Optimisation of Aircraft Performance and Mission Completion Through Research on the Pilot and Aircraft as an Overall System

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SUMMARY

The research aeroplane programme active in the United States for the past 20 years has been a catalyst for the focusing and direction of much of the aeronautical research. A continuing effort in optimisation of the pilot, aircraft, and subsystems into an overall system has been the main objective of the programme. The operational goal has been to assure the successful completion of the required research missions. As the programme has developed, a gradual but definite change in the role of the pilot, subsystems and aircraft relationship has been evident. The pilot's role has been strengthened to assure mission completion; subsystems now play a major role to provide adequate aeroplane handling and performance, and the requirements to meet satisfactory aerodynamic solutions are more challenging.

The philosophies and findings of the research aeroplane programme are in many respects directly applicable to the requirements for the development of successful future high-performance aircraft. One of the lessons could be the importance of an experimental or prototype aircraft as a basic requirement to the successful development of proposed aircraft of the future.

1. INTRODUCTION

The design of aircraft is a continuing process of compromising between many conflicting requirements. Each compromise, hopefully, is directed towards optimising the final design. During the past 20 years, an increasing number of new research tools have been developed that permit a greater degree of optimisation in aircraft design. Such research efforts as the development and improvement of transonic tunnels, exploratory research in flight through the research types of aircraft, the development of ground and flight simulators, the development of supersonic and hypersonic ground research facilities, as well as complex computing facilities, all have resulted in new design tools in this short time. These tools have given the researcher and designer great flexibility and capability so that designs can be optimised to previously unheard of limits, not only in paper studies but also in actual flight operations.

An important focal point for the development and expansion of these research tools in the United States has been the research aeroplane programme. This programme involved both the government and industry in the development and researching of 27 aircraft from the X–1 through the X–15 and included 14 prototype aircraft used as research vehicles.

The design philosophy and optimisation of a research-type aircraft has always considered the pilot as an integral and extremely important element of the overall design. Maximum use of the best and latest ground facilities and testing techniques has supported the programme, and often improvements or new facilities have been developed to meet the needs of these aircraft developments. Finally, the flight environment and operational conditions have been established at the vast testing area of Edwards, California, which permitted the fullest study of the pilot, the aeroplane and the subsystems involved. Consequently, each research aeroplane programme was an effort to optimise an overall system consisting of these elements.

It is well known that there has been a gradual but definite change in the role that the basic aircraft, subsystems and pilot play in providing an efficient and successful completion of the aircraft operational mission. This trend was recognised in the development of the research aeroplane programme which progressed from a relatively simple pilot-aircraft related programme to a complex pilot-aeroplane-subsystems related programme, supported by flight-related ground facilities.

The design and philosophy of this particular programme and the gradual progression in technology typified in this programme over the past 20 years can, in many respects, be pertinent to considerations of new proposals and developments of advanced aircraft. This paper, therefore, summarises the research findings as they pertain to the consideration of the aircraft and pilot optimisation as an overall system.

First, we shall consider the research conducted in the period when exploration of the transonic and supersonic speeds involved aircraft that derived their handling qualities from the configuration aerodynamics and the pilot was provided with relatively simple visual aids and essentially no subsystems. Second, we shall discuss the period when automatic systems, such as stability augmentation systems and air-induction control systems, were designed as integral parts of the overall design of the research aircraft and played an increasing role in providing adequate performance and handling characteristics.

SYMBOLS

a_n	normal acceleration, g
a_t	transverse acceleration, g
C_{l_β}	lateral stability, per degree
C_{n_β}	directional stability, per degree
$C_{n_{\delta_a}}$	roll control parameter
h_p	altitude, ft
i_t	incidence angle of all-movable tail, degree
M	Mach number
$\frac{n_{z\alpha}}{\omega_\theta}$	flight-path control to stability ratio
p	rolling angular velocity, radians/sec
q	pitching angular velocity, radians/sec
r	yawing angular velocity, radians/sec
$T_{1/2}$	time to damp to one-half amplitude, sec
t	time, sec or min
α	angle of attack, degree
β	angle of sideslip, degree
δ_a	aileron deflection, degree
δ_e	elevator deflection, degree
δ_r	rudder deflection, degree
ζ_d	damping ratio of Dutch roll mode
$\zeta_d\omega_d$	Dutch roll damping, radians/sec
ζ_θ	damping ratio of longitudinal short-period mode
θ	pitch attitude, degree
$\ddot{\theta}$	pitching acceleration, deg/sec^2
ω	undamped natural frequency, radians/sec
ω_d	Dutch roll frequency, radians/sec

2. ORIGINAL RESEARCH AIRCRAFT

The research aircraft and the prototype aircraft used as research aircraft in the first period were as follows:

D–558–I
D–558–II
X–1A
B–47
B–52
F–100A

X–1B
X–1C
X–1D
X–1E
X–2
X–3
X–4
X–5
XF–91A
XF–92A
F–100C
F–101
YF–102
F–102A
F–104A
F–104B
F–105
F–106
F–107
F5D
KC–135

These aircraft represented concepts incorporating various wing thicknesses, swept and delta wings, various sizes and horizontal-tail positions and tailless configurations. The class basically researched the aerodynamics of the aircraft and pilot performance capabilities.

The research from these aircraft provided information that supported the following facts:

1. It was possible to obtain controlled supersonic flight without automatic systems to aid the pilot; however, there were several problem areas associated with such flight.
   (*a*) The transonic speed regions of mixed flows caused aircraft buffeting, aircraft and control surface nonlinearity and large drag increases.
   (*b*) Low damping of angular motions at high speed, primarly in yaw and roll.
   (*c*) Pilot-induced oscillations, resulting from low natural damping and highly effective nonlinear controls in the longitudinal case, and caused by dihedral effects and aileron yaw characteristics in the lateral-directional case.
   (*d*) Divergence in aircraft motion during rolls that involves interaction of the aerodynamic and centrifugal forces — associated with weight distribution or low directional stability.
2. The generation of over-pressure at ground levels from supersonic flight operation that required precise flight profiles to reduce the effect of the sonic-boom phenomenon.

The results of divergence in aircraft motions are still design considerations in certain advanced designs. Figure 1 shows flight results of the X–3 research aircraft at transonic speeds during rolling manoeuvres with violent excursions in pitch and yaw. These divergent motions result primarily from the weight distribution associated with a long, slender body. Any practical application of increasing the aerodynamic static directional stability with this particular design would not have prevented the occurrence.

