An Analytical and Flight-Test Approach to the Reduction of Pilot-Induced Oscillation Susceptibility

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The problem of pilot-induced oscillations (PIO) has plagued the designer of high-performance aircraft since the advent of the irreversible control system. The techniques and methods of systems analysis, simulation, and full-scale flight test were used to obtain a solution to this problem on the Northrop Norair T-38A trainer.

Nomenclature

F_{BW} = effective bobweight force, lb
F_E = force error signal, lb
F_S = pilot's applied force, lb
fn = undamped natural frequency, cps
g = gravitational acceleration constant, ft/sec²
G_I = inner loop transfer function, g/lb
G_p = pilot's transfer function, lb/g
j = $(-1)^{1/2}$
K_p = pilot's gain, lb/deg
1_{BW} = distance from center of gravity to the mass center of the bobweight effectiveness, ft
1_{panel} = distance from center of gravity to the front cockpit, ft
N_z = normal load factor, g
s = Laplace operator d/dt, $\times$ sec^{-1}
T_N = neuromuscular lag of pilot's transfer function, sec
T_s = hydraulic servo valve time constant, sec
δ_H = horizontal stabilizer displacement, deg
δ_S = longitudinal stick displacement, in.
ζ = damping ratio
ω = circular frequency, rad/sec
ω_n = undamped natural circular frequency, rad/sec
ω_D = natural damped circular frequency, rad/sec
τ = pilot's reaction time constant, sec
θ_0 = pitch angle output of loop, deg
θ_I = pitch angle input of loop, deg

Introduction

The problem of pilot-induced oscillations (PIO) has been of significant concern since the advent of irreversible control systems in modern high-performance transonic and supersonic aircraft. The phenomenon is recognized as a dynamic instability of the pilot, control system, and airframe combination. The program described herein utilized analytical and experimental techniques to reduce the PIO susceptibility of the Northrop Norair USAF T-38A supersonic trainer.

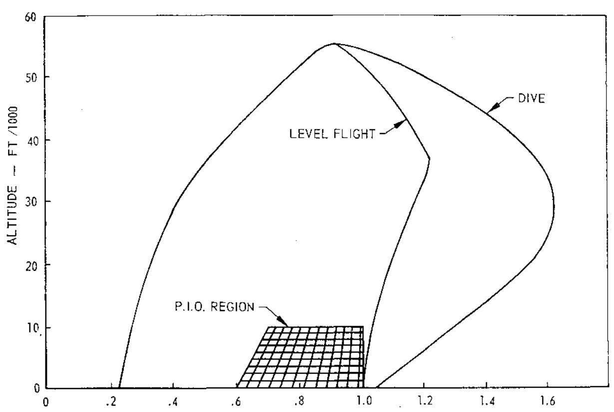

Fig. 1 T-38A flight envelope.

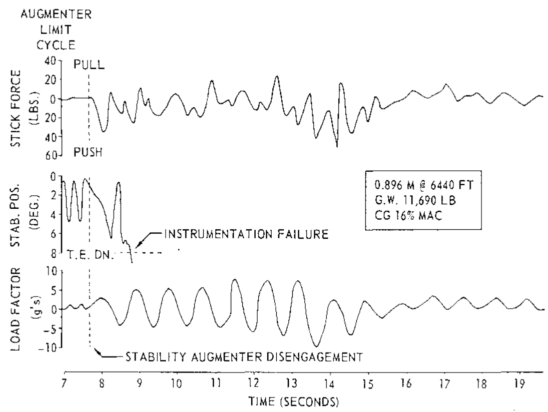

Fig. 2 Pilot-induced oscillation time history.

The T-38A satisfies a training requirement for performance and handling qualities typical of modern fighter aircraft; hence, handling qualities exhibited by century series aircraft are also characteristic of the T-38A. This similarity contributed to the high degree of PIO susceptibility that existed in a portion of the flight envelope, as shown in Fig. 1.

Most programs of this type are initiated by a large number of pilot comments and little or no quantitative data. Not so in this case! Largely by coincidence, the most severe case of PIO occurred in an aircraft that was instrumented to measure meaningful parameters during a test run on which the stability augmenter malfunctioned. A portion of the time history is shown in Fig. 2. Rapid buildup of normal load factor occurred at the aircraft's short-period natural frequency. Pilot inputs at this frequency initiated the oscilla-

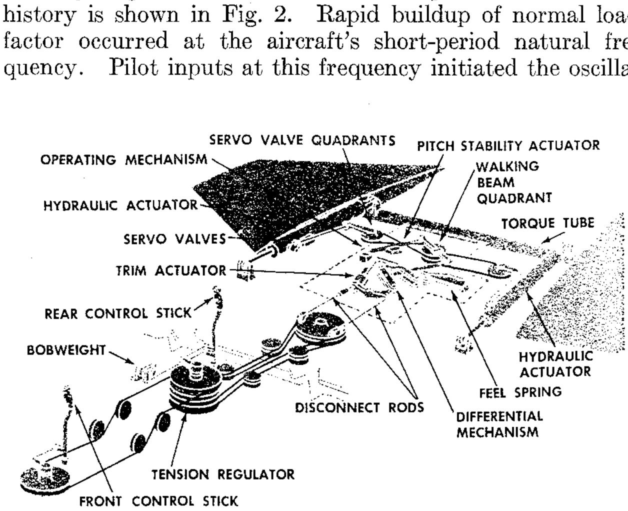

Fig. 3 T-38A longitudinal control system.

