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Evolution, Revolution, and Challenges of Handling Qualities

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Nomenclature

b	=	wing span, ft
L_α	=	zero in pitch attitude-to-elevator transfer function, rad/s
$\angle n_{z_p}/F_{es}(j\omega_c)$	=	phase angle of normal acceleration-to-stick force at pilot station measured at criterion frequency, deg
p	=	body-axis roll rate, rad/s
$pb/2V$	=	wing helix angle, rad
S	=	slope of pitch attitude-to-stick force frequency response measured between 1 and 6 rad/s, dB/octave
V	=	aircraft velocity, ft/s
V_{con}	=	maximum airspeed for vertical/short takeoff and landing airplane conversion from short takeoff and landing mode to airplane mode
v_e	=	equivalent sideward airspeed, ft/s
$\angle Y_p(j\omega_{BW})$	=	phase angle of pilot compensation at bandwidth frequency, deg
$\Delta G(q)$	=	pitch rate overshoot measured from frequency response, dB
$\angle\theta/F_{es}(j\omega_c)$	=	phase angle of pitch attitude-to-stick force measured at criterion frequency, deg
$\lvert\theta(j\omega)/\theta_c(j\omega)\rvert_{\max}$	=	resonance peak in closed-loop pitch attitude frequency response, dB
τ_e	=	equivalent systems time delay, s
τ_n	=	human operator neuromotor lag, s
τ_p	=	pilot reaction time, s
$\tau_{p\theta}$	=	phase-delay parameter, s
$\Phi(j\omega_c)$	=	normal acceleration parameter, $\angle n_{z_p}/F_{es}(j\omega_c) - 14.3\omega_c$, deg
ϕ	=	bank angle, deg
$\lvert\phi/v_e\rvert$	=	rolling parameter for lateral response, deg/ft/s
ω_{BW}	=	closed-loop bandwidth frequency for Neal–Smith criteria, rad/s
ω_{BW_γ}	=	flight-path bandwidth frequency, rad/s
ω_{BW_θ}	=	pitch attitude bandwidth frequency, rad/s
ω_c	=	criterion frequency, $6 + 0.24S$, rad/s
$1/C_{1/2}$	=	damping parameter, inverse of number of cycles for lateral oscillations to damp to half-amplitude (non-dimensional)

Introduction

THE past 25 years have seen both evolutionary and revolutionary changes in handling qualities and in the ways that they are specified. In the late 1970s and early 1980s, the hot topic was whether to free L_α. In the 1990s it became pilot-induced oscillations (PIOs) and later the possible elimination of specifications altogether. Today, the most critical issues in handling qualities may be how to extend them to pilotless aircraft [uninhabited aerial vehicles (UAVs)] and how to prevent undesirable phenomena such as PIOs and structural interactions. There is an impression among the program management community (and, unfortunately, in some disciplines of the engineering community as well) that handling qualities are not an issue today. This impression is wrong.

This paper provides a summary of the evolution of handling qualities by focusing on their specification and of the revolution by focusing on the contents of those specifications. It is not intended to be a comprehensive historical treatise on handling qualities; for that, the reader is referred to Phillips,[1] Ashkenas,[2] and Abzug and Larrabee.[3] Instead, the goal of this paper is to convey the path that has been followed to get where we are in the specification of handling qualities for fixed-wing airplanes, helicopters, and vertical/short takeoff

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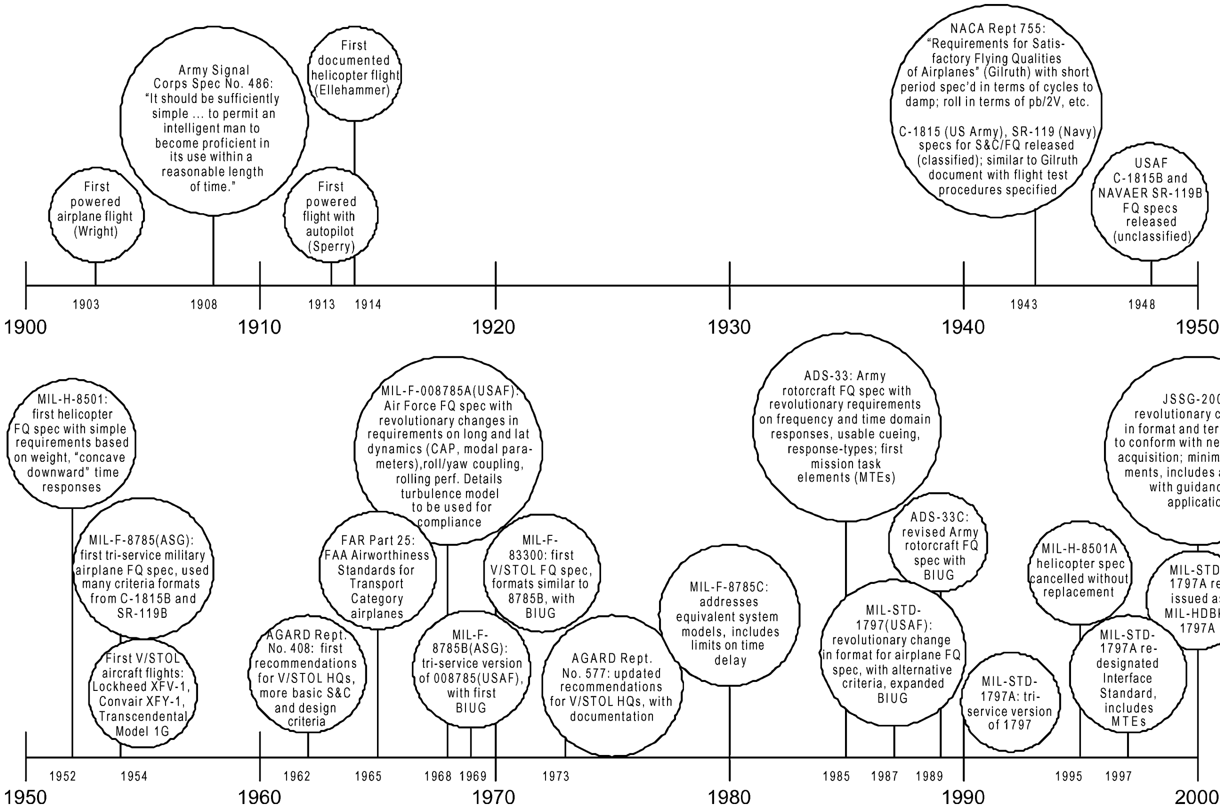


Fig. 1 Timeline for handling qualities, including selected significant firsts in aviation history.

and landing (V/STOL) aircraft and to show the open areas that lie ahead, at least for the near future.

Flying Qualities? Or Handling Qualities?

Most military and civil specifications explicitly refer to flying qualities, not handling qualities. (The former military specification for helicopters, MIL-H-8501A,[4] does both: It applies to "flying and ground handling qualities," hence, separating handling to mean ground handling only.) Phillips[1] defines flying qualities as "the stability and control characteristics that have an important bearing on the safety of flight and on the pilots' impressions of the ease of flying an airplane in steady flight and in maneuvers." In this paper, we intend to include the basic stability and control (S&C) characteristics referred to by Phillips and also to cover a more broad interpretation consistent with that put forth by Cooper and Harper[5]: handling qualities are "more than just stability and control characteristics. Other factors that influence the handling qualities are the cockpit interface (e.g., displays, controls), the aircraft environment (e.g., weather conditions, visibility, turbulence) and stress. . ." Cooper and Harper define handling qualities to be "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role." They also note that "the generally accepted meaning of 'Flying Qualities' is similar to this definition of 'Handling Qualities'. . . ."

In this paper, reference will be made to handling qualities except when specific reference is made to flying qualities specifications. This distinction is not meant to infer any change in meaning, but rather is done to be consistent with the familiar titles of the specifications themselves. For example, MIL-F-8785C[6] is perhaps the most widely known aircraft specification we will mention, but it is a flying qualities specification not a handling qualities specification.

Timeline

Interest in aircraft handling qualities is not new. It certainly began long before the Wright brothers' first powered flight in 1903. Though the term was not yet used, developers of gliders and unpowered aircraft in the centuries before the Wrights also had an interest in the subject.

For our purposes, however, the timeline may be started with the first flight of the Wright brothers because it spurred the most intense efforts to understand and quantify the stability, control, and dynamic responses of the flying machine. This timeline is shown graphically in Fig. 1. This timeline reflects the most significant achievements in handling qualities over the last century, marked by reference to the relevant specifications for those achievements.

Selected significant firsts in aviation history are also shown in Fig. 1 for reference, beginning, of course, with Orville Wright's 1903 first flight.

What might be interpreted as the first handling qualities requirement was released in January 1908. It was a one-page document outlining the performance requirements for an aircraft in a sole-source procurement to the Wright brothers.[7] Among the requirements was the single line: "It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time." Fortunately, there were no requirements on what was meant by an intelligent man or a reasonable time.

It may be argued that the first real specification for flying qualities was written by Gilruth and published by NACA in 1943.[8] In the same year, the U.S. Army Air Forces and U.S. Navy issued documents (both originally carrying confidential classifications because they were issued during World War II) that specified "Stability and Control Requirements for Airplanes."[9] The military documents had requirements that were similar in form to those written by Gilruth. Requirements for longitudinal and lateral–directional short-period motions specified only a single limit on number of cycles to damp; rolling performance was specified in terms of the rolling parameter $pb/2V$. One difference between the sets of specifications is that the military documents included flight-test procedures for compliance, whereas the Gilruth report[8] discussed design considerations for each of the requirements.

In 1948, the classified military specifications were reissued in revised format without classification.[10] They were still essentially

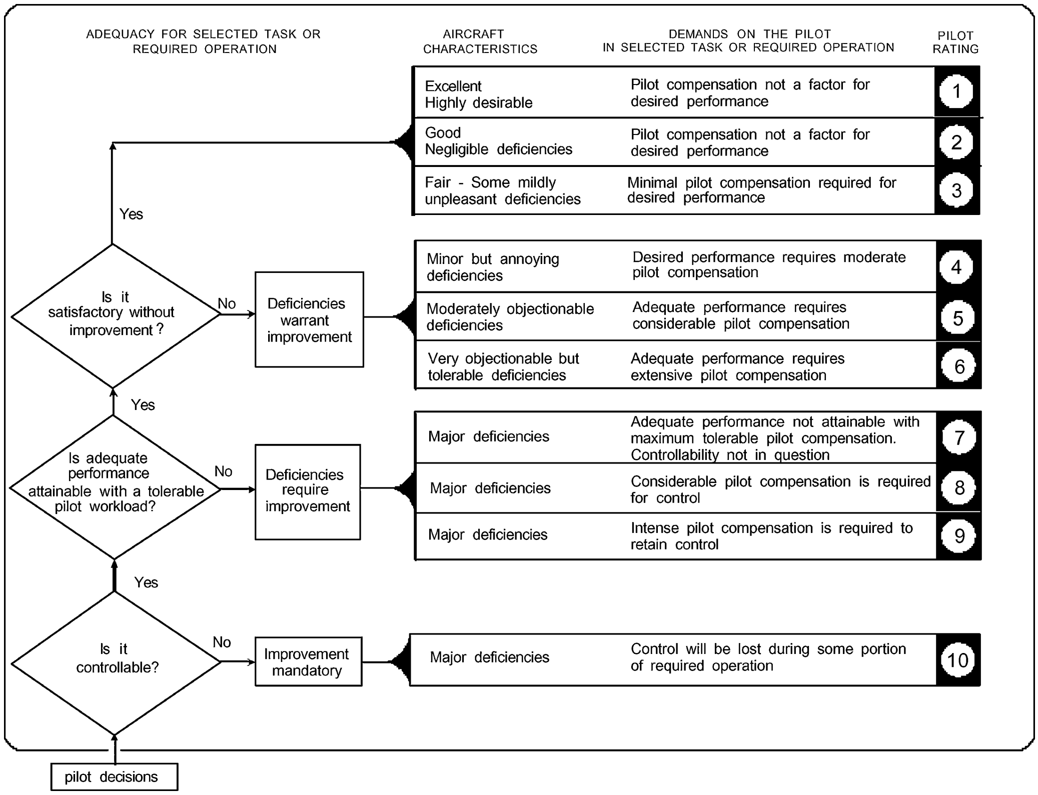


Fig. 2 Cooper–Harper HQR Scale.[5]

S&C specifications. The first helicopter flying (and ground handling) qualities specification, MIL-H-8501, was released in 1952,[4] with relatively simple time-response requirements on stability, and control power and damping requirements stated in terms of weight and inertia. A single triservice specification for fixed-wing airplanes, MIL-F-8785, was issued in 1954,[11] with more elaborate requirements for control characteristics but still relatively simple limits on modal responses. Lateral–directional oscillatory mode requirements were more complex, with a damping parameter $1/C_{1/2}$ specified in terms of a rolling parameter $|\phi/v_e|$. For the first time, requirements for power- and boost-control systems were included.

