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Roll Response Criteria for Transport Aircraft with Advanced Flight Control Systems

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Two experimental programs have been carried out on a ground-based simulator in which a number of characteristics of a roll-rate-command/bank-angle-hold system have been investigated for transport aircraft in the approach and landing flight phase. The results indicate that the existing roll response criteria are, in many cases, too lenient. This surprising observation suggests that advanced flight control systems must comply with stricter criteria than conventional systems to obtain the same degree of pilot approval. It is concluded that a pilot, having available a more precise flight control system, increases the internal "standard" according to which he judges handling qualities. Based on these results existing criteria are redefined and new criteria formats are proposed.

Nomenclature

KIAS	= knots indicated airspeed
p	= roll rate, level of significance
p_{max}	= maximum attainable roll rate
$\dot{p}_{max}$	= maximum attainable roll acceleration
R	= multiple regression coefficient
t	= time
T_p	= equivalent time delay
$t_{30\,deg}, t_{60\,deg}$	= time to roll through 30 or 60 deg, respectively
$t_{63\%}$	= effective roll mode time constant
Φ	= bank angle
Φ_{1s}	= bank angle after 1s of a step-type full lateral stick deflection
τ_R'	= equivalent roll mode time constant

I. Introduction

It is generally recognized that future large transport aircraft will most probably be equipped with advanced flight control systems, which are expected to provide improved performance and more economical flight operations. Expressions like "fly-by-wire" and "active control" have become familiar to the aircraft engineering community.

Since controllability of such aircraft as experienced by the pilot will be determined to a high degree by the characteristics of the flight control system, it is important that suitable criteria exist that are usable by the flight control system designer. Because the contemporary criteria for good flying qualities have been formulated on the basis of conventional aircraft characteristics, it should be investigated if these criteria are still applicable to aircraft with full-authority command and stability augmentation systems. It is obvious that the final approach and landing flight phase, being one of the most critical parts of the operational flight envelope for transport aircraft, should be considered first.

Several characteristics of subsonic transport aircraft fitted with advanced flight control systems have been under study for some time. The control system type considered to be most promising for CTOL transport aircraft in the landing approach is rate-command/attitude-hold.

Investigations directed at longitudinal flying qualities of such aircraft have been carried out, using moving-base flight simulators and aircraft.[1] In the last few years, the attention has been focused on the lateral-directional flying qualities of aircraft fitted with rate-command/attitude-hold flight control systems.

An investigation has been carried out in 1978 in which the roll control characteristics of a roll-rate-command/bank-angle-hold flight control system were varied. The results have been reported at the AIAA 6th Atmospheric Flight Mechanics Conference.[2] A problem arose in this investigation because the mechanization of the roll control system introduced lags in the roll response that were disliked by the pilots, and the maximum roll rate provided appeared to be on the low side. Furthermore a heading-hold system and a wings-leveller were mentioned as desirable features.

For these reasons it was decided to define a second experimental program in which the recommendations of the first program would be followed. Because time delays will most probably exist in future digital flight control systems (computational and conversion delays), it was decided to also devote part of the second experiment to investigation of the influence of pure time delays in the roll control system. The second experimental program was carried out in 1979, and the two experiments will be referred to as the "1978 experiment" and the "1979 experiment."

A description of the experiments, and the results of the pilot evaluation will be presented in the next sections. These results will be compared with the existing criteria for lateral-directional control to assess the applicability of these criteria for the control systems under study, and new criteria formats will be proposed. More details on flight control systems, experimental setup and the pilot commentary are presented in Ref. 3.

II. The Experiments

The Aircraft and Flight Control Systems

The baseline aircraft simulated was an F-28/Mk 6000, a medium-weight, two-engine jet transport to which the following modifications have been applied:

1) The horizontal tail surface has been reduced by 40%, and the stabilizer/elevator combination has been replaced by an all-flying tail.

2) A fly-by-wire control system has been designed to provide rate-command/attitude-hold properties for pitch, roll, and yaw motion (except in the 1978 experiments, where the standard rudder pedals-rudder connection has not been changed).

3) Pitch and roll control was performed using a side stick controller instead of a wheel/column combination.

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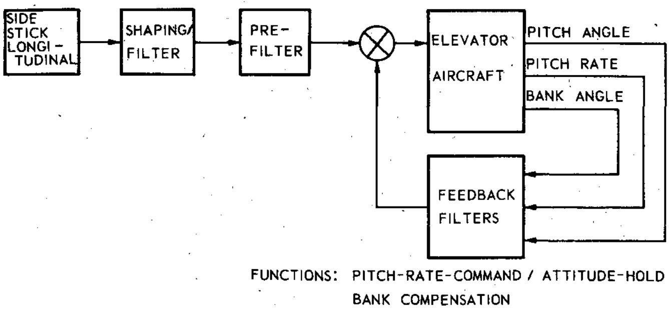

Fig. 1 Functional block diagram of the pitch control system in both 1978 and 1979 experiments.

