauts take control and land the vehicle manually. In normal operations, the only phase of flight in which flying qualities are important, therefore, is the landing approach and landing.

Early experience with the Orbiter during approach and landing tests revealed several problems that aggravated a pilot-induced oscillation during the landing flare. These problems included control rate limiting and excessive lag in the response of the control systems to pilot control. Despite correction of these problems, however, the orbiter landing characteristics remain undesirable.[58] A large amount of astronaut training in an Orbiter simulation airplane called the Shuttle Training Aircraft is required to obtain confidence in performing successful landings. Although it is generally assumed that stability augmentation can solve practically any stability and control problem caused by the aerodynamic characteristics of the vehicle, the main conclusion from the Shuttle experience is that not all aerodynamic problems can be solved in this way. The main problem with the Orbiter is that when the elevons are deflected to produce a change in the flight path angle, they produce a lift force on the vehicle, which initially causes the flight path to move in the incorrect direction. Though all tail-aft airplanes have this characteristic to some extent, the problem is much worse for the Orbiter than for any other airplane because of the vehicle's short tail moment arm and large inertia in pitch.[59] Time histories of the response of flight path to a step elevon input for the Orbiter as compared to a conventional airplane and to another delta-wing airplane are shown in Fig. 12. A lag of approximately 2.1 s occurs following a control input before the altitude of the Orbiter returns to its initial value and starts to move in the correct direction. This property is known to control engineers as a nonminimum phase characteristic. It is well known that with such a system the control gain must be limited below a certain value or instability will result. In this application, the gain of interest is the control deflection applied by the human pilot in response to deviation from the desired flight path, combined with the control system gain, or ratio between elevon deflection and stick deflection. During a flared landing, the human pilot tends to raise his gain as much as possible in order to maintain tight control. Such behavior in the case of the Orbiter would lead to a pilot-induced oscillation. The astronauts must be trained to keep a low gain in making flight-path corrections and, in case their gain tends to become too high, a device called a PIO suppressor has been installed, which detects control inputs at the frequency of the short-period motion and automatically reduces the gain of the control system.[60] With these provisions, successful landings of the Orbiter are possible, but the capability for correcting for disturbances due to turbulence is

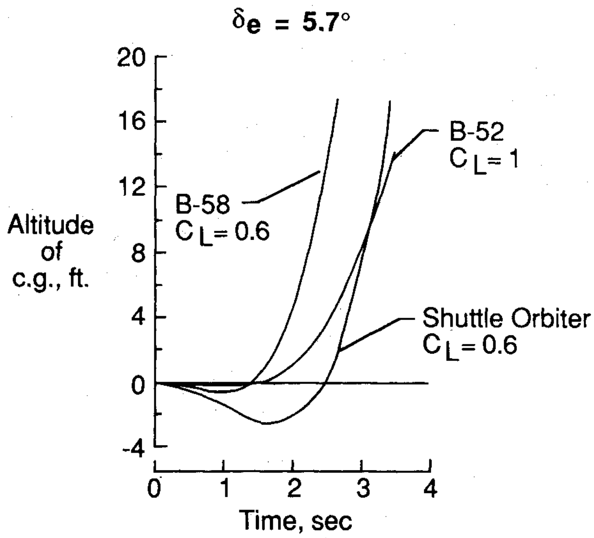

Fig. 12 Comparison of altitude response of three airplanes to a step elevator control input.

much reduced as compared to other airplanes. For this reason, in-flight simulation studies have been conducted to try to refine the longitudinal control system as far as possible.[61] To correct the problem on the Orbiter would require a longitudinal control surface capable of producing lift in the correct direction, such as a retractable canard surface mounted ahead of the wing.

The Orbiter, during its entry and landing approach, is required to perform only very gentle maneuvers and to maintain its angle of attack and sideslip within very narrow corridors in order to avoid excessive aerodynamic heating. In contrast, the fighter airplanes, such as the X29, are required to perform violent maneuvers and, if possible, to maintain adequate control beyond the stall. The digital control system can aid in providing such capabilities, but adequate control power must also be provided. Considerable research is currently being conducted on the use of jet controls or thrust vectoring to provide adequate control power. These new capabilities are likely to require additional flying-qualities research to explore these new regimes of flight.

Format of the Flying-Qualities Requirements

Since the publication of Gilruth's original flying-qualities requirements, the civil and military agencies in this country have followed different procedures for ensuring satisfactory flying qualities of new airplanes. In the certification of civil airplanes, the Federal Aviation Administration (FAA) has stated their requirements in qualitative terms, retaining the authority to rule out undesirable characteristics as determined by actual flight tests after the airplane is flown. Fortunately, most of the companies producing civil aircraft in this country have been sufficiently familiar with the military handling quality requirements to produce satisfactory airplanes for civil purposes. In the case of military airplanes, the Air Force and Navy published their own requirements, based originally on Gilruth's requirements, which stated many of the flying-qualities requirements in quantitative form and provided enough information to guide the designer in selecting the aerodynamic characteristics of a new airplane. These requirements have been revised several times, generally becoming more quantitative and including backup documents to outline the design procedures to be used in checking the requirements.

In recent years, a military directive has required that all military specifications be placed in a particular format. In this format, quantitative specifications are left blank in the statements of the requirements. These quantitative specifications are to be filled in through negotiations between the procuring agency and the contractor for each individual airplane.[62] The new Air Force flying qualities specification has been published as MIL-STD-1797 (USAF) dated March 31, 1987 and includes a lengthy backup document totalling some 700 pages, which presents the analysis procedures to be used by the contractor and the procuring agency in determining values and verification procedures. A coordinated triservice version is in the process of publication.

One of the major advantages of flying-qualities requirements in the past has been that they preserved knowledge previously derived in numerous tests of actual airplanes. It would be unfortunate if the ability to preserve this knowledge were lost as a result of the new format for the specifications. Obviously, a great deal of experience on the part of both the procuring agency and the contractor would be required with the new specification format to arrive at a satisfactory set of specifications for each new airplane. Such a format, however, offers the possibility of greater flexibility in handling the wider range of capabilities of digital control systems. The man hours expended in the design and testing of the control system of a modern military airplane probably exceed those used in the flight testing and analysis of data for all 16 airplanes used in formulating Gilruth's original flying-qualities requirements. Obviously, the possibility exists that new ideas may be explored and new capabilities developed.

Concluding Remarks

By comparison with other disciplines required in airplane design, the subject of flying qualities is in a less satisfactory state. The desirability of flying qualities still cannot be measured accurately, and prediction of flying qualities for a new or radically different control arrangement has not been placed on a quantitative bases. These conditions could perhaps be expected, because the flying qualities depend so strongly on the involvement of the human pilot, whose behavior is variable and imperfectly understood. The fact that flying-qualities requirements can be placed in quantitative form after sufficient experience with a particular class of airplanes gives hope that, with further progress in this field, more accurate predictions for new systems will be feasible. The research tools required for progress in this field, namely, simulators or specifically equipped airplanes, are very expensive to build and operate. Nevertheless, the failure to predict problems requiring the modification of a new airplane design can be even more expensive. Continued research in this field is certainly desirable to maintain the superiority of future American airplanes.

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