Also in 1954, the first variable-configuration V/STOL aircraft flew.[12] Eight years later, AGARD issued a document with recommendations for V/STOL handling qualities.[13] Shortly thereafter, the U.S. Federal Aviation Administration (FAA) issued its first airworthiness standards for civil aircraft, Federal Aviation Regulations (FAR) Parts 23[14] and 25.[15]

Perhaps the most significant revolution in handling qualities took place in the late 1950s and early 1960s as concern for dynamic responses shifted from cycles and times to damp to modal parameters: short-period damping and frequency, phugoid damping, roll time constant, etc. In addition, the critical importance of turbulence on the specification of flying qualities requirements was recognized. An organization first affiliated with Cornell University in Buffalo, New York, Cornell Aeronautical Laboratory [(CAL), later Calspan and now part of Veridian], was performing numerous flight research experiments with variable-stability aircraft. This work, along with Bihrle's efforts to describe the pilot's control of flight path in terms of a control anticipation parameter,[16] led to the creation of a revolutionary new military specification, first issued by the U.S. Air Force in 1968 as MIL-F-008785A(USAF)[17] and the next year as the triservice document MIL-F-8785B(ASG).[18] Complete documentation of turbulence models to be used for compliance was included as a part of the specification itself.

A breakthrough that accompanied the publication of MIL-F-8785B(ASG) was the issuance of a background information and user guide (BIUG)[19] authored by CAL and U.S. Air Force engineers and containing a wealth of supporting information and application guidance. Such BIUGs have now become almost essential as the specifications have continued to increase in sophistication. The original BIUG was released with export controls in place and, hence, was not easily obtained by non–U.S. entities.

An event of note that occurred in 1969 is not indicated on the timeline in Fig. 1. This was the publication of NASA TN D-5153,[5] by Cooper of NASA Ames Research Center and Harper of Calspan Corporation. Ratings scales for pilot opinion had been in use since at least the early 1950s, but this document represented the first formal publication of a guide to the evaluation of handling qualities with an accompanying 10-point scale (Fig. 2). The Cooper–Harper scale, sometimes called the handling qualities rating (HQR) scale, has become the worldwide standard for the quantification of pilot opinions based on performance of formal tasks with a given set of aircraft characteristics. The HQR scale has been shown to have some shortcomings, but its strengths far outweigh any weaknesses.

All military documents about fixed-wing aircraft released since 1969 reflect the fundamental requirements stated in MIL-F-8785B(ASG), as do many of the requirements of the first (and, so far, only) V/STOL military specification, MIL-F-83300,[20] issued in 1970 with its own BIUG.[21] The U.S. Air Force officially adopted MIL-F-83300 for all vertical-lift aircraft, including helicopters, though the U.S. Army and U.S. Navy continued to use MIL-H-8501A[4] until 1995.

A 1980 revision to the fixed-wing specification, MIL-F-8785C,[6] contained some apparently minor, but, in the ensuing years, controversial, revisions to address the equivalent airplane (discussed further later in this paper). A BIUG for this specification discusses some of the issues faced in the revision.[22]

A second revolution in handling qualities occurred in the early 1980s as the U.S. Army was formulating a replacement to the helicopter specification MIL-H-8501A. With the planned procurement of a new light helicopter, experimental [(LHX) now the RAH-66 Comanche], the U.S. Army funded efforts to devise new criteria that reflected the extreme environments in which modern helicopters were required to operate. The culmination was an aeronautical design standard- (ADS-) 33,[23] that included frequency-domain requirements and the interactions of visual cueing and displays. This document included the first specific mission tasks [mission task elements, (MTEs)] expected of the aircraft to demonstrate satisfactory handling qualities. For the first time, handling qualities requirements were written explicitly in terms of the Cooper–Harper HQR scale. More is written about this specification later in this paper.

A revision to the U.S. Army's specification, designated ADS-33C,[24] was issued in 1989 along with its now-ubiquitous BIUG[25] (again carrying a limited distribution statement). The most recent version of ADS-33 was issued in 2000 as ADS-33E-PRF.[26] The U.S. Army has declared it to be a performance specification (PRF).

Reflecting the same revolution in acquisition strategies through the 1980s, the fixed-wing specification underwent a revision to a MIL-STD plus MIL-HANDBOOK format leading to the appearance of the triservice MIL-STD-1797A[27] in 1990, and again in 2000, with the Joint Services specification guide JSSG-2001.[28] Both documents move away from the explicit requirements of their predecessors, instead offering alternatives with considerable discussion to help the user select the most appropriate criteria. These documents incorporate more than just the criteria contained in MIL-F-8785C because they include the works of many other researchers from the 1970s and 1980s. More discussion of the fixed-wing specifications follows in the next section.

Evolution: Airplane Handling Qualities Specifications and Their Requirements

Dynamic Criteria and Equivalent Systems

The understanding of airplane dynamics developed along with the development of the airplane itself. This led to the dominant modes of response, the short-period, phugoid, roll, Dutch roll, and spiral modes, which explained conventional airplane responses to acceptable accuracy initially. Military flying qualities requirements were specified in terms of acceptable values for parameters of these dominant modes. The introduction of S&C control augmentation began to change this situation, allowing for additional and/or higher-order modes plus arbitrary shaping of responses. Application of the classical mode parameters became more and more questionable. This ambiguity led to the equivalent system concept.[29] The equivalent system approach was included in the formulation of MIL-F-8785C published in 1980.

The equivalent system approach meant that the actual aircraft dynamics had to satisfy flying qualities requirements in terms of "equivalent classical systems which have responses most closely matching those of the actual aircraft"[6] (as an example, see Fig. 3). The military specification requirements then apply to those equivalent parameters rather than to any mode of the actual response. As explained by Moorhouse and Woodcock,[22] "In order to demonstrate compliance with the modal requirements of MIL-F-8785C, equivalent systems must first be defined to approximate the actual airplane dynamics . . . ."

The equivalent system had to be calculated by a least-squares match to the actual/predicted dynamics over an appropriate frequency range, but there was no requirement on the goodness of the fit. That question was subjectively addressed by the stated expectation from Moorhouse and Woodcock[22] that satisfactory flying qualities would be expected to result from a classical-type response that met the classical requirements. This preserved the existing database for the different flying qualities levels of the preceding version of the specification. There was also much discussion of this new method[22] and a caution that "no method should be used blindly, without exercise of engineering judgment."[22]

One explicit requirement was that all nonlinearities had to be included in the response that was matched. This was supposed to tell designers that the specification was not just to be applied to linear analyses.

At this time, it had also become apparent that an undesirable trend introduced by more and more augmentation was increased phase lag in the responses to pilot commands. This was addressed by a new specification parameter, equivalent system time delay. In terms of the frequency responses, this was to be a term, $e^{-\tau_e s}$ added on to the classical formulations. The term, τ_e, was supposed to be "total effective time delay contributed by all sources including high-frequency

HOS: $\dfrac{\dot{\theta}}{F_{es}} = \dfrac{170.7(0.274)(1)^2(14.1)(20.3)(23.5)[0.03,60]}{(0.368)(2)(15.8)(19.8)(24.7)[0.68,1.78][0.88,50][0.66,65]}$

LOES: $\dfrac{\dot{\theta}}{F_{es}} = \dfrac{0.0586(0.274)e^{-0.059s}}{[0.99,1.70]}$

Shorthand notation: $(1/T) = (s+1/T)$; $[\zeta,\omega_n] = [s^2 + 2\zeta\omega_n s + \omega_n^2]$

Mismatch = 18.1

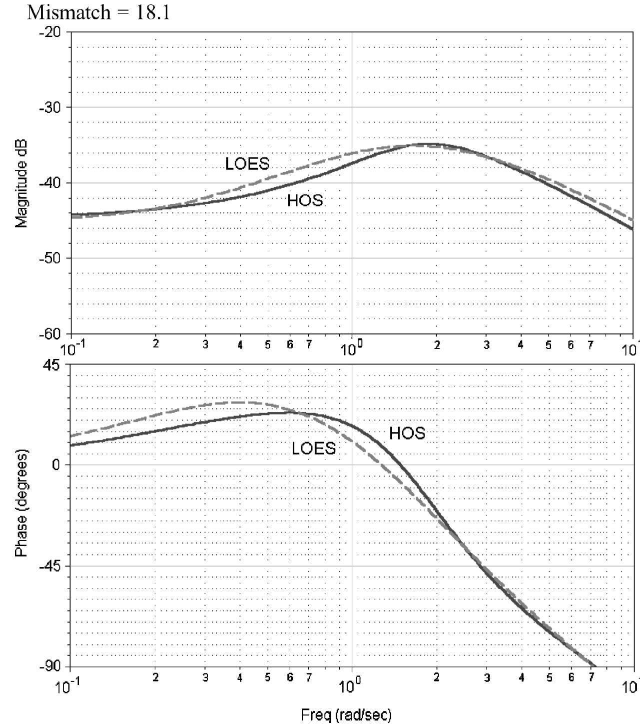


Fig. 3 Example application of the equivalent systems approach (F-18 in power approach[30]) with acceptable mismatch.

flight control system modes (actuators, compensation, etc.), digital sampling and computation delays, etc., etc."[22] A significant amount of data validated a degradation in pilot rating as this term increased, with the well-known (but often ignored) value of 100-ms maximum equivalent system time delay for Level 1 flying qualities.

Common mathematical algorithms for computing the equivalent system do so by minimizing a cost function, usually of the following form in the frequency domain:

$$M = \sum_{\omega_1}^{\omega_n} \left[(G_{\mathrm{HOS}} - G_{\mathrm{LOES}})^2 + a(\Phi_{\mathrm{HOS}} - \Phi_{\mathrm{LOES}})^2 \right]$$

The factor a specifies the relative weighting between gain and phase errors and M is interpreted as mismatch. The lower the value of M, the better the match. The mismatch of 18.1 for the example in Fig. 3 (see Ref. 30) is considered acceptable. No specific limits on mismatch have been developed. A mismatch above about 100 is usually interpreted as an indication of a poor equivalent system and is often associated with poor handling qualities.[31]

In summary, the equivalent system approach was supposed to represent the complete airplane dynamics and guide flight control designers to produce a system with good classical types of response modes that would be natural to a pilot. There are nuances that remained, but it is our opinion that this approach for classical response modes is still the most valid one in general terms.

