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Airplane Flying Qualities Specification Revision

C. R. Chalk*
Cornell Aeronautical Laboratory Inc., Buffalo, N. Y.

AND

R. K. Wilson†
Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio

The current military flying qualities specification, MIL-F-8785(ASG), "Flying Qualities of Piloted Airplanes," was adopted in 1954, most recently revised in 1959, and is in need of further revision to enhance its applicability to modern weapon systems. As part of a three-year program to update this specification, an interim revision has been prepared which will be proposed for formal adoption. The changes that have been made are extensive, and include those affecting the organization and framework for stating the requirements as well as changes to the individual requirements for longitudinal short-period characteristics, stick force gradients, Dutch roll, and roll control. New requirements govern the sideslip and roll-sideslip coupling responses to lateral control inputs. This paper discusses the rationale for these revisions and demonstrates how they are supported by experimental data and the characteristics of existing airplanes.

Nomenclature

F_s = elevator stick force
$j\omega$, $\zeta\omega_n$ = imaginary axis and real axis of s plane
K_ϕ = gain constant in roll-aileron transfer function
n_z = normal acceleration at center of gravity
p, q, r = roll, pitch, and yaw rates
p_n = amplitude of roll-rate response at Dutch roll peaks for step aileron input
$\measuredangle p/\beta$ = phase angle by which Dutch roll oscillation in sideslip leads Dutch roll oscillation in roll rate
s = Laplace operator
T_d = period of damped Dutch roll oscillation
$1/T_{h_1}$ = numerator factor of altitude-elevator transfer function
$1/T_{\theta_2}$ = numerator factor of attitude-elevator transfer function
V = velocity
α = angle of attack
β = angle of sideslip
γ = flight-path angle
δ_{AS}, δ_e = aileron stick deflection and elevator deflection
ζ_d = Dutch roll damping ratio
ζ_ϕ = numerator damping ratio in roll-aileron transfer function
θ, ϕ = pitch attitude and roll attitude
λ_R, λ_S = roll-mode root and spiral-mode root
τ_R = roll-mode time constant
$|\phi/\beta|_d$ = ratio of bank angle to sideslip in Dutch roll oscillation
ϕ/v_e = ratio of bank angle to equivalent side velocity in Dutch roll mode
ψ_n = angular coordinate of vector in s plane
ψ_β = phase angle of Dutch roll oscillation in sideslip response to step aileron input
ω_d = Dutch roll undamped natural frequency
ω_{SP} = undamped natural frequency of short-period mode
ω_ϕ = numerator frequency in roll-aileron transfer function

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* Section Head, Handling Qualities and Simulation Section, Flight Research Department.

† Group Leader, Handling Qualities Group, Control Criteria Branch, Flight Control Division. Member AIAA.

Introduction

THE current military flying qualities specification is MIL-F-8785(ASG), "Flying Qualities of Piloted Airplanes."[1] It was adopted in 1954 and revised in 1959, and is now in need of further revision to enhance its applicability to modern weapon systems. The Flight Dynamics Laboratory contracted with Cornell Aeronautical Laboratory (CAL) in 1966 for a three-year program to help prepare an interim revision of this specification. The interim revision[2] that resulted from this effort will be proposed for formal adoption in the fall of 1968.

In preparing the revision, careful consideration was given to the experience of those who had the responsibility for applying -8785 in system development. Meetings were held with governmental agencies and with representatives of many airframe and control equipment developers. Naturally, their comments varied, but enough of a pattern emerged to make it clear that not only were there shortcomings in the requirements themselves and in the organization of the overall specification, but the proper framework for stating the requirements was not provided by the initial portions of -8785.

The conclusion was reached, then, that the updating should concentrate on three objectives: 1) establish a more comprehensive framework that permits consideration of mission requirements, configurations, loadings, failure states, and flight envelopes in optimizing the design; 2) reorganize the material covered in the specification; 3) redefine the requirements that seem to be the source of greatest difficulty and include new requirements where necessary.

Framework of the Requirements

In the revised specification a framework has been provided which permits tailoring each requirement according to 1) the kind of airplane (class), 2) the job being done with the airplane (flight phase categories), and 3) how well the job must be done under various circumstances (levels).

Table 1 shows how these considerations are associated and graphically illustrates that full use of the framework would permit stating 36 different values for a given flying qualities parameter. Obviously there is seldom, if ever, enough information available to make such fine discriminations. Thus, in most cases the boxes are lumped together but not necessarily in the same pattern for each requirement. The framework, then, is comprised of classifications, flight phase categories, and levels. In the following paragraphs, each of these will be briefly defined.

Airplane Classification

The classes of -8785 are defined through lists of examples of the type of aircraft or missions that are associated with each class: Class I: primary trainer—observation, Class II: bomber—cargo, and Class III: fighter—interceptor. The distinctions between classes in the revised specification are drawn on the basis of size, maximum design gross weight, and design limit load factor supplemented by lists of aircraft type or mission. The aircraft classes of the revised specification are described as follows:

Class I: small, light-weight, medium maneuverability airplanes

Class II: medium-weight, low to medium maneuverability airplanes

Class III: large, heavy-weight, low-maneuverability airplanes

Class IV: high-maneuverability airplanes

Gross weight and limit load factor have been introduced explicitly because they are considered to be gages of the maneuvering capability of an airplane and they reflect the missions for which it will be used. The maneuverability and missions of existing airplanes correlate well with this classification system. The new Class II and Class III were introduced because large variations in gross weight have developed in the bomber, cargo, and utility types of airplanes, which were formerly grouped in Class II of -8785.