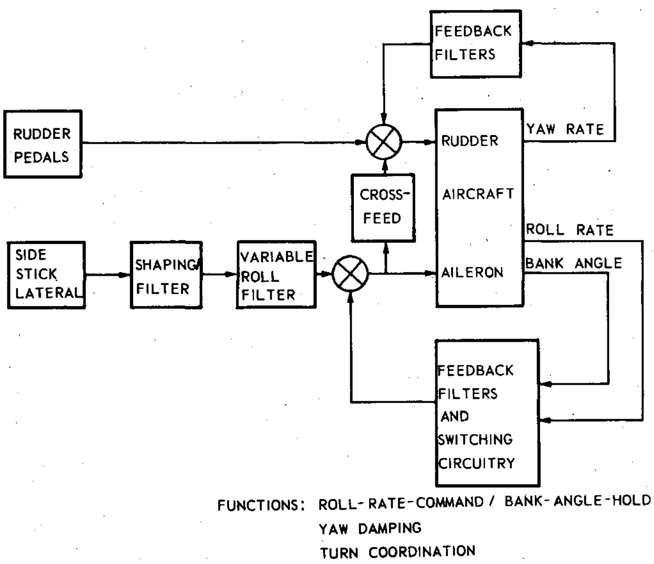

Fig. 2 Functional block diagram of the lateral-directional flight control system in the 1978 experiment.

The longitudinal control system, a block diagram of which is presented in Fig. 1, was designed such that a pitch-rate-command/attitude-hold system with satisfactory flying qualities was obtained.[1] A two-gradient pitch command filter has been used and bank compensation was included to relieve the pilot of the task of maintaining vertical equilibrium in turns.

A block diagram of the lateral-directional control system used in the 1978 experiment is presented in Fig. 2. A three-gradient roll command filter has been used.

Appropriate feedback of roll rate, and a switching circuit in the feedback of bank angle, provided the roll-rate-command/bank-angle-hold characteristics. A variable low-pass filter in the command path was used to vary the roll control characteristics.

A block diagram of the lateral-directional control system used in the 1979 experiment is presented in Fig. 3. Compared to the 1978 experiment a number of properties has been changed:

1) A lead filter has been introduced in the roll command path to cancel the lag introduced by the roll rate feedback loop.

2) A selectable pure time delay has been added to the command path.

3) Maximum available roll rate has been increased from 18 deg/s to 30 deg/s.

4) A wings-leveller, active at bank angles below 3 deg, has been added to the bank-angle-hold circuit.

5) A yaw-rate-command/heading-hold function has been installed for heading control with rudder pedals.

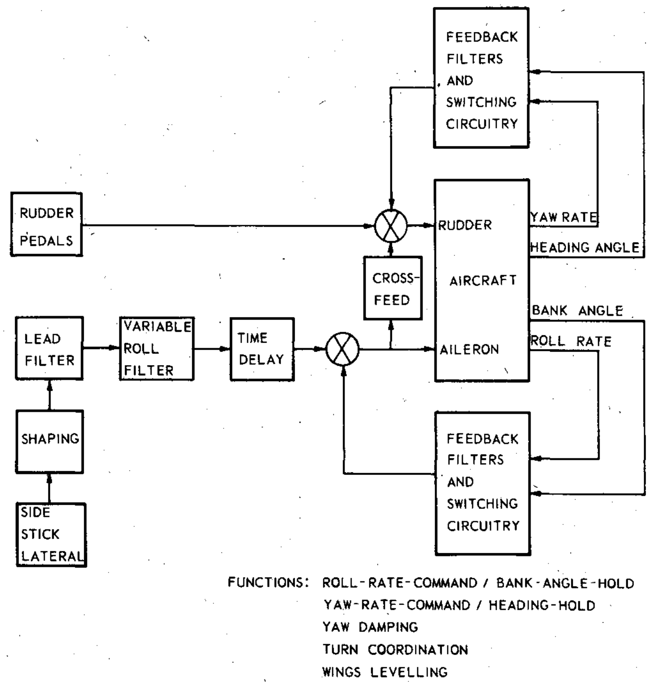

Fig. 3 Functional block diagram of the lateral-directional flight control system in the 1979 experiment.