Alternative Design and Specification Criteria

Although the equivalent systems technique proved to be a reasonably successful approach to specifying dynamic response for highly augmented aircraft, it had at least one weakness. The low-order equivalent system (LOES) form used for the match was a conventional response form, and thus the criteria, as published in MIL-F-8785C, constrained the dynamic response to a classical response form, that is, for longitudinal response, an alpha-command or a pitch-rate-command response type with no attitude hold. This was somewhat of a weakness because, with the advent of fly-by-wire control systems and, shortly thereafter, digital flight control computers, flight control engineers now had an unprecedented capability to tailor the dynamic response to optimize handling qualities for individual flight tasks throughout the flight envelope. Nuisance modes such as the phugoid and Dutch roll could now be eliminated, but the equivalent system form in use in MIL-F-8785C assumed their presence. Of course, new lower-order equivalent system forms could have been identified for each response type. (There were really only a handful that might plausibly prove useful.) However, no data existed to support criteria for such unconventional response types. Providing sufficient data for validated criteria for all of these additional response types would have been time consuming and costly; the very thing that the lower-order equivalent system approach had been created to avoid.

Consequently, research in the 1970s turned to devising new criteria that could be used to specify dynamic response characteristics regardless of response type. Such criteria could take advantage of the extensive conventional flying qualities data from past research without constraining the flight control engineer to a "classical" form. For obvious reasons, most of these criteria would focus on the shape of the aircraft's frequency response.

At the beginning of the decade, new data were becoming available for aircraft with higher-order control systems. One of the earliest, and most extensively used, databases from this time period is the Neal–Smith database.[32] This database was created using the NT-33A variable-stability aircraft, and Neal and Smith derived alternative criteria (described in more detail in the next section) from these data by wrapping a closed-loop pilot model around a model of the vehicle's longitudinal dynamics and control system. Pitch tracking performance of the pilot–vehicle system was specified, and the criteria were based on the compensation the pilot model was forced to adopt to meet the performance specification and on the closed-loop resonance of the pilot–vehicle system.

Technically, the Neal–Smith criteria still steered the control system engineer into a pitch-rate-command response form because the performance criteria assumed a pitch tracking task (for which this form is ideal, given the assumed pilot model) and the database consisted entirely of conventional (though higher-order) response types. Nevertheless, the criteria must be mentioned here because they were one of the most widely accepted alternative criteria and the database from which they were derived was also the foundation for many of the other alternative criteria to be addressed later. More recent applications of the criteria have led to changes in the methods, parameters, and boundaries, but none of the changes have proven to make the criteria universally applicable.[33]

Another approach, developed in the mid- to late 1970s, became known as the Smith–Geddes[34] criteria (also see Ref. 35). This approach, as originally conceived, included a mix of time-response and frequency-response criteria. The criteria of the time-response part specified the time to peak pitch rate following a step pitch control input. As with most other time-response criteria, this criterion favored pitch-rate-command response types because the data on which the criterion boundaries were based were exclusively conventional-response types.

The frequency-domain part of the Smith–Geddes[34] criteria consisted of three components. The first component was the average slope S of the amplitude curve of pitch attitude frequency response to stick force. This average slope was obtained from a straight line approximation of the amplitude curve over a frequency range in the heart of the pilot's frequency range of interest. The second component was the phase angle of the pitch attitude response to stick force at a specific frequency, $\angle\theta/F_{es}(j\omega_c)$. This frequency, known as the criterion frequency $\omega_c = 6 + 0.24S$, was basically an approximation of the crossover frequency of the closed-loop pilot–vehicle system.[36] The third component, known as the normal acceleration phase parameter $\Phi(j\omega_c)$, was computed from the phase angle of the normal acceleration response to stick force at the criterion frequency, $\angle n_{z_p}/F_{es}(j\omega_c) - 14.3\omega_c$.

The time-domain part of the Smith–Geddes criteria has not been widely used. The frequency-domain elements have been widely used but not necessarily accepted. The weakest part of the criteria seems to be the estimate of the criterion frequency. Some users, however, have found the criteria to be effective when a more accurate estimate of the actual crossover frequency is used. Another weakness of the criteria is that the values for the criteria boundaries were based on the Neal–Smith database (fighterlike dynamics), but the criteria have been claimed to be valid for all classes of aircraft. Consequently, when the Smith–Geddes criteria have been applied to larger aircraft, such as the B-1, B-2, and C-17, the criteria were impossible to meet without alteration, though they did accurately reflect trends, that is, improvement vs the criteria reflected improvement in aircraft handling.

Additional criteria, based on airplane pitch attitude bandwidth, were introduced in the late 1970s to account for the unusual response characteristics of aircraft with independent control of all six degrees of freedom.[37] These criteria were also applied to the Neal–Smith database (see Ref. 38), became part of MIL-STD-1797A, and are the primary response criteria in the rotorcraft specification ADS-33E-PRF. The bandwidth criteria are later discussed in more detail for their application to PIOs.

As the work on alternative criteria was accelerating in the United States, similar work was ongoing in Great Britain. A set of criteria, commonly referred to as the Gibson criteria, was under development at British Aerospace in the 1970s and 1980s.[39] A subset was adopted in MIL-STD-1797A.[27] As with the other alternative criteria, the Neal–Smith[32] data were used extensively in the development of elements of Gibson's criteria.[39] The criteria included in MIL-STD-1797A are intended to provide good pitch attitude characteristics by effectively specifying the minimum short-period frequency and maximum separation between the short-period and the pitch attitude-to-elevator zero and, as such, are more appropriate for initial design than for final verification of handling qualities. More recent handling qualities and PIO criteria have been published.[40]

Demonstrating Handling Qualities with the Pilot in the Loop

Need for Demonstration Maneuvers

It is recognized by the authors of this paper and others in the handling qualities community that the specification of handling qualities in a single reference will never be complete. Advances in flight control systems, cockpit controllers, and aircraft effectors may always outpace the advances in handling qualities criteria. In addition, some deficiencies in handling qualities, such as PIOs, may not always be exposed by these criteria. Furthermore, most requirements are intended to be applied to one axis at a time, and so there are no catch-all criteria that ensure that multiple-axis operations will be acceptable. Thus, the final verdict on the suitability of a prototype aircraft design must come from piloted evaluations.

This problem was addressed during the development of the rotorcraft specification, ADS-33E-PRF[26] (described later), by developing a menu of MTEs that precisely defined an evaluation task and the performance standards required. Such MTEs started as a few catch-all tasks, but were found to be extremely useful in simulation evaluations and flight-test assessment. They were expanded and refined and gradually took on a larger role relative to the quantitative criteria. It was soon recognized that a similar set of maneuvers was needed for fixed-wing aircraft. Until recently, flight testing for handling qualities in the fixed-wing community has consisted mostly of open-loop steps and doublets to verify dynamic characteristics against quantitative requirements taken from the military specifications. Typically, if closed-loop flight testing, such as Handling Qualities During Tracking, is conducted, it is introduced to the development process only after the prototype is flying.

Maneuver Set Requirements

The only way to ensure that pilot-in-the-loop testing is 1) performed, 2) performed to a consistent standard of judgment, and 3) required from the beginning is to specify the maneuvers and their definitions before procurement. Any such maneuver set should meet a number of specific requirements that include the following:

1) There must be applicability to specific MTEs. Following the lead of the rotorcraft specification, and using the mission-oriented approach proposed by Mitchell et al.,[41] MTEs that directly reflect the operational missions of current and future aircraft were defined for fixed-wing airplanes. A proposed categorization of these MTEs, divided on the basis of requirements for precision and aggressiveness, was then developed. The ultimate goal is to define a maneuver corresponding to every MTE.

2) There must be ease of flight testing. Some MTEs will be inherently hazardous for a new prototype design; for example, aerial refueling or precision landings will always be approached in a build-up program, rather than attempting such a maneuver early in a flight-test program. Others may be impractical from either a logistics or schedule standpoint. Most maneuvers that fail this requirement fall more into the category of aircraft performance or mission suitability tasks, rather than handling qualities evaluation tasks.

3) The task and constrain performance must be definable. This is simply an adjunct of the preceding objective: Maneuvers that are easily flight tested are those for which the task scenario is repeatable and handling qualities performance limits are definable.

4) There must be coverage of all levels of maneuver amplitude. Most of the handling qualities requirements and tasks in use today emphasize small-amplitude control. This certainly makes sense because problems endemic to modern aircraft will typically be exposed by such tasks. There is, however, a need to assure that the moderate- and large-amplitude characteristics of current and future aircraft are also acceptable. Although there are some such requirements (dealing with, for example, control force per g, time to roll through a specified bank angle, etc.), there is a shortage of tasks that emphasize maneuvering at elevated load factors or that involve load factor capture or large rolling maneuvers. These types of tasks are especially challenging in defining performance criteria that are both meaningful and measurable.

5) Adaptability to all aircraft types, classes, response types, and levels of visual cues must be required. A common criticism of the existing handling qualities requirements is that they have a fighter bias because almost all of the quantitative criteria were developed for, and apply primarily to, high-performance aircraft. There have been steps taken to remedy this situation, including development of pitch attitude and flight-path response requirements for transports.[41,42] The demonstration maneuvers must also reflect all classes of aircraft. In some cases, of course, the specific MTE relates to a specific class of aircraft; for example, tracking a combat maneuvering target would not be expected to apply to transports. On the other hand, some tasks may apply to all classes, including not only landing, but also in-flight refueling as the receiver.

Catalog of Fixed-Wing Aircraft Maneuvers

In June 1995, the military standard for flying qualities of piloted aircraft became a Department of Defense interface standard.[27] This modification to the standard included several recommended maneuvers for the evaluation of handling qualities. These 13 maneuvers represent the first step toward an integrated document, with both quantitative and qualitative requirements, for fixed-wing aircraft. The 13 maneuvers in the notice of change to MIL-STD-1797A were as follows: 1) air-to-air gross acquisition; 2) air-to-ground gross acquisition; 3) air-to-air fine tracking; 4) air-to-ground fine tracking; 5) close formation; 6) aerial refueling, boom tracking; 7) aerial refueling, probe-and-drogue; 8) offset precision landing, approach; 9) offset precision landing, touchdown (conventional aircraft); 10) offset precision landing, touchdown (short takeoff and landing aircraft); 11) offset precision landing, rollout and takeoff roll; 12) takeoff rotation; and 13) takeoff climbout.

The next step in developing a more complete set of demonstration maneuvers was a USAF-sponsored demonstration maneuvers program[43] that resulted in a maneuver catalog.[44] The preceding maneuvers made up the core set of the demonstration maneuvers. Several of them have undergone modification or clarification, whereas others were used essentially intact. A number of the Standard Evaluation Maneuver Set tasks that were developed by McDonnell Douglas for high-angle-of-attack flight evaluations[45] were also included in the final document following a flight-test evaluation using the NASA F/A-18 High Alpha Research Vehicle.[46]

As part of the demonstration maneuvers program, consideration was given to a number of fundamental issues before revising existing maneuvers or defining new ones. The first issue was overshoot requirements. For the maneuvers included in the maneuver catalog,[43] initial overshoot of the target within a specified magnitude limit was permitted. Next, attempts were made to maintain operational relevance whenever possible. Some maneuvers, however, emphasized an isolated vehicle response, whereas others featured tightened performance requirements to better expose deficient handling qualities that may have otherwise been missed. The performance requirements were defined to facilitate use of the Cooper–Harper HQR scale, but not to be rigid pass/fail criteria. Furthermore, the maneuvers that feature continuous closed-loop control were also used to assess PIO tendencies. Finally, the maneuver descriptions do not mandate flight condition or aircraft configuration. It is left to the end user to conduct evaluations with a particular maneuver at all relevant flight conditions and in all relevant aircraft configurations.

The maneuver catalog is designed to be a living document in that revisions and additions are anticipated and desired. For example, the recent work involving the assessment of the ground handling of a U.S. Navy aircraft produced a set of ground handling maneuvers.[47] These maneuvers would enhance the existing catalog by addressing an area that has been largely ignored. Other enhancements may include carrier operations for naval aircraft and for V/STOL operations, as very recent work for the V-22 program[48,49] has demonstrated and as the Joint Strike Fighter (JSF) program moves forward.

