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HANDLING QUALITIES REQUIREMENTS FOR CONTROL CONFIGURED VEHICLES

R. J. Woodcock and F. L. George
Air Force Flight Dynamics Laboratory

SUMMARY

The rapid emergence of fly-by-wire and control-configured vehicle concepts challenges us to account adequately for their potential effects on flying qualities. Failure mode probabilities and consequences must be considered. Adequate controllability must be provided for aerodynamically unstable aircraft at extreme flight conditions. Nonclassical overall dynamics of highly augmented aircraft create the need for new approaches to specifying design criteria. New control modes such as direct force require definition of boundaries for usefulness as well as desirability. These considerations are being incorporated in the continuing effort at the AF Flight Dynamics Laboratory to review and revise the formal military flying qualities requirements. This paper will review the rationale and present current results addressing the above considerations with regard to Military Specification MIL-F-8785B, "Flying Qualities of Piloted Airplanes".

INTRODUCTION

Recently we were asked to clear for flight testing an airplane which, without added ballast, was predicted to be somewhat unstable if the stability augmentation system (SAS) should fail. Considering the expected degree of inaccuracy in aerodynamic and reliability predictions, we recommended putting the center of gravity somewhat forward of the SAS-off maneuver point--where stick force and deflection per g go to zero. Contrary to the MIL-F-8785B requirement, we did not feel compelled to insist on a c.g. location that would assure static speed stability.

"What?", our Laboratory Deputy Director asked. "Here we've put so much of our resources into developing control-configured vehicles to tolerate relaxed static stability, and now you tell me all that refinement isn't necessary--you say a plain unaugmented airplane can fly that way safely. Have we wasted all that time and money?"

Well, there is more to CCV than that in several dimensions, including the degree of allowable bare-airframe instability. But he had made a valid point one that has bothered some of us all along. We know through observation that pilots can control a moderately unstable vehicle in the right circumstances. Haven't helicopters been flying for a long time--and unstable airplanes too! Quoting Amos Root's observations of the Wright brothers' experiments at the

Huffman Prairie in the summer of 1904[1],

> "When I first saw the apparatus it persisted in going up and down like the waves of the sea. Sometimes it would dig its nose into the dirt, almost in spite of the engineer. After repeated experiments it was finally cured of its foolish tricks, and was made to go like a steady old horse. This work, mind you, was all new. Nobody living could give them any advice. It was like exploring a new and unknown domain. Shall I tell you how they cured it of bobbing up and down? Simply by loading its nose or front steering-apparatus with cast iron. In my ignorance I thought the engine was not large enough; but when fifty pounds of iron was fastened to its 'nose' (as I will persist in calling it), it came down a tolerably straight line and carried the burden with ease. There was a reason for this that I cannot explain here... Over one hundred flights have been made during the past summer. Some of them reached perhaps 50 or 60 feet above the ground. On both these long trips seventy pounds instead of fifty of cast iron was carried on the 'nose'."

Or read Maj. Gen. Benjamin D. Foulois' account[2] of his experience at Ft. Sam Houston in 1910 as the U.S. Army's airplane pilot:

> "We wanted to develop the airplane into a stable platform for air reconnaissance work. Old Number One was the last of the Kitty Hawk models, and with its two elevators out in front it was about as stable as a bucking bronco. We continued experimenting there while the Wright brothers made modifications back at Dayton, Ohio. When one of the elevators up front was moved around to the back, stability improved somewhat but not enough. I later found out that by using just one elevator, the rear one, I had a platform that worked very well. I could let go of the levers and make notes and sketches. It got to be an airplane that could be used for real military reconnaissance."

Charles Gibbs-Smith writes[3]

> "So when the Wrights built their first glider in 1900 it incorporated two ideas which the brothers were to utilise throughout their early work--the intentionally unstable aeroplane which could be kept flying satisfactorily only by the pilot's skill, and the warping of the wings for control in roll. 'We therefore resolved', wrote Wilbur, 'to try a fundamentally different principle. We would arrange the machine so that it would not tend to right itself.'"

This was truly instability, as we have seen from the preceding accounts. It was exactly that concept of instability--to a manageable degree--that led Lilienthal, Chanute and the Wrights to succeed where the "chauffeurs" of highly stable airplanes could not achieve controlled flight. But the early fliers had a rather high accident rate which must be attributed in part to the vehicle's instability. Our tolerance today may be less, even for emergencies, considering the higher speeds and poor weather to which our flying now is subject.