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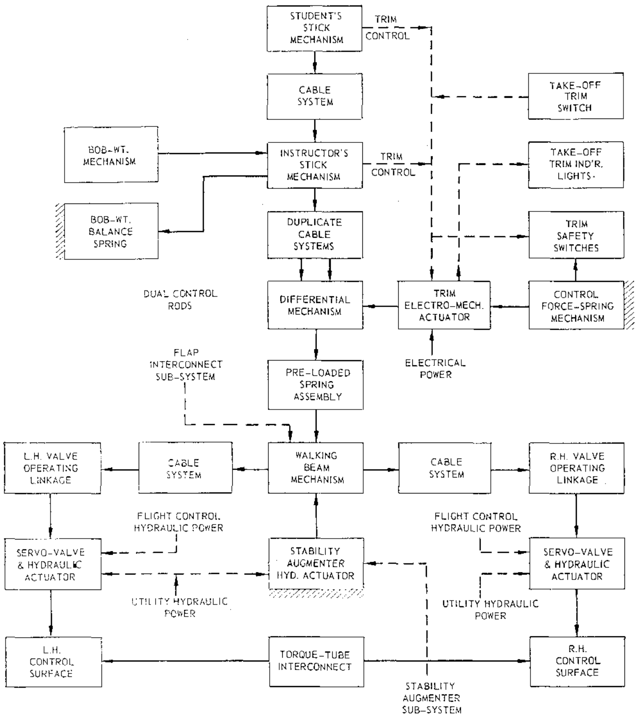

Fig. 4 T-38A longitudinal control system block diagram.

tion and led to it reaching $\pm 9\,g$. Recovery occurred when the frequency of the pilot inputs was varied.

The general philosophy of simplicity, easy maintainability, and a high degree of reliability was followed in the design of the T-38 flight control system. It features two independent hydraulic systems supplying tandem actuators, as shown in the pictorial and block diagrams of Figs. 3 and 4, respectively. Note the absence of sophisticated, complicated features; the system utilizes fixed stick-to-surface gearing, a simple artificial feel spring, and a parallel trim system.

From the beginning, the PIO program was limited by several considerations that defined the outside limits of the program. These precluded changes to the basic airframe configuration, major redesign of the control system, compromise of the concept of control system design simplicity, and degradation of the fighter-like handling qualities. Furthermore, less than five months time was available over all, from go-ahead to release of final design recommendations.

Solution to the problem utilized a unified approach encompassing system analysis, system simulation, and full-scale flight test. Specialists in the various disciplines (mechanical design, system dynamics, stability and control, simulator mechanics, and flight test) maintained close liaison through all phases of the program. They provided direct technical inputs and utilized the feedback of results to improve the quality of each successive step.

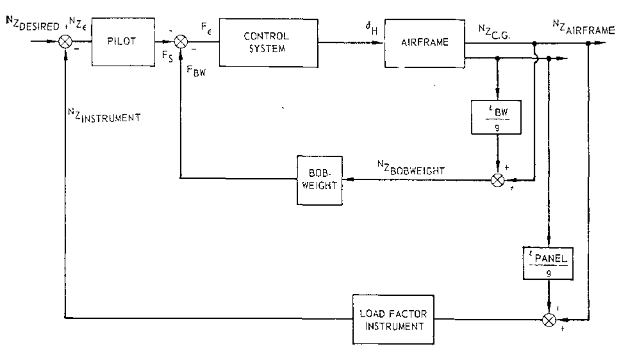

Fig. 5 Pilot-control system-airframe loop.

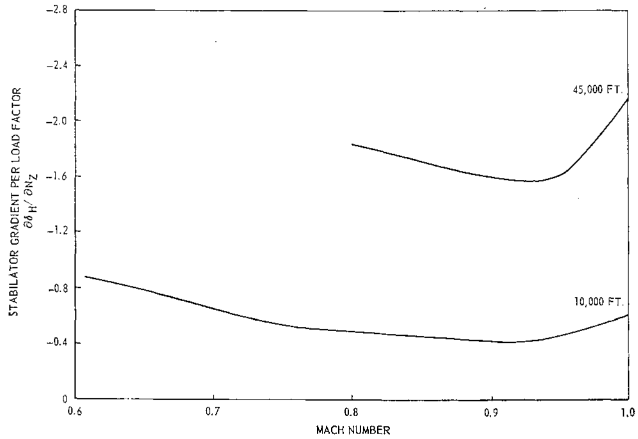

Fig. 6 Stick-fixed maneuvering characteristics.

Analysis Concept

Approach to solution of the PIO problem involved consideration of all elements of the pilot-controls-airframe loop, shown in Fig. 5, and their interrelationships.