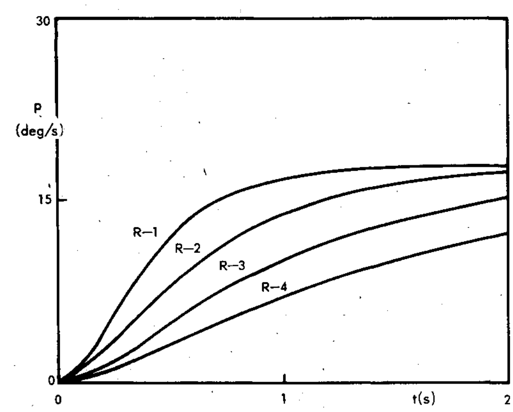

Fig. 4 Roll rate response to a step-type full lateral control deflection in the 1978 experiment.

In both experiments, a yaw damper and an aileron-rudder crossfeed filter for turn-coordination were part of the lateral-directional flight control system.

The Choice of the Flight Control System Parameters

The 1978 Experiment

Four configurations of interest have been selected by varying the time constant of the command path roll filter an appropriate amount. The variation was equivalent to a change of roll mode time constant for an unchanged value of maximum available roll rate. The roll rate responses to a step-type maximum lateral side stick deflection are presented for the configurations R-1 through R-4 in Fig. 4. The roll rate responses show an initial delay as compared to a purely first-order response.

The 1979 Experiment

Eight configurations of interest have been selected that can be subdivided into three groups:

Group 1: Roll mode time constant has been varied by varying the time constant of the forward loop roll filter while maximum available roll rate was kept constant at a high value—configurations T-1, T-2, T-3, T-4.

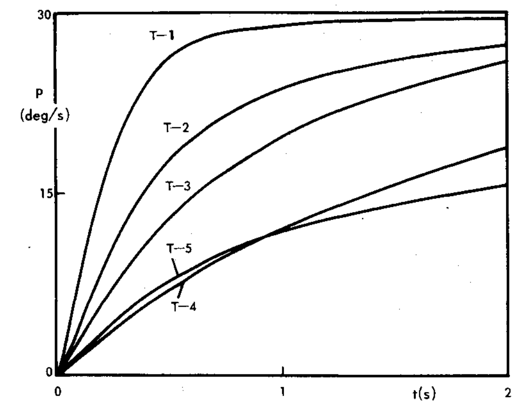

Fig. 5 Roll rate response to a step-type full lateral control deflection in the 1979 experiment (roll mode time constant—T-1, T-2, T-3, T-4—and maximum available roll rate—T-3, T-5).

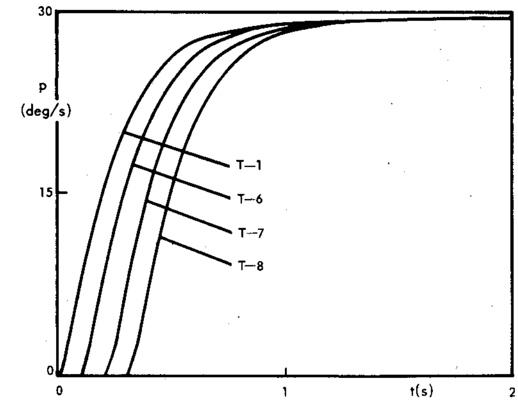

Fig. 6 Roll rate response to a step-type full lateral control deflection in the 1979 experiment (time delay variation).

Group 2: Maximum available roll rate was varied for one value of the roll mode time constant—configurations T-3, T-5. The roll rate responses to a step-type maximum lateral stick deflection is shown for configurations T-1 thru T-5 in Fig. 5.

Group 3: The magnitude of a pure time delay in the command path has been varied—T-1, T-6, T-7, T-8. The roll rate responses to a step-type maximum lateral side stick deflection are presented for these configurations in Fig. 6.

Simulated Environmental Disturbances

Three wind profiles have been used randomly throughout the experiments. In all profiles, the wind velocity and azimuth angle varied linearly with altitude from 305 m (1000 ft) to 122 m (400 ft). Wind velocity reduced in this interval from 15.4 m/s (30 knots) to 7.7 m/s (15 knots), and the azimuth angle changed 90 deg. At runway altitude the mean wind was in runway direction, or 90 deg left or right crosswind, so 67% of the landings were carried out in crosswind.

The turbulence model, used to generate turbulence components was structured according to the model described in Ref. 4. The standard deviation of the turbulence velocity was chosen to be one-tenth of the wind velocity at each altitude, which is a reasonable approximation for a neutrally stable atmosphere.