Even the Wrights soon recognized the need for improvement. In addition to ballasting for a forward c.g. and moving the canard surface to the tail in order to move the neutral stability point aft, they also investigated automatic means[4]. It is interesting to note that their Patent No. 2913 for automatic stabilization preceded Gen. Foulois' rearranging the control surfaces with the Wrights' help. For pitch, "a pivoted vane acting under the influence of wind pressure" sensed angle of attack to control a supply of compressed air which actuated the elevator. A pendulum was specified "for lateral control". Operation of these devices would not move the pilot's control levers. In 1914 Orville Wright was awarded the Collier Trophy for his work on automatic stabilization.

BACKGROUND OF CURRENT ACTIVITY

Why, then, have we been less willing in recent times to accept instability, even for emergencies? A number of reasons, each with some degree of validity, have led to this conservatism:

> Until recent times the failure rates of stability augmentation equipment gave the expectation of frequently experiencing the basic-airframe characteristics. Greater redundancy was not attractive because of the increased cost and the maintenance burden to keep it all operating.
>
> Little is yet known about the cumulative effects of several poor flying qualities together, except that an aircraft that is safe with any one "unacceptable" quality can become unflyable with some combinations of these characteristics. Further, a number of plausible single and multiple failures can degrade several handling qualities. Loss of just the pitch axis of augmentation, for example, could degrade damping, frequency, maneuvering force gradients, friction and backlash. A pilot-induced-oscillation could not be stopped by clamping the control stick if $d\,\delta_e/d\,n_z$ is unstable.
>
> Viable designs have generally been possible with basically stable airframes--at least for conventional airplanes.
>
> Little experience has been obtained to define instability boundaries suitable for the speeds, tasks, and weather that are now commonly encountered in operating aircraft.

> From the data collected for MIL-F-8785B[5] the tolerable amount of instability is a function of total damping; the data are insufficient, however, to draw a valid requirement. "After studying the available data, it is obvious that many factors influence the amount of instability which can be handled. Because even a small instability can be quite dangerous under some circumstances, it was decided to require the airplane to be statically stable even for Level 3."

We need to reexamine these conservative requirements in order to provide more guidance on the circumstances and amounts in which instability is safe. We solicit the opinions of those present.

MIL-F-8785B AND CCV'S

In developing MIL-F-8785B we gave much thought to the conditions for allowing degraded flying qualities. We wanted to account as much as possible for real-world problems without overly complicating the requirements. Two causes of degradation were considered. Flying qualities giving less performance or requiring more pilot attention are allowed outside the military-specified Operational Flight Envelopes. This allows some capability for adapting to changes in mission without unduly penalizing a design for having a larger flight envelope than required. After relatively infrequent failures (nominally once per hundred flights) this same level of degradation, Level 2, is allowed in the Operational Flight Envelope, and further degradation is allowed outside those boundaries. Only rarely (once in 10,000 flights) is degradation beyond Level 2 allowed in the Operational Flight Envelope. In any case Level 3 is a relatively safe floor. Degradation beyond Level 3 requires special consideration on a case-by-case basis, thus in principle giving the procuring activity the power of decision. The Special Failure States which are subject to this approval are of several categories. In some cases other specifications or design practices give acceptable assurance: the basic aircraft structure is a common reliability standard. In other cases judgment must be used to establish a point of diminishing returns: two, or three or four hydraulic systems are used to power essential flight controls, for example. There also will be cases in which failure is expected to be extremely remote in probability, but the cost of a change or addition to preclude the failure or limit its effect is small enough to warrant disapproval of a Special Failure State. In still other cases approval may be granted if special design or test requirements are met.

Despite an occasional opinion to the contrary, MIL-F-8785B does apply to CCV's - as far as the specification goes. Although the 8785B treatment of response to atmospheric disturbances is weak in general, clearly the requirements and the Level structure apply to conventional stability and control augmentation. The Special Failure States provide a mechanism "to assure that the flight safety, flying qualities and reliability aspects of dependence on stability augmentation and other forms of system complication will be considered fully". The limitations for CCV application are a lack of requirements on direct force control, and the expression of many requirements in terms of classical modal parameters. I would like to evoke discussion of these matters now, at this meeting.