Figure 2 shows a similar occurrence with the X–1 aeroplane at supersonic

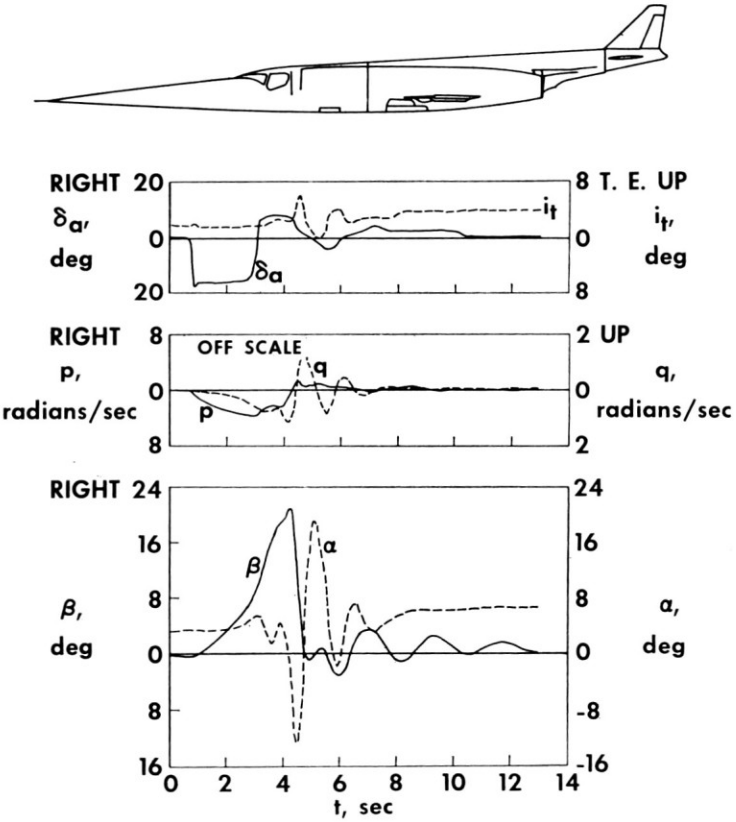

FIG. 1 — Lateral-longitudinal coupling problems
$M = 1$, $h_p = 25{,}000$ ft

speeds. In this case, the aircraft motions illustrated were initiated from a yawing excursion due to low directional stability. The yawing and rolling motions resulted in aerodynamic and inertial coupling of the aircraft. Generally, the result of too low a level of static directional stability has manifested itself in two levels of concern for aircraft operation: highly manoeuvrable aircraft with the potential of flight results similar to the X–1, and large transport aircraft with yawing (snaking) oscillation potentials.

It was found to be unsound to attempt to generalise dynamic behaviour similar to that experienced in the X–1, X–3 and other high-performance aircraft. The detailed aerodynamic and inertial characteristics of the individual aircraft were so intimately associated with the final result that each aircraft had to be treated separately. It was also found unsound to study the stability and control characteristics without a pilot at the controls, as had been done

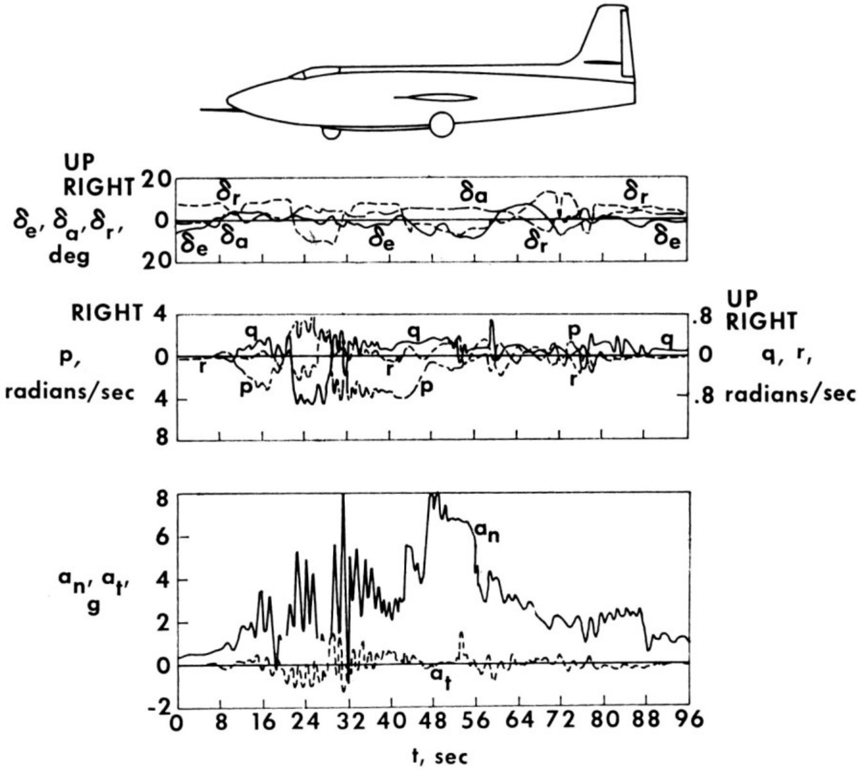

FIG. 2 — Directional divergence at supersonic speeds

in the past from the use of step inputs to a simulator. It was during this period that piloted ground simulators began to play an important role in the flight planning and analysis of the flight results. Minimum consideration was given to studying the electronic systems in an effort to improve the characteristics of this original group of research aircraft, although the aerodynamic deficiencies were well known. However, it was found that many potentially dangerous characteristics would be controlled if the pilot–aeroplane system was considered as an overall system and researched by means of simulators.

Various design changes through the years, such as thinner wing sections, adjustable and manoeuvring stabilisers and wing sweep, have improved some of the transonic flight characteristics. However, because of design compromise requirements, there is no assurance that future aircraft will not have some of these undesirable characteristics. Considerations of over-speed situations of present jet transports and the new generation of executive jet transports, for instance, can serve to illustrate these situations.