Flight Procedures

The evaluation pilots received written information on the experiments concerning aircraft and aircraft controls, task to be carried out, rating scales to be used, comment card, etc. In the 1978 experiment, no information concerning the nature of the parameters varied was given to the pilots. Pilot commentary and ratings in these experiments have led to the decision to inform the pilots in the 1979 experiment on the fact that the investigation was directed at lateral-directional control properties, and that longitudinal control remained unchanged.

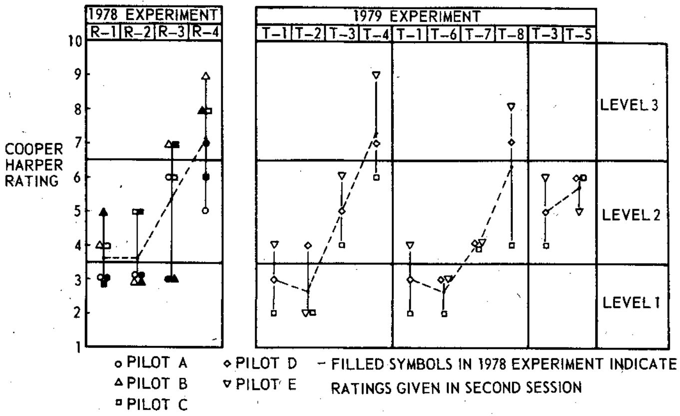

Fig. 7 Cooper-Harper ratings for lateral-directional handling qualities.

Each approach consisted of a localizer capture at 1500 ft, appropriate flap and gear selection, glide slope capture, and speed reduction to final approach speed 125 KIAS. At cloud base, 91.4 m (300 ft), a localizer offset of 83.5 m (1 dot on the ILS indicator), which was introduced randomly to the left or the right, was removed, thus forcing the pilot to make a visual side step maneuver before landing. In each session, a pilot carried out five approaches and landings with the same configuration under different (wind profile and side step direction) conditions. Familiarization runs were allowed in a structured manner before each session, and for each pilot the first two complete sessions were regarded as familiarization.

In each experiment, three evaluation pilots, experienced in medium and heavy weight transport aircraft, have evaluated all configurations. (One pilot participated in both experiments.)

Care was taken that the pilots evaluated the configurations in a pseudorandomized order, to ensure that the inevitable "carry-over" effects of what is learned in one configuration to the next would be different for each pilot. In the 1978 experiment, the four configurations (R-1 to R-4) have been evaluated twice by each pilot to investigate consistency in these kind of investigations. Both simulator programs consisted of, in total, 240 measurement runs and 240 familiarization runs.

III. Results

Performance Measures

Measures of the pilot aircraft performance have been taken in the following form. Standard deviations of a number of aircraft quantities (attitudes, rates, ILS deviations, stick and throttle deflections, etc.) on the approach have been computed. Furthermore a number of aircraft quantities has been determined at cloudbreak, over the runway threshold, and at touchdown. The measures have been analyzed using non-parametrical statistical methods, and the results were that only for a few performance measures significant differences between configurations could be established. Actual differences were very small, so it is concluded that the pilots have adapted their control behavior to the different aircraft and flight control system parameters in such a way that performance was only slightly affected by the parameter variation.

Cooper-Harper Ratings

At the end of each session, the pilots had to assign a Cooper-Harper rating for lateral-directional handling qualities. The results of the ratings in both experiments are presented in Fig. 7. The ratings of all pilots have been averaged for each configuration, and these values are connected by dotted lines. Because many subjective factors play a role in the pilot's selection of the Cooper-Harper rating, a scatter of plus and minus one rating unit is not unusual. Furthermore, differences in pilot background and experience may introduce different interpretation of the descriptions in the Cooper-Harper scale.

An impression of pilot consistency can be obtained by studying the ratings of the 1978 experiment, in which all configurations have been evaluated twice. The ratings for configuration R-3 vary considerably between first and second evaluation session for pilots A and B. In one of these cases, the pilot commentary indicated that difficulties in pitch control had deviated his attention from the roll control.

In the 1979 experiment, the pilots were informed that lateral-directional characteristics were the subject of investigation. Probably due to better guided attention, the ratings were less varying between the pilots than in the 1978 experiment. From the pilot commentary in both experiments, it was concluded that the ratings were mainly assessed by the task during the visual segment of the approach and the landing.

The following observation concerning lateral-directional handling qualities for aircraft with flight-control systems as used in the described experiments can be drawn:

1) For aircraft with roll control characteristics, as in the 1978 experiments, a Cooper-Harper = 3.5 boundary is close to configuration R-2, and a Cooper-Harper = 6.5 boundary lies somewhere in between configurations R-3 and R-4.