Criteria describing the basic handling qualities an aircraft should exhibit are set forth in a number of specifications and studies. Initially, there is the military specification.[1] More detailed information can be found in reports of studies carried out by the Cornell Aeronautical Laboratories.[2,3] Desirable control system characteristics have also been investigated by NASA and much valuable information presented in their reports.[4–6] Comparison of the criteria available from the above sources with characteristics of the T-38A revealed a number of factors conducive to a high degree of PIO susceptibility. The following factors were considered to be significant in this regard: 1) the low ratio of stabilator motion to load factor ($\partial\delta_H/\partial N_z$), shown in Fig. 6; 2) the low ratio of control force to load factor ($\partial F_s/\partial N_z$), shown in Fig. 7; 3) the variation of the transfer function N_z/Fs with frequency, shown in Fig. 8; 4) the low ratio of stick motion to load factor ($\partial\delta_s/\partial N_z$), shown in Fig. 9; 5) the asymmetry of stick motion required to produce symmetrical stabilator motion in nose-up and nose-down directions; 6) the airframe short-period natural frequency and damping ratio, shown in Fig. 10; 7) the close proximity between the airframe's short-period natural frequency and the natural frequency and time constant of the control system and hydraulic actuators, respectively.

The airframe stick-fixed maneuver characteristics, indicated in Fig. 6, are typical of those of century series fighters. The relatively low value of $\partial\delta_H/\partial N_z$, present in the Mach number range of 0.8 to 0.925, leads to a high gain in the forward part of the over-all loop. Thus, a portion of the loop gain, the aircraft gain, is relatively high.

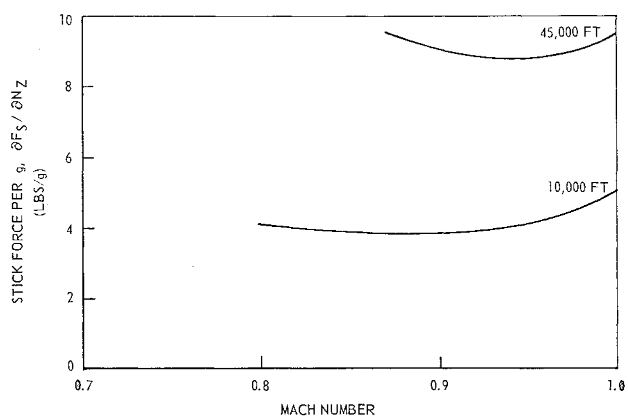

Fig. 7 Stick-free maneuvering characteristics.

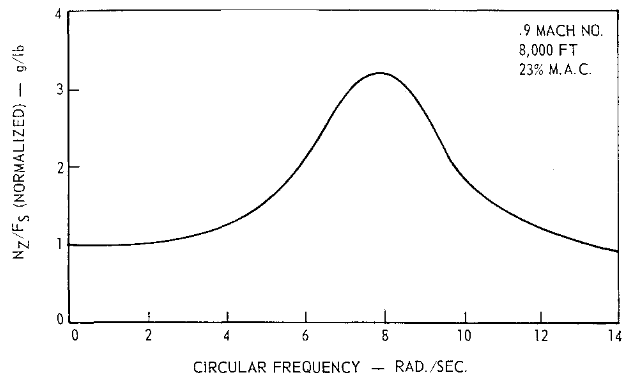

Fig. 8 Variation of maneuvering gradient with frequency.

The stick displacement per load factor ($\partial\delta_s/\partial N_z$), shown in Fig. 9, exhibits similar variation with Mach number. The nearly constant gradient with Mach number in the region from 0.8 to 0.925 results from the small change in trim point of the control system in this region. Thus, again, part of the loop gain, including airframe and control system (displacement) is relatively high.

Since the spring gradient with control stick displacement was linear and constant, the resulting stick force per load factor, illustrated in Fig. 7, was also low as would be expected. Here again, the loop gain including control system (force) and airframe, has a relatively large value.

To this point, discussion has been limited to the static gains within the loop. However, the problem is primarily dynamic in nature. Hence, the airframe short-period natural frequency and damping ratio and their relationship to control system dynamic characteristics enters into the picture. These are measured in terms of dynamic stick force per g which is illustrated in Fig. 8. The significant factor here is the peaking of response at the frequency of 8 rad/sec. This provides an inherent capacity for overcontrol with rapid or abrupt inputs.

Thus, it is seen that many of the significant variables combined in the direction of increased PIO susceptibility. However, increasing altitude is shown to effect a marked change in these characteristics. The net result is an increase in the pilot's gain margin, i.e., allowance for greater variation in the pilot's gain before the loop becomes unstable. The effect that is illustrated in Fig. 11 shows the large difference in the pilot's gain margin between 10,000 and 25,000 ft.

System Analysis

In the analysis, the system was considered a multiloop control system in which the pilot acted as both sensor and controller. The analytical objective was evaluation of the effects of reducing the open-loop gain of this system. Dynamic stability of this loop was investigated through variations in the dynamic characteristics of its components.

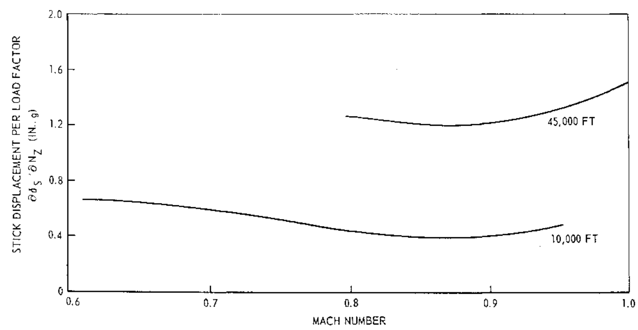

Fig. 9 Stick displacement maneuvering characteristics.

