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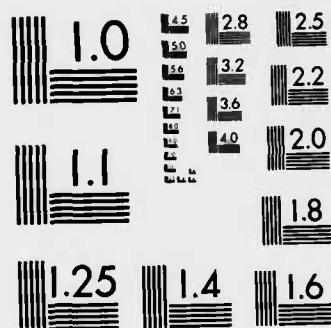   AEROSPACE RESEARCH AND DEVELOPMENT NEUILLY..
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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

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AGARD ADVISORY REPORT No. 186

Technical Evaluation Report

on

Criteria for Handling Qualities of Military Aircraft

NORTH ATLANTIC TREATY ORGANIZATION

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Advisory Report No.186

TECHNICAL EVALUATION REPORT

on

CRITERIA FOR HANDLING QUALITIES

OF MILITARY AIRCRAFT

by

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U.S.A.

This Advisory Report was prepared at the request of the Flight
Mechanics Panel of AGARD

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ON
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INTRODUCTION

From its inception, the Flight Mechanics Panel has had a strong interest in aircraft handling qualities requirements and design criteris. Although the last previous Panel meeting with "Handling Qualities Criteria" in its title was in 1971 (at Braunschweig), other meetings before and since have had handling qualities among their concerns. Notable recent examples are the Symposium on Combat Aircraft Manoeuvrability (Florence, 1981, AGARD-CP-319) and the Symposium on Stability and Control (Ottawa, 1978, AGARD-CP-260). The large size of the group which assembled at Fort Worth indicates continued strong interest in many quarters.

Very evidently tbis has been the aircraft handling qualities season. In addition to this four-day meeting (AGARD-CP-333), several other well-attended conferences with an international flavor have been held in the US within a short time. The season started in March with the four-day, Air Force- sponsored "Design Criteria for the Future of Flight Controls" assembly of handling qualities and flight control system people in Dayton (Proceedings are beingpublished as an AFWAL TR). It continued at Moffett Field the week before this AGARD meeting: an American Helicopter Society/NASA-sponsored Specialists Meeting on Helicopter Handling Qualities (NASA CP2219). In addition the programs of San Diego AIAA Atmospheric Flight Mechanics and Guidance & Control Conferences in August have a strong flavor of flying qualities. The previous (October 1981) FMP meeting in Florence, on Combat Aircraft Manoeuvrability, also dealt significantly with handling qualities. Truly tbis is a remarkable period. With the needs expressed so strongly, perhaps there is hope for renewed emphasis on achieving progress in this field.

Each specification writer and designer must perforce choose one or more specific approaches. It would seem wise to be acquainted with all the methods, and to use different ones to gain various insights. Static margin retains meaning for laying out a design, though it does not describe aircraft dynamics at all well. Gain & phase margins and "robustness" have special significance to a flight controls designer, but must be supplemented by other parameters to describe flying qualities adequately - and these forms have no direct meaning to airframe designers. This communications problem among different kinds of specialists bas been responsible for serious handling problems which had to be corrected on U.S. aircraft. As aircraft rely more heavily on the flight control system for stabilization, dynamic flying qualities requirements are stated in terms of performance rather than design, and flight control designers have difficulty seeing the relevance of traditional-type requirements to heavily augmented systems, we need to promote actively an improved understanding across disciplines.

With this thought in mind, and because of the author's present preoccupation with revision of the U.S. military flying qualities requirements, this report surveys essentially all the material presented in a paper-by-paper presentation. This form facilitates attribution of each of the many approaches to its source, where more detail may be found. For longitudinal short-period handling, a tabulation is given to sort out the many different expressions of relatively few results. There do not seem to be enough mentions of lateral-directional or other handling questions for airplanes to make any such tabulation necessary. The U.S. and Canadian helicopter papers leave no doubt that these organizations coordinate their work well. It appears that operational aspects too are viewed in the same general way on both sides of the Atlantic. Following a description of the panel discussion, a summary attempts to draw all these factors together and indicate directions for further development.

SESSION I - PRESENT STATUS OF CRITERIA
          Chairmen: Dr. John Buhrman, NLR and Ronald O. Anderson, AFWAL

Dr. Buhrman recalls the 1971 FMP meeting at Ottawa, which commissioned a study committee that led to Arthur Barnes' AGARD Advisory Report No. 89, Handling Qualities Specification Deficiencies. At the 1978 FMP Stability and Control symposium, again in Ottawa, the question was asked: are new criteria needed for the advanced flight control systems? Some answered yes; some no, the concept of equivalent systems would make present requirements valid. This Fort Worth meeting is a follow-up, with the standard AGARD question, "Where do we go from here?" The large number of papers submitted indicates that strong interest continues.

Ron Anderson notes that bandling qualities criteria are put to use rapidly and widely. He recounts Steve Osder's (Sperry Phoenix) story of the mainland Chinese who asked him during bis visit, "Do you have sometbing better to use than 8785B?"

1. Present Status of Flying Qualities Criteria for Conventional Aircraft - In a general overview, Moorbouse and Woodcock decry the diminished confidence in their flying qualities specification, MIL-F-8785B/C (1,2), on the part of flight control system designers, as seen in recent aircraft design: "if an airplane design does not meet the criteria, then the criteria need improving". The flight control difficulties wbicb it seems most of our new military airplanes have experienced are traced to (a) neglect of the pilot's dynamics in closing the loop for precise tasks and (b) operational tasks more critical than tbose envisioned in specification or design. An example of tbe former is too much effective time delay introduced through higher-order terms in the fligbt control system. Tbe A-10 exemplifies tbe difficulty witb task definition: stability augmentation adequate for a straigbt-in dive bombing run did not allow the airplane to settle onto the target closely enough when tbe approach involved gross maneuvering (in order to enhance survivability), forcing redesign of augmentation.

After surveying some open- and closed-loop, frequency- and time-domain criteria for longitudinal short-period motion and for beading control, recent and fortbcoming specification changes are discussed. In MIL-F-8785C (November 1980) the concept of equivalent low-order classical systems was made explicit; this change points out the fallacy of taking particular poles of the transfer function when other poles influence the response in the same frequency range. A related cbange of significance is to account for actual time delays and the lags introduced by actuators, prefilters and compensation by placing limits on the equivalent time delay. Problems can arise in interpretation and possibly in response matching, but the approach is generally effective in extending the present data base to higher-order systems. Current specification revision effort is concentrating on (a) a thorough review and update of flying qualities requirements and (b) presentation of alternatives to facilitate tailoring requirements to specific needs. Projected researcb includes consideration of the changing role of tbe pilot as missions become more complex and demanding and, as in an integrated flight/fire control system, different kinds of blends of piloted and automatic control are introduced. Another line of research deals witb nonlinearities: for example actuator deflection and rate limiting, residual oscillations and stall/post-stall behavior.

A pressing immediate need is to convince tbe flight control design community of the need for judicious use of all these flying qualities requirements. Other issues are the determination of critical requirements for various tasks and missions,the implications of flying qualities requirements on aircraft cost and performance, criteria on pilot-in-the-loop behavior, and the proper complementary roles of analysis, simulation and fligbt test.

2. Status of VTOL and VSTOL Flying Qualities Criteria Development-Where Are We and Where Are We Going - Clark and Goldstein summarize the deficiencies they see in their current flying qualities specifications for V/STOL aircraft (MIL-F-83300) and belicopters (MIL-H-8501A). Their wide-ranging needs encompass day and nigbt operation of fixed- and rotary-wing aircraft from aircraft carriers and destroyers.

For a "one-step" decelerating transition to hover, Hoh and Ashkenas (2-17) have made more specific the 1972 AGARD R-594 control/display tradeoff curve:

MINIMUM LEVEL OF HOVER CONTROL AUGMENTATION
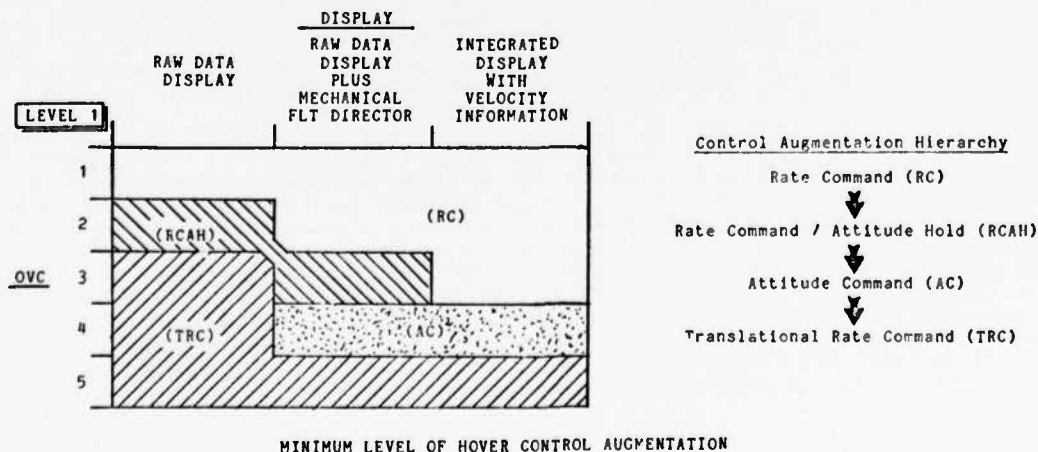
OVCs (Outside Visual Cues) range in clarity from 1, the best, to 5, full IMC. A similar curve is presented for Level 2 flying qualities. For V/STOL as for CTOL aircraft an equivalent system approach looks promising. Reference 2-18 proposes different bounds on these equivalent transfer-function parameters for rate and attitude control systems, along with a time-response criterion to determine which requirements should apply. For translation rate command a simpler equivalent system describes the velocity response to pilot input; X-22A flight-derived boundaries are suggested in terms of gain and lag time constant. The illustrated minimum augmentation levels seem to furnish a way to codify or

consolidate these different requirements for various control/display concepts. Secondary responses are always a concern for VSTOL aircraft; STI has proposed a bound on modal coupling in height control. "Now that hover requirements appear to be better defined", the transition and forward flight regimes are being addressed in current studies.