2) For aircraft with roll control characteristics with approximately first-order behavior, as in the 1979 experiment, the Cooper-Harper = 3.5 boundary for roll mode time constant variation is situated between configurations T-2 and T-3, and the Cooper-Harper = 6.5 boundary is situated between T-3 and T-4.

3) For the pure time delay variation in the 1979 experiment, the Cooper-Harper = 3.5 boundary is situated between configuration T-6 and T-7, and the Cooper-Harper = 6.5 boundary is very close to configuration T-8. No boundary is passed in the T-3, T-5 group.

A more detailed analysis of how these observations are related to existing handling qualities criteria will be presented in Sec. IV.

Effort Ratings

After completion of each run, the pilots had to indicate the effort that was required for a number of subtasks, by assigning so-called effort ratings on a number of scales. Nonadjectival, 10-point rating scales have been used, a higher number indicating more effort required. To be able to compare effort ratings given by different pilots (each with a personal rating style), the ratings for each subtask have been normalized per pilot. In this way, all effort ratings are brought on the same level (mean value zero, standard deviation one), and averaging over pilots is allowed.

Using a nonparametric statistical test (the Wilcoxon matched-pairs signed-ranks test), observed differences between effort ratings for different configurations have been tested for its significance. The results of this analysis are presented for the effort rating on roll control in Fig. 8, in which average values and standard deviations of the normalized effort rating in the measurement runs are presented. Significantly different effort levels ($p < 0.05$) are separated in this figure by dotted lines. (The results of the effort ratings on other piloting task items is presented in the formal report.[3] Apart from a few interesting details, the trends do not differ much from the results for roll control effort ratings.)

It is very interesting to compare the position of the significance boundaries in Fig. 8 with the position of the C-H = 3.5 and C-H = 6.5 boundaries in Fig. 7. The results suggest that passing the C-H = 3.5 or C-H = 6.5 boundary leads to a significantly different effort rating.

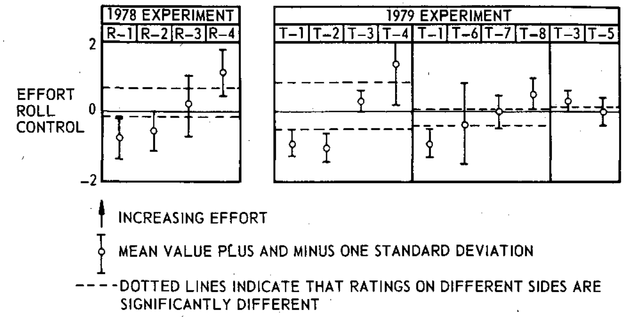

Fig. 8 Mean values and standard deviations of the normalized effort ratings on roll control.

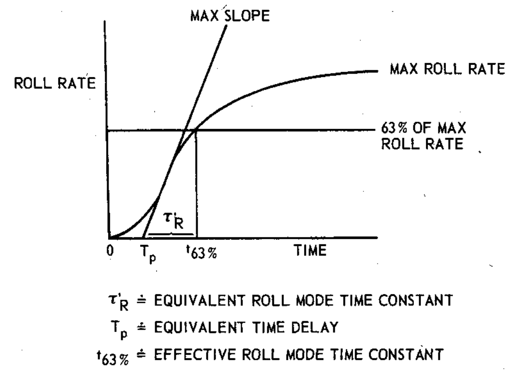

Fig. 9 Definition of effective and equivalent roll mode time constant, and of equivalent time delay, using the roll rate response to a step-type control input.

IV. Interpretation of the Results in Relation to Flying Qualities Criteria

Comparison with Contemporary Criteria

An inspection of the contemporary criteria in the form of airworthiness standards and specifications has been carried out. In the following documents, relevant quantitative criteria have been found:

1) US Military Specifications—Flying Qualities of Piloted Airplanes (Mil. Spec.)[5] and its background information and User Guide[6]
2) British Civil Airworthiness Requirements[7]
3) ICAO Airworthiness Technical Manual[8]
4) SAE Aerospace Recommended Practice[9]

The roll control systems used in the present investigations have characteristics that are unconventional, so the applicability of the existing criteria is not straightforward. The roll mode time constant, being one of the main criterion parameters in the existing specifications, is not a uniquely defined parameter in the control systems under study because of the delay in the response of some of the configurations. Therefore, the definition as suggested in Ref. 10, which is based on a time history of the roll response to a step-type control input, is used as shown in Fig. 9. The time to reach 63% of the maximum roll rate is selected as effective roll mode time constant $t_{63\%}$.