Table 1 Framework for stating requirements

Class	Flight phase category	Level 1	Level 2	Level 3
I	A B C			
II	A B C			
III	A B C			
IV	A B C			

Table 2 Flight phases

Nonterminal flight phases

Category A: Those nonterminal flight phases that require rapid maneuvering, precision tracking, or precise flight-path control

1. Air-to-air combat
2. Ground attack
3. Weapon delivery or launch
4. Aerial delivery
5. Aerial recovery
6. Reconnaissance platform
7. In-flight refueling (receiver)
8. Terrain following
9. Antisubmarine search
10. Close formation flying

Category B: Those nonterminal flight phases that are normally accomplished using gradual maneuvers; although accurate flight-path control may be required, precision tracking is not necessary

1. Climb
2. Cruise
3. Loiter
4. Glide
5. In-flight refueling (tanker)
6. Descent
7. Emergency descent
8. Emergency deceleration

Terminal flight phases

Category C: Terminal flight phases consisting of the following

1. Takeoff
2. Approach
3. Waveoff (go-around)
4. Landing

Flight Phases

The current version of -8785 extends implicit recognition to the fact that there should be distinctions between the flying qualities required for different control tasks, or flight phases. This recognition in -8785 is, however, very sketchy, and is only introduced in the requirements dealing with damping of the short-period and Dutch roll oscillations through the distinctions between armed and unarmed airplanes.

The approach taken in the -8785 revision is to divide the mission flight phases into three categories. First, the flight phases are divided into terminal and nonterminal groups. The nonterminal flight phases are further divided into two categories as defined in Table 2.

Levels

The third part of the framework provides for quantifying flying qualities requirements in terms of three levels, and it must be determined a priori what the specified flying qualities are supposed to represent with respect to airplane operational capability. The emphasis could be placed on maintaining safety of flight, or on the capability to complete the mission. It was concluded that since -8785 applies to military vehicles, emphasis should be placed on completing the mission. An association then emerges between the three levels and the pilot rating scale developed by Cooper and Harper[3] (see Table 3).

Application of Levels

Through the concept of levels, recognition can be given to the possibility that, during its service life, an airplane may be operated in conditions which are not normal conditions.

Table 3 Pilot rating scale

CONTROLLABLE Capable of being controlled or managed in context of mission with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations, good enough without improvement. Clearly adequate for mission	Excellent, highly desirable.	A1
			Good, pleasant, well behaved.	A2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	A3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	A4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	A5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	A6
	UNACCEPTABLE Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	U7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	U8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	U9
UNCONTROLLABLE Control will be lost during some portion of the mission.			Uncontrollable in mission	10

The abnormality could consist of being at a flight condition outside the operational envelope, or of experiencing some system failure, or both. The fact that the flying qualities should be expected to degrade in these situations is acknowledged and the levels provide the means for specifying the amount of degradation to be permitted.

Although the exact terminology for relating flying qualities levels to system reliability is still under review, the general idea being considered is illustrated in Table 4. In this table, the flying qualities levels are related to the combination of flight envelope and failure state for which they apply. The basic idea is that the more often a pilot is faced with a certain condition of operation of the airplane systems, the more favorable the flying qualities should be for that state. In the presentation of Table 4, three degrees of system reliability have been considered. In Table 4, the levels are defined and related to the circumstances for which each level must be provided.

In summary, the quantitative requirements in the revised -8785 are stated, where applicable, in terms of 1) class of airplane—I, II, III, IV, 2) flight phase category—A, B, C, and 3) level—1, 2, 3, as illustrated in Table 1. The revised -8785 contains a number of new requirements, three of which will be outlined in the following paragraphs.

Roll-Sideslip Coupling

This section of the proposed specification puts requirements on the coupling that can exist between roll and sideslip during moderate bank-angle-change maneuvers such as turn entry or acquiring and tracking a target. The requirements in this section are directed at the same considerations with which the authors of -8785 were concerned when they made the Dutch roll damping a function of ϕ/v_e and included requirements prohibiting roll-rate reversals and limiting sideslip caused by adverse yaw during abrupt turn entries. From a flying qualities viewpoint, roll-sideslip coupling is manifested in three general ways depending on the $|\phi/\beta|_d$ response ratio.

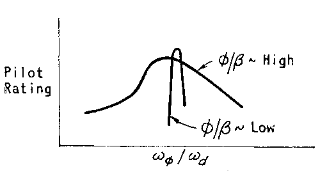

Fig. 1 Pilot rating as a function of ω_ϕ/ω_d.

For low $|\phi/\beta|_d$ ratios, sideslip per se is important to the pilot. For these cases, if roll or roll control excites sideslip, the flying qualities can be degraded by such motions as an oscillation of the nose on the horizon during a turn, by a lag or initial reversal in yaw rate during a turn entry, or by making it difficult for a pilot to quickly and precisely take up a given heading. In addition, the pilot cannot damp Dutch roll oscillations through the use of aileron control only. For larger $|\phi/\beta|_d$ ratios, the coupling of sideslip with roll and roll rate becomes important, causing oscillations in roll rate and ratcheting of bank angle or lateral-directional pilot-induced oscillations. In this case, the pilot may have difficulty in controlling roll rate or in acquiring a given bank angle. For very large values of $|\phi/\beta|_d$, the sensitivity of roll to rudder pedal inputs or the roll response to side gusts may be so severe as to limit the utility of the airplane. The lifting body vehicles are typical of airplanes with this manifestation of roll-sideslip coupling.