The Navy's concern with helicopter flying qualities is accentuated by the need for operation from ships in noncalm seas. However, in most respects the Navy's concerns parallel the Army's (Paper 11). Naval Air Development Center is augmenting the Army's funding of helicopter specification revision.

Required roll control power seems to be a function of both the mission and the helicopter weight; required yaw damping a function not only of yaw control sensitivity but of rotor type; mission-related control power requirements are too few. But dynamic response criteria seem generally adequate, though lenient except for a lack of guidance on lateral-directional response in VFR missions.

The discussion brought out the need to calibrate evaluation pilots and the need for additional systematic evaluations in carefully designed experiments to generate flying qualities requirements. For the wide variety of V/STOL aircraft, making the requirements applicable to all must be done with care.

SESSION II - GAINS ACHIEVED IN THE SEVENTIES, AND FUTURE PROSPECTS (CTOL AIRCRAFT)
Chairmen: Dr. Peter G. Hamel, DFVLR and Charles R. Chalk, Calspan

3. Equivalent Systems Criteria for Handling Qualities of Military Aircraft - Hodgkinson points out that, considering higher-order flight control systems and structural modes, it is universal practice to use a reduced-order response model for dynamic analysis or simulation. Although Neal and Smith's (3-4) Nichols plots accommodate systems of any order, their method uses a simple first-order pilot model. Further, a requirement is normally written in terms of a limited number of parameters. The MIL-F-8785C short-period requirements are stated in a "specification space" of four dimensions: τ, ω_{SP}, n/α, and ζ_{SP}. Neal and Smith's criteria have two dimensions: pilot compensation and peak overshoot. A Cooper-Harper pilot rating is one-dimensional. Defining mismatch as the difference, in frequency response in this instance, between any higher-order system and a minimum-order system, both characterized by the specification parameters, "The challenge is to find minimum order systems which, conceptually, span the specification space of other specification methods."

It was amply demonstrated at this meeting that different sets of dimensions can be used to describe short-period motion, each set providing its own particular insights. Effective time delay, for example, is a phase lag which, being proportional to frequency, limits the bandwidth of pilot-vehicle response. Hodgkinson shows time delay to correlate with pilot ratings.

By adding terms to classical second-order short-period transfer functions to make them of higher order, mismatch was found to be most critical to pilot rating "in a central frequency region (about 2 to 4 radians per second)" - for both up-and-away flight (3-4) and approach & landing (3-6). But "In practice, the weighting [heavier at those frequencies] changed the equivalent system parameters very little."

High correlation is found between Neal and Smith's pilot compensation angle and the equivalent short-period frequency, but with different lines of regression for each of three values of $1/T_{\theta2}$ (Data of 3-4 and 3-6). High correlation is also shown between Hoh's (paper 9) bandwidth frequency and the equivalent short-period frequency. Hodgkinson compares similar systems of different order against two criteria in an attempt to show that "All methods for higher order systems are in a real sense equivalent system methods."

Later Chalk suggested that a way out of the problem with requirements of limited dimensionality applied to higher-order systems might be to use envelopes, say in gain-phase space (i.e. Nichols charts) rather than gain and phase margins. Hodgkinson hesitated, feeling that the dimensionality problem still exists with envelopes such as the C* time history criteria.

4. Pilot Handling Qualities Design Criteria for High Order Flight Control Systems - Gibson points out that undesirable control response characteristics "Invariably...turn out to be unlike traditional ones, and the question to be answered is 'What are the desired traditional characteristics?'...A large part of any flight is conducted in an open loop precognitive manner" but some tasks involve pursuit or compensatory tracking. For those, "Failure to [provide good open-loop response] may well result in additional closed loop control being forced upon the pilot as he endeavours to compensate by overdriving or smoothing unsatisfactory time response."

The step-command time response parameters pitch-rate overshoot, pitch-attitude dropback, flight-path time delay and normal-acceleration envelopes are used to derive from available data and existing requirements a set of criteria which may be interpreted readily for aircraft with higher-order flight control systems. A little pitch rate overshoot is necessary to minimize closed-loop control problems. Subsidence ratio and Bihrle's CAP ($\ddot{\theta}_0/n_{z\infty}$) are kept as important parameters, but time delay does not seem to have been a problem - perhaps concern has been implicit. Similar roll-response

requirements are possible. The transfer functions of Gibson's Table 1 yield analytical expressions:

$$\text{Rise Time } t_{n_z} = [\pi - \text{Tan}^{-1}(\sqrt{1 - \zeta^2}/\zeta)]/(\omega_n\sqrt{1 - \zeta^2}), \; \zeta \leq 1; \qquad t_{n_z} \to \infty, \; \zeta \geq 1$$

$$\text{Effective Flight Path Time Delay } t_\gamma = 2\zeta/\omega_n$$

$$\text{Normalized Dropback } DB/q = T_{\theta_2} - t_\gamma$$

For tracking, "It is possible to define an envelope of aircraft attitude response which is very 'robust', in the sense that the pilot can achieve good closed loop control with a wide range of gain and delay only." Nichols charts, presenting both open- and closed-loop frequency response, are appropriate and facilitate analysis. The desired open-loop response of the aircraft and gain-plus-time-delay pilot is K/s-like at low and moderate frequencies, attenuated sufficiently at high frequency; a 0.3 Hz crossover frequency has been found suitable for all tasks. On the basis of Boothe et al.'s data (4-1), task-dependent boundaries are drawn on the Nichols chart for optimum flying qualities for <u>pitch</u> tracking - this can be done for roll too. (He notes an anomalous Level 2 indication for in-flight refueling characteristics rated "excellent"). Note that time delay is an inherent consideration in this approach. Similar guides for landing approach are also presented. In addition, for refueling and landing approach larger values of attitude dropback appear satisfactory, with corresponding very large T_{θ_2} and small n_z/α; there, path response seems more important.

"It has always proved sufficient to treat the 'rapid PIO' as a single loop attitude response", a somewhat controversial statement. A guide to avoidance of pilot-induced oscillations involves the Nichols chart with aircraft and a synchronous pilot, adding to the boundaries the criteria that 180 deg phase lag must occur at a "frequency beyond the range of significant pilot activity (say above 1.5 Hz)" and response attenuation must be sufficient at the 180 deg phase lag frequency. PIOs are seen to result from the pilot's inability to reduce gain quickly enough when confronted by a sudden change in gain margin - as with spring-bobweight feel systems, or actuator saturation with high forward-path gains.

Effective time delay is seen as an unreal contrivance, with significant time delay unlikely even in a digital system. The suggested approach to phase lag is to strive in design to limit the flight control system contribution to, say, 30 deg for all frequencies below 1.5 Hz or preferably even 2 Hz.

Evidence is found that at low speed, pilots prefer stick force gains related to pitch attitude response rather than to normal acceleration.

One example cited of successful application of these criteria is the digital, fly-by-wire, variable-gain Jaguar research airplane. In fixed-base simulation and in flight, it could perform an operational mission in its reversionary mode.

5. <u>Gain</u> <u>and</u> <u>Phase</u> <u>Margin</u> <u>as</u> <u>a</u> <u>Basis</u> <u>of</u> <u>Longitudinal</u> <u>Flying</u> <u>Qualities</u> <u>Evaluation</u> - Röger and Beh used Neal and Smith's data (5-2) to derive handling qualities criteria in classical servo analysis terms for the short-term response of pitch attitude to control force, assuming loop closure by a simple unity-gain pilot. A plot of gain margin vs phase margin is divided into regions of Level 1 (good, steady), Level 2 (too slow or fast response) and Level 3 (PIO tendency) regions. An additional requirement limits the amount of departure of θ/F_s from $[\dot{\theta}/F_s]_\infty/\omega$, i.e. pure integration, for Level 1 and Level 2 (Gibson's observation of the need for some pitch rate overshoot or attitude "dropback" seems at variance with this). The criteria can be applied directly to any order of linear system, and they offer insight on the effects of aircraft parameters such as natural frequency, damping ratio, pitch numerator time constant, time delay, stick force per g and M_α.

6. <u>Les</u> <u>Commandes</u> <u>de</u> <u>Vol</u> <u>Electriques:</u> <u>vers</u> <u>de</u> <u>Nouvelles</u> <u>Normes</u> <u>de</u> <u>Jugement</u> <u>des</u> <u>Qualités</u> <u>de</u> <u>Vol</u> - <u>un</u> <u>Exemple:</u> <u>le</u> <u>Mirage</u> <u>2000</u> - Mathe cites the objectives of introducing significant relaxed static stability. Direct benefits are performance gains, particularly in approach speeds and maneuver capability; an indirect benefit is aerodynamic optimization. The electric flight control system is fundamental to the design: it facilitates stabilization. For safety the system has quadruply redundant elevon-command, triply redundant rudder, with some reconfiguration capability. With goals to provide relatively simple quasilinear, uncoupled response and to stay well within the limits of validity of the criteria used, the prototype's flight control system required only minimal adjustment during flight test.