Current wind-tunnel research is directed towards improving the undesirable

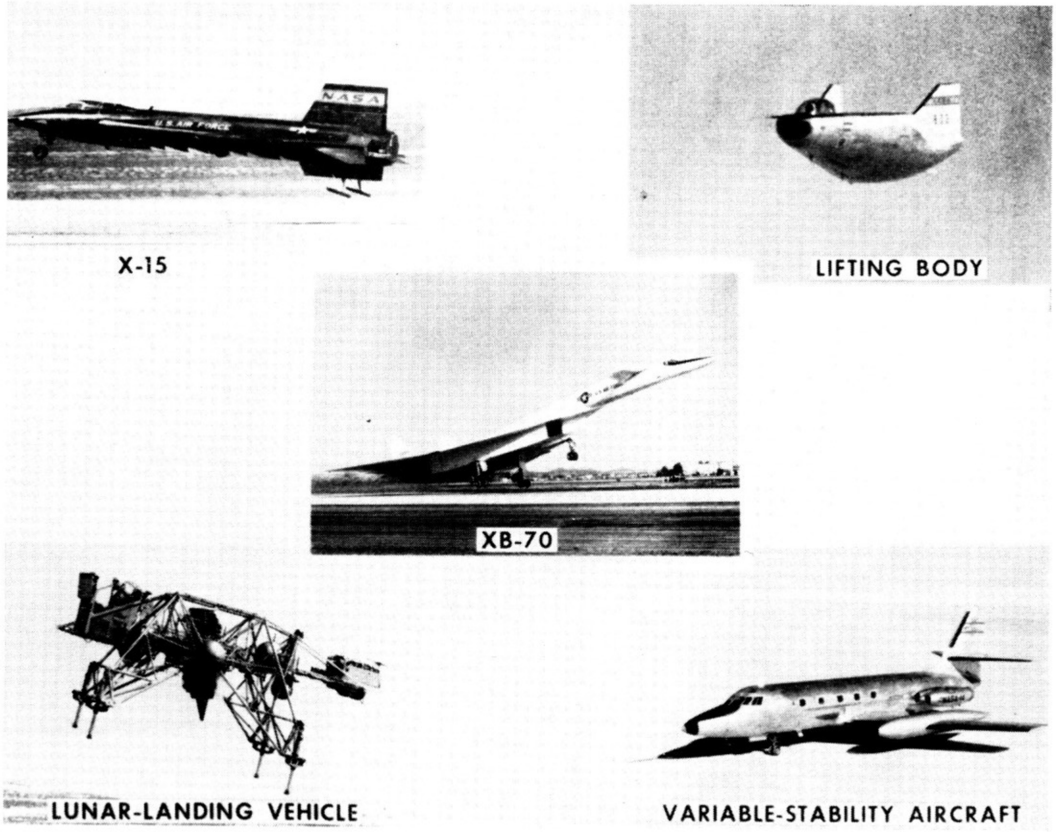

FIG. 3 — Advanced research aircraft

transonic characteristics, such as high lift, instability, buffeting and drag, by increasing the critical Mach number for wing–fuselage combinations. Results of these efforts, however, have not yet reached an application stage even for research flight investigations.

3. ADVANCED RESEARCH AIRCRAFT

The research effort has been directed in recent years to a new generation of research aircraft where optimisation of the role of the aeroplane and pilot takes into consideration automatic subsystems. Figure 3 is a composite photograph of these new research aircraft that typify this aircraft, pilot and systems research relationship. The X–15 (upper left) represents a research tool with which to explore the supersonic and hypersonic speed regimes. Many of the lessons and concerns of previous research aircraft were considered in the X–15 programme. The need to explore the role of systems in the X–15 was fully realised. The LLRV† (lower left) was developed to research the pilot's role in performing a lunar-surface landing. The principles and concepts of this flight programme involved the integration of the vehicle, systems and the pilot and are directly applicable to the landing and take-off operation of VTOL aircraft. The lifting body (upper right) represents an entirely new concept in aerodynamic design. Since the configuration is designed from atmospheric re-entry considerations, it is basically in contradiction to rules for good design for transonic and low speed. For this reason, the role of systems has been emphasised in this research application. The XB–70 (centre) represents a research tool for studying problems of an efficient supersonic cruise aircraft of the Mach number 3·0 category. The small jet transport (lower right) has been modified to incorporate a variable–stability and control system whereby wind-tunnel and ground-simulator results for a large variety of advanced aircraft types may be programmed into actual flight operations.

Operational aspects

The X–15 has generally been identified with hypersonic re-entry speeds, altitude operation greater than 200,000 feet and space research; however, equal attention has been given to supersonic and hypersonic research at altitudes less than 100,000 feet.

Many aspects of the programme development, pilot display requirements, pilot, systems and aircraft relationships of the X–15 and XB–70 are similar to those expected for advanced cruise and tactical high-performance aircraft

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† Lunar Landing Research Vehicle.

of the future. The operational profile of altitude, flight-path attitude and time with Mach number for the X–15, XB–70 and a supersonic–hypersonic cruise aircraft shown in Fig. 4 illustrates some of these similarities.

The X–15 is launched at subsonic speeds, accelerates at low lift through the transonic speed to supersonic speeds, rotates to a predetermined aeroplane attitude of approximately 20°, levels off at a predetermined altitude and completes research missions requiring range and speed achievements with definite limits of structural temperature, dynamic pressure and load factor. Efficient supersonic and hypersonic cruise aircraft and tactical aircraft of the future will be faced with quite similar operational requirements and limitations.

The XB–70 so far in its exploratory flight programme has traversed the ransonic area at altitudes less than the X–15 and climbed at lower attitudes to achieve its supersonic cruise conditions. In the future, flight profiles approximating cruise aircraft of the future will be conducted. The profiles of advanced supersonic cruise types of aircraft in Fig. 4 are calculated with adherence to strict sonic-boom overpressure limits. Although the accelerations and the operational times are different for the X–15, the problems of transonic transition, climb attitudes and cruise–altitude attainment are similar.

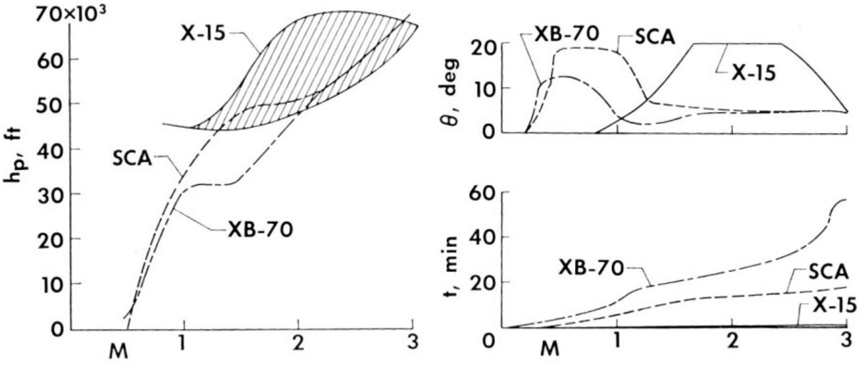

FIG. 4 — Operational comparison

Flight profiles of the high-altitude supersonic–hypersonic cruise type conducted with the X–15 require angle of attack and aircraft attitude as prime operational display requirements to the pilot. Angle of attack is used as a prime display during the rotation and transit portions of flight to establish aircraft climb attitude and cruise altitude. Aircraft attitude is the prime display for stabilised flight conditions. There are continual cross-checks on velocity, rate of climb, elapsed time, altitude, Mach number, dynamic pressure and structural temperature by the pilot within the cockpit. A continuous exchange of information is provided through radio and radar links with a ground-based installation.