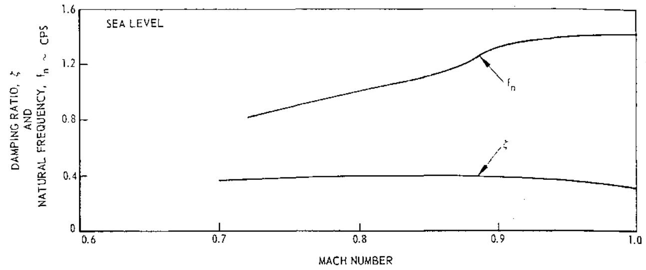

Fig. 10 Stick-fixed airframe short-period dynamics.

Previous work had established the fact that changes in mechanical components of the control system would alter pilot opinions of aircraft response.[7] With the background of this knowledge, systems analysts investigated characteristics of both the major and minor parts of the over-all loop. Digital computer techniques were utilized to expedite this analysis. Systems Technology Incorporated,[8] retained in a consulting capacity, contributed to this analysis as well.

The inner loop (N_{zBW}/F_s) was analyzed to show the effect of the following dynamic characteristics on its performance: 1) control system natural frequency as influenced by feel spring gradient and reflected inertia, 2) control system displacement gain, i.e., stick-to-surface gearing, 3) time constant of the hydraulic servo valve-actuator combination, 4) mechanical bobweight effectiveness, and 5) the control system force gain as influenced by the feel spring gradient and the stick-to-surface gearing. The result of varying each is shown in the comparison of the characteristics exhibited by the initial and final systems, as illustrated in Fig. 12.

The points of this root locus plot illustrate the relative importance of each of the physical parameters. The inverse time constant $1/T_s$ and the system's natural frequency ω_c both tend to push the root loci out into the unstable region as the values become smaller. Another way to say it is that dynamic coupling of the aircraft and control system approaches a resonant condition. The gain margin has at least doubled with the final system, as the position of the closed loop pole illustrates in the final system's loci. In fact, the loop performance indicates existence of an independent stick mode with frequency of $\omega_{c\ \mathrm{final}}$, as well as airframe response equal to the stick fixed short-period characteristic shown with the frequency $\omega_{\mathrm{short\ period}}$. These characteristics were later verified in flight test by both airframe response traces and the stick displacement trace during a stick-free dynamic-stability test point.

The outer or major loop was analyzed with the analog form of the pilot as $[(e_{-\tau S})/K_p(T_nS + 1)]$. This form was

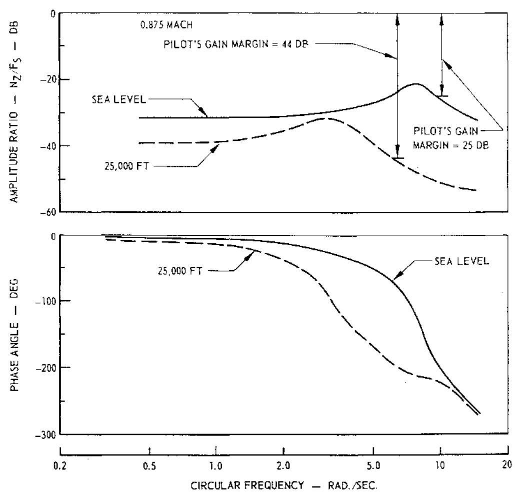

Fig. 11 Control system-airframe frequency response.

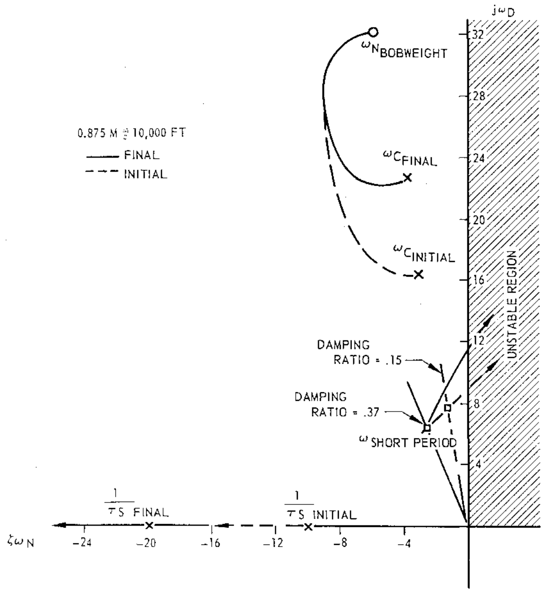

Fig. 12 Simulator study of effects on variation of servo valve and feel spring.

considered to represent the nominal value required by the pilot to obtain the desired handling qualities. Of course, the most rudimentary form of the transfer function that the pilot can obtain is the pure gain K_p, which was used to indicate the gain margin characteristics in Fig. 11. The root locus, shown in Fig. 13, which in this case is abbreviated for clarity, indicated that the final system has improved the characteristics significantly, in fact, to the extent that the desired area of loop stability[9] was reached. These results were further verified by pilot comments during flight testing of the system.