During the flight program the angle of attack and load factor limiter evolved, at the cost of some complexity, to (a) incorporate an "elastic stop" which permits limit load factor to be exceeded (in order to prevent a crash) with additional pilot effort, (b) adjust the stop to the lower limit load factor for heavy store configurations (with a pilot-operated switch), and (c) extend the protection down to zero airspeed. Lateral-directional augmentation was also modified to deter loss of control at high angle of attack, down to zero airspeed; it was not necessary to limit roll rate. With experience, pilots have become willing to trust the augmentation and limiters, and want complete protection. The airplane has few limitations which the pilot must observe; most of that is done aerodynamically or automatically.

A motion picture impressively illustrated extreme maneuvers such as vertical rolls with full aft stick, held to zero airspeed. The first three flights to extreme angles of attack were done with the limiter inoperative because of insufficient confidence in it. They believe in thorough testing at high angle of attack, since in service pilots will do everything possible at one time or another. No spin chute was fitted.

7. Handling Qualities of Transports with Advanced Control Systems - Mooij compares ground-based and in-flight simulator results of a search for dynamic flying qualities criteria directly applicable to aircraft with highly augmented flight control systems - in particular, of the attitude hold/rate command type - in approach and landing. Elimination of the pilot's attitude and speed stabilization tasks* is seen as a most helpful step, and a good way to facilitate the performance gains that are possible with "relaxed static stability"; but the applicability of existing criteria had not been demonstrated. With such a system, pilot control is intermittent, more relaxed, and aircraft response to turbulence is reduced. In order to retain control harmony, the pitch and roll axes should have similar forms of control.

The flight and ground-based simulator results are generally comparable, except in two respects. More difficulty with speed control was evident in flight. Also, the evaluation of direct lift control was confounded by an unintentionally enhanced high-frequency normal-acceleration response in flight. However, comparable excitation of the simulated aircraft's structural modes is a valid consideration, or possibly the limited simulator motion "can mask a problem area which can develop in real flight."

Two criteria, C* (7-33) and a criterion for large advanced supersonic aircraft (7-34) were found inapplicable to the present results. The MIL-F-8785C (ω_e^2/n_{α_e}) boundary was found too lenient, and for low n_{α_e} a need is seen to consider short-period damping simultaneously rather than independently. Rise time and settling time appear to do that adequately. The format of the θ_{MAX}/n_{ss} criteria of Ref. 7-35 "is considered especially appropriate" with large pitch-rate overshoot, although numerical values of the upper limit are smaller than prior results in up-and-away flight. The only closed-loop criterion found applicable was the Neal-Smith one (7-43), but with the more stringent limits of 0dB pitch overshoot and 45 deg of pilot lead compensation with the same 1.2-sec bandwidth proposed by Chalk (7-35). For path control, since "altitude loop performance obtainable depends among others on pilot compensation used in the inner loop", a closed-loop type of requirement is indicated. "Based on flight simulator evaluations only", a minimum outer-loop bandwidth of 0.55 rad/sec is proposed. [Calspan, in a study of large aircraft in take-off and landing (3), tentatively picked .5 sec].

For roll, pilot rating was found to correlate well with just roll-mode equivalent time constant and equivalent time delay, taken together. MIL-F-8735C's allowable time constant seems too large, its allowable time delay too small when roll-mode time constant is short. Flight and ground simulator results agree fairly well.

8. Handling Qualities Criteria for Longitudinal Control - In a search for short-period criteria directly applicable to highly augmented aircraft, three authors present successively more detailed suggestions. All transfer functions of the aircraft are to be in the form of equivalent classical systems.

Neuhuber examines the time-response to a step command. For initial response "a good 'rule of thumb'" for maneuver flaps is to place the "initial pole of rotation...at the pilot's station"; he thinks the stringent MIL Spec [8785B] time-delay limit "justifiable". Considering roll acceleration in turn entries, a maximum n_z slope of 1.6 to 3.6 g/sec is recommended. Both rapid rise and good damping can be achieved simultaneously by (nonlinear) gain adjustment depending on $n_z(t)/n_z(\infty)$.

Diederich finds an optimum value of Bihrle's (8-17) control anticipation parameter (CAP) and relates CAP to an "overshoot ratio (resonance amplitude)". He notes that in MIL-F-8785B the flying qualities level boundaries correspond to pilot opinion rating (POR) of POR=CAP for CAP≥1, POR=1/CAP for CAP≤1. Using the same rule for damping ratio, he draws $\omega_n - \zeta$ boundaries which are similar to - but somewhat more restrictive than - those of MIL-F-8785. Of several possibilities for expressing these proposed requirements, he recommends Nichols-chart boundaries on frequency response of the augmented airplane sans pilot. Correlation with the Neal-Smith and LAHOS (Smith) data is claimed (8-6, 8-18). Finally, "it is recommended to use more than one criterion simultaneously."

Going further, Brauser uses a pilot model with gains, information input and processor leads, a neuromuscular lag and a time delay for closed-loop attitude control. He postulates that the pilot adopts lead T_v and adjusts his gain so that $(1+T_v s)(1+T\theta s)$ $\approx 1 + (2\zeta_{sp}/\omega_{sp})s + (1/\omega_{sp}^2)s^2$, trying to maintain a 3.5 rad/sec bandwidth. Constraints are introduced on pilot lead, total effective time delay,...From analysis with this model, he draws Bode-plot amplitude and phase boundaries for good flying qualities, claiming good correspondence with Diederich's results. Various insights and examples are offered. For maneuvering, his pilot model switches closed-loop control from attitude to pitch rate; this produces optimum force gradients within the 8785B Level 1 range of stick force per g.

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* - Nevertheless, in these investigations no autothrottle was used. Attitude stabilization and rate command were achieved through proportional plus integral control of pitch and roll rates, with steady-turn coordination and a wings-leveler.

9. <u>Bandwidth - A Criterion for Highly Augmented Airplanes</u> - Hoh and Mitchell first cite open-loop criteria for determining the bandwidth of an aircraft (for a given mode of control, at a given flight condition), requiring a minimum 45 deg phase margin and 6dB gain margin. An additional time-delay-type parameter is found necessary to correlate the Neal-Smith data (9-1) - they settle on the slope of phase vs frequency between $\omega_{180\ deg}$ and $2\omega_{180\ deg}$. Using these two parameters, they use available flight data to draw Level 1 and 2 boundaries for short-term pitching response of the augmented (but unpiloted) airplane in both up-and-away flight and approach and landing. They show good correlation for Level 1 bandwidth [after all, some unstable airplanes (having no bandwidth) have been judged Level 2.] There is some indication of an upper limit on satisfactory (Level 1) bandwidth; they note a seeming acceptance of a more abrupt response in tracking target aircraft than in other tasks. The frequency-response amplitude "shelf" of the pitch rate response can hinder strict interpretation of gain margin in some cases, but a little judgment would rate all those cases as potentially having poor flying qualities. For flight determination of the required aircraft frequency response, fast Fourier transform of a pilot-controlled frequency sweep can work well. Hoh emphasizes the importance of having a high-bandwidth task for evaluation.

The bandwidth concept is general, but parameter boundaries vary with the task, control strategy, etc; the controlled element could include aspects such as display.

10. <u>Handling Qualities Aspects of CTOL Aircraft with Advanced Flight Controls</u> - Hanke seeks a better understanding of the short-term relationship between attitude control and path control in landing approach. Classically (for a natural, or conventional control system) pilots control flight-path inclination by regulating pitch attitude as an inner loop. With a rate command/attitude hold (RC/AH) system, however, pilots found this inner stabilization loop largely unnecessary: pilot control is intermittent and pulse-like, on approaches (without landing) in their variable-stability airplane with such a system.

For the conventional form of control, the MIL-F-8785C parameter $\omega_n^2/(n/\alpha)$ is an equivalent, too-restrictive form of the more basic CAP $= \ddot\theta_o/\Delta n_{ss}$ (10-10); the equivalent-system $\omega_n^2/(n/\alpha)_e$ is a further equivalent, then, that loses some clarity of meaning. On landing approach, $n/\alpha \simeq C_{L\alpha}/C_L$ varies only slightly for aircraft of any one size or class - indicating that without direct lift control (DLC), n/α is not an important parameter per se. Also, he relates the Neal-Smith (10-14) Level 1 pitch resonance/lead or lag compensation boundary plus the 8785 upper limit on damping ratio to the entire 8785 $\omega_n^2/(n/\alpha)$ boundary. In addition he cites Mooij's results (10-15, with RC/AH) to support the interpretation of $\omega_n^2/(n/\alpha)$ as entirely a pitch parameter.

The surprising result of flight evaluations (10-6) that washed-out DLC hurts rather than helps (even though various pitch response criteria are met with the DLC) is attributed to decreased frequency separation between inner-loop attitude and outer-loop path control. Pilot effort and Cooper-Harper ratings vary according to $\gamma-\theta$ phase separation (equivalent to frequency separation). For a classical, non-DLC airplane this phase separation, $\phi(\gamma/\theta)$ becomes $-\tan^{-1}(-Z_w\omega_n)\simeq-\tan^{-1}(\omega_n T_{\theta 2})$, which Hanke shows [as have Mitchell and Hoh (4)] to correlate with the lower $\omega_n^2/(n/\alpha)$ boundary of MIL-F-8785 - so that boundary also applies for path control if $1/T_{\theta 2}$ is interpreted as $-Z_w V/g$ "Although this $[1/T_{\theta 2} = -Z_w V/g]$ is questionable" for highly augmented aircraft. "Both too large and too small loop bandwidth separation will lead to handling problems." The preliminary recommendation for large transport aircraft is 50 deg γ/θ lag, not less than 30 deg when pitch response is sluggish. [For equal $1/T_{\theta 2}$ and ω_n (no separation), $\phi(\gamma/\theta)|_{\omega n} = -\tan^{-1}(\omega_n T_{\theta 2})$ is -45 deg; for -50 deg, $1/T_{\theta 2}$ is 0.84 ω_n, for -30 deg, 1.7ω_n if the classical approximation holds]. If the frequency separation must be specified directly, a closed-loop analysis with pilot model is involved for the general case.