At various times in the X–15 programme, deviations have occurred during flight where appreciable differences in end-point objectives became critical in terms of exceeding structural temperature or dynamic pressure. Figure 5 shows two examples of flights to achieve cruise–flight altitudes less than 100,000 feet. The upper portion of the figure shows an attempt to cruise at 81,000 feet where angle of attack and attitude were adhered to very closely with satisfactory results. The lower plot shows a flight that deviated approximately 3° for approximately 10 seconds and never fully reached the intended profile. The actual altitude exceeded the intended altitude by approximately

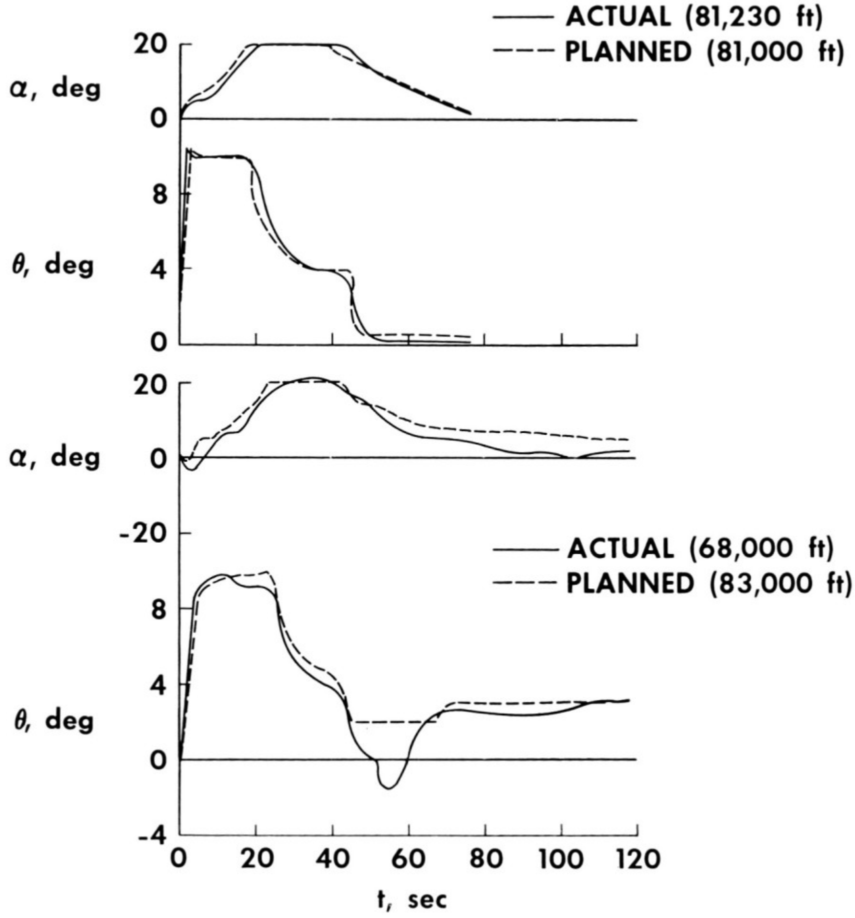

FIG. 5 — Effect on climb performance

15,000 feet. Differences have occurred in other flights that were smaller in magnitude, but more critical in terms of structural temperature and loads.

Simulator studies of the X–15 for Mach numbers of 3 to 6 at altitudes of 70,000 feet to 80,000 feet show that a constant deviation of 1° in angle of attack during the cruise portion of the flight can result in approximately a 15,000-foot deviation in planned cruise altitude.

The foregoing has shown that by flying precisely a predetermined angle of attack and pitch attitude, a predetermined peak altitude can be achieved with precision. It has also shown that when these parameters are not flown with precision the peak altitude achieved varies by a large amount. As the pilot is flying on the intended climb schedule, many other parameters are cross-checked to assure that the climb schedule is being followed. If, at these check points, it is determined that the profile plan has deviated, the pilot must mentally determine what corrective action should be taken. He must consider all of the constraints of the aircraft when he makes this decision, and he must determine what impact corrective action will have on later flight conditions. This places an additional workload on the pilot and, if the wrong action is taken, can result in catastrophic consequences. With this in mind, a research programme has been implemented on the X–15 to investigate climb guidance and corridor control. The programme utilises a high-speed digital computer to generate simple fly-to-null guidance commands. The commands are up-dated at a high rate of speed and take into account the present dynamic conditions of the aeroplane, the constraints of the aeroplane, the desired end objectives of the flight and a prediction of future *g* loads and peak dynamic pressures.

Aeroplane–Systems–Piloting relationships

The X–15 was designed with systems to provide adequate handling for safe flight based on wind-tunnel and ground-simulation results. Different systems with variations in capability were provided for research purposes. The X–15 programme at its present stage of development is more systems-orientated than during its first exploratory flights. In the first phases of the programme, total confidence was placed in the pilot, simplified displays and aircraft structural integrity. Questions and unknowns existed in stability and control, general handling and in the systems that provide stability augmentation and accurate guidance. As confidence was gained in system improvement and reliability and flight knowledge of the aeroplane characteristics, the programme became more systems-orientated. It is of interest to note that the original pilot team with minimum systems background training became more systems-orientated as the programme progressed. Pilots with systems background training, assigned later in the programme, quickly became adapted to the systems-orientated programme.

Considerable attention was given to the X–15 design to provide as much aerodynamic stability and control as possible. For example, much research was directed towards providing sufficient aerodynamic directional stability to eliminate any possibility of divergence as experienced in other high-performance aircraft. The aircraft was designed with a large vertical tail, top and bottom of the fuselage, with thick trailing edges.