Thrust/speed brake requirements were considered but omitted as beyond the scope of the specification. We are having second thoughts on that now, and will try to arrange with the propulsion people for adequate coverage somehow between the two disciplines. A lack of experience with direct lift or side-force controllers still precludes definitive requirements for those control modes--despite the Japanese' successful use of an automatic maneuvering flap in air combat in 1943; on the outstanding Kawanishi Shiden (George) fighter.[6]

THE FORM OF DYNAMIC REQUIREMENTS

Reference to short-period, dutch-roll, etc. modes is not as much a hindrance to CCV application as one might first suspect. The idea, of course, is to state the requirements in a form we are familiar with, in terms consistent with the aircraft characteristics that form the data base. Conventional stability augmentation modifies the parameters but not the form of the response. Recent flight control system designs, however, show a tendency to introduce additional dynamic modes at frequencies on the order of the aircraft response frequencies, giving rise to overall motions unlike the conventional response. A'Harrah[7], for one, has pointed out the difficulty in associating short-period requirements with a particular pair of poles on a root locus. Nevertheless it is often possible to find an equivalent classical aircraft which matches the response of a more complicated dynamic system reasonably well over a suitable time period or frequency range. Then it should be valid to compare those equivalent parameters with modal requirements. We realize the need for a more generally applicable alternative and hope to do better, at least with longitudinal requirements, in our current revision effort.

Alternative longitudinal requirements are being investigated which should be more generally applicable, but at first these will seem to be of less direct use to the airframe designer. One possibility is Neal and Smith's[8] closed-loop criteria which utilize pilot-vehicle analysis with a specified pilot describing function and parameter adjustment rules. Other possibilities, semi-empirical in origin, involve properties of the open-loop Bode phase angle vs frequency curve. Ideally a requirement should apply to all of:

> The complete airplane attitude response including all pertinent modes (e.g., both phugoid and short period)
>
> The airplane plus flight control system (i.e., including lags and time delays)
>
> The various control element forms resulting from current flight control augmentation concepts

The basic inner attitude response features which are necessary regardless of outer-loop control problems or auxiliary control (e.g., direct lift)

Variations in pilot control technique (e.g., closed-loop bandwidth) with control task or flight phase.

(adapted from Ref. 9).

CURRENT ACTIVITY REGARDING LONGITUDINAL REQUIREMENTS

We are also examining "envelope" criteria in the time and frequency domains--for example Malcom and Tobie's C*[10] and the McDonnell Aircraft refinement.[11] C* is a rational parameter to investigate and the envelopes facilitate design. While the specific criteria which have been developed may work for the particular configurations investigated, they seem to lack validity in general application. The refined C* and $\dot{C}$* criteria do not seem to match the time-history ratings of Ref. 8 Vol. II much better than the original C* criteria do. However, as reference 12 points out, it is not realistic to expect any single criterion to encompass all potential faults, especially for high-order or multi-mode systems.

Since the publication of MIL-F-8785B in 1969, a number of research contracts have been sponsored by the AF Flight Dynamics Lab both to generate data and to develop new requirements that encompass new technology. Among the proposed requirements currently being reviewed are the Calspan proposed longitudinal maneuvering criteria in reference 13. Longitudinal attitude and normal acceleration control is related to frequency response characteristics, considering desirable pilot compensation needs. An attractive feature is elimination of the need to identify short period frequency and damping - a real advantage for highly augmented airplanes. However, measurement of a slope and phase angle from the pitch frequency response amplitude versus phase angle plot is required. This does necessitate knowledge of the aircraft/flight control system longitudinal frequency response function. The practicality of identification with currently available computer algorithms and flight test data commonly recorded is being evaluated. Also being investigated is the practicality of generating an equivalent transfer function which would allow presentation of requirements in terms of "equivalent" parameters or, perhaps, required pilot compensation parameters. This concept of incorporating pilot workload and transfer functions relates requirements more directly to the designer; but the difficulty of accurately fitting an arbitrary frequency response curve with a specified transfer function form is significant.

A recent experimental program[14] studied the task dependence of requirements such as those described above. Using the AF variable stability T-33, variations in pilot rating were shown for some high-order configurations as a function of evaluation task. The configurations most affected by task variation all exhibited relatively high dominant natural frequencies. In evaluating the Calspan proposed requirements, Mayhew[15] illustrated the influence of closed-loop bandwidth on Neal and Smith's flying qualities parameters. He has also shown the relationship between the proposed requirements and the current familiar short period criteria. While the Calspan proposal includes some provision for bandwidth variation, further evaluation will determine if additional provision is required.