Revolution: Rotorcraft Specifications

First Specification: MIL-H-8501

The helicopter handling qualities specification MIL-H-8501A[4] was a 1961 revision of a 1958 document. There was no related report to explain the basis or rationale for the various handling qualities criteria. The primary requirements consisted of limits on simple time-domain parameters such as control stick force and position gradients with speed; frequency and damping of oscillatory modes; normal acceleration response to a step input; and angular displacements in response to control steps that are a function of the helicopter weight. Some distinction was made between day visual flight rules and night instrument flight rules requirements, but flight in low-visibility conditions was not considered.

Several studies were performed to assess the usefulness of MIL-H-8501A. For example, in 1967 Ashkenas and Walton[50] compared the various requirements with analytically derived criteria and any available handling qualities data. Even with linear analysis and sparse data, the study did identify many inconsistencies and shortcomings in the requirements. The requirements did nothing to address the highly coupled mode characteristics that helicopters exhibit, let alone the significant cross couplings and nonlinearities. With the development of MIL-F-8785B[18] in 1969, it became obvious that MIL-H-8501A also lacked many aspects of basic structure, such as systematic treatment of levels of flying qualities, flight envelopes, and reliability.

Despite recognized shortcomings, through the 1970s and 1980s the U.S. Army and Navy continued to base their handling qualities requirements on MIL-H-8501A. For example, the handling qualities portions of the prime item development specifications for the UH-60[51] and AH-64[52] were essentially MIL-H-8501A. Similarly, the U.S. Navy based the handling qualities requirements for the SH-2, SH-60, and CH-53 procurements on MIL-H-8501A.

In 1980, Key performed a review of the MIL-H-8501A shortcomings that had manifested themselves during the UH-60 and AH-64 developments,[53] and in 1982 Goldstein performed a similar review for the SH-60B and CH-53D U.S. Navy helicopters.[54] Both papers showed instances where the requirements were met but the helicopter was deficient, or failed and it was acceptable.

Several attempts were made to update MIL-H-8501A. A notable example resulted in a draft by Pacer Systems in 1972. It contained several new ideas and suggested improvements, but like other attempts was foiled by a lack of systematic data on which to base criteria. A final document was never published.

V/STOL Requirements: MIL-F-83300

Although there was a scarcity of handling qualities data for helicopters, by the late 1960s much work had been performed to understand the handling qualities of a hovering vehicle. Specifically vehicles with modest aerodynamic effects and relatively linear, uncoupled characteristics such as seemed to characterize emerging V/STOL aircraft. The USAF sponsored work to develop a specification for V/STOL aircraft and to include helicopters as far as possible. The result was published as MIL-F-83300[20] in 1970, and a related BIUG was published in 1971.[21]

MIL-F-83300 followed the fixed-wing aircraft specification MIL-F-8785B very closely in format and structure and in the parameters used for many of the requirements. It explicitly addressed hover and low-speed flight up to 35 kn and a forward flight or transition regime between 35 kn and V_{con}. At V_{con}, the requirements were to blend into those of MIL-F-8785B.

This specification was adopted by the USAF for helicopters (though none were ever procured to this standard) as well as V/STOL aircraft. Neither the U.S. Army nor the Navy adopted MIL-F-83300 for helicopters, instead, as noted earlier, they continued to use MIL-H-8501A. In 1972, Green[55] provided a long list of reasons why MIL-F-83300 was not acceptable for helicopters, and this probably had something to do with the decision not to adopt it. In hindsight, the author of this section, who was also a primary author of MIL-F-83300 and ADS-33, believes this was a wise decision. Not only were the helicopter idiosyncrasies of strong inter-axis couplings and significant nonlinearities not adequately addressed, but all of the S&C data available at that time had been generated using typical V/STOL flight tasks, that is, sedate hovering and low-speed maneuvering, or approach and landing. Such tasks were hardly representative of the U.S. Navy's ship landing or Army's nap-of-the-Earth flying, especially in poor visibility. As Cooper and Harper state in their classic report,[5] "handling qualities are those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks require in support of an aircraft role." Hence, data were needed that related to the appropriate task and level of precision.

In the early 1980s the U.S. Navy sponsored some work to revise MIL-F-83300. One result was a report by Hoh and Mitchell,[56] published in 1986. The primary revisions proposed were to replace the time-response metrics for dynamic response with a frequency-response measure (bandwidth) that had been developed to handle V/STOL aircraft with thrust vectoring capability. The Hoh–Mitchell recommendations were never incorporated into a revision of MIL-F-83300. The Navy adopted MIL-H-83300 for V/STOL aircraft and has been using it to guide development of the V-22 tilt rotor, as discussed later in the "Challenges" section.

Current Specification ADS-33

By the mid-1970s, concerned specialists knew that a new helicopter handling qualities specification was needed, but also recognized that the necessary database did not exist. A major thrust to develop such a database was eventually undertaken by the U.S. Army Aeroflightdynamics Directorate with the help of NASA Ames Research Center. The primary tools for handling qualities research are ground-based and in-flight simulators. NASA operated some of the most advanced ground-based simulators, but initially they had significant limitations for helicopters performing tasks representative of Army missions. The most advanced computers lacked the capacity to represent a realistic helicopter model in real time. Visual systems could only provide a low-detail, low-resolution, narrow field of view image of the out-the-window scene, not very representative of flying down amongst the trees. It took many years to overcome most of these limitations. Fortunately the Canadian National Research Council Flight Research Laboratory operated an in-flight simulator in the form of a variable-stability Bell 205[57] and generously collaborated on many investigations such as the multi-axis side stick controller study.[58] The combination of ground-based survey investigations and in-flight validation eventually generated a significant body of data on which quite substantial criteria could be based. In later years the DLR, German Aerospace Research Laboratories added to the team with their variable stability BO 105. To this date the United States does not have an equivalent in-flight simulation capability, and funding to even keep the NASA simulators up to date is in question.

Significant effort to develop criteria and a new specification started in 1982. A version, hurriedly prepared to be available for a pending U.S. Army program to develop a new light scout–attack helicopter (LHX), was adopted by the U.S. Army as ADS-33 in 1985. Revisions to refine and expand the coverage continued into 2000 with the version ADS-33E-PRF.[26] A draft test guide for the specification was produced in 2002.[59] Time lines of various versions and activities are shown in Fig. 4.

ADS-33 not only produced criteria based on a substantial research database, but also introduced several concepts that have

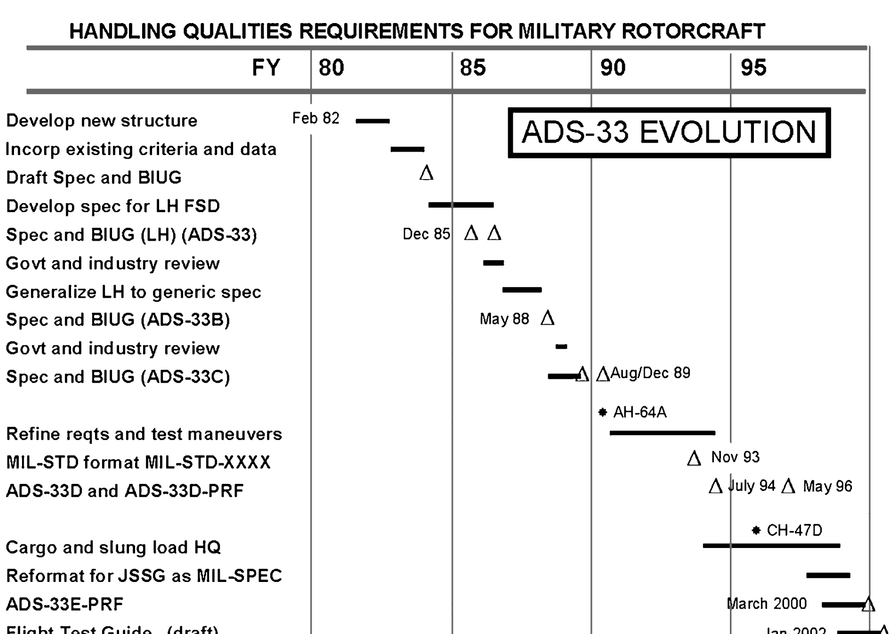


Fig. 4 Timeline for the development of the rotorcraft handling qualities specification ADS-33.

revolutionized the topic of handling qualities specification, design, test and evaluation. Innovations include 1) an empirical method for determining the quality of visual cues actually available in the design when in the operational environment [visual cue rating and usable cue environment (UCE)]; 2) a menu of tasks (MTE) that are appropriate for each helicopter category (scout, attack, utility, cargo, and configurations with external sling loads); 3) a description of each MTE in sufficient detail for it to be used by test pilots in formal evaluations which includes the evaluation task objectives, the required maneuver, an appropriate test course or ground references, and desired and adequate performance standards; 4) stability or stabilization requirements that are graded according to the visual environment that will be encountered (UCE); 5) control and maneuvering requirements that depend on the applicable MTE; 6) new parameters for specifying required short-term response to control (bandwidth); 7) new parameters for specifying required moderate- and large-amplitude control power (attitude quickness); and 8) new parameters for specifying allowable pitch–roll cross coupling during aggressive maneuvers. Descriptions of each of these topics are contained in ADS-33E-PRF.[26] Background data and rationale are given in the BIUG.[25] Clearly space in this paper will not accommodate even a summary of these topics; thus, interested readers should consult the referenced documents.

Some of the revolutionary concepts introduced in the rotorcraft specification have slowly made their way into the fixed-wing and V/STOL worlds. The overall specification format satisfies the 1994 Department of Defense edict that specifications must be "in the form of performance standards and must be tailorable for a specific end item."[60] Another innovation of ADS-33E-PRF was the way in which tailoring was incorporated into the overall structure. This tailoring process and an illustration of how it all fits together in a system development is described next.

Structure of ADS-33E-PRF

The structure of ADS-33E-PRF is indicated in Fig. 5. Tailoring the requirements for application to a specific rotorcraft is performed as follows. The operational missions should have been defined by the user and included in the system specification for the rotorcraft. Knowledge of these operational missions is used as a basis for selecting the applicable MTE from the provided candidates. The system specification should also have defined the desired operational environment, specifically, the visibility and light level and performance capabilities of any pilot's vision aids. Also defined by the user should be the desired extent of instrument meteorological conditions capability, slope landing capability, and the degree of divided attention.

Once the specific helicopter's tailoring items have been determined, selection of the applicable requirements and standards are explicitly prescribed. Procedures are given for determining the UCE using the planned vision aids. Related to the UCE are the required response types that define the amount of stabilization required. ADS-33E-PRF makes a direct connection between the selected MTEs and the required agility. The required agility and required response types together define which boundaries of the handling qualities design criteria apply and which performance standards must be met, thus completing the tailoring.

The next step in using ADS-33E-PRF is to determine how well the rotorcraft design meets the design criteria throughout the operational flight envelope (OFE) and service flight envelope (SFE). How well the helicopter design meets the quantitative criteria may be determined analytically once the basic aerodynamic and flight control characteristics have been estimated. Together they provide a predicted level of handling qualities. Compliance with ADS-33 may, therefore, be evaluated early in the design process.

Once the design process has evolved to piloted simulation or flight, a sample of test pilots can fly the applicable MTEs and provide evaluation comments and handling qualities ratings. The results of these evaluations provide an assigned level of handling qualities.

By the time the rotorcraft is ready for system verification review, the developer should have made analytical and simulation assessments, backed up with flight data. OFE and SFE boundaries should be defined and correlated with the structural and aerodynamic limits. Margins between the OFE and the SFE limits will have been assessed, and appropriate cautions and warnings developed. A failure modes and effects analysis will have been accomplished, and the handling qualities associated with the identified failed states will have been assessed according to the reliability requirements.