For purely first-order systems, the effective roll mode time constant is exactly equal to the actual roll mode time constant, but for the control systems in which phase lags or time delays are involved the effective roll mode time constant can be defined as the result of an equivalent time delay and an equivalent roll mode time constant. The definition adopted is that equivalent time delay, T_p, is equal to the time to the intersection of the maximum roll rate slope line and zero roll rate as shown in Fig. 9. Equivalent roll mode time constant, τ_R', is then defined as the effective roll mode time constant

Table 1 Parameters used in flying qualities criteria

Parameter	Units	1978 Experiment				1979 Experiment							
		R-1	R-2	R-3	R-4	T-1	T-2	T-3	T-4	T-5	T-6	T-7	T-8
$t_{63\%}$	s	0.45	0.75	1.20	1.75	0.25	0.55	0.90	2.00	0.90	0.35	0.45	0.55
T_p	s	0.08	0.09	0.12	0.15	0.02	0.03	0.04	0.04	0.04	0.12	0.22	0.32
τ_R'	s	0.37	0.66	1.08	1.60	0.23	0.52	0.86	1.96	0.86	0.23	0.23	0.23
$t_{30\,\mathrm{deg}}$	s	2.2	2.4	2.8	3.25	1.25	1.6	1.8	2.4	2.6	1.35	1.45	1.55
$t_{60\,\mathrm{deg}}$	s	3.6	4,0	4.5	5.0	2.3	2.7	3.0	3.8	4.2	2.4	2.5	2.6
p_{max}	deg/s	18	18	18	18	30	30	30	30	18	30	30	30
$\dot{p}_{max}$	deg/s^2	31	19	12.5	8.5	99	52	36	18	22	99	99	99
Φ_{1s}	deg	10.4	7.5	4.9	3.3	22.3	15.8	11.9	6.7	7.1	19.4	16.5	13.7

minus the equivalent time delay. In the existing criteria, the roll mode time constant is used to indicate the quickness of the roll response. Because equivalent roll mode time constant and equivalent time delay both contribute to the quickness of the roll response, for the control systems of the present investigations the sum of both, being the effective roll mode time constant should be used when comparing the results of the present experiments with the existing criteria. The values of T_p, $t_{63\%}$ and τ_R' for the configurations of the present experiments are indicated in Table 1 together with the values for the parameters of the other criteria that will be used in this section.

Mil. Spec.[5]

The Mil. Spec. requirements are specified for different classes of aircraft in different flight phases. For the present investigations, the attention will be focused on Class II and Class III aircraft (medium and heavy weight transports) in flight phase category C (among others approach and landing). Three levels of flying qualities are distinguished, which are related to the Cooper-Harper rating scale in the following way:

Level 1 (satisfactory flying qualities): $1 \leq \text{C-H} < 3.5$

Level 2 (acceptable flying qualities): $3.5 < \text{C-H} < 6.5$

Level 3 (unacceptable flying qualities): $6.5 < \text{C-H} \leq 9$

The roll control criteria expressed in the Mil. Spec. are specified in maximum roll mode time constant ($t_{63\%}$), and minimum time to reach 30 deg bank angle after a step-type lateral control input ($t_{30\,\mathrm{deg}}$) as shown in Fig. 10.

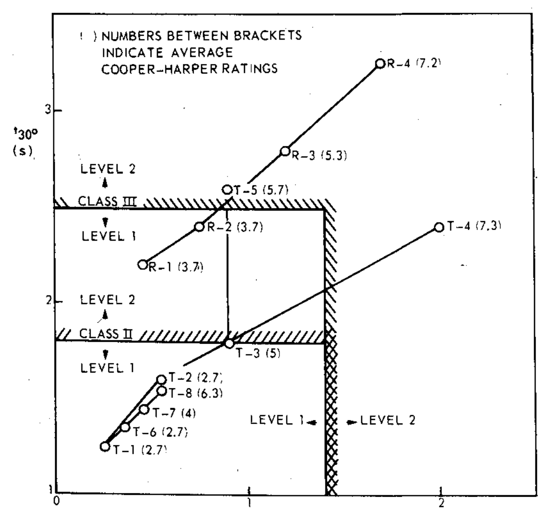

Fig. 10 Comparison with the roll response criteria in the Mil. Spec.[5]

The positions of the configurations used in the present experiments are indicated in Fig. 10 with the average Cooper-Harper ratings they received.