A suggested criterion would combine this phase lag with the Neal-Smith pilot compensation, noting "that large transport aircraft show no tendency to closed loop resonance [the other Neal-Smith parameter]". [Reference 8-18 indicates, however, frequent pilot-induced oscillation tendencies (generally attributable to lags and delays) in approaches carried on further, to flare and touchdown].

With inner-loop augmentation such as RC/AH, for landing approach this frequency separation is not a factor because the pilot need not regulate pitch - the FCS does that for him - and so washed-out DLC is helpful in cases of sluggish pitch dynamics. "Pilots commented that with DLC vertical speed variation could be initiated and stopped very precisely...Nevertheless the γ/θ relationship remains important for path control. Boundaries for path control with augmented inner loop have to be established."

SESSION III - GAINS ACHIEVED IN THE SEVENTIES, AND FUTURE PROSPECTS
          (STOL AND VTOL AIRCRAFT)
          Chairmen: Horst Wunnenberg, Dornier GmbH & Robert R. Lynn, Bell
          Helicopter Textron, Inc.

11. <u>The Status of Military Helicopter Handling-Qualities Criteria</u> - According to Key, present specifications on helicopter flying qualities are inadequate. Although MIL-F-83300 has "broad coverage of important handling qualities aspects and [a] systematic structure..., it is primarily based on V/STOL data, and explicit helicopter characteristics are only lightly covered. MIL-H-8501A and [modifications for recent procurements] do specifically address helicopters and [have] long familiarity. However, they have rather sparse coverage..., many shortcomings [and a lack of] systematic

treatment of flight envelopes and failures. All of these specifications lack mission-oriented criteria and are basically for [visual meteorological conditions]". The night, nap-of-earth (NOE) mission is of particular concern, along with the Navy's shipboard landings in high sea states. The need is for "an integrated treatment of vehicle dynamics, flight control system characteristics, cockpit controllers, displays and vision aids" as they affect all of the pilot's tasks. Helicopters are basically more complicated than airplanes: statically and dynamically coupled, nonlinear, with more degrees of freedom, more low-speed flight tasks. Responses change character with several configuration variables.

To correct these specification deficiencies insofar as possible, the Army and Navy are starting a contracted effort on flying qualities requirements for rotorcraft, including high-speed and novel configurations and evolving forms of controllers. An initial phase will develop a new specification structure, incorporate existing criteria and define critical gaps. A second phase will incorporate new material and draft, coordinate and review the specification and backup report. Publication is expected in FY85. Gathering systematic handling data in-flight for low-level Army mission tasks is limited by safety considerations.

12. L'Impact de la CAG (Commande Automatique Généralisée) sur les Qualités de Vol des Hélicoptères - With individual blade control supplementing - eventually replacing - the swashplate's limited, monocyclic control capability, Kretz envisions a number of improvements (shown in figure) through active control. Handling improvements will be needed because of these trends: higher disk loading, the nap-of-the-earth mission, advanced VTOL rotor concepts, higher advance ratios (μ) and blade loadings (C_L). Optimal control techniques will be extremely valuable in the quest for improved handling qualities. A simple model of the helicopter rotor, the rotor transfer matrix, makes this possible. Control bandwidths of at least 30 Hz are seen.

ACTIVE CONTROL OF HELICOPTER ROTORS
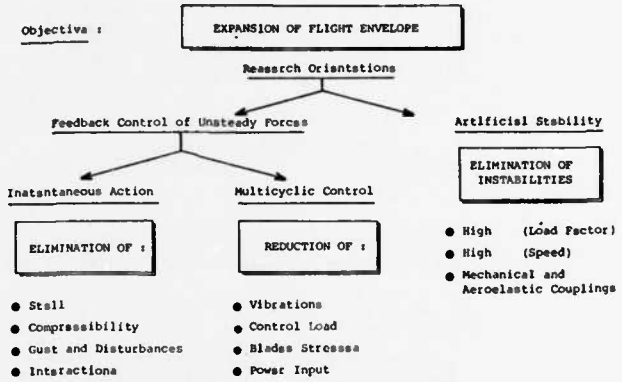
While it is premature to review all the handling qualities improvements possible, one item is presented: prevention of retreating blade tip stall. Typically, 8% of the power can be saved at $\mu = 0.3$, $C_L = 0.6$. At high forward speeds, sustained maneuverability is enhanced. This application has been demonstrated in a wind tunnel.

No need is seen for basic modification of existing handling criteria or analysis techniques. Kalman's weighting function, however, may be used to provide more insight. We must remember that in addition to performance, the pilot workload required is an important flying qualities factor. This leads us back to pilot opinion or a pilot model which accounts for fatigue, etc.

13. Operational Criteria for the Handling Qualities of Helicopters - Major Steward lists handling qualities he feels essential or helpful for combat helicopters, stressing the anti-armor mission: "flight at and below obstacle height, to aid concealment, achieving surprise and reducing vulnerability, is likely to remain the primary combat helicopter tactic...it is agility derived from the inter-related performance and handling qualities which gives the combat helicopter its inherent battleworthiness," but improvements must be affordable.

Ground taxiing, take-off and landing capability is needed on all likely surfaces, including slopes up to 10 deg, and in winds from all directions. For low-level and contour flight, -0.5g for several seconds and -1g transients have been used in Lynx trials. Hands-off cruise would permit crew attention to other duties. Rapid actions to avoid unexpected obstacles "frequently cause the rotor to accelerate into an autorotative condition, requiring pilot action to prevent an overspeed. In addition, at low level, [height] control becomes very demanding at large bank angles..., and a means of controlling [these] excursions" would be helpful. For carefree maneuvering capability, a 3 or 4 g maneuver capability is desired without reaching a limitation; observance of any limitations should not require attention to cockpit instruments.

Nap-of-the-earth (NOE) flight would benefit from handling qualities that would allow higher speeds, around the minimum power speed. Low and negative-g flight may be encountered, but of shorter duration. "NOE flight will be characterized by frequent accelerations and decelerations throughout the speed range of hover to maximum dash," including the "quick-stop" and decelerating turn, with cross-coupling problems to be kept in hand. Loss of concealment, view restrictions, ground clearance, and precise control are factors. All axes of response are important. "At 100 kts, roll rates up to 100 °/s were found to be likely whilst at 60 kts on a small triple bend task, very high roll rates up to 150 °/s were called for; maximum pitch rates demanded were typically 20-30 °/s.

An automated hover is desirable, likely essential. Precise height and directional control are required; vulnerable time at altitude must be minimized, with rapid, precise masking and unmasking, and minimum vibration for good aim. For evasive maneuvering at hover, more than the usual 5% thrust margin may be required.

Against the Hind air-to-air threat, flight will be at a very low level, placing maximum strain on the crew. Running and hiding "requires maximum agility in the hover, at low speed, and in a maximum performance dash", although in helicopter vs helicopter engagements both high positive and negative load factors would be of benefit.

For night and adverse weather operation, the limited field of view of pilot vision-aids "requires continuous head motion by the pilot". An effective automatic hover control is likely to be essential.

With shorter training, and in a reduced flight envelope for extended fatigue life, "good handling qualities to the limits of the flight envelope would make a significant contribution".

14. <u>Flight</u> <u>Experiments</u> <u>with</u> <u>Integrated</u> <u>Isometric</u> <u>Side-Arm</u> <u>Controllers</u> <u>in</u> <u>a</u> <u>Variable-Stability</u> <u>Helicopter</u> - Sinclair describes two series of evaluations of three- and four-axis controllers with integral trimming. The first evaluations proved that several combinations of control axes were workable although the twist-collective configuration was prone to reverse commands. "Pilots adapted with suprising ease and speed" to different control modes for the augmented, autostabilized helicopter. A control position indicator proved adequate for maneuvers requiring knowledge of tip path plane orientation; otherwise, the force feedback alone was sufficient. With controlled, high-workload flight task sequences (but on cleared, level ground), in the second evaluation the conventional controls were slightly superior in precision and ease of operation - attributed to pilots' greater familiarity with them. The 3-axis hand controller with yaw-control pedals was marginally preferable to the 4-axis handle. Both ease and precision of control appear to improve as pilots gain experience with the side-arm controllers. Recent incorporation of a small amount of side-stick motion appears to provide useful feedback information.

SESSION IV - CRITERIA FOR HANDLING QUALITIES AT HIGH ANGLE OF
            ATTACK (INCL. STALL, POST STALL AND SPIN)
            Chairman: J W Britton, RAE Bedford

15. <u>Stability</u> <u>and</u> <u>Control</u> <u>Requirements</u> <u>for</u> <u>Tactical</u> <u>High</u> <u>Angle</u> <u>of</u> <u>Attack</u> <u>Maneuvering</u> - Przibilla and Krause point out that high angle of attack (α) should not be considered a special mode of flight, but just an extension of the normal flight regime. Rolling should be about the velocity vector in order to avoid large sideslip angles. For a delta-wing plus canard configuration with leading-edge and trailing-edge flaps, two vertical fins and thrust vectoring, Krause showed pitch, roll and yaw control power from 0 to 90 deg α, indicating the significant contribution of thrust vectoring in pitch and yaw. Past 30 deg α the roll control power reduced to about 1/3, but remained effective to 90 deg. The yaw divergence parameter $C_{n_\beta dyn}$ remained positive, but rudder effectiveness and the lateral control divergence parameter approached zero at extreme α. At off-trim conditions (e.g., heavily loaded canard) all spin parameters became strongly negative. However, with sideslip angle and rate plus yaw and roll rate feedback to roll and yaw surfaces (surface rates to 50 deg/sec), the airplane could be kept under control at all αs, maneuvering to 70 deg α.