In the following paragraphs, the development of the requirement limiting roll-rate oscillations following abrupt aileron inputs is discussed. Until recently, most research directed at roll-sideslip coupling has been concerned mainly with the effects of yaw due to aileron $N\delta'_{AS}$. The results of these studies have been presented in terms of the parameters ω_ϕ/ω_d and $|\phi/\beta|_d$, and illustrated by plots similar to Fig. 1.

Table 4 Application of levels

Failure state \ Flight envelope	Operational flight envelope	Service flight envelope
Normal function and probable failure states $P^a > 10^{-2}$	Level 1 Clearly adequate for the flight phase	Level 2 May have deficiencies which warrant improvement but adequate for the flight phase
Reasonably probable failure states $10^{-2} > P^a > 10^{-4}$	Level 2	Level 3 Can be controlled or managed in context of the mission
Remotely probable failure states $10^{-4} > P^a > 10^{-7}$	Level 3	No requirements

^{a} Probability of failure state occurring on a given flight.

The parameter ω_ϕ/ω_d is a measure of the relative distance from the origin of the zeros represented by the factors of the quadratic in the numerator of Eq. (1) and the Dutch roll roots represented by the factors of the quadratic in the denominator of Eq. (1)

$$\frac{p(s)}{\delta_{AS}(s)} = \frac{K\phi s(s^2 + 2\zeta_\phi\omega_\phi s + \omega_\phi^2)}{(s + \lambda_s)(s + \lambda_R)(s^2 + 2\zeta_d\omega_d s + \omega_d^2)} \qquad (1)$$

In Fig. 2, typical locations of the factors of the ϕ/δ_{AS} transfer function are illustrated together with time histories of the roll-rate and sideslip responses to a step aileron input. Figures 2a and 2b are typical for adverse $N'\delta_{AS}$ and Figs. 2c and 2d are typical for proverse $N'\delta_{AS}$.

Recently, experiments have been performed (Refs. 13–17 of AIAA Paper 68-245)[4] which extend our understanding of the effect of parameters other than $N'\delta_{AS}$, such as $N'_p - (g/V)$, on the roll and sideslip responses and the associated flying qualities. This work has shown that the flying qualities are strongly dependent on the magnitude and phase of the Dutch roll oscillation that is excited by aileron inputs. Figures 2e–2h primarily illustrate the effect of $N'_p - (g/V)$ on the location of the ϕ/δ_{AS} transfer function factors and the associated roll rate and sideslip time histories. Figures 2e and 2f are typical for positive $N'_p - (g/V)$ and Figs. 2g and 2h are typical for negative $N'_p - (g/V)$. Figure 2 thus illustrates the combined effects of $N'\delta_{AS}$ and N'_p on the location of the ϕ/δ_{AS} transfer function factors and the associated roll-rate and sideslip time histories.

The experimental data show that the optimum location of the zero is below and to the left of the pole, with generally decreasing levels of desirability when the zero is located above or to the right of the pole or further away from the pole. From a root locus analysis, it can be shown that when the zero lies below or to the left of the Dutch roll pole, the closed-loop damping increases when the pilot closes a bank angle to aileron loop. The reason for this in physical terms is that roll control inputs proportional to bank angle errors cause yawing moments which tend to damp oscillations in sideslip. Thus, the Dutch roll damps out more quickly closed loop than open loop.

Conversely, it can be shown that when the zero lies above or to the right of the Dutch roll pole, the closed-loop damping decreases when the pilot applies aileron inputs proportional to bank angle errors. The physical explanation for this is that roll control inputs tend to excite or sustain oscillations in sideslip which then sustain oscillations in roll through the coupling derivatives. Thus, the Dutch roll damps less quickly closed loop than open loop and can even go unstable closed loop, i.e., Pilot Induced Oscillation (PIO). Figure 3 illustrates a representative area of acceptable zero locations for the $\phi/_{AS}$ transfer function.

Since the parameter ω_ϕ/ω_d only indicates the relative distance of the zero and the pole from the origin, ω_ϕ/ω_d does not adequately describe the situation. Therefore, the possibility of specifying roll-sideslip coupling limits by specifying areas of acceptable zero locations for the ϕ/δ_{AS} transfer function on the complex plane was investigated. One of the main shortcomings of this approach is that it requires knowledge of the location of the zero of the ϕ/δ_{AS} transfer function which may be difficult to determine from flight test data. Another shortcoming is that since the amount of Dutch roll excitation that a pilot sees is a function of Dutch roll damping and of the roll mode time constant, it would be expected that the acceptable area would be larger for high Dutch roll damping than for low Dutch roll damping and the area would be larger for low roll damping than for high roll damping. Also, since the amount of Dutch roll excitation in roll is proportional to the ratio of ω_ϕ/ω_d, the acceptable area would be expected to shrink in size as ω_d decreased and grow in size as ω_d increased. Thus, a requirement in terms of zero locations would be awkward to state because of its dependence, as illustrated in Fig. 4, on the Dutch roll and roll-mode root locations.