Simulation

As analysis progressed, recommended changes were designed into hardware for tests using the simulation technique. This study utilized a fixed-base simulator in which the complete control system was duplicated exactly as it is installed in the aircraft. The aircraft short-period dynamics were programed on an analog computer and associated nonlinear equipment.

An oscilloscope and load factor instrument were used to indicate aircraft motion to the pilot. A target was presented as a dot and the aircraft as a horizontal line on the oscilloscope. The task was to maintain zero error by holding the line on the dot. The target was driven by two apparently random functions; one was a series of steps and ramps, and the other the sum of four sine waves of different frequencies and amplitudes. A shortcoming of the simulation was lack of motion cues. An attempt to compensate for this was made by giving the pilot control of altitude instead of pitch angle or load factor. This method of presentation introduced lag to the loop and gave a tendency toward destabilizing the response. Pilots agreed that the simulation was acceptable despite its limitations.

The primary system components investigated were varied according to their respective physical characteristics. Three spring gradients and two servo valve time constants were used in the simulation. The spring gradient changes produced an effective gain change and varied control system natural frequency. The variation of servo valve gain yielded different time constants. The results of both are summarized in Fig. 14. The force gradient increase has a somewhat greater effect than the time constant change, but the over-all effect is best with both changes. It was realized that a general increase in the force gradient would impair the maneuvering qualities of the airplane. Hence, a bi-gradient spring was studied and its effects were determined to be favorable. A tri-gradient spring was finally resolved to be the best solution during the flight-test program.

One weakness of the simulation was the lack of adequate representation of bobweight effectiveness. However, the flight-test results proved the validity of the recommendation that was based on analysis to reduce bobweight effectiveness.

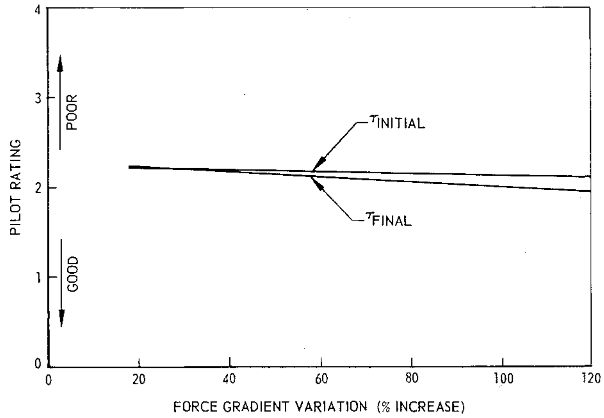

Fig. 14 Stick-free mode dynamics.

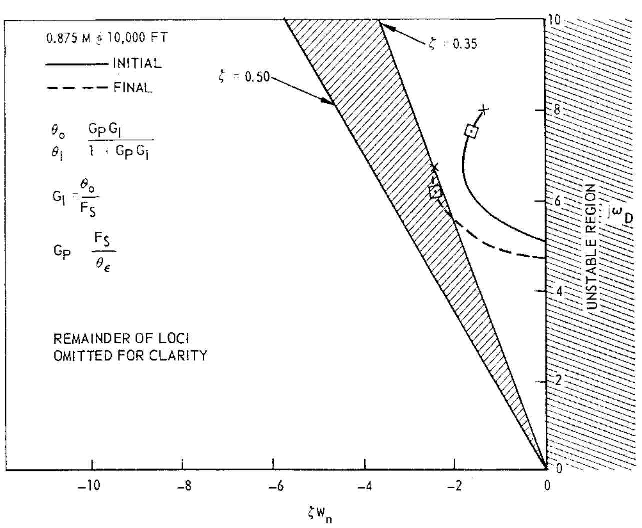

Fig. 13 Control system frequency response.

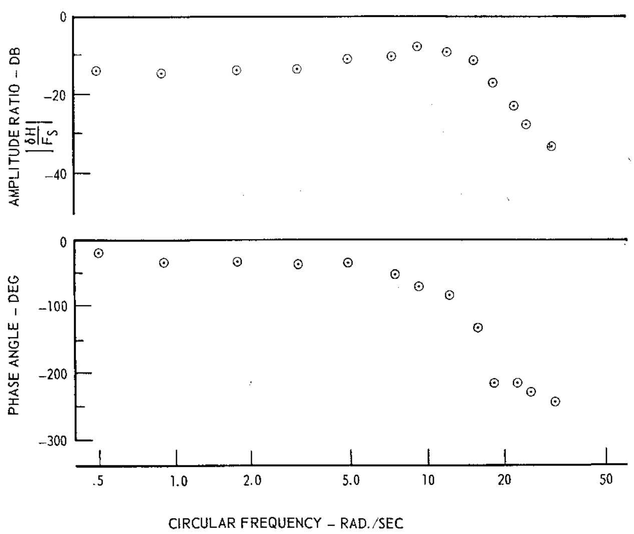

Fig. 15 Pilot-control-system airframe dynamics.