16. <u>Experience</u> <u>of</u> <u>Non-Linear</u> <u>High</u> <u>Incidence</u> <u>Aerodynamic</u> <u>Characteristics</u> - Booker and McKay show a typical progression as angle of attack (α) increases: buffet, wing rock, deteriorating lateral handling, departure and spin - or, at a given equivalent airspeed, as far as the structure will permit. Handling is the limiting factor at low to moderate speeds. Useful experimental facilities are wind tunnels (for static tests with uniform or shaped flow, oscillatory or rolling motion, or spinning in vertical flow), free-flight models, unmanned and manned simulators and, finally, the prototype aircraft.

To illustrate the importance of aerodynamic nonlinearities, nose-down stabilizer settings can decrease directional and lateral stability (although with relaxed static stability, the opposite trim might be a <u>help</u>; but something else is then likely to bite). At high α and possibly more generally, nonlinear directional stability can become worse at large sideslip.

The aircraft's design role should be considered carefully to determine whether carefree maneuvering warrants the cost in system complexity, etc. Checkout on a flight simulator helps define vehicle and flight control system problems, to the extent one has confidence in the input data.

Flight results (the FMP meeting announcement had Tornado in the paper's title) show quite good correlation between the predicted onset of an unstable roll/spiral mode and loss of control at small sideslip angles, and between predicted conditions for zero lateral control divergence parameter and the departure boundary (at lower α) in large sideslips. The difference in α reading of windward and leeward probes gives the conservative possibility of using the larger reading for departure protection. With external stores, the high-α change in C_{n_β} was offset, or more, by the effect of the less negative stabilizer setting. As a general rule an aircraft should be cleared for the

maneuvers and the stores demanded by its operational role, but have maneuver restrictions imposed elsewhere so as not to compromise the design unduly.

17. <u>A Comparison of Analytical Techniques for Predicting Stability Boundaries for Some Types of Aerodynamic or Coss-Coupling Nonlinearities</u> - Citing the attractiveness of analytically derived stability boundaries, and the need for descriptive criteria of that sort, Ross points to the length and possible inconclusiveness of any series of computed responses, e.g. for spin and departure. She shows those second-order product-type nonlinearities which still allow analytic solution for equilibrium conditions and stability. Using Mehra's technique, a linearized analysis leads to the definition of "bifurcation surfaces" (in the control or state space) which describe limit cycles or stability boundaries. Her other example is cubic nonlinearities in sideslip, leading to wing rock or departure. It was found (and checked by exact solution) that with such cubic nonlinearities the magnitude of limit cycle or divergence boundaries for motion about a zero equilibrium point was just double that predicted by linearized analysis. In Ross' experience, the linear analysis has never been less conservative than the nonlinear; discussion brought out that STI experience agrees. The small effect of neglecting the gravity terms is demonstrated.

For analysis of any nonlinearity it is the magnitude of response, rather than of input, which needs emphasis (in general, concentrate on the variables associated with the major nonlinearities). At high angle of attack, she prefers the linear velocities v,w to angular α, β - although there seems to be merit in using incidence magnitudeσ and incidence-plane angle λ as in Hopkin's ARC R&M 3562.

SESSION V - SPECIAL PROBLEMS
            Chairmen: Jean-Michel Duc, D.R.E.T. & Donald T.Berry, NASA Dryden

18. <u>Effect of Control System Delays on Fighter Flying Qualities</u> - Smith and Bailey attribute many of the handling problems of recent aircraft (F-16, YF-17, F-18, Tornado, AFTI-F-16, Shuttle are cited) to excessive effective time delay: transport delay plus the phase shift caused by added higher-order elements. These two types of contributors have similar effects, but low- and mid-frequency elements alter amplitude as well as phase. Higher-order flight control systems have been the largest lag or delay contributors. Digital mechanizations add some sampling delay, but more importantly they encourage the cascading of dynamic elements. Excessive time delay causes pilot-induced oscillation tendencies as a pilot attempts to increase the closed-loop bandwidtb to perform demanding tasks (in one case, large breakout force did not produce a PIO tendency whereas time delay did).

Two measures are used. A good deal of data and the current specification use the "equivalent delay" time found by matching the actual frequency response with an equivalent lower-order, classical transfer function. A time-domain "effective delay" has also been used, based on the maximum slope of the response to an abrupt step pilot command. Only for high-frequency elements can the two methods be expected to give the same delay. Gibson claims that his criterion, involving the frequency for zero phase margin and the attenuation tbere, is more powerful than time delay.

Several longitudinal and lateral-directional flight evaluations yield similar results: a threshold of approximately 120 milliseconds equivalent delay and a pilot-rating degradation of roughly 1 per 30 ms in tight tracking tasks up-and-away, or during approach and landing. The much reduced sensitivity seen in ground-based simulations, comparable to that in less stressful fligbt evaluations, illustrstes that "realistic stress levels cannot be properly replicated in ground based simulators." Thus potential flying qualities "cliffs" may not be found in ground simulators.

Flying qualities criteria need to account directly for the total apparent time delay. MIL-F-8785C and proposed MIL STD equivalent time delays, Hoh's proposed bandwidtb vs delay-parameter, and the Neal-Smith criteria are discussed. The latter could be improved by incorporating sensitivity to bandwidtb. Tbe equivalent systems approach seems more complicated, controversial and of more limited utility than it need be.

In roll, less time delay can be tolerated at either very short or very long roll mode time constants.

19. <u>Prepared Comments on the Preceding Paper</u> - Capt Bakker comments from his experience that tbe F-16 head-up display (HUD) introduces additional time delay, "30 ms for the flight path marker presentation and...up to 50 ms in AOA presentation". Those delays would add directly to the total equivalent delay when tbe pilot controls to those HUD symbols - leaving only 80 ms instead of 130 ms for the flight control system before an impact on flying qualities would be felt.

He comments too on the F-16's n_z + α control law for landing, whicb makes attitude control less precise and the airplane sensitive to gusts. Removal of the α signal upon main-gear strut compression causes a sudden trim cbange. With sensitive stabilizer control, tail strikes are possible on take-off and landing. A slower α fadeout and change to a pitch rate command system, using α only at bigher αs, have been evaluated and recommended.

20.   **An Example of Longitudinal and Transversal Oscillation Coupling: The Epsilon Aircraft "Cork Screw".**   - Irvoas described a divergent pitch-roll-yaw "corkscrew" motion while sideslipping the prototype Epsilon (a light primary trainer for the Armée de l'Air). This unpredicted oscillation, for which no flying qualities requirements exist, could reach ± 2 deg sideslip, ± 1.25 deg angle of attack. Two aerodynamic nonlinearities, $C_n(\beta,\alpha)$ and $C_m(\beta,\alpha)$, were found to be the cause. Also the propeller slipstream modifies the fin yawing moment contribution. A simplified 4-degree-of-freedom analysis yielded criteria that large positive $C_{n\alpha}C_{m\beta}$ and small $-C_{n_r}C_{n\beta}$ lead to this trouble. Relocating the horizontal stabilizer down and aft, and modifying the tail surfaces, changed these characteristics, completely eliminating the problem for the production airplane.

McRuer pointed out the significance of C_{n_α} and C_{m_β} also on loss of control at high angle of attack.

21. **Advanced Flight Control Design Techniques and Handling Qualities Requirements** - Cunningham and Pope decry the inadequacy of specifications and design methods based on single-input response and decoupled loops when multi-input, multi-axis dynamic coupling and high levels of augmentation are becoming prevalent. Even linear quadratic Gaussian (LQG) theory only guarantees robustness for full state feedback, which normally is not done. They show an expansion (Ref. 21-5) of basic feedback principles to the multi-input, multi-output case. This expansion involves the maximum and minimum singular values of the system matrices, a generalization of phase and gain margins. A system's singular values are compared to performance and uncertainty bounds, to determine suitable control laws to achieve a large loop transfer function to make errors small, attenuated at high frequency to stay within bounds on model uncertainties and sensor noise & uncertainties. They demonstrate a "recovery procedure" to extract a robust partial state feedback system from a LQG full-state design, utilizing a Kalman-Bucy filter. They think this approach to be greatly preferable to a classical "single-loop-at-a-time" approach, which is "not generally reliable in achieving the design objectives...The difficulty is that the selected set of scalar design functions are not necessarily related to the system's actual feedback properties."

Although the C* boundaries used in the example seem not to correlate well with flying qualities ratings, most any other criteria could be used with the method presented. Also, this frequency response method can accommodate any time delays in the actual system, leaving only the pilot's time delay to be accounted for otherwise [a pilot model might be included?]. The inherent robustness of the design should help allow for variations in pilot characteristics and for aircraft nonlinearities.