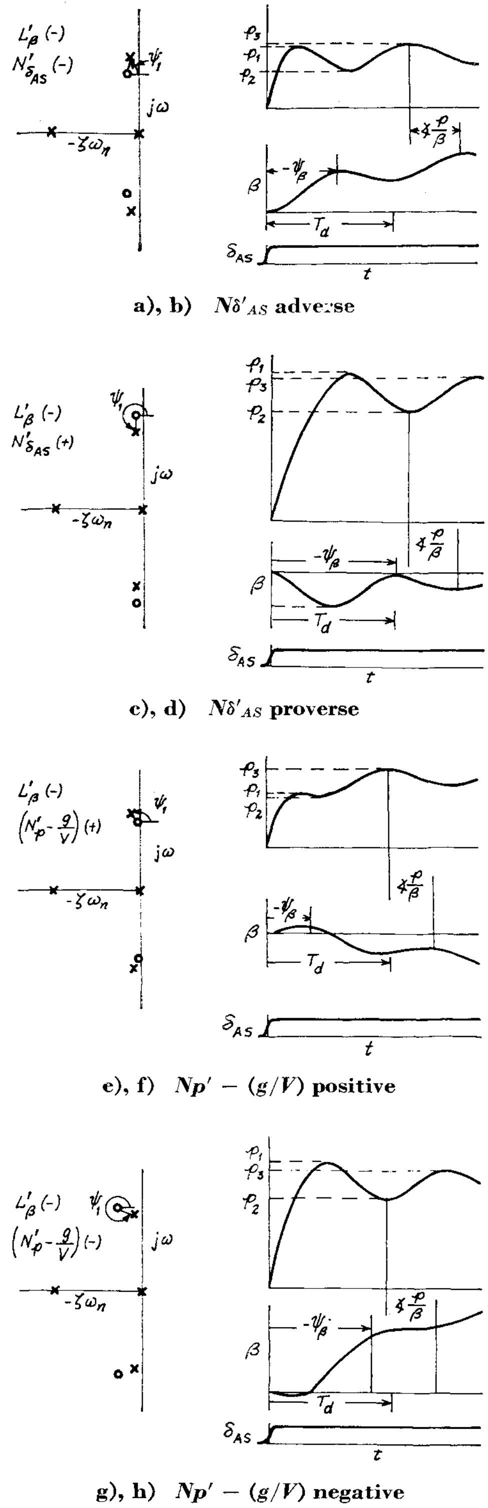

Fig. 2 ϕ/δ_{AS} transfer-function factors and time-history responses of p and β for δ_{AS}.

Analysis of experimental data (in particular the study of pilot comments associated with each configuration) led to the conclusion that a requirement limiting the degradation of flying qualities due to excitation of the Dutch roll mode in the roll-rate response could be based on the ratio

$$p_{osc}/p_{AV} = (p_1 - p_2)/(p_1 + p_2)$$

or

$$\frac{(p_1 + p_3 - 2p_2)}{(p_1 + p_3 + 2p_2)} \approx \frac{\text{magnitude of Dutch roll in roll-rate response}}{\text{average roll rate}}$$

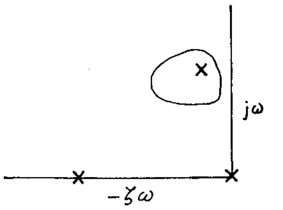

Fig. 3 Contour of acceptable zero locations in the ϕ/δ_{AS} transfer function.

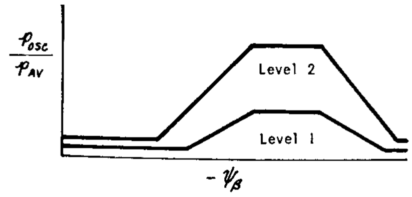

Fig. 5 Roll-rate oscillation limitations.

for a step aileron stick command. It was further concluded that the magnitude of this ratio permitted by the requirement should be a function of the phase of the Dutch roll oscillation in sideslip, ψ_β, that results from the aileron step input. Examples of these measurements are shown on the time-history plots in Figs. 2b, 2d, 2f, and 2h. The form of the requirement is illustrated in Fig. 5.

The requirements illustrated in Fig. 5 were developed from experimental measurements of p_{osc}/p_{AV} and ψ_β taken from as many and as widely different configurations as were available. In general, the correlation of all available data was very good. The form of the requirement and the parameters used in its statement can be related to the factors of the ϕ/δ_{AS} transfer function and the time histories of roll rate and sideslip following a step aileron command.

When the Level 1 or the Level 2 boundaries of Fig. 5 are mapped onto the s plane, they define areas around the Dutch roll pole essentially as indicated in Figs. 4a and 4b. Thus, the ratio p_{osc}/p_{AV} is a function of the distance the zero is separated from the Dutch roll pole, the Dutch roll frequency, the Dutch roll damping, and the roll-mode time constant. As was stated earlier, the distance the zero can be separated from the Dutch roll pole while maintaining a given level of flying qualities is dependent on the angular position of the zero with respect to the pole. As illustrated in Fig. 4a, the zero can be much further to the left of the pole than it can be to the right of the pole for a given level of flying qualities. If this angular orientation of the zero relative to the pole ψ_1 in Figs. 2a, 2c, 2e, and 2g is plotted vs the phase angle ψ_β from Figs. 2b, 2d, 2f, and 2h, the plot in Fig. 6 is obtained.