The variation of dynamics in the 1978 experiment (R-1 through R-4) seems to confirm the Level 1/Level 2 boundary on $t_{30\,\mathrm{deg}}$ for Class III aircraft. However, the fact that configurations T-3 and T-5 received about the same ratings indicates that probably for configurations without initial delay, $t_{30\,\mathrm{deg}}$ is not the most appropriate parameter. Assuming that the effective roll mode time constant $t_{63\%}$ is a better discriminator, the results indicate that the Level 1/Level 2 boundary should be very much lower than the value used in the Mil. Spec. ($t_{63\%} < 0.7$ s instead of 1.4 s).

The most recent revision of the Mil. Spec. (8785 C) puts a limit on allowable "equivalent" time delay in flight control systems irrespective of airplane class, with upper values of 0.1 s for satisfactory flying qualities and 0.2 s for acceptable flying qualities. However, these values are based on research carried out for fighter aircraft. The fact that in the present experiments a configuration with an equivalent time delay of 0.12 s (T-6) was considered as satisfactory by all pilots and a configuration with an equivalent delay of 0.22 s (T-7) was only just unsatisfactory, suggests that for transport aircraft having a flight control system with a small equivalent roll mode time constant, the time delay limit may possibly be less severe.

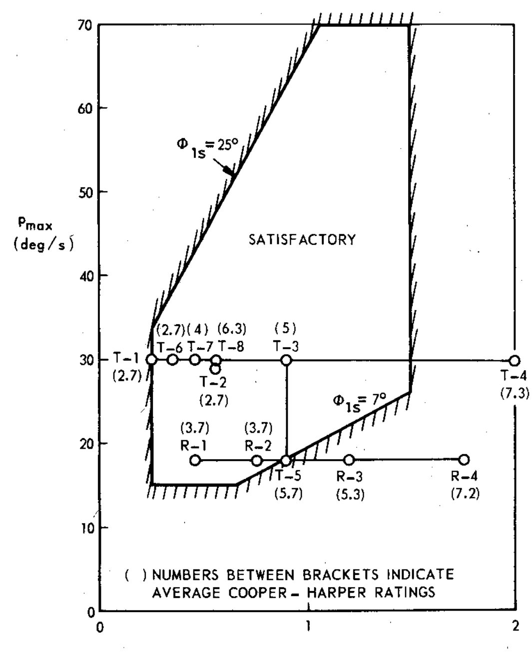

Fig. 11 Comparison with the roll response criterion in SAE ARP[9].

BCAR[7] and ICAO[8] Criteria

Time to roll through an angle of 60 deg is the quantity mentioned in these references with 7 s as the maximum value for acceptable roll performance. All presently investigated configurations perform the required bank angle change in less than 5 s (Table 1), so if a criterion of this form should discriminate for the control systems under consideration, its limiting value should be lower. Furthermore, the ICAO requirement that the available roll rate should be larger than 12-15 deg/s was satisfied by all configurations in the investigation.

SAE, ARP[9]

The roll response criterion used for transports in approach is presented in the form of a plot of maximum available roll rate vs roll mode time constant as shown in Fig. 11. The positions of the configurations of the present experiments, using $t_{63\%}$ for roll mode time constant, are indicated in Fig. 11, with the average Cooper-Harper ratings they received in the evaluation. Because time delay changes the value of $t_{63\%}$ only a small amount, a criterion in this form does not discriminate for the changes in T-6, T-7, and T-8. The boundaries shown in Fig. 11 for bank angle attainable in 1 s (ϕ_{1s}), discriminate properly for configurations R-1 through R-4. To explain the rating for T-3, the boundary on roll mode time constant should be shifted from 1.5 s to 0.7 s.

Criteria Proposed in Lateral-Directional Flying Qualities Investigations

An inspection has been made of the investigations used for the establishment of the contemporary criteria,[11-14] and of more recent literature on investigations directed at lateral-directional flying qualities criteria.[15-20] A comparison of the values of the criteria parameters for the present configurations and the boundaries mentioned in this literature will be given next.

Maximum Roll Acceleration/Roll Mode Time Constant[11,12,19]

Criteria are presented in the form of pilot iso-opinion lines in a plot of maximum roll acceleration vs roll mode time constant. In Fig. 12, the positions of the present configurations are indicated in the most strict criterion form of Ref. 12, with the average Cooper-Harper rating they received in the evaluations. Obviously, the criterion is much too wide to explain the present results. A reduction of the boundary on roll mode time constant, as indicated for the Mil. Spec. criterion, is necessary. Moreover, variation of time delay is not "punished" much in this criterion.