22. **Analyse du Rôle des Asservissements pour un Avion Subsonique à Stabilité Longitudinale Réduite** - Iannarelli presents approximate formulas and charts to show the relationships among various static stability margins with both "elementary" or "natural" and "elaborated" augmentation - the latter being either autotrim or flight-path angle hold. He wants to keep control force per g relatively constant over the speed and center-of-gravity ranges (Although no Mach no. effects per se on aerodynamics are considered, m_v is accounted for) while (a) meeting the minimum control force/speed gradient requirements; (b) keeping a fairly constant, short incidence-response time (allowing for the servo bandwidth), (c) keeping short-period and phugoid frequencies well separated and (d) maintaining enough short-period damping. The insights are valuable, especially to those who think in traditional terms of static and maneuver margins. He points out some implications of possible failures in mechanical and electrical flight control systems. For feedback, angle of attack does not seem to be a good parameter.

SESSION VI - TECHNIQUES FOR THE DETERMINATION OF HANDLING QUALITIES
        Chairmen: F.N. Stoliker, AFFTC and
        Prof L M B C Campos, Instituto Superior Tecnico

23. **Development of Handling Qualities Testing in the 70's. A New Direction** - Schofield, Twisdale, Kitto and Ashurst trace the evolution of flight testing at Edwards AFB up to the current System Identification From Tracking (SIFT) techniques. "...it is historically evident that handling qualities testing necessarily (and beneficially) spans" the duration of a flight test program. SIFT involves acquisition of both quantitative data and pilot opinion in aggressive tracking maneuvers. From the records, frequency responses are extracted; multiple inputs can be handled. The combination of pilot comments and identified aircraft characteristics for the same maneuver is particularly helpful. Aggressiveness in tracking is the key both to exposing handling deficiencies and to satisfactory quantitative and qualititative identification. "Our experience was that air-to-air tracking was a 'global' test maneuver for evaluating handling qualities...If handling qualities were optimized for air-to-air tracking, they turned out to be optimized for all other tasks as well." Statistical measures have proved variable and generally unreliable; also, they do not measure pilot mental workload.

Pilots can exercise effective control at frequencies up to 10 rad/sec, beyond which pilot input has been observed to be reduced. Even for nominally lower-bandwidth tasks - and for large aircraft - very aggressive control is warranted in order to assure adequate control in unusual, critical situations. "If you've got a handling qualities problem, you'd darn well better know during flight test that that problem is there."

Higher-frequency target maneuvering would be helpful, but AFFTC is investigating use of the head-up display as a more practical step; a programmed target also would allow extraction of pilot transfer functions, which cannot be done with the present method.

24. <u>Experience with System Identification From Tracking (SIFT) Flight-Test-Techniques at the German Air Force Flight Test Center</u> - Buchacher presents the case of a CH-53 helicopter with a slung load. Severe vertical oscillations had been experienced on two occasions, stopped only by dropping the load. Theoretical analysis and flight-measured normal-acceleration response confirmed an 11r/s, lightly damped oscillation with a heavy cargo load. In flight test an uncontrollable vertical oscillation was excited by an abrupt collective pitch input. At 11r/s the pilot cannot exercise effective control but he still has some effect. Modeled as a gain and 0.2-sec time delay, the pilot would contribute large additional lag.

Frequency response data were obtained in tracking tasks, using a UH-1D as a target. In one test "All vertical oscillations were of small amplitude and could be corrected again by systematically 'freezing in' the controls and by releasing the collective trim", indicating a PIO. But the last oscillation apparently excited an "air resonance" at about the same frequency (related to the difference between main rotor and lead-lag frequencies) to amplify the oscillation further. The cargo had to be dropped in order to recover.

Chalk mentioned a "roll ratcheting" at 17 rad/sec with a very short roll time constant. It was agreed that measurements ought to go to at least 20 rad/sec in order not to miss any significant pilot-control frequencies.

25. <u>Prediction of Aircraft Handling Qualities Using Analytical Models of the Human Pilot</u> - Hess refers to his pilot model (25-3), giving a brief exposition of the cost function used to optimize the model: the integral of a linear quadratic function of pitch attitude and control input rate. He is thus able to relate pilot-induced oscillation (PIO) tendencies and pilot ratings from a number of moving-base and in-flight evaluations to his calculated crossover frequency for the piloted aircraft: a regression of the crossover frequency indicates a tendency for increased pilot gain, leading to PIO. The analysis, being linear, would not be expected to pick up PIO tendencies from nonlinear causes; also visual cues, not motions, are assumed. He presents an empirical metric which correlates with Cooper-Harper rating for 31 ground and flight cases: $POR = K_i[(\tau + \tau_D)/\tau]^4 J$, where K_i is a different constant for each data set (task), τ is the pilot's time delay (nominally .2 sec), τ_D is the equivalent time delay of the aircraft, and J is the cost index.

He observes that tracking low-bandwidth turbulence appears to cause less rating degradation than does discrete-command following or abrupt maneuvers. The longer allowable time delay for the low-bandwidth task accounts for the need for the time delay term in the metric. The method seems to "hold up reasonably well" in lateral and multi-axis tasks.

26. <u>Simulation for Predicting Flying Qualities</u> - Reynolds compares in-flight simulation to ground-based simulation with various motion and visual cues. For instrument-flying training, the limited motion of ground-based simulators has doubtful value except as a cue for engine failure. Although after the first flight of a new design the pilot may comment that "it flew just like the simulator", he may in fact not be referring to flying qualities per se. Also, sometimes psychological or political factors influence an evaluation, e.g. competition during ground simulation to fly the real vehicle. "Further progress in [assessing proper simulators and techniques] seems to be hampered by the lack of definitive data."

The YF-16 roll sensitivity was first optimized in ground-based simulation, lacking a good roll acceleration cue. This sensitivity was reduced by a factor of 18 by the end of the flight test program. For "another" lightweight fighter prototype, in variable-stability NT-33 flight simulations a flight control system "designed and developed with the benefit of a ground simulator with large motion capability" was found to be susceptible to pilot-induced oscillations (PIOs). Although the data are scattered, ground-based simulation with motion (NASA Ames FSAA) and in-flight simulation (USAF/Calspan TIFS) found comparable Level 2 flying qualities boundaries for relaxed static stability in a supersonic transport. A new problem in roll control of large airplanes was only apparent in flight: the cockpit lateral acceleration associated with height above the flight-path roll axis. Shuttle landing experience illustrates the need for high-gain pilot control in order to bring out some handling deficiencies, and the difficulty of motivating pilots to do that in ground-based simulators. The opposite rating trends for direct lift control (a help in ground simulation, worse in flight, Ref. 26-12) may be real, because of limited ground simulator motion; or they may be the result of unintentional normal-acceleration oversensitivity in flight (Paper 7)[See also Paper 10].

Some rules of thumb seem to hold but need further study: cut roll sensitivity in half from the ground-based optimum; touchdown rate of sink is half the value from the ground-based simulator; if flying qualities are good in ground-based simulation they will be good in flight, except that PIOs are hard to get on the ground; poor flying qualities on the ground are unreliable indicators of characteristics in flight. Remaining motion-cue questions include the significance of transfer functions of platform motion, cueing thresholds and the adequacy of motion cues for turbulence.

Representative of present capability, the TIFS airplane has minimum response delays of about 0.1 sec. Digital computation gives considerable flexibility, although large n_z/α or speed mismatch tends to limit the allowable amplititude of motions. In general, eye height cannot be matched if actual touchdowns are made in order to get higher pilot gain.

Cost of in-flight simulation per hour is comparable to that of elaborate ground simulation, he says, although productivity in approach and landing evaluations is higher on the ground because of the simulator's reset capability. The role of in-flight simulation has been to complement analysis and ground-based simulation for research, design verification, flight-test crew training, a test bed for flight hardware, and study of discrepancies between the actual vehicle and other simulations & predictions.

PANEL DISCUSSION

Ralph A'Harrah	– Assoc. Director, Air Vehicle Technology, US Naval Air Development Center
Dr. Peter Hamel	– Director, Institut fur Flugmechanik, DFVLR
Larry Dooley	– Head, Rotary Wing Handling Qualities, Bell Helicopter
Donald T. Berry	– Head, Man-Machine Dynamics Section, NASA Dryden
Chester Miller	– Dir, Aeromechanics, F-18 Flight Control Integration, McDonnell Acft.
John Gibson	– Handling Qualities Consultant, British Aerospace, Warton
Harold Mooij	– Deputy Head Flight Dynamics, NLR

Peter Orme, British Aerospace pilot, was impatient with our collective inability to turn out an airplane with completely good flying qualities. He traced this lack partly to the limitations of ground-based simulation. Lower pilot gain than in flight is the result of differences in task, stress and cues. Simulators' visual cues are not adequate; he thinks stress might be heightened by increasing their verisimilitude. Berry, commenting that simulator limitations are not well defined, pointed to the need for research, and the need to document simulations thoroughly. Rotary-wing simulation in nap-of-earth flight was cited as (a) needing increased visual fidelity and (b) more in need of piloted simulation because so many nonlinearities limit analysis. LaBurthe has measured pilot stress; it is there. In simulation he sees three lacks which reduce pilot stress: noise, workload simulation (e.g. radio communication) and means to forecast the status of the aircraft. Then he asked, "How can we possibly define the quality of good motion cues?" Nobody answered.

Capt. Fuller sees aircrews becoming systems managers; the increasing complexity of the job makes it harder to keep ahead of the airplane, and we have no requirements about this interface. The crew has to look out, not inside the cockpit. He believes that performance – mission performance – should be sacrificed if necessary to get the best flying or ride qualities.

Capt. Bakker asked the effect of in-flight simulator limitations: load factor, speed, etc. Many tasks involve only smaller motions, but there are physical limitations which must be considered, so that for fighter-type maneuvers and some other situations a more capable simulator is needed.