In the development of Ref. 4, it was shown that when L'_β is negative

$$\psi_\beta \doteq \psi_1 + \cos^{-1}\zeta - 360° \tag{2}$$

for a wide range of lateral-directional stability derivatives. It is recognized that airplanes can have large positive values of L'_β and in this case Eq. (2) is modified by 180°:

$$\psi_\beta \doteq \psi_1 + \cos^{-1}\zeta - 180° \tag{3}$$

Because of this, the actual requirement of Fig. 5 has two ψ_β scales, one for airplanes with negative L'_β and one for airplanes with positive L'_β. The sign of L'_β is reflected in the value of $\measuredangle p/\beta$. Thus, the ψ_β scale to be used on Fig. 5 can be determined from the magnitude of $\measuredangle p/\beta$ if L'_β is not known.

In Fig. 7, the values of ψ_β and ψ_1 are plotted for a number of the existing airplanes for which data are given in Ref. 12 of AIAA Paper 68–245. From this plot, it is seen that Eqs. (2) and (3) are very good approximations of the actual relation between ψ_β and ψ_1.

The discussion of the roll-sideslip coupling requirement will be concluded with the observation that the statement of the requirement in Fig. 5 in terms of p_{osc}/p_{AV} and ψ_β leaves the designer free to trade off all the factors which influence this aspect of the flying qualities and does not require that only the damping ratio be increased as a function of ϕ/v_e. Experience has shown that the latter is not only too restrictive but also may not achieve the desired result.

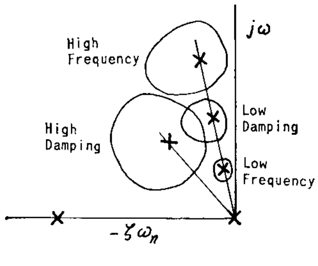

Fig. 4a Effect of Dutch roll root on acceptable zero location area.

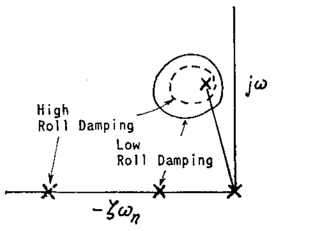

Fig. 4b Effect of roll damping on acceptable zero location area.

Flight-Path Stability

It is well recognized that operation on the backside of the drag curve in the landing approach leads to serious problems in airspeed and flight-path control. References 34–47[4] show that airspeed behavior, when elevator is used to control attitude and flight path, is characterized by a first-order root that becomes unstable at speeds below minimum drag speed. Specifically, Ref. 37[4] uses closed-loop analysis to show that the instability can be stabilized with an airspeed-to-throttle loop, but the degree of instability and the required stabilizing throttle activity will progressively increase with reduced approach speeds. The pilot's throttle workload is proportional to the closed-loop instability encountered and, in turn, proportional to the open-loop low-frequency-zero, $1/T_{h_1}$, in the attitude to elevator transfer function.

The following approximate expression for computing $1/T_{h_1}$ is developed in Ref. 33[4]:

$$\frac{1}{T_{h_1}} \doteq -X'_u + \left(X_w - \frac{g}{V}\right)\frac{(M'_u Z_{\delta_e} - M_{\delta_e} Z'_u)}{(M_w Z_{\delta_e} - M_{\delta_e} Z_w)} + X_{\delta_e}\frac{(M_w Z'_u - M'_u Z_w)}{(M_w Z_{\delta_e} - M_{\delta_e} Z_w)} \tag{4}$$

Working with the altitude-to-elevator and airspeed-to-elevator transfer functions, it can be shown that the value of $1/T_{h_1}$ is directly related to the local slope of the climb angle vs airspeed curve for constant throttle:

$$1/T_{h_1} \doteq -g\,(d\gamma/dV) \tag{5}$$

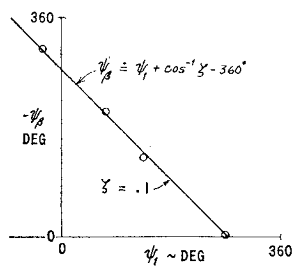

Fig. 6 Relation between ψ_1 and ψ_β.

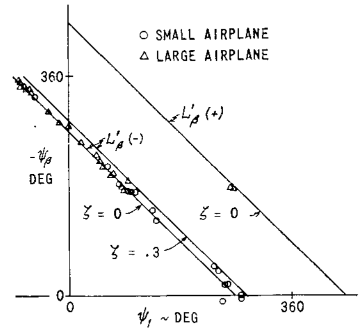

Fig. 7 Relation between ψ_1 and ψ_β for several existing airplanes.

In addition, $1/T_{h_1}$ is related to the slope of the trimmed thrust required vs velocity curve by the following expression:

$$1/T_{h_1} \doteq (1/m)\, dT_R/dV \qquad (6)$$

Figure 8 illustrates typical variations of pilot rating and throttle activity with $1/T_{h_1}$ which were observed in the experiments of Refs. 33 and 38–40.[4]

On the basis of the foregoing analytical and experimental results together with flight experience documented for a number of actual airplanes, it was decided to include a requirement on flight-path stability in the revised specification. The requirement applies for the landing approach phase and is stated in terms of limiting values of the local slope of the climb angle vs airspeed curve at constant throttle. The form of the requirement is illustrated in Fig. 9. The parameter $d\gamma/dV$ was selected because it is both easy to calculate and feasible to measure from simple flight-test maneuvers using readily available instrumentation.