The next series of figures shows the typical development of the aeroplane-systems–pilot relationship for the X–15. The data are directed towards obtaining satisfactory Dutch roll handling characteristics for the aeroplane and are in terms of operating envelopes of angle of attack and Mach number. The upper portion of Fig. 6 shows the Dutch roll damping for the original X–15 aeroplane configuration. The operating envelope was restricted because of areas where the aeroplane would become divergent and the time

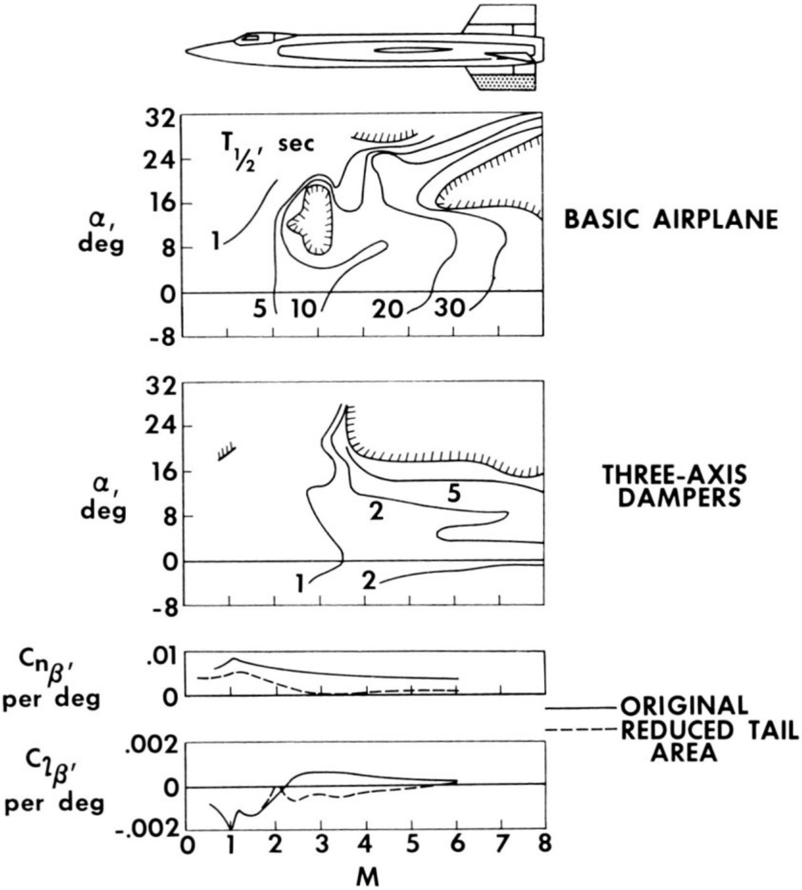

FIG. 6 — Dutch roll damping, damper effect

to damp was excessively high. A three-axis damper system reduced the time to damp to satisfactory levels, as shown in the centre plot, but the aircraft was restricted by divergence at the higher angles of attack. The lower plots show the static directional stability C_{n_β} and lateral stability C_{l_β} versus Mach number. The X–15 had sufficient static directional stability by acceptable standards, but the occurrence of positive C_{l_β} produced an uncontrollable dynamic situation. The dashed lines indicate the data obtained with the vertical tail reduced to the extent indicated in the sketch of the aeroplane. Although the directional stability was reduced approximately 25 per cent, it did provide negative C_{l_β} through the Mach number range and resulted in significant improvements in the dynamic characteristics of the aeroplane. The improvements are shown in the data of Fig. 7 for the reduced vertical-tail area. The aircraft with damper has had good handling characteristics throughout the angle-of-attack and Mach number range; without dampers it has been satisfactory for the emergency mode of operation.

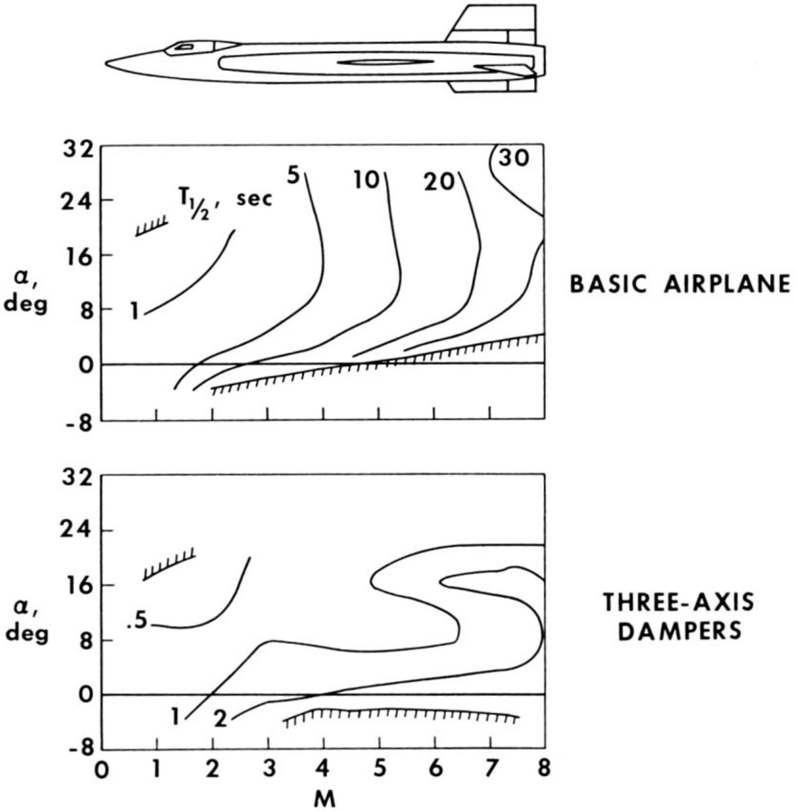

FIG. 7 — Dutch roll damping, vertical-tail effect

To utilise the full capability of the X–15, as will probably be the case in future designs, drag-producing devices are required. Figure 8 shows the detrimental effect on the Dutch roll damping of the use of drag devices deployed on the upper and lower vertical tails. A divergent region exists at high Mach number and high angle of attack. In future planned programmes for the aeroplane, it will be necessary to eliminate the divergent area. Simulator tests of a damper interconnect that introduces a roll control have essentially eliminated the divergent area, as shown in the lower portion of the figure. Similar damper arrangements were used successfully in the early stages of the X–15 programme.