Moorhouse, noting a concentration of effort on longitudinal short-term motion, hopes to spur further lateral-directional study. That applies also to helicopters, it was said. Lateral-directional criteria are more difficult, according to Rickard, as well as lacking and badly needed. Wunnenberg and Balmer stated manufacturers' views that requirements be well founded and applied only where needed. To that, Lewis commented on consequent needs and difficulty of change later on. Helicopter flying qualities requirements are not yet well defined; neither are their missions. Miller feels a need to be held to meet valid criteria. He believes he has the rapport with procuring activities to negotiate any questionable requirements [but American manufacturers are not unanimous in this view]. Moorhouse, seconding Miller, pointed out that missions change during the life of an aircraft. The greater competition in the U.S. demands a rather formal relationship between the military and the contractors in the initial stages.

Schofield opined that the SIFT technique can identify good and bad flying qualities and the frequency response of the vehicle, but is not particularly good for directly determining why. He values the lower-order equivalent system for sorting out the design implications. Buchacher would like to see a specification in the form of a pilot model which could be applied to any aircraft. Lewis recalled that helicopter pilots adapted more easily to handle a shuttle landing simulation than did outstanding airplane test pilots; experience can't necessarily be extended to exotic configurations.

Schanzer and Hamel relate landing difficulties with wind shear and gusts to low-frequency handling qualities.

In MIL-F-8785C the emphasis on failure transients has shifted, according to Woodcock, from requiring very small transients to allowing larger values that are more practical and also give some notice of the occurrence.

On the question of task definition, Key hopes to group and characterize families of tasks. Evaluations need to have the essence of appropriate tasks represented in more structured form.

Gibson had found short-period frequency and damping requirements insufficient for Tornado pitch response (though adequate for n_z). For the "superaugmented" fly-by-wire Jaguar, because "there were no handling criteria suitable to that kind of control system" they developed their own (see Paper 4). Alterations in the forward path and command shaping were used to meet these criteria and provide good handling for both airplanes.

Dooley commented that the Army's nap-of-the-earth mission is now driving helicopter handling requirement development. He prefers task performance criteria, but recognizes the need to translate these into design. Woodcock pointed out the importance of workload as well as task performance, and our present lack of a good grasp on workload.

Woodcock cited a TIFS flight evaluation involving both angle-of-attack stabilization and superaugmentation of basically unstable large transport airplanes. Data from both were consistent and indicate that an extension of the present form of requirements may fit both cases. A'Harrah too perceives a lot of credible guidance for higher-order systems in present requirements. He feels that emphasis now should be on forming a good working relationship between the flying qualities and flight control systems communities.

EVALUATION

A quick glance at Table 1 is enough to see that far more was said about short-period motion, or the longitudinal short-term response, than on any other aspect of airplane handling. Generally, treatments were based on either a classical second-order "equivalent system" with an additional time delay or on the complete (linear) transfer functions of the augmented airplane.

We see several adaptations of older criteria to particular design uses, and styles ranging from static & maneuver margins to Kalman filters. Thus we have a variety of tools for cross-checking different aspects of short-term handling. Correlation with flight data is claimed for each method, but some of the papers would have had more impact if the correlations - or at least some measure of them - had been shown. With the sparse data base used in so many ways it is refreshing to see a few new sets of flight data. Each one adds to our understanding, and suggests useful new or revised criteria. However, they also raise unanswered questions: just what use is direct lift control? Why do ground-based and in-flight simulation give different answers to that question? How different are some critical piloting tasks with conventional and rate command/attitude hold controls? What are reasonable task performance standards for various mission phases and classes of aircraft? Definitive answers are needed for designing the next generation of aircraft.

Authors' opinions remain divided about the merits of the "equivalent system" approach mandated by current U.S. military flying qualities requirements. This seems to be due in part to continuing confusion over the significance of n/α, the ratio of steady-state normal-acceleration and angle-of-attack sensitivities. Should this be considered proportional to the effective pitch numerator inverse time constant $1/T_{\theta 2}$? Certainly pitch control is an important inner loop for most demanding flying tasks (including the final airborne stages of landing even a RC/AH-type aircraft, according to recent USAF/Calspan flight evaluations, Ref 3). Both lower and upper bounds on $\omega_{SP} T_{\theta 2}$ seem warranted (among the reasons: lower, for frequency separation between outer-loop path and inner-loop attitude control or to preclude "negative attitude dropback"; upper, to limit the tendency to bobble with abrupt command inputs). There is also a rationale for bounding ω_{SP} with limiting values of $\omega_{SP}^2/(n/\alpha)$, and several speakers at this conference consider Bihrle's original CAP, $\ddot{\theta}_0/n_{z_\infty}$, to have validity in itself. While things may work out if the effective value of $1/T_{\theta 2}$ is close to $- Z_w$ and the pilot is forward of the instantaneous center of rotation, in general some additional requirement is needed to assure adequate flight-path control. Both Mooij and Chalk suggest a minimum bandwidth of about .55 r/s for path control with the pilot closing an inner attitude loop. These authors and others have also suggested a modified Control Anticipation Parameter: for example,

$$CAP = |F_e/n_p|_{ss} |\ddot{\theta}/F_e|_{max}$$

The meeting saw a consensus that time delay is an extremely important flying qualities parameter related to pilot-induced oscillation (PIO) tendency, however the parameter is defined. But opinions differed on what its bounds should be (due to differences in the tasks investigated?) Presently MIL-F-8785C limits equivalent and actual delay between the pilot's control input and airplane motion response to 0.1 sec for Level 1, and Clark (Paper 2) quotes the same value for hover and low-speed attitude control. Hoh's proposed revision would make that a function of pitch bandwidth, but no more than 0.06 sec. for up-and-away flight. But Mooij and van Gool "observe that an equivalent time delay of 0.2 s...has not degraded pilot opinion". And Brauser found that "τ_a increases the PIO tendencies if its value exceeds 0.3 sec.", for pilot-in-the-loop analysis results correlated with the Neal-Smith criteria. Smith has found a much greater sensitivity to increasing delay, once past the threshold, in flight than in ground-based

Table I - Airplane Short-Period Motion Discussions

Paper No., Subject	Short-Period Parameters	Correlation or Source	Other Subjects Discussed
1. Status of Flying Qualities Criteria	$\omega^2/(n/\alpha)$, T_{θ_2}, CAP, ωT_θ, ω_{BW}, τ, t_q, S, $\not\geq\theta/F_s(j\omega_c)$, C*, TRP, $\Delta q_2/\Delta q_1$, Δt, $\lvert\theta/\theta_c\rvert_{max}$, $\not\geq pc$, $\Delta A/\Delta\not\geq$, $rms\theta_e$, time on target, Paper Pilot parameters	Incidental	Dutch roll, a_y in rolls
3. Equivalent Systems	τ, $\lvert\theta/\theta_c\rvert_{max}$, $\not\geq pc$, ω_θ, ω_{BW}	Neal-Smith*, LAHOS* for ω_θ & (presumably) ω_{BW}	τ for V/STOL ϕ response
4. Higher-Order Systems	θ dropback, t_γ (delay), t_{n_z} (rise time), n_z hang-on, q_{max}/q, $\omega_n T_{\theta_2}$, ζ, $\lvert\theta/F_s\rvert$, $\not\geq\theta/F_s$	8785B for n_z time response & F_s/n, 2 Phase & LAHOS for dropback, Hall* for PIO, LAHOS + acft for Nichols	"can also apply to ϕ"
5. Gain, Phase Margins	F_s/n, ω, ζ, T_{θ_2}, τ interpreted as GM, ϕM, max. departure from K/S	Neal & Smith	–
7. Rate Cmd/ Attitude Hold	ω_{n_q}, τ_q, K_{DLC} varied, ω_{n_q}, n_{α_e}, $\lvert\theta/\theta_c\rvert_{max}$, $\not\geq pc$, ω_{BW-h}, $\ddot{\theta}_{max}/n_{p_{SS}}$, T_{rise}, τ_e. (C*, $\theta/\dot{\theta}_{ss}$, $\Delta A/\Delta\not\geq$, ϕ, $d\phi/d\omega$ discarded)	NLR simulator*, TIFS flt eval.*	Equivalent roll time constant, delay
8. Longitudinal Control	Step n_{z_c}: n_z delay, rise time, ζ Dynamic: ω_n, ζ, $\dot{\theta}/\delta_{STEP}$, roots, $\lvert\theta/\theta_c\rvert$, $\not\geq\theta/\theta_c$ Piloted: τ_e, ζ_k, ω_k, $\bar{K}*$	 N-S*, 8785B* <u>criteria</u>	–
9. Bandwidth	ω_{BW}, τ_p	N-S*, LAHOS*	Heading BW for wings-level turn
10. HQ with Advanced Flight Controls, DLC, RC/AH	ω_{sp}^2/n_α discarded – use ω_{sp}, ζ_{sp}, T_{θ_2}, $\dot{\theta}/\dot{\theta}_{ss}$, $\lvert\theta/\theta_c\rvert_{max}$, $\not\geq pc$, $\phi(\gamma/\theta)\lvert\omega_{sp}$ or ω_θ	DFVLR DLC var.* Assorted acft	–
18. Effect of Time Delay	τ_E, τ_{Eff}, τ_p	LAHOS*, ESP*, HOS*	Roll τ, T_R
19. Time Delay in Display, +	Total τ, M_δ, α stability, FCS mode-switching transient	F-16	
21. FCS Design Techniques	C*(t), $\underline{o}(\omega)$, $\bar{\sigma}(\omega)$	–	Ride quality
22. Control Augmentation for Subsonic Aircraft	F_q, F_α, X_G $\partial F_s/\partial n_z$, response time	–	F_v, $\partial F_s/\partial V$
23. System Ident. in Flt Test	$q(j\omega)/\delta(j\omega)$; pipper error discarded	–	Coupling
25. Prediction of Pilot Ratings	$Y_p Y_c = \theta(s)/\theta_e(s)$, K_1	F-8 DFBW*, Arnold*, LAHOS*, Miller*, N-S*, Stengel*, Sammonds*	Wings-level turn
26. Flying Qualities Simulation	Pitch PIO in landing Relaxed static stability Direct lift control	–	Roll: $L_{F_{as}}$, a_y

*Correlation data are shown

simulation - a possible explanation of some of our airplane development troubles of recent years. Bakker pointed out the obvious but easily overlooked contribution that a director display can make to the total effective time delay. On a Nichols plot such as Gibson´s, time delay results in less attenuation at -180 deg open-loop phase, a trend in pitch response which he associates with PIO tendency. At another meeting A´Harrah opined that proper interpretation of present MIL-F-8785 requirements, including phase lag or time delay, is sufficient to avoid the PIOs we have seen.