A different approach to flying qualities criteria, amenable to use in the design phase, is based on the "paper pilot" concept first proposed by Anderson[16]. Reference 12 developed a computerized method of handling qualities analysis based on this idea which showed relatively good correlation for "conventional" airplanes - but less successful for designs representative of CCV technology. However, this result is not conclusive because the empirical nature of the criteria involved require a good data base for validation. Such a basis does not exist for CCV airplanes. Hence, the general approach does warrant further study for future application.

CURRENT ACTIVITY REGARDING LATERAL-DIRECTIONAL REQUIREMENTS

The present lateral-directional dynamic requirements are intended to minimize undesirable yaw due to roll, and dutch-roll excitation. These goals may be satisfied by the basic airplane design or by incorporating augmentation (with proper attention to reliability). Consequently, these requirements are consistent to a high degree with CCV design approaches. Specification of response characteristics such as p_{osc}/p_{av} is consistent with the philosophy being explored for the longitudinal requirements, though modal items are not.

Reference 9 has proposed a new requirement for heading control which is intended to address the problem of adverse yaw more directly. The approach is to evaluate the roll-yaw control coordination required in a turn against a desirable standard for a coordinated turn. Obviously this criterion could be applied to design of a CCV system as well as evaluation of conventional airplanes. General applicability of this criterion (or some variation thereof) to CCV designs incorporating different control modes to achieve heading control remains to be investigated, although reference 9 indicates the criterion is insensitive to airplane class or type. Also, as with the proposed longitudinal requirements, the practicality of measuring or identifying the response characteristics needed remains to be established.

Direct side force control is frequently mentioned in conjunction with CCV and as noted previously is an area where definitive flying qualities data are scarce. Before such data can be generated, a complete understanding of the way pilots employ direct side force in various tasks (Flight Phases) must be developed. For example, they may in some cases employ side force to perform either a flat turn or side slip in tracking. Another application could be to trim out a crosswind effect. Also, the effect of interaction with other controls and with other subsystems such as displays must be explored. Recent efforts at AFFDL have looked at the weapon delivery task[17] and STOL landing[18]. Additional work currently underway will hopefully bring us to the point of developing some new requirements.

Display interaction and cockpit controller characteristics in general require further study before definitive requirements can be developed to encompass some aspects of CCV technology. In some cases, it is simply a matter of generating data. For example, pilot rating and performance data are necessary to develop quantitative requirements on force levels and gradients (including nonlinearities) for sidesticks. Display interaction must be considered when evaluating flying qualities as a function of task and also as a function of control mode. For example, the evaluation of direct side force control for weapon delivery mentioned above considered only fixed gunsights. To complete the evaluation it will be necessary to consider the effect of active gunsights on the pilot's use of direct side foce.

LIMITING FACTORS

In concluding, then, we reiterate that in many respects the current flying qualities requirements are compatible with CCV technology. In some areas, new requirements or expansion of old ones is needed. In these areas, where new requirements are being formulated, we are certainly considering CCV and where necessary attempting to gather new data. The following basic flying qualities considerations, however, might be termed as limitations on the general application of CCV technology.

How much static instability can be tolerated safely? An absolute bound is apparent from "critical task" studies[19], which show that divergence of a simple system is controllable if its time to double amplitude is within certain bounds, depending upon pilot workload. Boeing SST simulations[20] found a criterion of $T_2 \geq 6$ sec to set the safe aft c.g. limit. The critical task has also been used as a side task in pilot-vehicle studies, the magnitude of the controllable unstable time constant being a measure of pilot workload[21]. The amount of divergence, then, which can be handled safely is seen to depend upon the amount of attention a pilot can devote to controlling it. That in turn is a function of the task's inherent difficulty (e.g., landing approach *vs* cruise) and the level of other flying qualities (e.g., concurrent failures of command augmentation or in another axis of stability augmentation)[9].

Another necessary limit on static instability is the amount of control remaining for recovery. Proposed criteria have ranged from little more than static balance[22] to MIL-F-83300's[23] half the nominal control moment (for forward flight) and specified attitude changes in 1 second (for hover). Sensitivity to gusts is a consideration. Any requirement is bound to be somewhat arbitrary because experience is limited. Here too we solicit opinions and data.