ADS-33 was applied to the U.S. Army's LHX design. It provided a valuable basis for handling qualities assessment of the competing designs. During detailed design and development of the winning design, the RAH-66 Comanche, handling qualities specialists found it gave them a level of credibility when making design tradeoffs that would previously have gone unheeded.

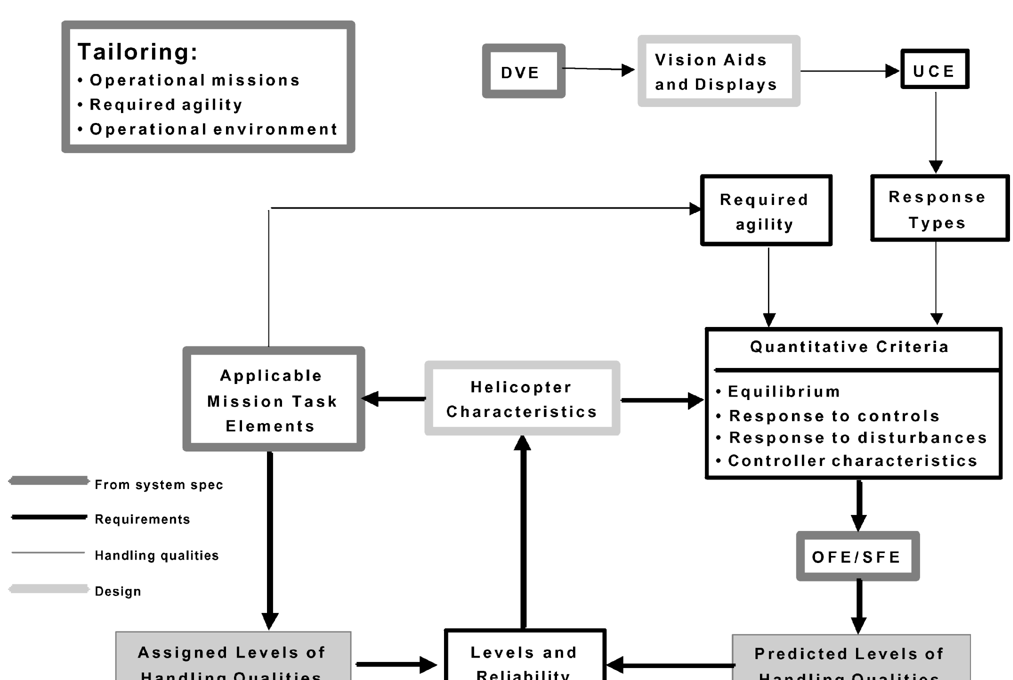


Fig. 5 Structure of ADS-33E-PRF.

Challenges

The preceding sections of this paper have illustrated the evolutionary and revolutionary changes in handling qualities and their specification. There remain challenges to be addressed. In this section, four of those challenges will be discussed. In all cases, the minimum necessary background information is available to understand the challenges, though the database required to turn this information into new criteria (or design guides) may not yet exist. Each of these discussions highlights our current understanding of the issues.

Pilot Modeling for Handling Qualities Applications

Analytical criteria for the specification of handling qualities come in two forms. There are open-loop criteria, such as limits on measured responses or on modes, such as the conventional airplane criteria. Open-loop criteria are based on the expectations and requirements of the pilot in performing closed-loop tasks, but the requirements themselves make no assumptions about pilot control structure. Closed-loop criteria, by contrast, assume pilot feedback structures and, hence, are dependent on the adequacy and accuracy of the pilot model forms. Until the past 20 years or so, closed-loop criteria have been relegated to design guidance only because of the challenges of specifying the pilot models to be used.

Pilot-model-centered handling qualities analysis and design has a number of advantages because effects of variations in pilot compensation can be evaluated over a range of different assumed task bandwidths. Thus, it is possible to determine possible causes of variations in pilot opinion. In addition, the very real problem of identifying the effects of multi-axis control can be addressed most easily by using pilot models. The challenge here is in defining the forms of pilot models to be used for such analysis. The following discusses our current knowledge of this challenge.

Origin of Control Theoretic Pilot Modeling

Numerous mathematical models of human operator behavior have been developed over the past 55 years, starting with the early work of Tustin.[61] Most pilot models used in flying qualities analysis today have been developed to model a pilot engaged in a compensatory tracking task. A compensatory tracking task is one in which the pilot is provided with a display of some tracking error that is to be regulated by the pilot through appropriate stick inputs.

Most pilot models are based on the idea that a pilot's behavior is similar to that of a well-tuned feedback control system, subject to the constraints of the human operator. These constraints account for a pilot's finite reaction time, limitations on limb-manipulator bandwidth and a remnant that includes the effects of divided attention, observation noise, and control input errors. Both classical and optimal control theoretic pilot models have evolved over the years.

Classical Pilot Models and Handling Qualities Prediction

A number of flying qualities prediction techniques that are based on pilot models have been proposed over the past three decades.[32,62–65] A version of the Neal-Smith criteria,[32] developed in 1970, was included in MIL-STD-1797A.[27] The Neal–Smith criteria can provide estimates of pitch-axis flying qualities using results based on an analysis of the closed-loop pilot–vehicle system shown in Fig. 6.

Flying qualities levels are associated with regions in the two-dimensional plane, shown in Fig. 7. Flying qualities estimates are functions of closed-loop resonant peak ($|\theta(j\omega)/\theta_c(j\omega)|_{\max}$dB) and the pilot-model phase angle, exclusive of time delay, evaluated at a frequency representative of the mission task $\angle Y_p(j\omega_{BW})$. The closed-loop resonant peak is used as a frequency-domain measure of performance, whereas the pilot-model phase angle is related to workload.

It is well known that a human operator's perception of workload is influenced by the amount of phase compensation required to attain acceptable levels of performance.[66] The boundaries in Fig. 7 were established by correlating HQRs recorded from flight experiments with closed-loop resonance and pilot phase compensation parameters. These parameters are generated using a pilot model that is

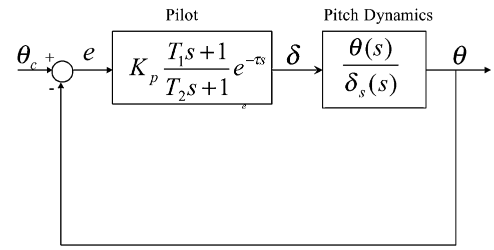


Fig. 6 Closed-loop pilot–vehicle system.

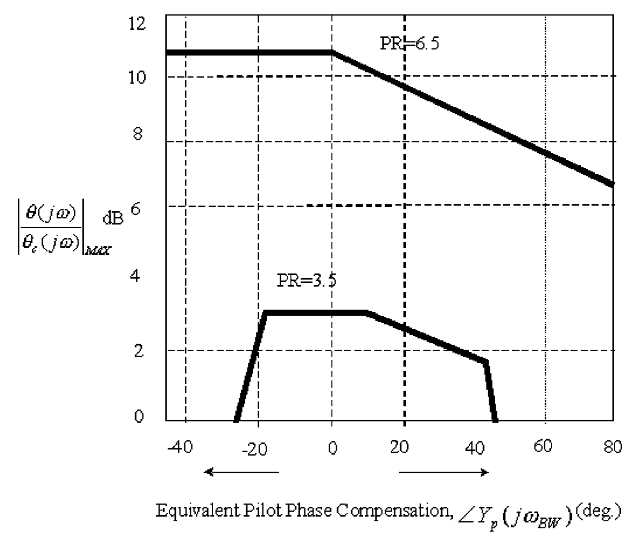


Fig. 7 Neal–Smith criteria.[32]

tuned using a specific set of rules[32] devised by Neal and Smith. The flight-test data used to create the Neal–Smith criteria were gathered from a series of in-flight simulations that used the USAF/Calspan NT-33A vehicle to vary systematically the pitch dynamics of the vehicle for the purpose of gathering HQRs for a wide range of aircraft dynamics.

Handling Qualities Prediction via Optimal Control Pilot Models

The fidelity of the Neal–Smith[32] pilot model is limited because the structure of the model is constrained to that of a gain, a lead-lag filter, and time delay. Although such a model structure can provide good matches to experimentally obtained data in the region of the open-loop pilot–vehicle gain crossover frequency, it fails to capture the characteristic low-frequency phase droop and higher frequency resonant peaks or shelves that are commonly observed in experimental data.[36,67] McRuer et al.[36] demonstrate that a fifth-order pilot model with time delay can provide an excellent match to describing function data for a single-axis compensatory tracking task. Higher-order optimal control models (OCMs) are capable of capturing the salient features of experimental frequency-response data over a wide frequency range.

The original OCM[67] and its many variants[63,64,68–70] assume that the pilot behaves optimally subject to human limitations. The pilot models are computed using results from linear quadratic Gaussian (LQG) control theory. Recent research[69] using a fixed-order modified optimal control model has concluded that a fifth-order pilot-model structure with time delay is the minimum structure that can accurately characterize a pilot's response over a wide frequency range. This research also indicates that frequency-weighted mean-squared tracking error must replace the traditional mean-squared tracking error in the OCM performance index to capture the low-frequency phase droop phenomenon that is frequently observed in experimental data. The frequency weighting reflects that a pilot is less tolerant of long-term tracking errors than short-term errors.

There is also a body of work in the area that has concentrated on using high-fidelity optimal control pilot models to predict handling qualities ratings.[62,64,71] Bacon and Schmidt[62] developed a method of predicting flying qualities levels based on closed-loop resonance and pilot phase compensation parameters generated by a high-fidelity OCM. In Russia, Efremov[63,64] has used a similar OCM-based approach to develop the Moscow Aviation Institute (MAI) criteria. The MAI criteria also use the familiar closed-loop resonant peak for a performance metric and a specially defined pilot phase compensation parameter as a workload metric. The pilot phase compensation is obtained by determining the maximum- and minimum-phase compensation generated by the pilot model. The MAI definition of phase compensation is based on the notion of an optimum controlled element that is a function of the task, that is, input spectrum, and operator time delay. For a given task and operator time delay, there exists a controlled element that requires only gain compensation by the pilot to achieve minimum rms tracking error. Determination of the optimum controlled element is based upon a Wiener approach (see Refs. 63 and 64). Once the optimum controlled element is determined, an OCM analysis is performed. The OCM phase for the optimum controlled element is used as a standard of comparison for all other OCMs for different controlled elements. That is, the maximum- and minimum-phase compensation is defined as the maximum or minimum difference between the OCM phase for a given controlled element and the OCM phase for the optimum controlled element. MAI has shown that the OCM can provide accurate frequency-response descriptions of experimental data and that the OCM-based metrics correlate to HQRs.

In any case, OCM models have much higher fidelity than the simple Neal–Smith pilot model[32] and it has been shown that there exists a strong correlation between the performance and workload parameters generated by these sophisticated models and Cooper–Harper ratings.[5]

Other Uses for Pilot Models

One advantage that OCM methods have over classical methods is that they provide a systematic way to model human operators engaged in multi-axis tracking tasks. This multi-axis modeling capability is inherent in the LQG formulation and can be combined with divided-attention models to predict human operator response in cases where the pilot must maintain precise control of more than one axis, for example, simultaneous pitch and roll tracking.

Control synthesis algorithms have been proposed that make use of optimal pilot models to optimize aircraft handling qualities.[72–74] These techniques make use of empirically derived relationships between observed HQRs and a quadratic performance index that models the pilot's objectives. This performance index includes mean-squared tracking error (tracking performance) and a weighted-mean-squared manipulator rate term (an indication of pilot compensation). These methods are based on the idea that an aircraft control system can be designed by adjusting control system design parameters so that the estimated HQR is minimized. For a given control design, one can close the loop around the augmented aircraft with an optimal control pilot model and compute the cost function as well as a HQR estimate. The control system parameters are then iteratively adjusted until a design results that has optimal flying qualities.