Short-Period Mode

In specifying longitudinal short-period dynamics, it would be desirable to use criteria that are descriptive of the airplane responses directly important to the pilot. This would allow the designer the greatest freedom in the use of various combinations of airframe and control system dynamics to achieve the desired over-all responses. Unfortunately, specification of short-period dynamics in this form is not possible at the present time, because of the lack of systematic flying qualities data obtained for various control system-airframe dynamics in combination with various types of feel system dynamics. Also, the response of the airplane to pilot inputs is only a partial description of longitudinal dynamics, since short-period response to turbulence is also important. For these reasons, it was decided to use conventional short-period modal parameters as criteria for the present revision of -8785, treating control system dynamics separately.

It is generally agreed that short-period frequency and damping alone are not sufficient to describe the acceptability of airplane longitudinal dynamics. In Ref. 41[4] the effects on handling qualities of the parameters L_α, V, and n_z/α were explored. Reference 42[4] expresses the idea that $1/T_{\theta_2}$ is of primary importance, because it appears in the numerator of the pitch attitude to elevator transfer function. References 43–45[4] are based on the premise that pitch-rate response is of primary importance at low speed and normal acceleration response at the pilot's station is of primary importance at high speed. From this premise, Refs. 43 and 44[4] conclude that the short-period frequency should be a function of $1/T_{\theta_2}$ for low values of n_z/α and that it should be a function of n_z/α when n_z/α is large. Reference 45[4] recommends envelopes on the weighted sum of the pitch rate and normal acceleration responses to a step stick force command. In Refs. 46 and 47[4] the relationship between initial pitch acceleration and steady-state normal acceleration is discussed and related to the short-period frequency and n_z/α. The theories discussed in Refs. 46 and 47[4] best explain pilot objections to excessively high and low short-period frequencies, and have therefore been used as a framework to mold the available pilot rating data into short-period frequency requirements.

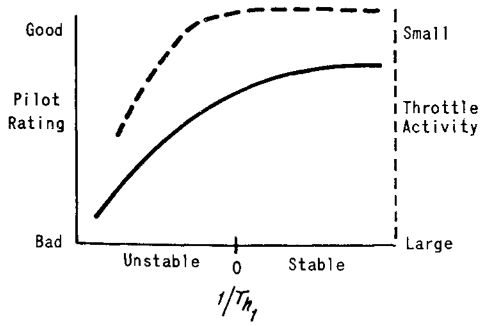

Fig. 8 Typical variation of pilot rating and throttle activity with the parameter $1/T_{h_1}$.

The following is a summary of the way in which the pilot comments from the variable stability airplane programs of Refs. 47–55[4] can be interpreted best. In the flight programs of Refs. 47 and 48,[4] the pilots were required to vary the control gearing and select an optimum or best compromise value for use in the evaluation of each short-period configuration. By increasing the control gain, it was always possible, regardless of the flight condition or short-period configuration, to make the sensitivity too high with the result that the response was abrupt and gross for small control inputs. Conversely, it was always possible to make the gain so low that large stick motions and heavy control forces were necessary to generate any airplane response at all. The pilot would vary the control gain between these extreme situations and search for the optimum value or, as was often the case, the least objectionable compromise value. From these experiments, it was observed that for each flight condition there was a range of short-period frequencies for which the pilots could select rather well-defined optimum control gains, but at lower and at higher short-period frequencies they would encounter conflicting requirements which imposed unsatisfactory compromises in the selection of the control gain. When the short-period frequency was too low, the pilots found that a control gain that gave a good sensitivity for tracking and initiating maneuvers would result in steady control forces that were too light during gross maneuvers or steady turns. Conversely, a control gain that gave comfortable and safe steady forces would result in low sensitivity and lack of initial response. Regardless of the control gain selected, the pilot would find that a control input large enough to initiate a maneuver satisfactorily would have to be relaxed as the response developed in order to prevent overcontrol or overshooting the desired steady state. For flight conditions where the airplane had considerable normal acceleration capability, this situation would usually lead to a comment that the airplane tends to "dig in," i.e., once a response starts it tends to grow. In order to fly an airplane with these characteristics, the pilot must use rather complicated control motions and anticipate the growth of the airplane response. These configurations are downrated quite severely.

When the short-period frequency was too high, the pilots found that a control gain that gave good sensitivity for tracking and initiating maneuvers would result in excessively heavy steady forces in turns and restricted maneuverability. Con-

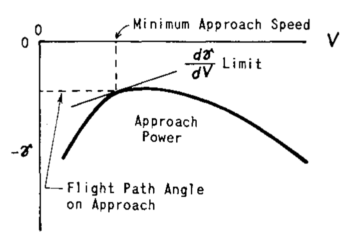

Fig. 9 Flight-path stability requirement.

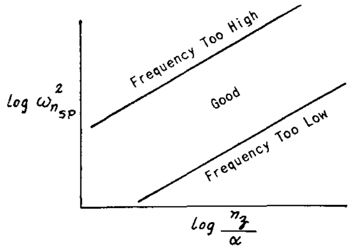

Fig. 10 Short-period frequency as function of n_z/α.

versely, a control gain that gave comfortable and safe steady forces would result in oversensitivity and abrupt initial response when tracking or initiating maneuvers. In order to fly an airplane with these characteristics, the pilot must either accept excessively heavy maneuvering forces or he must use caution to smooth his control inputs to avoid abrupt responses. Either of these techniques can be adopted with less detriment than when control anticipation is required and it has been found that the pilot ratings deteriorate less rapidly for too high short-period frequencies than they do when the frequency is too low. It has also been observed from the variable stability airplane experiments that the values of short-period frequency which are considered too low or too high appear to be a function of the value of n_z/α at which the evaluations were made. The observed characteristic is illustrated in Fig. 10.