Table 1 Cooper rating system

Use	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
Normal operation	Satisfactory	1	Excellent, includes optimum	Yes	Yes
		2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	4	Acceptable, but with unpleasant characteristics	Yes	Yes
		5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency conditions only[a]	Doubtful	Yes
No operation	Unacceptable	7	Unacceptable even for emergency condition[a]	No	Doubtful
		8	Unacceptable—dangerous	No	No
		9	Unacceptable—uncontrollable	No	No
...	Catastrophic	10	Motions possibly violent enough to prevent pilot escape	No	No

[a] Failure of a stability augmenter

Frequency response tests were also performed on the fixed-base simulator to evaluate each change and to obtain proper values for the various transfer functions. These tests provided the control system time constants, natural frequencies and damping ratios that were needed in the analytical study for evaluation of each successive component change. Input to the control system was through a force-producing servo attached to the forward cockpit control stick. Various force levels were applied through the frequency range from 0.08 to 10 cps for each test. Figure 15 shows typical data obtained from these tests.

Flight Test

The flight development phase consisted of working with the variables which were defined both by simulation and analysis as being important. The over-all key variable was the open loop gain, which is defined in the expression below:

$$K_{\text{open loop}} = \frac{(K_{\text{bobweight}})\ (K_{\text{airframe}})}{(K_{\text{gearing}})\ (K_{\text{force spring}})}$$

A program objective was the reduction of this gain to 50% of the original value.

Data were obtained with standard stability and control instrumentation which was supplemented by measurements at significant points in the control system. Measurements were recorded on a 50-channel oscillograph which, with its 12-in.-wide paper, allowed trace sensitivities to be maintained at a desirable level.

The control system was defined statically by ground calibrations following each change. Dynamic tests were also performed using both the frequency response and transient response methods. The frequency response data from the airplane showed that its damping ratio was lower than that which was indicated by the simulator tests. Close study of the static characteristics indicated that the force hysteresis band on the simulator was greater than that of the aircraft. Because the lower damping ratio and reduced friction level are desirable, this difference was not cause for concern. The nonlinear variation with stick displacement of the control system undamped natural frequency, and damping ratio was obtained from the transient response method.

The final step in the process came when each change was tested in flight. Test objectives were to provide recorded data for quantitative analysis and pilot comments to allow a realistic appraisal of system performance from the viewpoint of its user, the pilot. Periods between changes were held to a minimum in order to maintain a continuing fresh plane of reference. All configurations were investigated using a standard test card that included the following maneuvers.

1) Following takeoff and acceleration to climb speed: abrupt (over) rotation and correction to climb attitude.

2) At 0.9 Mach number and 8000 ft: abrupt pullups from level flight to 2, 3, and 4 g load factors; abrupt pullup and pushover sequences performed from level flight with target load factors of 2 and 0 g, 3 and 0 g, respectively; stick releases from symmetrical pullups, at 2, 3, and 4 g load factors; and sinusoidal stick cycles of approximately $\pm\frac{1}{2}$-in. amplitude at frequencies from 0.3 to 2.5 cps performed by following an oscillating tone transmitted from the ground. In addition to these specific tests, a general evaluation of handling qualities was made in formation flight, air-to-air tracking, approaches, and landings.

Three pilots participated in almost all phases of the development; two were Northrop Norair pilots and the third an Air Force Flight Test Center test pilot. All have broad experience connected with high-performance aircraft testing. Following each flight, the pilots were asked to comment on

Table 2 McDonnel PIO tendency rating

Numerical rating	Description
1	None; no tendency for pilot to induce undesirable oscillation, no tendency to get out of phase with, or to lag behind, aircraft motion.
2	None to possible; undesirable motion may be induced but can be damped by pilot effort.
3	Possible; undesirable motion easily induced but can be damped by pilot effort.
4	Possible to probable; oscillations tend to diverge. Pilot may be required to release stick.
5	Probable; oscillations tend to diverge. Pilot must release stick to stop motion.
6	Highly probable; disturbance or normal pilot control may cause divergent oscillation. Pilot must release stick to stop motion.

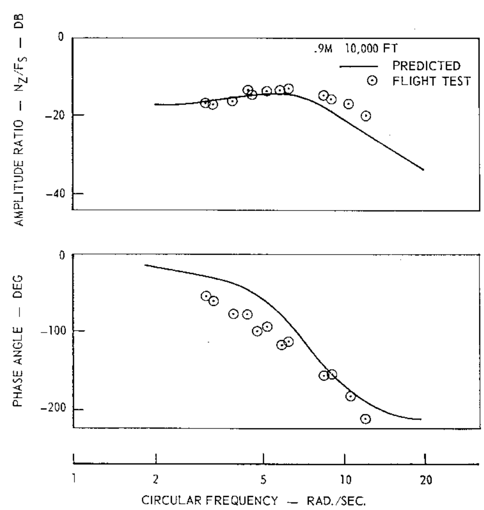

Fig. 16 Comparison of flight-test and predicted data.