OCMs also have features that allow an analyst to model the interaction between the operator's time delay and phase compensation. The OCM can also account for different levels of physical conditioning or aggressiveness by varying the bandwidth of the pilot's response through selection of a neuromotor lag time constant. The neuromotor lag time constant effectively drives all of the state feedback gains in the OCM so that they are optimal subject to the band-limited nature of the pilot's response. The neuromotor lag, therefore, provides a means of characterizing "high-gain" (high-bandwidth) and "low-gain" (low-bandwidth) pilots. Low values of τ_n correspond to aggressive or high-bandwidth pilot behavior, whereas higher values of τ_n reflect the behavior of low-bandwidth pilots. Pilot reaction time τ_p is another physiological parameter that varies among the population. Pilot time delay has a significant effect on performance and workload. Figure 8 shows OCM-based estimates of closed-loop resonance and pilot phase compensation

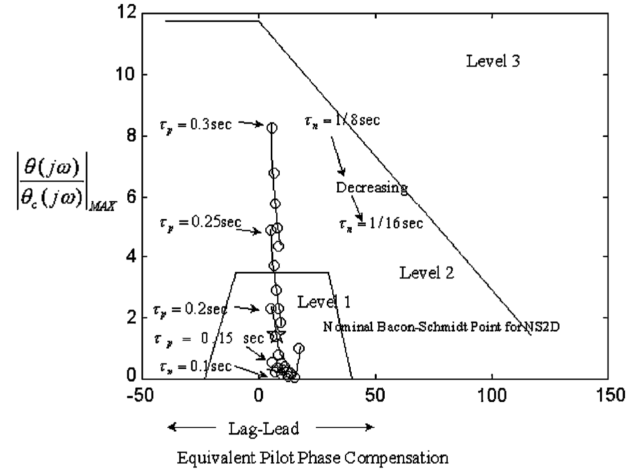


Fig. 8 Sensitivity of estimated pilot ratings to variations in physiological parameters for Neal–Smith[32] criteria of Fig. 7.

for a range of neuromotor lag time constants and time delays for a fixed set of vehicle dynamics.

One can see that optimal-control-based models can provide a means to explore the sensitivity of pilot ratings to variations in physiological parameters. The use of performance and workload metrics from OCMs has also been proposed as a way of resolving conflicts resulting from inter/intrapilot Cooper–Harper rating variability.[71]

Handling Qualities Requirements for Fixed-Winged V/STOLs

Before the development of the rotorcraft handling qualities specifications that resulted in ADS-33E-PRF,[26] considerable work was done to update the variable-configuration V/STOL specification MIL-F-83300.[20] As the rotorcraft work continued, the interest in upgrading MIL-F-83300 waned, and no modifications have been produced since its origination in 1970. That specification is woefully out of date, despite that two ongoing development programs (the V-22 and F-35 JSF) needed such a modern document. The following discussion outlines the challenges of developing V/STOL aircraft with out-of-date specifications and serves to highlight the most obvious shortcomings of a modern V/STOL document.

Unique V/STOL Characteristics

Modern aircraft often take advantage of the benefits of vectored thrust to enhance mission effectiveness. While this enhanced capability increases operational usefulness, it also presents certain design challenges to ensure that the aircraft can safely be piloted with enough precision to accomplish successfully all its primary mission objectives (night operations, over water, with turbulence, carrying an external load, with a fatigued pilot, etc.). At low airspeeds, thrust must be used to provide a combination of lift and control power. As airspeed increases, a logical blending from thrust to aerodynamics is required. The unique characteristics of the powered-lift V/STOL in the regime between thrustborne and wingborne flight require unique handling qualities design methods.

The familiar military specifications address the airplane mode characteristics (MIL-F-8785C) and V/STOL characteristics (MIL-F-83300) with minimal or no attention to the flying qualities requirements for transition or the advantages of operating entire mission scenarios at intermediate thrust vector settings. The modern rotorcraft military specification, ADS-33E-PRF,[26] is a significant improvement requiring quantitative data, qualitative data, and MTE evaluations to demonstrate acceptable aircraft handling qualities. However, this specification does not currently address the capabilities or characteristics of variable thrust vector aircraft.

As such, there is no published set of comprehensive design requirements that specifically address variable thrust vector aircraft mission capabilities or the unique flying qualities characteristics of those aircraft. Individual programs have been left to their own devices to develop a list of flying qualities requirements, scavenging

Table 1 V-22 MTE

Helicopter mode (nacelles 75 deg)	Conversion mode (nacelles < 75 and > 0 deg)	Airplane mode (0-deg nacelles)	Variable nacelles
Precision hover	Short takeoff	Altitude change	Aborted departure
Lateral reposition	Altitude change	Bank angle capture and hold	Run-on landing
Hover pedal turn	Bank angle capture and hold	Formation flight	Level acceleration
Vertical reposition	Formation flight	Aerial refueling	Level deceleration
Vertical takeoff			Formation flight
Vertical landing			
Formation flight			

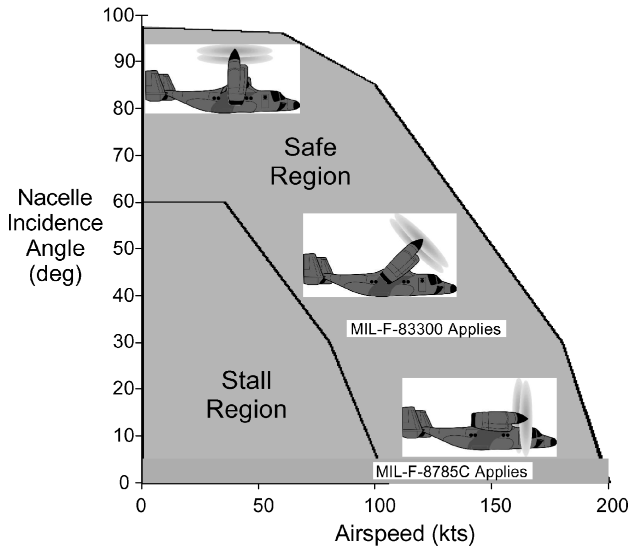


Fig. 9 V-22 military specification applicability.

from old helicopter or airplane specification documents. What falls out is a long list of design goals from multiple military specification documents that must be analyzed to show compliance. Because many of the design goals simply do not apply, numerous design "exceptions" will be required to address the thrust vector characteristics of the aircraft being designed. These exceptions add work to convince the user community that the aircraft provides adequate flying qualities to perform the mission without specifically meeting every line item in the helicopter or airplane specification documents.

V-22 Osprey Example

The V-22 Osprey full scale development program began in the mid-1980s and was aimed at developing a multi-service, all-weather, special operations, amphibious aircraft with vertical/short field takeoff and landing capabilities not available without utilizing thrust vector, or tilt-rotor capability. The applicable military specifications at the time of contract release were MIL-F-83300 for V/STOL operations and MIL-F-8785C for airplane operations.

The V-22 contract specifies that the airplane specification be applied when the thrust vector setting is forward (nacelles at 0 deg) and the V/STOL mode specification elsewhere (nacelles greater than 0 deg), as shown in Fig. 9.

To allow for unique handling qualities characteristics not encompassed by these specifications, however, the aircraft can be considered satisfactory in total if it meets the following flying qualities requirements: Level 1, within OFE and Level 2, within SFE. Level 1 flying qualities are defined in terms of Cooper–Harper pilot ratings between 1 and 3.5 and Level 2 flying qualities between 3.5 and 6.5. However, at its outset the V-22 procurement defined no specific mission relatable tasks. To fill this void, the V-22 program developed a set of MTEs that are used to verify that the aircraft flying qualities are satisfactory in total, and more have been developed to augment the original list[48,49] (Table 1).

MTEs alone, however, do not replace analytical criteria. The MTEs can be applied only after a reasonable simulation model of the aircraft has been assembled, and this can be years after the initial design has been established. Quantitative criteria dealing with closed-loop response, interaxis coupling, control power, and basic stability are needed for powered-lift V/STOLs.

The benefits of vectored thrust are numerous. The military specifications do not address these unique aircraft flying qualities characteristics in a single modern comprehensive document. The military community would benefit if a single military specification were developed to address the unique flying qualities characteristics of vectored thrust aircraft with qualitative, quantitative, and MTE requirements, similar to ADS-33.

PIOs

PIOs (sometimes referred to as pilot-in-the-loop oscillations or pilot-involved oscillations) are a special subset of handling qualities that require special attention. Because "handling qualities" refers to those characteristics of the aircraft that govern its response under continual piloted control, we can consider handling qualities to be important throughout the aircraft's flight. By contrast, PIOs are "rare, unexpected, and unintended excursions in aircraft attitude and flight path caused by anomalous interactions between the aircraft and pilot."[75]

Hopefully, most aircraft go through their entire operational lifetimes without exhibiting a PIO. PIO must be addressed as a unique, but related, subset of HQ. As we have seen in the past decade or so, PIOs occur on a startlingly regular basis, and methods are needed to design for PIO prevention.

A considerable amount of work was performed in the 1990s to develop methods to prevent and predict PIO. Still, it is likely that PIOs will continue to occur. The following summarizes our current knowledge of the phenomenon and its prevention. More work, to expand the knowledge for all forms of nonlinearity, including multiple control effectors with multiple rate and position limits, must be done. The challenge is to take what we know and extend it to what we do not know.

PIO in the Specifications

The military handling qualities specifications have addressed PIO, usually without identifying it as such. PIO can occur as a result of deficiencies in basic handling qualities characteristics, and because the specifications define what is desirable, meeting those specifications provides a first level of protection against the phenomenon. Also, the specifications were considered minimum requirements so that only meeting boundary conditions may need some improvement but can be expected to not lead to PIO. For the flight conditions of the YF-22 crash, every pitch axis metric violated MIL-F-8785C boundaries, even the small-amplitude linear characteristics.[76]

In 1995, the Smith–Geddes[34] criteria were introduced in the fixed-wing standard MIL-STD-1797A[27] to address specifically PIO, though these criteria have not met universal acceptance, as discussed earlier.

For PIOs that result from linear aircraft dynamics, meeting the specifications should reduce the risk. Properly applied, the military specifications are also meant to account for the effects of common nonlinearities by requiring compliance for small and large control inputs. In reality, however, most severe PIOs that have occurred since at least the 1950s have involved some degree of nonlinear response that was neither expected nor accounted for by the military specifications.

Following some highly publicized events with commercial aircraft such as the MD-11,[77] the U.S. FAA became concerned about the occurrence of PIOs in civil transports. Several proposed flight-test methods were drafted and distributed starting in the mid-1990s. The most recent version is included in the FAA's flight-test certification guide.[78] In recent years, more PIOs have been reported in civil aircraft, and as of this writing a working group comprising members of the FAA, Europe's Joint Aviation Authority, and industry is attempting to come to an agreement on a joint plan for testing for PIO. No formal action for developing an FAR dealing with PIO has been announced.

HQ and PIO

PIO occurs when something causes the aircraft response to be 180 deg out-of-phase with the pilot having sufficient command gain to excite the system. It results from inappropriate flight control system (FCS) design, such as excessive filtering or lags, or frequently due to nonlinear events such as saturation of control rate or position limits at too low a command. The nature of most PIOs is such that the airplane, up until the onset of the oscillation, is stable and seemingly well behaved; then encounter with some form of "trigger" leads the pilot into a situation where the closed-loop, pilot–vehicle system is neutrally damped or unstable (Fig. 10).