In the analysis of Ref. 46,[4] it is assumed that the initial pitch acceleration is the response that is of concern to the pilot when he initiates a maneuver and that the steady-state response of concern is the normal acceleration experienced in a pull up. By assuming constant speed equations of motion and by applying the initial value theorem to the $\ddot{\theta}/\delta_e$ transfer function and the final value theorem to the n_z/δ_e transfer function, the following expression can be written for the ratio of initial pitch acceleration to steady-state normal acceleration:

$$\frac{\ddot{\theta}/\delta_e|_{t=0+}}{n_z/\delta_e|_{ss}} = \frac{\omega_n^2(M_{\delta_e} + Z_{\delta_e}M_{\dot{w}})}{(V/g)(Z_{\delta_e}M_w - M_{\delta_e}Z_w)} \qquad (7)$$

For constant-speed equations of motion, the numerator factor of the θ/δ_e transfer function is

$$\frac{1}{T_{\theta_2}} = \frac{Z_{\delta_e}M_w - M_{\delta_e}Z_w}{M_{\delta_e} + Z_{\delta_e}M_{\dot{w}}} \qquad (8)$$

Therefore, by substituting Eq. (8) into Eq. (7), Eq. (9) is obtained which relates the ratio of initial pitch acceleration to steady-state normal acceleration to the short-period frequency squared, the true speed, and the θ/δ_e transfer-function numerator factor $1/T_{\theta_2}$

$$(\ddot{\theta}/\delta_e|_{t=0+})/(n_z/\delta_e|_{ss}) = \omega_n^2/[(V/g)(1/T_{\theta_2})] \qquad (9)$$

The ratio of steady-state normal acceleration to steady-state angle of attack is given by the following expression:

$$\frac{n_z}{\alpha} \equiv \frac{n_z/\delta_e|_{ss}}{\alpha/\delta_e|_{ss}} = \frac{V}{g}\frac{Z_{\delta_e}M_w - M_{\delta_e}Z_w}{M_{\delta_e} - (1/V)Z_{\delta_e}M_q} \qquad (10)$$

By comparing Eqs. (8–10) it is observed that when

$$|M_{\delta_e}| \gg |Z_{\delta_e}M_{\dot{w}}|, \ |M_{\delta_e}| \gg |(1/V)Z_{\delta_e}M_q| \qquad (11)$$

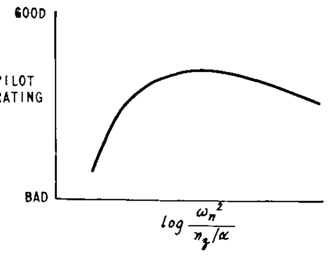

Fig. 11 Pilot rating as a function of $\omega_n^2/(n_z/\alpha)$.

then

$$n_z/\alpha \doteq (V/g)(1/T_{\theta_2}) \doteq (V/g)(Z_{\delta_e}M_w - M_{\delta_e}Z_w)/M_{\delta_e} \qquad (12)$$

Thus, the observed trend in the research data illustrated in Fig. 10 is consistent with the hypothesis that the ratio of initial pitch acceleration should be in proportion to the steady-state normal acceleration.

The pilot comments concerning the compromise between sensitivity and steady-state maneuvering forces can also be related to transfer-function characteristics. Assuming negligible control-system dynamics or transport lag, the sensitivity or initial pitch acceleration per pound of force can be expressed as

$$M_{F_s} = (\partial\delta_e/\partial F_s)\, M_{\delta_e} \qquad (13)$$

and the stick force per unit normal acceleration can be expressed as

$$F_s/n_z \doteq \omega_n^2/[M_{F_s}(n_z/\alpha)] \qquad (14)$$

where the assumptions of Eq. (11) have again been made. If Eq. (14) is rewritten as follows:

$$(F_s/n_z)\, M_{F_s} \doteq \omega_n^2/(n_z/\alpha) \qquad (15)$$

it can be seen that when $\omega_n^2/(n_z/\alpha)$ is small, either the stick force per g must be reduced to maintain satisfactory sensitivity or the sensitivity must be reduced to maintain satisfactory stick force per g in maneuvers. If $\omega_n^2/(n_z/\alpha)$ is too small, i.e., less than the lower limit illustrated in Fig. 10, the pilot will not be able to achieve a satisfactory compromise between sensitivity and steady forces and, depending on the individual, may select one or the other extreme. For example, one pilot in Ref. 47[4] selected a low control gain in this situation so that the control forces were high, thus tending to guard against overcontrol, while the other pilot in Ref. 47[4] selected the control gain on the basis of sensitivity and accepted the light steady forces that resulted. Both pilots, however, considered these configurations unacceptable and gave them pilot ratings of 7–10.