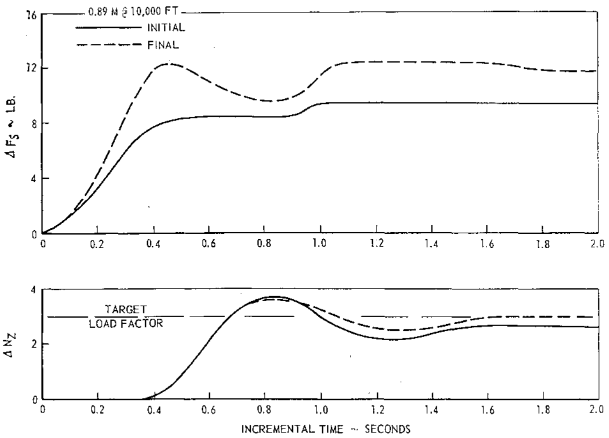

Fig. 17 Response to abrupt input.

maneuvering forces and gradients, ability to hit target load factors, variation in response of airplane and control system with frequency, symmetry of response, i.e., nose up and nose down, control system characteristics such as centering and smoothness, degree of PIO susceptibility. Each flight was rated using the Cooper and McDonnell scales, which are presented in Tables 1 and 2.

Possibly the most informative maneuvers, both quantitative and qualitative, were the sinusoidal inputs and the abrupt pull-ups to target load factors. In the case of the sinusoidal input, the pilot determined the stick excursion, forward and aft, required to produce between $\pm 1\ g$ at the low frequencies. He then attempted to maintain constant input amplitude for the higher frequency test points. Amplification and attenuation of response was recognizable, as was the difference in response to aft and forward stick motions. A comparison between test and analytical data is shown in Fig. 16, which is typical of the matches obtained. The control system's influence on over-all response of the system was clearly seen in the abrupt pullups. Each was performed with as rapid a control input as the pilot considered safe. Comparison of maneuvers performed with the initial and final control systems installed is shown in Fig. 17. It can be seen that the rate of force buildup was significantly higher with the final system but that the load factor overshoot was smaller and the final steady-state load factor error was also smaller.

Analysis of flight-test data showed good correlation between pilot ratings and maximum reduction in the dynamic stick force gradient (F_s/N_z), as shown in Fig. 18. This parameter inherently accounts for all the static and dynamic variables affected during the program. The initial system showed a 70% reduction with frequency and received a PIO rating of 4. As changes were made during the development process, the reduction in time constant and increase in control system natural frequency reduced the dynamic stick force gradient further, i.e., to 40%, with an accompanying improvement in pilot PIO rating to 2. These results correlated well with the analytical predictions made using both the root locus and frequency response techniques.

Each term in the open-loop gain expression was changed in the course of the flight-test program. The final system has the increased feel spring gradient around neutral, a stick to surface gearing modification, and changed bobweight effectiveness. A comparison between initial and final control systems is presented in Figs. 19–21.

The force spring gain for initial displacement was changed, as shown in Fig. 19, through use of a tri-gradient feel spring. The final spring design evolved through two interim springs both of which were of the linear type, each with a stiffer rate. Evaluation of these springs provided valuable guidance leading to selection of each of the gradients of the final spring. Comparison of the final and initial springs shows that the force gain ($\Delta\delta_s/\Delta F_s$) of the former is always lower. This also insures that the natural frequency of the final system will be higher. The multigradient feature provides a relatively stiff gradient either side of force trim which, via two

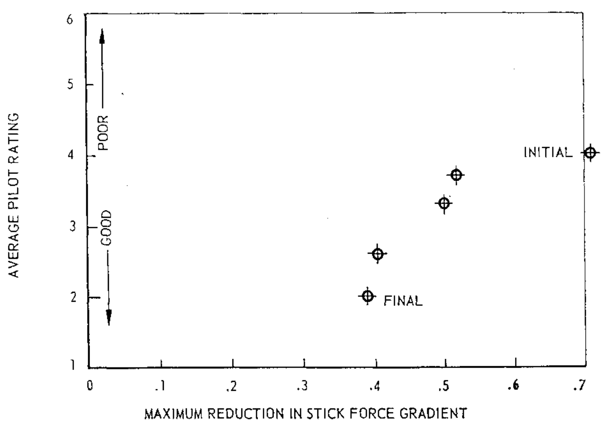

Fig. 18 Effect of dynamic stick force gradient on pilot rating.

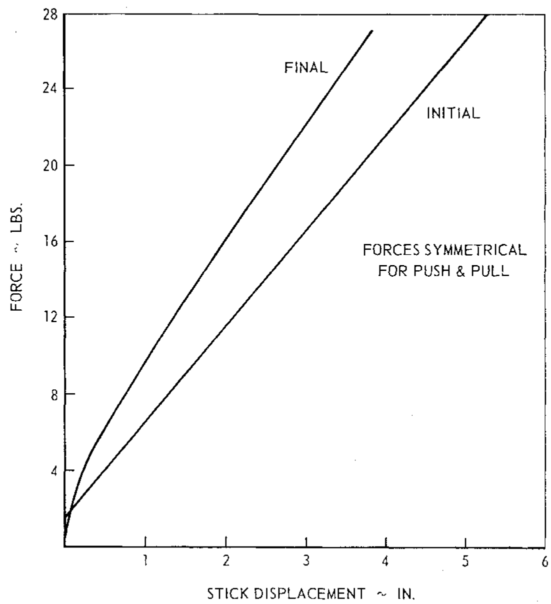

Fig. 19 Feel spring change.