PIOs have occurred during the development process for almost every new airplane. Frequently the severity of the oscillations is sufficiently low that the PIO is detected, and fixes are applied to the airplane's FCS with little or no public acknowledgment of the event. Occasionally, however, either the severity, the frequency of occurrence, or the consequences of the PIO are such that it becomes headline news, for example, the YF-22 of Fig. 10 event that led to a gear-up landing and subsequent fire.[79]

Despite the ubiquitous nature of PIOs, it is also true that they always come as a surprise to the pilot and to the developers of the airplane. Typically, after a PIO has been encountered in flight, an intense research effort is undertaken to determine the causes of the event and to understand why the tendency to PIO could have gone undiscovered for so long. In the case of the YF-22, among the findings of an accident review board were the need for application of analytical criteria throughout the development process and the requirement for high-gain, closed-loop tracking tasks for evaluation of PIO susceptibility.[76]

In a report for the USAF, Mitchell and Hoh[33] outlined 10 steps for reducing the risk of PIO. The 10 steps are summarized next.

1. Be prepared for PIO. Experience has clearly demonstrated that it is almost impossible to avoid PIO in some form during the development process for any airplane. Given the wide variety of possible conditions, airplane designs, and triggers, it is practically impossible to make an airplane absolutely PIO proof for its entire lifetime. If PIO is possible, the best defense against surprise encounters is to be prepared for the eventuality. This is especially important in a success-oriented development program, where the unexpected occurrence of PIO can threaten to cripple the entire project. Exploration for PIO should become a routine element in all phases of the development of a new aircraft.

2. Design for PIO resistance. This may seem like motherhood: After all, who is going to design for PIO susceptibility? However, the goal is to assure that the aerodynamics, FCS, effector sizes and actuators, and cockpit control inceptors are all specified with the prospects of PIO in mind.

3. Apply valid prediction criteria early in the design process. As soon as the first set of aerodynamic derivatives is estimated, it should be possible to begin to apply criteria. Full application will require knowledge not only of the unaugmented airframe, but also of expected types and levels of augmentation, including, as early in the process as possible, reasonable models of surface actuators and cockpit inceptor dynamics.

Criteria recommended for application are based on pitch attitude and flight-path bandwidth and pitch rate overshoot, using the parameters defined in Figs. 11 and 12. It is preferable that the parameters always be measured with the dynamics of the cockpit control feel system included. Because this is sometimes impractical, such as during preliminary design, where the cockpit configuration has not been fully defined, the parameters may also be measured with the feel system excluded, though a different set of limits must then be applied.[33]

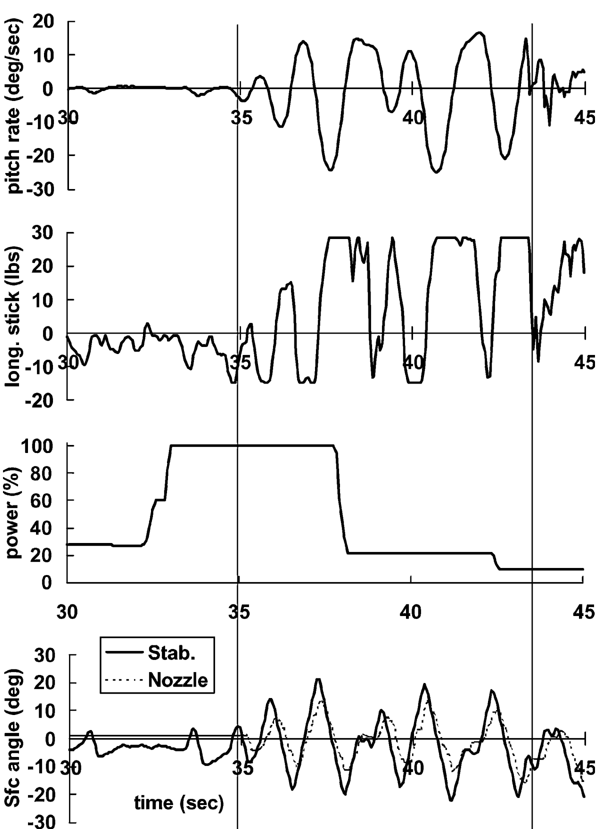


Fig. 10 Time history of the YF-22 PIO.

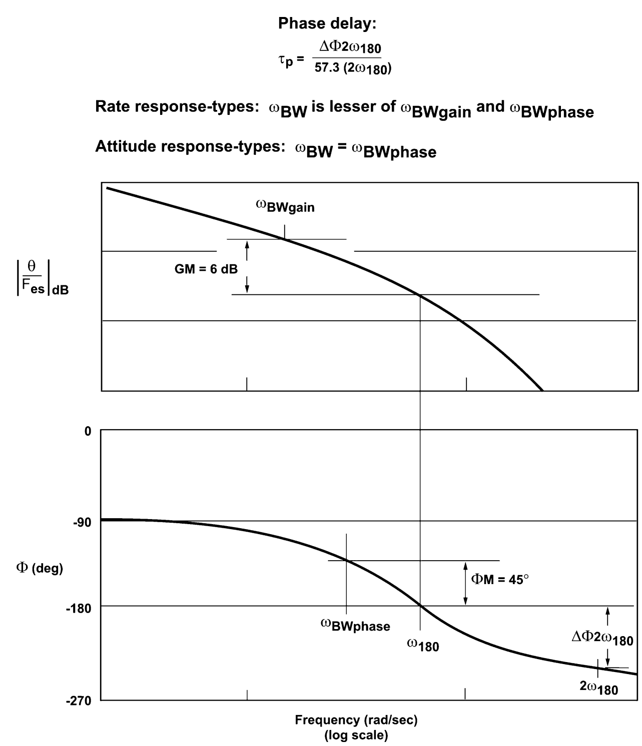


Fig. 11 Definitions of pitch attitude bandwidth and phase delay[33] (flight-path bandwidth ω_{BW_γ} is measured from γ/F_{es} and is defined as $\omega_{BW_{phase}}$).

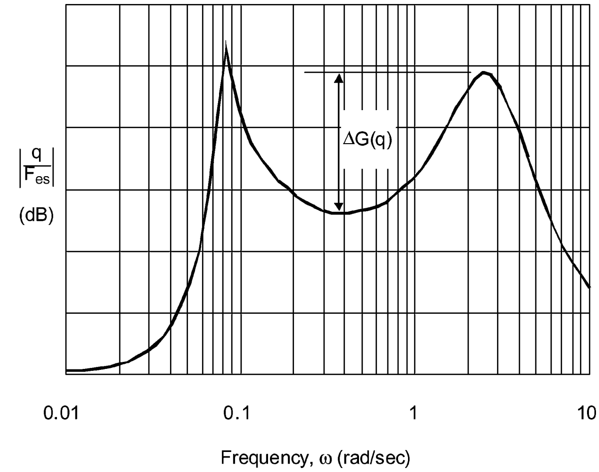


Fig. 12 Definition of pitch rate overshoot parameter $\Delta G(q)$.

The core of the criteria is a crossplot of angular attitude bandwidth frequency vs phase delay. Bandwidth measures the basic stability of the airplane and determines the frequency range over which piloted control is possible with a minimum of pilot equalization. Phase delay measures the high-frequency phase loss if the pilot operates at high frequencies.

For the pitch requirements, there are regions where PIO is unlikely on the basis of the attitude bandwidth characteristics alone. In some instances high pitch-rate overshoot is a contributor, and limits are placed on the frequency-domain-based metric $\Delta G(q)$ (Fig. 12). In others, inadequate flight-path control is the culprit, so that limits are placed on flight-path bandwidth frequency ω_{BW_γ}.

Requirements on pitch attitude bandwidth vs phase delay are presented in Fig. 13 (feel system included in the aircraft model). (The lines dividing PIO boundaries in Figs. 13 are intentionally very wide. There is no clear division between no-PIO and PIO, and we want to emphasize this fact.) Similar pitch requirements when the cockpit control feel system is not known, and for roll PIO, have been developed.[33]

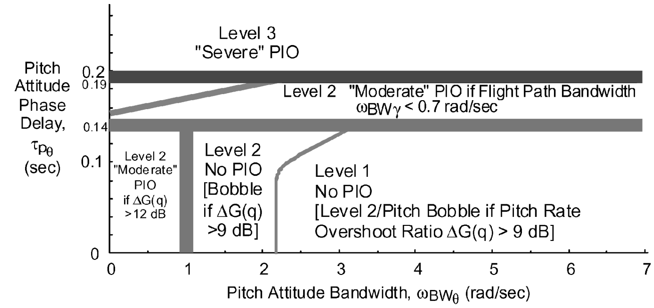
4. Continue to apply criteria as the accuracy of the model improves. There will be a natural increase in sophistication for the aerodynamics and control system models; there should be a system in place for immediate application of the PIO prevention criteria every time a certain milestone is met.

5. Use high-gain maneuvers to evaluate PIO tendency in piloted simulations. If ground-based simulation is used to evaluate the new vehicle's characteristics, a minimum set of pilot-in-the-loop, high-gain maneuvers must be evaluated. At this stage, any warnings of PIO tendency by any pilot should be investigated.

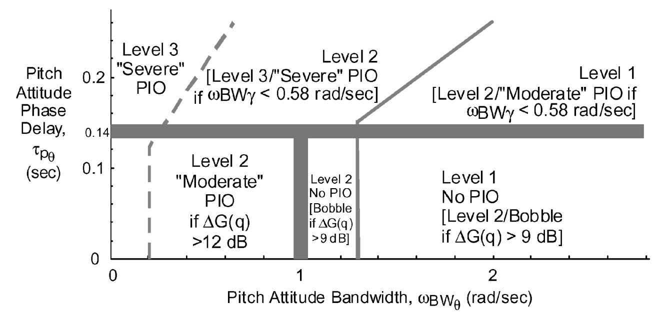
There is always an initial reluctance to fly certain maneuvers because they are not operationally relevant, or because no experienced, trained pilot would ever do that in the air. It must be stressed that PIOs are also not operationally relevant, and unusually high-gain or large-amplitude tasks are used in simulations because it is simply not possible to replicate every possible scenario for PIO. Tasks should include, but not be limited to, attitude captures, precision landings, aerial refueling (or close-formation flight), and command tracking. Pilots should always be aware of the potential for PIO when any task is flown, even if it is not intended to look specifically for PIO. Engineers and pilots must work together in simulations, because it is possible that PIOs can go undetected by the pilot.

6. Apply PIO detection and prevention devices during developmental flight testing. As with simulation, flight testing must include maneuvers intended specifically to look for PIO. In addition, reliable real-time PIO detection devices, either onboard or operated remotely via telemetry, will help monitor the occurrence of PIOs. Such devices may include active intervention to prevent or recover from PIOs.

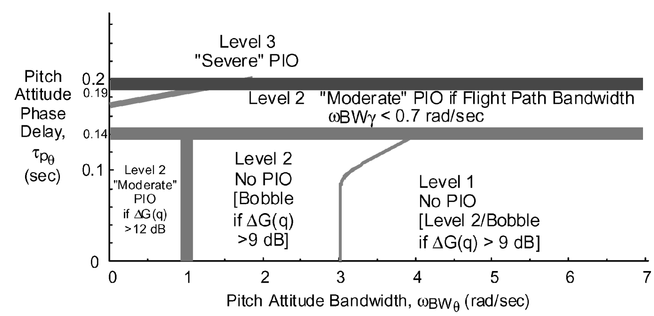
7. Extend test inputs and application of criteria to large input amplitudes. The fundamental theory behind bandwidth is that it is a



a) Fighters, landing



b) Transports, landing



c) All classes, pitch tracking

Fig. 13 PIO criteria for pitch response[33] (dynamics of the cockpit control feel system included).

measure of piloted closed-loop activity and, hence, is most effective for describing small-amplitude control inputs. There is a natural reduction in bandwidth for any physical system as input amplitude increases beyond a certain value, resulting from limitations of the airplane, limiting on actuator rates and positions, etc. Still, experience has shown that the bandwidth criteria defined earlier are very effective at predicting PIO susceptibility for quite large inputs.[80] If any of the PIO-susceptible regions is reached for a reasonable input size, PIO is likely. Frequency sweeping should emphasize input amplitudes that result in aircraft responses at and above the bandwidth frequency that approach the operational limits for the aircraft. The data obtained in such sweeps will both enhance the fidelity of simulation models and help prevent large-amplitude PIOs.