Referring again to Eq. (15) and considering the case where $\omega_n^2/(n_z/\alpha)$ is large, it can be seen that either the stick force/g must be increased to maintain satisfactory sensitivity or the sensitivity must be increased to maintain comfortable stick forces in maneuvers. If $\omega_n^2/(n_z/\alpha)$ is too large, i.e., greater than the upper limit illustrated in Fig. 10, the pilot again will not be able to achieve an acceptable compromise and will downrate the configuration. When presented this situation, both pilots in Ref. 47[4] and the pilot in Ref. 48[4] selected the control gain so as to keep the sensitivity from being too high, thus reducing the abruptness and tendency to bobble for small inputs. This, of course, caused heavy steady forces during sustained maneuvers and turns and resulted in less satisfactory pilot ratings. As was mentioned before, the high

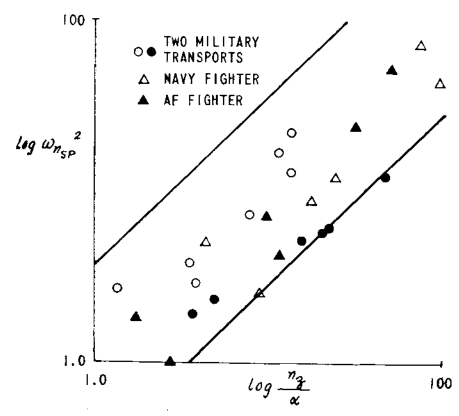

Fig. 12 Short-period frequency of existing airplanes as a function of n_z/α.

$\omega_n^2/(n_z/\alpha)$ situation is less difficult to cope with than is the case where $\omega_n^2/(n_z/\alpha)$ is too low. This is illustrated in Fig. 11, which shows the trend of pilot rating with $\omega_n^2/(n_z/\alpha)$ that has been observed.

On the basis of the foregoing considerations and the very good correlation of variable stability airplane data that is obtained when the data are considered in this manner, a requirement on short-period frequency in the form of Fig. 10 has been included in the revised specification. In Fig. 12, the short-period frequency of a number of the existing airplanes in various flight conditions considered in Ref. 12[4] has been plotted vs n_z/α with lines of constant $\omega_n^2/(n_z/\alpha)$ indicated.

The data in Fig. 12 illustrate the trend of increased short-period frequency when n_z/α is large and lower short-period frequency when n_z/α is low. For a given airplane, the values of n_z/α and ω_n^2 are proportional to dynamic pressure; thus, as dynamic pressure is increased, both ω_n^2 and n_z/α increase and the point on Fig. 12 moves parallel to the constant $\omega_n^2/(n_z/\alpha)$ lines. A short-period frequency requirement in the form of Fig. 10 has implications for the design of augmentation systems in that it should be more permissive for fixed gain systems than single ω_n vs ζ bull's eye requirements and it takes the emphasis off invariant models for self-adaptive systems. The available variable stability airplane data indicate that the minimum short-period frequency required for the landing approach task is lower than that required for up-and-away maneuvering, but the major functional dependence is with n_z/α.

It is possible that there may be absolute limits on ω_n and n_z/α. For very low values of n_z/α, the angle of attack and pitch attitude changes required to curve the flight path may become excessive and when $1/T_{\theta_2}$ becomes very small, the response time of flight-path angle to pitch attitude changes may become too long. Thus, there may be limits expressible in terms of these parameters which would determine when it is necessary to change the mode of control of flight path from rotation of the whole airplane through use of the elevator to use of direct control of lift through thrust vectoring or circulation control by flap actuation, etc. However, there is insufficient experimental flight-test data to establish such limits in this revision to the specification, and if limits on these parameters are included, they will be based on analysis or ground simulation results.

Short-Period Damping

The previous discussion of short-period frequency pertains to what is important to the pilot when the short-period damping is satisfactory. However, everyone agrees that short-period damping is also important. When the damping is too low, the airplane response overshoots and oscillates and the response of the airplane to turbulence is greatly increased. When the damping is too high, the response becomes sluggish. Therefore, upper and lower limits have been established for short-period damping ratio. The form of the short-period frequency and damping ratio requirements is illustrated in Fig. 13 for two widely different values of n_z/α.

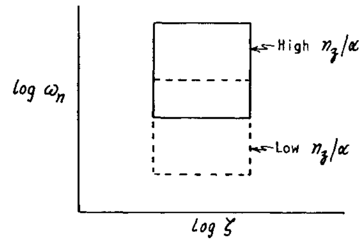

Fig. 13 Short-period frequency and damping ratio requirements.

Concluding Discussion

In an article of this nature, it has not been possible to include or to discuss in detail all of the research work, simulation data, and experience, which form the background for the revised requirements. Nor has it been possible to discuss the possible flight-test and data analysis procedures which might be used best to verify or demonstrate compliance with the requirements. As part of the general program for revision and updating of the specification, it is planned that a document entitled "Background Information and User Guide" will be prepared in which the intent of each requirement will be discussed together with the available information and data upon which the requirement has been based. In addition, potential flight-test and data analysis procedures will be discussed to give guidance in regard to flight-test maneuvers, control inputs, parameters to measure, some considerations of instrumentation and possible data analysis methods. Since flying qualities research, flight testing, and airplane design are all areas which are active and progressive, it is obvious that there will be a continuing need to update the flying qualities specification and to modify the "Background Information and User Guide" document to keep pace with new developments in these areas.

In conclusion, a revision of MIL-F-8785(ASG) has been prepared and is undergoing review by interested agencies at the present time. Following this review, and the additional modifications that will result, the revised specification will be proposed for adoption as the replacement for the present -8785. The revised specification has been called an "interim revision" to make the point that additional efforts to refine the requirements and introduce new ones will continue beyond the completion of the current revision, probably for an indefinite period of time.

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[3] Harper, R. P., Cooper, G. E., "A Revised Pilot Rating Scale for the Evaluation of Handling Qualities," Rept. 153, 1966, Cornell Aeronautical Lab.

[4] Chalk, C. R. and Wilson, R. K., "Airplane Flying Qualities Specification Review," Paper 68-245, AIAA.