Control surface rate must also be adequate, even in emergency conditions. A 1972 General Dynamics study shows convincing time histories of the wild maneuvers that can result from insufficient surface rate for stability augmentation. In an internal study, Watson, Bennett and Kouri systematically varied the parameters of "a small CCV fighter airplane design", seeking generalized design criteria. That at least is a start toward a specification requirement.

From considerations leading to the current requirements^5, we have the following discussion relative to instability and Failure States of the airplane.

The Level 3 requirements generally apply in the worst possible Failure States. Except for approved Special Failure States, then, MIL-F-8785's static stability requirement does not permit basic-airframe speed instability (elevator surface fixed). Cases will arise, however, in which the procuring activity is asked to consider allowing basic-airframe instability as a Special Failure State. Even if the reliability of stability augmentation should be judged sufficiently high, or if the degree of instability seems acceptable in itself, a number of aspects of combined airframe-flight control system behavior in normal operation need to be examined before accepting appreciable instability in a Special Failure State.

Obviously, extremes of either stability or instability require more control to balance the airplane throughout an angle-of-attack range. In the stable case, at the control limit the airplane at least has a restoring tendency. But when an airplane has an unstable variation of elevator-surface position with airspeed, the surface position required to maintain off-trim airspeeds is in a direction which reduces the control available to initiate recovery to the trim speed. If the unstable gradient is large enough, the pilot could fly far enough off the trim speed that there would be no elevator control available for recovery. With the elevator against the stops, the airspeed would continue to diverge and the pilot would be powerless to prevent it from doing so. Examples of this behavior can be found in Mach tuck for subsonic airplanes and during wave-offs for some propeller-driven airplanes.

For Airplane Normal States, then, over the entire permissible range of speed and altitude, safety comparable to that of a stable basic airframe would require pilot-control and control-surface authority to balance the airplane at positive and negative ultimate load factors, with some margin of control power remaining, wherever the basic airframe is unstable. (In flight test, of course, limit load factor would not intentionally be exceeded.) For a given configuration, the elevator surface and control positions for balance determine the amount of control authority left for stabilization and control. The relative authority and interactions of command, augmentation and trim controls are important considerations. Authority and rate saturation may be particularly important for dual-purpose controls such as elevons. With aerodynamic instability and higher-order flight control system dynamics, limit cycles also become of increasing concern.

In both Normal and Failure States, the augmentation must maintain appropriate levels of stability in responses to both control and disturbance inputs. For a basically unstable airframe, the sizes of these inputs should be stated specifically, rather than taking a primarily qualitative approach. Some margin above structural design gusts and turbulence might be suitable. The required augmentation authority may exceed the pilot's control authority. Hard-over failures should be made impossible in the flight control system; engine-failure transients conceivably could be critical. Large control inputs of various forms and phasing should be considered. The response to disturbances during commanded maneuvers must be considered. The effect of flight at off-trim conditions on all these factors must be examined.

Particular attention is needed for the stall and spin recovery requirements. Increased dependence on control systems and artificial stability makes survivability after damage or failure an important consideration for high-angle-of-attack flight.

Stall limiters and departure preventers are already developed as fixes for current fighter airplanes--the F-111 Stall Inhibitor System[24] and the A-7 departure preventer[25], for example. Manufacturers whose aircraft do not need such devices expound on the air combat advantage attainable at extreme angles of attack: rapid deceleration, for example, to change positions with an enemy attacking from the rear. Certainly aerodynamic design for stall/post-stall stability remains an important consideration for CCV design, in order to avoid completely uncontrollable situations. The Air Force Flight Test Center's Stall/Post-Stall/Spin Flight Test Demonstration Requirements for Airplanes, MIL-S-83691A, rightfully stresses the need to demonstrate extreme resistance to loss of control. The required testing subjects all aircraft to a degree of "gross" abuse beyond normal maneuvers. Highly maneuverable aircraft are to be even more completely wrung out. Thus limiters, while certainly useful, can supplement but not replace aerodynamic design at high angle of attack.

In determining the adequacy of stall limiters, control authority and rate, one must choose the size of disturbance to be allowed for. Turbulence level is important; both MIL-F-8785B and the proposed MIL-F-9490D flight control system specification give models and intensities for turbulence up to thunderstorm intensities. Single disturbances are likely to be critical. These include gusts, wind shear, wakes of buildings, etc. near the runway and jet wakes. The British revisers of AvP 970 flying qualities requirements are considering, in addition to Gaussian turbulence, pairs of ramp gusts to evoke the worst response. Glyn Jones' development of this approach is proceeding.[26]

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