While digital computation does not directly add a long time delay, in some cases the computer nevertheless has heen the source of much of the incresse. Sampling adds a little delay. But digital computation offers so many possibilities that American flight control designers have been enticed to "take advantage of having a computer." As a result the airplane ends up as a much higher-order system with a much longer equivalent time delay than it need have. But we have hsd excessive delays in analog control systems too. Everyone concerned with flying qualities needs to stress to his flight control system counterparts the importance of minimizing the effective time delay.

For other reasons also we need to work more closely with flight control system designers. While Maj. Steward (paper 13) brought out the increasingly severe mission requirements for combat helicopters, the same trend is seen for airplanes. Sqdn Ldr Barnes (Ref. 5) gives one account of the problems. With pilots´ time occupied more in systems management, less attention is left for flying the airplane. Stabilization and automatic control systems must he tailored to ease the pilot´s workload with due regard for safety and for retention of pilot control capshility to supplement or take over automated functions as may be necessary. As a starter, some papers cite the help offered hy attitude hold/rate command systems, forward-path integration and wing levelers (these features do carry a need for special sttention to stall hehavior). Other sspects are cooperation of pilot and fire control system (Cord, Ref. 6), pilot and flight control system (Schmidt, Ref. 7).

Another reason advsnced for the elusiveness of PIOs is the influence of the task, the environment and the pilot´s aggressiveness, or "gain", in pursuing it. Rogers "Cliff" Smith was, I believe, the first to designate this phenomenon: only when tracking a target, runwsy aim point, etc. with sufficient intensity would a seemingly henign sircraft fall off a "flying qualities cliff" into a PIO. At this meeting a number of people expressed agreement. Perhaps Schofield stated it as clearly as anyone, talking about AFFTC´s SIFT technique. Under questioning, he advocated use of aggressive tracking as a general evaluation tool, whatever the airplane´s size or operational role, to bring out any handling deficiencies that might otherwise go undetected until a sufficiently stressful situation inevitably comes up in service. Short of PIOs, however, he has found tracking performance measures too variable to be of any use; pilot comments and ratings, however, are remarkably consistent and useful in getting at the nature of any problems.

A few papers and a spectacular motion picture treated flight at high angles of attack, a region in which most handling requirements are qualitative. Mirage 2000 pilots, initially distrustful of load-factor and incidence limiters, have gotten to trust the soft limiters. An MBB design showed the usefulness of very high angles of attack in air combat, and of thrust vectoring for control at extreme incidence - provided, of course, that the engine maintains sufficient thrust. Booker, pointing to the cost of providing carefree maneuvering, advised restricting such design to aircraft which really need the capability in order to perform their mission, and restricting aircraft maneuvering in other cases to an extent that would not interfere with the mission. We see here the continuing argument ahout the utility of flight at extreme incidence. At Florence (AGARD-CP-319) it seemed quite helpful in one-on-one combat hut possibly dangerous if more enemy aircraft were involved. But then the many-on-many situation seems to degenerate into purely a matter of numbers. One present paper, by Ross, holds some hope for the analytical tractability of aircraft problems involving inertial and aerodynamic nonlinearities. Equilihrium conditions can be found, bifurcation boundaries traced, and even some cases witb simple nonlinearities analyzed for stahility.

Flight control system and hsndling robustness was a design consideration in one paper, from the standpoint of meeting performance requirements while allowing for a range of uncertainties in a linear system. Although during the meeting relaxed static stahility got much attention, that too was directed at linear flight control systems. In the end, robustness must also connote having enough control authority and rate to avoid problems with limiting. This aspect was only mentioned in passing. One would hope that the reason for this seeming slight is a universal recognition of its vital importance, so that no need was felt to belahor the point. For further discussion, see A´Harrah & Woodcock (Ref. 8) or Moorhouse & Woodcock (Paper 1 or Ref. 9).

Criteria for lateral-directional handling remain inadequate. The slight of this subject evident in Table 1 is attributed to the difficulty of solution. Could the bandwidth concept he useful here? An encouraging sign, however, is the success in analyzing some particular nonlinear, coupled behavior at low incidence (Irvoas, Paper 20) and high incidence (Ross, Paper 17). The roll response, especially at high angle of attack, poses an unresolved dilemma. If we concede the desirability of rolling about the flight path in order to suppress Dutch roll, adverse yaw and the nonminimum-phase pendulum effect in tracking, we get unwanted, often large, lateral acceleration of the pilot. Mitchell and Herbst (at Florence) have identified a possible solution in use of

direct side-force control to raise the roll axis, keeping it parallel to the flight path, if the drag penality of side-force surfaces would be acceptable.

Handling qualities of short-take-off-and-landing vehicles, rotary-wing aircraft in general and also V/STOL aircraft are in a more primitive state, reflecting at least three factors: (1) the inherent difficulties & complications, (2) the (perhaps consequent) shortage of attention to development of generalized requirements and (3) the emergence of extremely severe mission requirements, expressed so emphatically by Maj Steward. We plan to expand the U.S. military airplane flying qualities specification to cover STOL aircraft. The U.S. Army program (with Navy help) to replace the 1961-vintage MIL-H-8501A with a more nearly adequate flying qualities specification for rotary wing aircraft is long overdue. Likewise, the Navy's work on V/STOL requirements is sorely needed if successful aircraft are to be developed for advanced missions: night & bad-weather operation, basing on small ships. In these applications particularly we see a clear relationship between task requirements and control/display complexity.

The equivalent system approach has been shown (Clark & Goldstein, Paper 2) to have application to V/STOL as well as conventional aircraft. However, the need to vary the form of the requirements with the type of stabilization seems unfortunate. Also unfortunate is a seeming need to specialize some handling requirements to particular configurations among the varied possibilities. Perhaps here also some form of bandwidth criterion would produce more homogeneous requirements. On the other hand, to be expected – and sought – is the definition of handling requirements in terms of different tasks. With some results in hand for hover and low-speed flight, work is starting on criteria (which have been almost entirely qualitative) for conversion and forward flight. Another program is evaluating multi-axis controllers made feasible by switching from mechanical to electrical or optical signal transmission; these controllers might even find application for direct force control in airplanes.

Helicopter handling qualities traditionally are poor, cross-coupled, nonlinear, sometimes unstable; and the present emphasis is on more demanding missions. With such tasks as nap-of-earth (NOE) flight it seems helicopter pilots are asked to do a more dangerous and difficult flying task with inherently poorer flying qualities than those that confront airplane pilots. One could not escape the impression that such helicopter piloting requires machismo in large amounts. The "superaugmentation", "active control technology", etc. finding their way into fixed-wing aircraft will also extend helicopter mission capability greatly, provided that they can be made reliable enough and maintainable in operational situations. This would appear to be a fertile field for exploiting Kretz' concept of independently controlling each rotor blade sans swashplate. Formulation of suitable handling requirements for these tasks is a special challenge because of (a) flight safety limitations on in-flight evaluation and (b) the need for a better outside visual scene than can now be presented in ground-based simulation. Since the SIFT technique has already found application to helicopters (Buchacher, paper 24), perhaps some evaluation tasks and maneuvers can be found which are safer, yet intensive enough to bring out any problems of actual full-bore NOE flight.

Lastly, some personal observations. It is very evident that the data base for handling criteria needs to be expanded for all aircraft as performance and mission demands expand. Both analytical and experimental approaches need to be pursued. We have seen some acceptance of simple pilot-vehicle analysis, for example the single-loop Neal-Smith criteria for tracking tasks and the concept of an outer-loop path-control bandwidth. However, we don't really understand pilot workload and our ability to measure it is poor. ONERA, NASA-BBN and similar efforts to develop better models of aircrew action should lead to a better understanding of the way in which tasks influence the requirements. At the other end of the spectrum we have seen the unique value of in-flight simulation, and flight experience is important in gaining acceptance of requirements. In order to develop flying qualities criteria adequate for the needs we foresee, we will have to build a data base through utilizing existing variable-stability-and-control aircraft where they have capability and also to advocate more capable vehicles of that sort in order to reach out far enough.

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acceleration, use of aircraft attitudes, and usage was to characterized by frequent accelerations and decelerations throughout the speed range of hover to maximum dash," including the "quick-stop" and decelerating turn, with cross-coupling problems to be kept in hand. Loss of concealment, view restrictions, ground clearance, and precise control are factors. All axes of response are important. "At 100 kts, roll rates up to 100 °/s were found to be likely whilst at 60 kts on a small triple bend task, very high roll rates up to 150°/s were called for; maximum pitch rates demanded were typically 20-30 °/s.

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