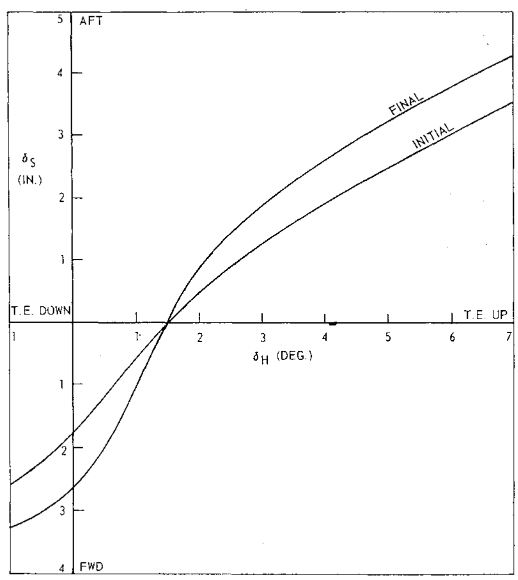

Fig. 20 Controls gearing change.

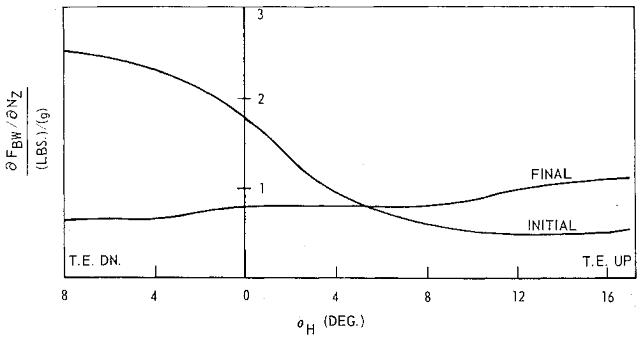

Fig. 21 Changes in total bobweight effectiveness.

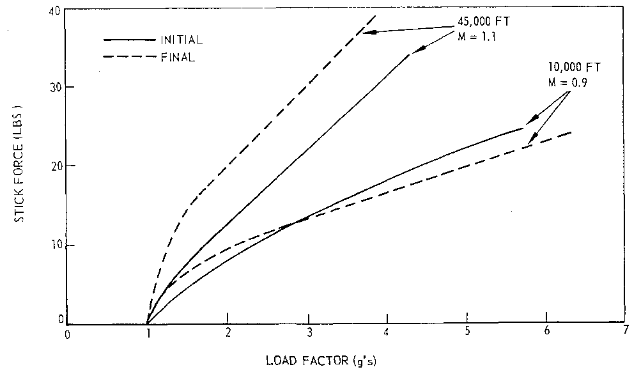

Fig. 22 Changes in maneuvering characteristics.

transition points, terminates smoothly with a gradient that is only slightly greater than that of the initial spring. Thus, the reduction in PIO susceptibility was obtained without introducing high force gradients for large stick displacements.

The displacement gain was modified by a change in stick-to-surface gearing. Comparison of the final and initial gearing shown in the trim position used in the PIO region is presented in Fig. 20. It can be seen that over and above a general decrease in the gain $(\partial\delta_H/\partial\delta_s)$ for the $-1°$ stabilator region the range of low (and constant) gain is extended considerably in the push direction. This considerably reduced pushover sensitivity, a key factor in the PIO shown in Fig. 2. The nearly equal slopes for larger surface motions precludes increased gradients where such excursions are required.

The change in bobweight effectiveness is shown in Fig. 21, which shows a substantial decrease between the initial and final systems for the range of stabilator position used for trim and normal maneuvering in the flight regime of maximum PIO susceptibility. At the larger trailing edge-up stabilator displacements, where the final bobweight gain exceeds that of the initial system, the airframe stability has increased to the extent that the increased bob-weight gain is of no consequence from the standpoint of system stability.

Change in maneuvering force characteristics is shown in Fig. 22. In the high PIO susceptibility flight region a marked increase in gradient was provided immediately on either side of 1 g. This resulted in higher forces initially. However, at higher load factors the gradient is actually lower, which is the result of the lowered bobweight effectiveness. The maneuvering characteristics at the high-altitude supersonic point shown indicate higher control forces, principally the result of the high spring gradients just out of neutral, but identical maneuvering force gradients above 1.5 g. This increased gradient around trim substantially improved the capability for well-trimmed level flight.

An undesirable by-product of the control system revisions was the substantial increase in trim changes resulting from thrust variations and speed brake deflections. With the initial control system, these characteristics were inherently compensated for during changes in longitudinal acceleration because of the weaker spring and larger longitudinal bobweight effectiveness. For example, the normal nose-up pitch trim change that speed brake extension produced was corrected for by forward stick motion in response to the deceleration. This "built-in" trim compensation was lost by the increase in stick centering and reduction of response to longitudinal acceleration resulting from bobweight redesign. As a result of the improved handling characteristics in the 1 g region in all parts of the flight envelope it was possible to eliminate the artificial pitch damping system without adversely affecting flying qualities.

Summary

Results of this program indicate clearly that the pilot-induced-oscillation problem can be reduced significantly through changes in control system components alone. Through the integrated use of system analysis, simulation, and flight-test techniques these efforts can be optimized, and conclusive results can be achieved more speedily and efficiently.

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