8. Update ground simulation models with flight data. This is a step that is always desired in a developmental program, but experience has shown that it is not always done, or at least not in a timely manner. It should be possible to continue to make use of ground simulation to search for PIO, but the simulator is only as good as the model. A regular process must be implemented to keep the simulation model as up to date as possible, and regular sessions should be scheduled to look for PIO tendencies with the updated model.

9. Include PIO recognition as a part of the training syllabus for pilots. Whether the aircraft is commercial or military, there is always a potential for the occurrence of PIO in follow-on flight testing or operational use. This may be as a result of a design flaw, an excursion into untested flight conditions or loadings, or following a failure. It is not likely that the typical fleet pilot will encounter

Table 2 Examples of lowest structural vibration frequencies

Aircraft	Frequency, rad/s
B-1	13
Concorde	13+
C-5A	11
National Aerospace Plane	~18
SCR designs	~ 6.5

PIO very often and, perhaps, never. Pilots who are aware of the characteristics of PIO, however, are much more prepared for dealing with the event and for accurately reporting it to cognizant agencies.

10. Be prepared for PIO. See step 1. If there is one overwhelming recommendation that can be made, it is that all parties involved in the development of a new aircraft must always be prepared for the occurrence of PIO. It should not come as a complete surprise.

Structural Interactions

The effects of flexibility on the flight dynamics of aircraft have been shown to be quite significant, especially as the frequencies of the elastic modes become lower and approach those of the rigid-body modes. The handling characteristics of such vehicles are altered significantly from those of a rigid vehicle,[81] and the design of the FCS may become drastically more complex.[82,83]

Shown in Table 2, for example, are the lowest frequencies of the structural vibration modes for several flight vehicles. These data show that these frequencies can be lower than 3 Hz, and in some advanced supersonic–transport configurations [supersonic cruise research (SCR) in Table 2] the frequencies are as low as 1 Hz. Some are well within the bandwidth of the pilot and primary FCS, and others may certainly be excited by turbulence.

In this discussion, results from two simulations will be presented, involving two similar aircraft. (A more detailed description can be found in Ref. 84.) The simulations were performed in NASA Langley Research Center's Visual-Motion Simulator[85] facility. The results from these studies demonstrate a phenomenon known as biodynamic coupling and feedthrough, which lead to significantly degraded handling characteristics. Also it will be demonstrated that this phenomenon is directly related to the vehicle's elastic effects. That is, if the vehicle were more rigid, the phenomenon would not be present.

For the first study, a model of a large, swept-wing, high-speed aircraft with a conventional empennage was used. The pitch-rate-to-elevator frequency responses (radian per second per degree) for the elastic- and (two similar) rigid-vehicle models are shown in Fig. 14. The short-period modal frequency near 2 rad/s, and the first aeroelastic modal frequency near 2 Hz, are evident. This simulation used a precision-tracking task, with artificially generated commands displayed on a heads-up display. One of the important experimental variables was the in-vacuo vibration frequency of the first symmetric fuselage mode ω_1, a parameter in the dynamic model. Of interest was the effect of this modal frequency on the handling characteristics, with everything else (task and all other parameters in the dynamic model) held constant.

The results from the first experiment are presented in Fig. 15, in which the degradation in handling qualities as only the first elastic modal frequency is reduced is clearly evident. The handling qualities of the vehicle if it was purely rigid (all elastic deformations held at zero in the simulation) were rated Level 1, whereas the handling characteristics of the baseline vehicle (with lowest frequency of 2 Hz) were given an average HQR of about 4.5, or Level 2. Finally, the handling characteristics degraded to Level 3, or an average HQR of around 7, when the lowest elastic mode frequency was reduced to 1.4 Hz.

Drawing from the earlier study, a second dynamic-aeroelastic simulation was performed in NASA Langley Research Center's Visual-Motion Simulator.[85] The vehicle in this case was an even larger high-speed aircraft, with weight at the study flight condition around 300,000 lb and a length of over 250 ft. The wing was a double delta, and the lowest vibration frequencies were around 1 Hz. The three lowest-frequency modes in each axis were modeled for a total of six elastic modes.

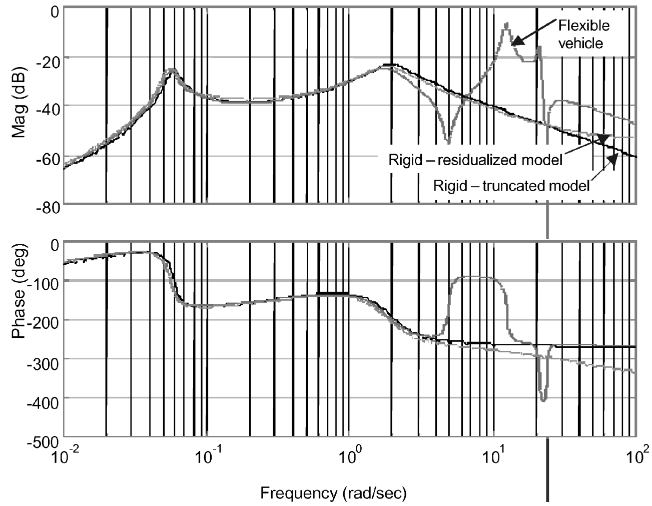


Fig. 14 Pitch rate to elevator frequency responses, flexible and rigid models.

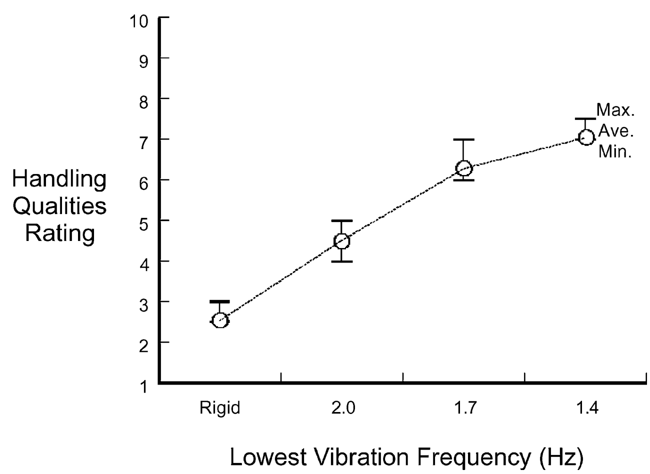


Fig. 15 Effect of increased flexibility on HQR.

Six test pilots were asked to compare maneuvers performed with and without aeroservoelastic dynamic effects (ASE) present in the real-time simulation model. The pilots' HQRs for a lateral-offset landing maneuver are shown in Fig. 16. The offset landing task is a challenging maneuver that requires the pilot to correct aggressively for a 300-ft lateral offset from the runway centerline at an altitude of 250 ft. Results indicate that the presence of dynamic aeroelastic effects in the simulation model greatly degraded the aircraft handling qualities, particularly in the lateral axis in this task. In some cases lateral/directional HQRs degraded from Level 1 to Level 3 as a result of the aeroelastic effects.

Pilot comments indicated that cockpit vibrations due to aeroelasticity degraded the ratings for at least two subtly different reasons. The first is that the vibration environment simply had a negative impact on the comfort level or ride qualities at the pilot station. Therefore, pilots increased their ratings because the extreme vibrations tended to increase their perception of workload.

Pilots also remarked that cockpit vibrations tended to influence the precision of their control inputs. Some pilots indicated that the vibrations actually resulted in involuntary control inputs. This aeroelastic effect is referred to as biodynamic feedthrough.[86] In some cases, the combination of the aeroelastic aircraft, the control stick, and the pilot's biomechanical dynamics may result in a closed-loop system that is unstable or lightly damped. In such instances, cockpit

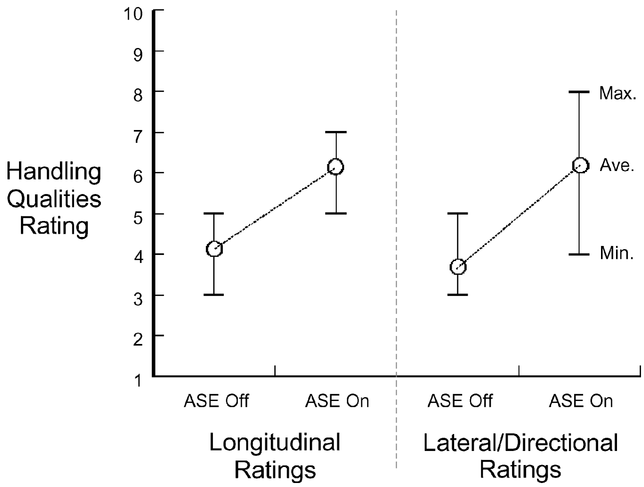


Fig. 16 Effect of presence of ASE modes on HQRs for an advanced transport (NASA Langley Research Center simulation).

vibrations may cause resonance of the pilot's biodynamic frame, resulting in sustained feedthrough of aeroelastic vibrations back into the control stick, a condition that is referred to as biodynamic coupling. An analytical model of a similar coupling phenomenon was presented by Smith and Montgomery,[87] based on the analysis of flight data. The phenomenon is evidenced by a resonant peak in the power spectrum of the pilot's stick inputs at the frequency of one or more of the dynamic elastic modes. The tendency to couple with structural modes appears to increase when pilots tighten their grip on the stick, often in preparation for the flare as the aircraft nears the runway. The phenomenon is influenced by design of the control inceptor and control laws, piloting style, and probably even various aspects of the pilot's physical stature. These results highlight the importance of modeling and simulation of aeroelastic effects when assessing the flying qualities of large flexible aircraft.

Conclusions

The evolutionary and revolutionary changes to handling qualities that have occurred in the past 10 years have not lessened their importance. Despite the increasing focus on unpiloted aircraft, there will be, for the foreseeable future at least, a requirement to design and verify the existence of desirable handling qualities in piloted aircraft.

The familiar handling qualities document for fixed-wing airplanes, MIL-STD-1797A, has been relegated to handbook status, but it remains an excellent design guide. The V/STOL document, MIL-F-83300, has not been updated since its release over 30 years ago and is sorely out of date. Still, it, too, should be considered a reference source for V/STOL aircraft. The triservice rotorcraft specification, MIL-H-8501A, is retired and, for the U.S. Army at least, replaced by the ADS-33E-PRF. The latter serves as the most modern, thorough handling qualities specification.

Though most of the documents are retired, their goals should not be ignored: to provide satisfactory handling qualities for any type of air vehicle. Proper application of criteria requires an understanding of the field of handling qualities, and it is a mistake to assume that the field has outpaced our knowledge base and the associated criteria. The specifications and associated handbooks make valuable reference documents.

A number of significant challenges have been identified in this paper.

1) With no contractual obligation to comply with the specifications, the handling qualities engineer will find it more difficult than ever to convince program management when changes in aircraft design to improve handling qualities are justified, or alternatively to oppose other changes that are degrading the handling qualities.

2) Application of the intent of the specifications with no contractual obligation to conform to the detailed requirements calls for greater understanding of the criteria.

3) The expert must be well versed in pilot modeling and the interactions between pilot and aircraft. Effects of multi-axis control must be fully understood and quantified.

4) Work needs to be done to provide more updated guidance to designers of fixed-wing V/STOL aircraft.

5) PIO continue to occur and likely will always occur, and so methods for their prediction and suppression must be refined.

6) The impact of flexible modes on handling qualities, especially as transport aircraft continue to grow in size, must be thoroughly understood and quantified.

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