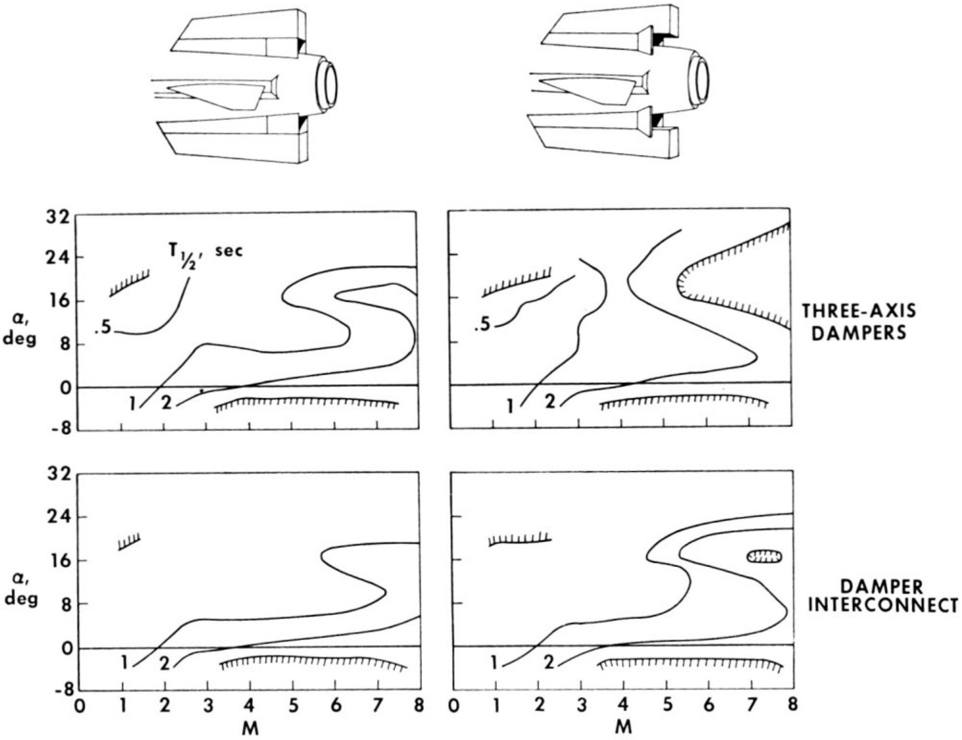

FIGURE 8

Fɪɢ. 8 — Dutch roll damping, drag-brake effect

These data are typical of the continuing effort in the X–15 programme to produce an optimisation of aeroplane, systems and pilot relationships. Additional wind-tunnel tests have been made, simulator studies are continually being up-dated on the basis of flight data and additional flight tests are continuing with aeroplane and systems improvements based on simulator studies. There are always reservations on the accuracy of the simulator results; hence, the gradual probing of suspected flight problem areas of interest is made with the pilot in full command. These types of approaches will be typical of future high-performance aircraft characterised by low aerodynamic damping. For, with low damping, small nonlinear aerodynamic moments with coupled control moments and principal-axis inclinations will become predominant in influencing the handling characteristics of these aircraft. Unfortunately, these moments are closely associated with detail design of a particular aircraft and are not generally predictable with sufficient accuracy until the configuration has been tested in the wind tunnel. The data, as in the past, may differ appreciably in the flight article. Fortunately, though, these moments are usually amenable to small configuration changes and artificial devices without requiring major configurational changes when they are determined under controlled flight tests.

After approximately one year of exploratory testing with the XB–70, it is evident that a continuing effort in wind-tunnel and ground-simulator data review and up-dating based on flight data will be necessary. Further tailoring of the aeroplane and systems relationships in flight will be required within the next two years to optimise the full utilisation of the total aircraft system. Figure 9 illustrates the stability areas of interest developed from the exploratory tests. Efforts similar to those of the X–15 programme will be expended to determine, or optimise, the aeroplane's overall system, based on the knowledge obtained from the exploratory flight tests. As with the X–15, the lateral-stability parameter C_{l_β} is a predominant factor, together with the directional-stability parameter C_{n_β}, in understanding and improving the lateral handling characteristics. The yawing moment due to roll associated with the parameter $C_{n_{\delta_a}}$ has received considerable attention in an effort to provide good lateral handling qualities for the XB–70.

The XB–70 has provided the first flight research evidence of the importance of detailed propulsion and airframe matching to assure safe and efficient supersonic cruise flight. The past 10 years has witnessed intensive efforts towards matching the airframe and systems to provide adequate aeroplane handling. It appears evident that we should now be on the threshold of equally intensive efforts to optimise and integrate the propulsion aerodynamics and systems and to relate these integrations to the airframe-systems integration.

Handling qualities

Much progress has been made in the design of aircraft to make them aerodynamically stable; however, as attempts are made to optimise the more advanced designs in terms of maximum performance, the stability margins are soon reduced to questionable levels. The designer considers many criteria

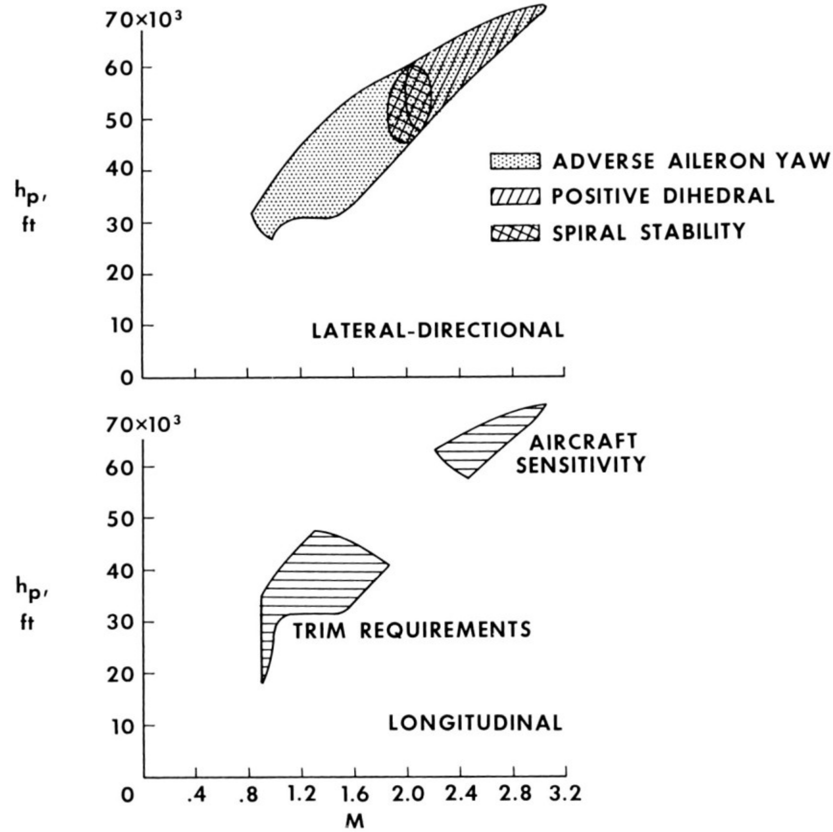

FIG. 9 — XB–70 stability areas of interest

and stability derivatives are refined to extremes, often beyond the accuracy of the pre-design data. The actual application of these refinements, however, are still directed to pilot's impressions and ratings. Although pilot rating is much more of an art than a science, the test pilot's impressions give valuable clues for identifying various systems or aerodynamic deficiencies that can, and do, result in system augmentation or aerodynamic improvements. The research aeroplane programme has continually attempted to rationalise the pilot's impressions to the measured stability parameters to provide a basis for specifying design criteria.

Figure 10 shows handling-qualities data for the X–15 and XB–70 aeroplanes in terms of the longitudinal short-period oscillation. Although numerous approaches are being used by organisations, theoreticians and experimenters in attempts to define acceptable handling qualities in terms of the aeroplane characteristics, a parameter combination does not exist that

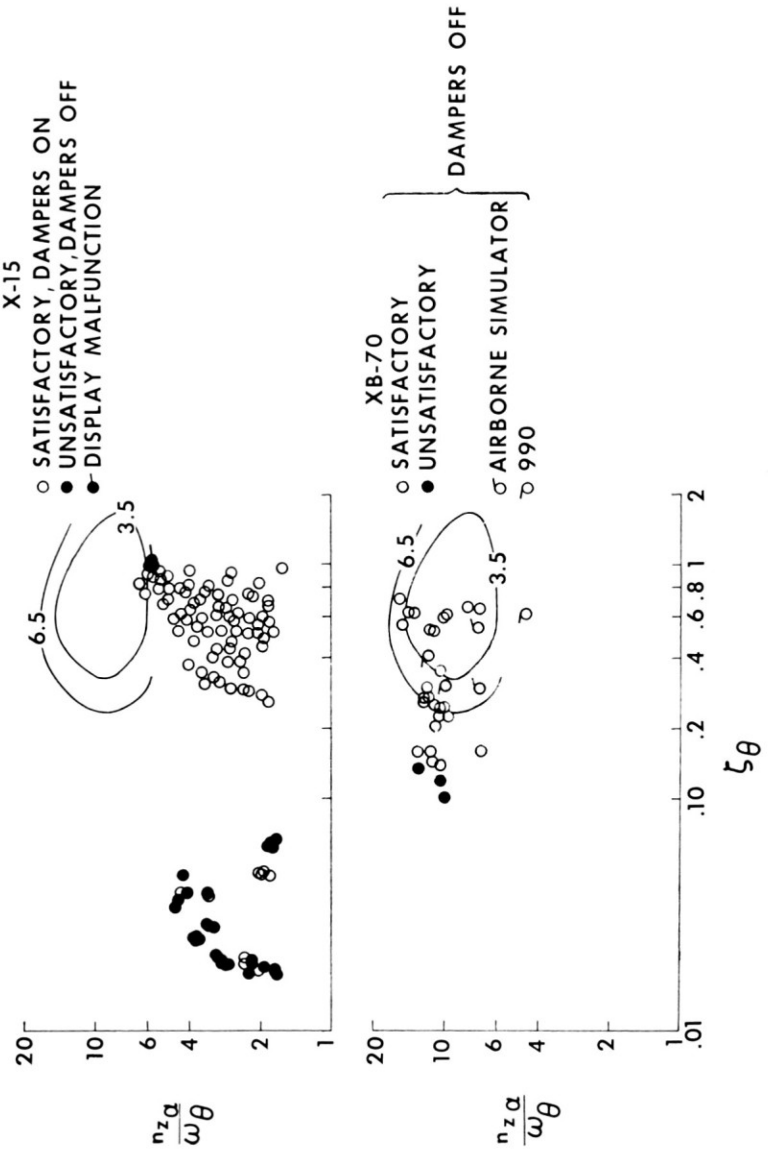

FIG. 10 — Longitudinal short-period characteristics

provides a solution at the present time. The parameter of flight-path control to stability was presented by Kehrer to this Congress at its last session and has been considered extensively by other experimenters. It is used here primarily for those reasons and is related to damping ratio. Included for reference are boundaries considered by air transport designers and developed by Harper and Chalk based on flight-simulation and ground-simulator work. The areas within the boundaries correspond to pilot ratings up to 3·5 as satisfactory and 6·5 as unsatisfactory. The X–15 data were selected for flight missions to achieve level-flight conditions at altitudes less than 100,000 feet. The open symbols indicate satisfactory handling with dampers on, generally at damping ratios greater than 0·10. With the dampers off, the aircraft has been rated unsatisfactory for normal operations, but satisfactory for emergency cases and has completed missions in this configuration. The ratings are applicable for hypersonic as well as supersonic speeds.

For the larger aircraft with longer exposure time, satisfactory ratings have been given to the XB–70, the 990, and the airborne simulator flown with SST type of characteristics for damping ratios greater than 0·15. The conditions flown for these ratings were for the dampers-off case.

In terms of the referenced boundaries it would appear, based on these flight data, that the boundaries may be too restrictive.

An analysis of the lateral-directional dynamics in terms of handling characteristics considers static stability and damping levels. It has been generally accepted, as in the longitudinal case, that a damping ratio of 0·10 defines a lower limit for satisfactory handling qualities.

For a damping ratio less than 0·10, the frequency versus damping relationships do not predict adequately handling qualities. Figure 11 shows the frequency and damping relationships for the X–15 and XB–70 for pilot ratings of satisfactory and unsatisfactory. These data tend to illustrate that many phenomena other than frequency and damping affect lateral-directional handling qualities. For both aircraft there is approximately the same number of satisfactory ratings as unsatisfactory ratings at a damping ratio less than 0·10.

The literature is heavy with attempts to arrive at an analysis and solution to a set of parameters that can define adequate lateral characteristics. Assumptions that consider aileron control to predominate have resulted in a dispersion of pilot impressions. Attempts to consider only the lateral mode have been unsuccessful. Present studies with the research aircraft are stressing the interaction of the Dutch roll and roll-mode characteristics. These kinds of data again illustrate the need for additional research, both in ground simulation and in flight for a variety of high-performance configurations to better define handling-qualities criteria.

The lunar-landing research vehicle (LLRV) is essentially a non-aerodynamic variable-stability vehicle and has been used, in addition to its lunar

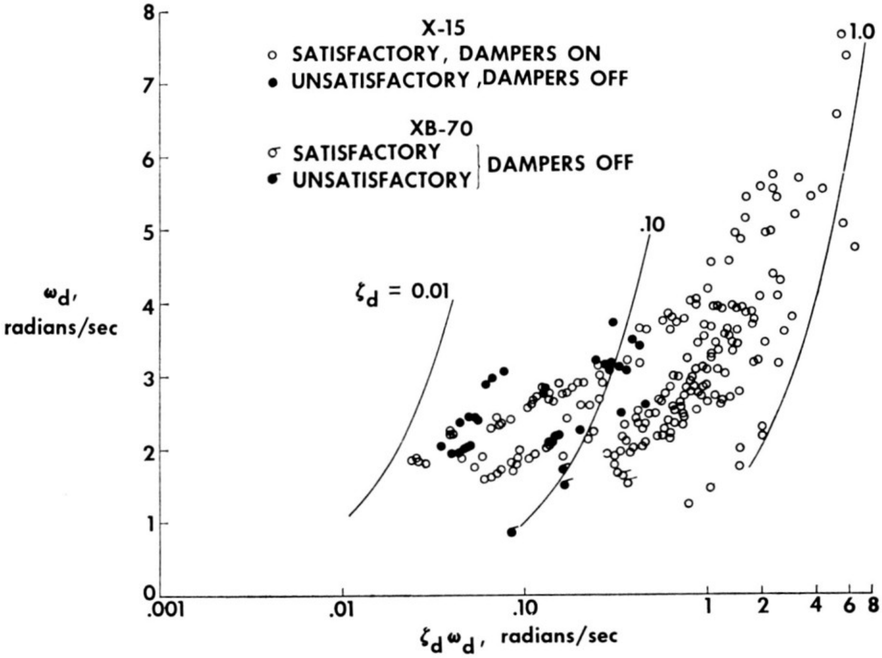

FIG. 11 — Lateral short-period characteristics

support mission, to study VTOL piloting problems. There are applications of VTOL where proportional rate command with on–off acceleration control can be attractive. Results of this type of control are compared in Fig. 12 with typical proportional acceleration. The greater control power required for the proportional acceleration for equivalent ratings is obvious. Attitude command control has received attention recently in tests of the LLRV. Preliminary results indicate that attitude command is easier to fly than rate command, with more precise control and reduced pilot fatigue for long flight durations.

Flight and ground co-ordination research

The lifting-body research vehicles support a programme that emphasises the wind-tunnel, ground simulation and flight relationships. The programme has again emphasised the need for detailed wind-tunnel results to approximate the flight characteristics and to provide guidelines for specifying the systems characteristics. The increasing use of ground simulation has done much to further emphasise this need before actual flight tests. Each lifting-body configuration is tested at low speeds in a full-scale wind-tunnel before

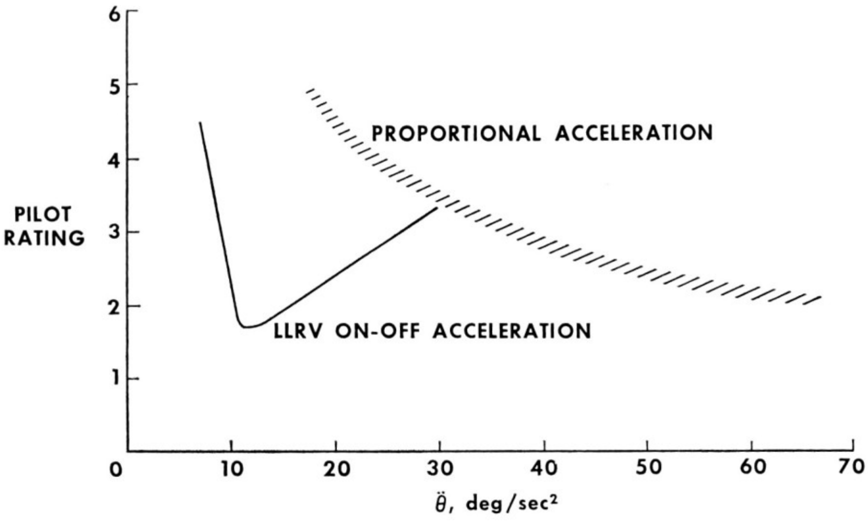

FIG. 12 — LLRV research on VTOL control

flight tests. It was necessary in the first configuration to repeat the full-scale wind-tunnel tests after the flight tests to better define the wind-tunnel and flight-result relationships. The present high-speed configuration programme is requiring a continual readjusting and re-analysis of wind-tunnel, ground-simulation and flight-test results.

The airborne flight simulator is a research tool that is being used to provide the visual and motion cues for a wide variety of proposed aircraft characteristics and for suspected critical or problem areas of present research or prototype aircraft. The variable stability and control features allow the aircraft to explore a wide variety of handling-qualities parameters not possible in a one-aeroplane type or class. At present, the research is directed specifically to the supersonic cruise class of aircraft. It is providing the flight-simulation element in the XB–70 programme. The programme involves the basic wind-tunnel, ground-simulation results and the actual flight results of the XB–70 aeroplane. The research up to the present time involving the XB–70 simulation has vividly emphasised the requirement to extend the ground-simulation results into the actual flight environment. Discrepancies found between the XB–70 ground simulation and XB–70 flight tests were traced first to discrepancies in wind-tunnel and flight-test results. With these corrections, additional discrepancies between ground simulation and flight tests were found during flight simulation, using the airborne simulator. Pilots flying the simulator became acutely aware of the piloting task in marginal control areas simulated for the XB–70 that had not been so apparent in the ground-based simulation. The simulation of the stresses, motivations and visual cues appears to be the significant contribution that airborne simulation can make.

4. CONCLUDING REMARKS

There has been a gradual, but definite, change in the role of the pilot, systems and aircraft relationship in the research directed towards optimisation of high-speed, long-range efficient aircraft. The pilot's role has been strengthened to assure mission completion but the pilot, as an individual, in the future will require training that emphasises a systems-orientated background. He can be trained to perform active stabilisation in most situations; however, on-line stabilisation results in undue fatigue. Primarily, the pilot's attention should be devoted to management of the systems with detailed attention to operational functions. Systems will play a major role in providing adequate handling characteristics for acceptable performance. Basic aircraft design will be an increasingly challenging effort to provide acceptable aerodynamic stability and control characteristics, together with acceptable performance.

The development of the ground and flight simulator has provided a valuable tool in bridging the gap between wind-tunnel and flight testing, thus providing a greater degree of optimisation before flight tests. It is important, however, to realise that neither wind-tunnel, ground simulation, nor flight tests will provide, individually, satisfactory results. The proper proportioning of the effort and timing in all three of these areas needs to be considered collectively.

The predominance of small aerodynamic effects and interactions of aerodynamic derivatives that affect the handling characteristics of high-performance aircraft has placed greater demands for detailed wind-tunnel data. The role of the ground simulator has aided in emphasising the need for these data before flight tests. By the same reasoning, greater demands will be placed on precise and controlled flight tests to provide the data necessary to up-date the wind-tunnel and ground-simulator results in the final development of the overall aircraft system. The experimental or prototype aircraft in the long-range development plan of the more complex advanced aircraft should be given serious consideration as a basic requirement to a successful development programme.

Many of the well-known transonic problems, because of design compromise requirements, need to be considered continuously in the design of future advanced aircraft. The pilot will be required to act as the prime adaptive control system during the flight exploration of these new designs.

The use of angle-of-attack and aircraft-attitude presentation used in the past for the research pilot to assure safe exploratory flights and valuable research information should now receive prime consideration by designers in the commercial and military application of high-performance aircraft of the future. For the more complex operational situations, automatic programming of flight profiles for pilot-monitoring may be required.