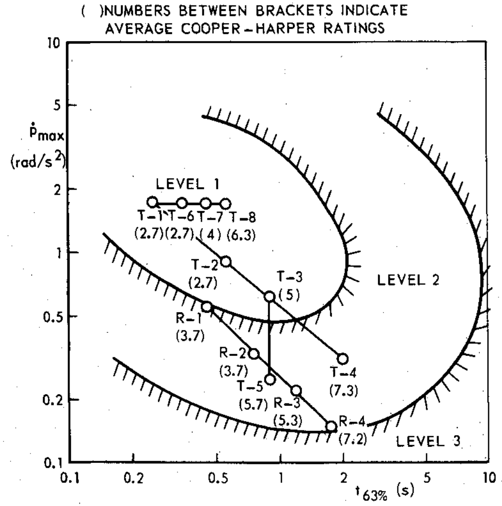

Fig. 12 Comparison with the roll response criterion of Barnes.[12]

Bank Angle Attainable in a Certain Time[12,13,15,16]

Bank angle in 1 s is advocated as a sensible criterion in several studies, and minimum values of 7 and 8 deg for satisfactory handling qualities have been mentioned. The values of bank angle attainable in 1 s are indicated for the configurations used in the present investigations in Fig. 13 with the Cooper-Harper ratings they received. The ratings in the 1978 experiment seem to confirm a Level 1/Level 2 boundary of 7 deg, but, according to this criterion, the configurations of the 1979 experiment are all in the satisfactory region. In view of this discrepancy, the criterion does not seem applicable for the configurations under study.

Closed-Loop Criterion Parameters

Analytical investigations[13,20] have indicated that characteristics of the closed loop of pilot and aircraft in a roll or heading tracking task can provide valuable insight in the handling qualities of an aircraft.

Most promising in this respect is the approach taken in Ref. 21 for pitch control, which was also applied successfully in the longitudinal experiments described in Ref. 1. However, it was not possible to find good correlation between the parameters of the closed-loop criterion when applied to the roll control characteristics and the Cooper-Harper ratings.

Multiple Regression Analysis

A general method exists to determine a combination of variables which predict another variable in the best way, and this method is called multiple regression. For the results of the present experiments a multiple regression has been carried out of the average Cooper-Harper ratings on the flying qualities parameters mentioned in the preceding sections. The best

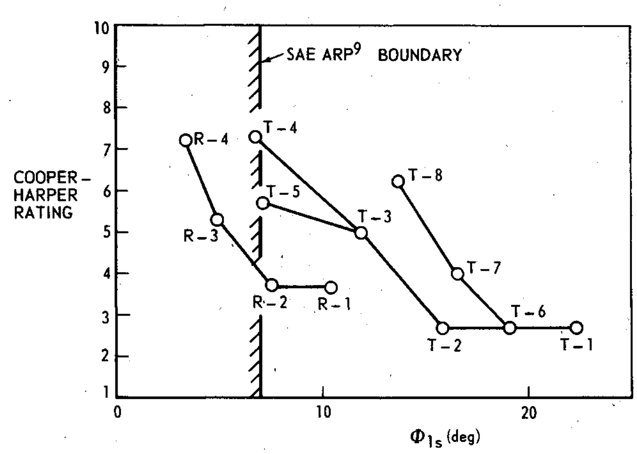

Fig. 13 Bank angle attainable in 1 s.

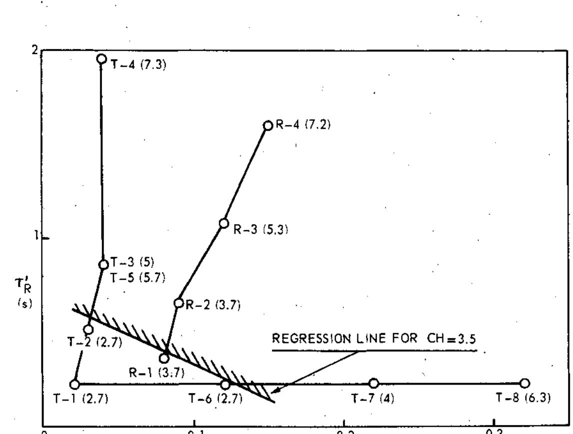

Fig. 14 Proposed roll response criterion based on linear regression analysis.

estimate, which is statistically significant, is given by the following equation:

$$\text{C-H}_{\text{est}} = 1.6 + 2.7\,\tau_R' + 10T_p$$

The multiple regression coefficient of this equation is $R = 0.92$, which means that 85% of the variance of the Cooper-Harper ratings can be "explained" by this combination of variables.

The Cooper-Harper ratings are presented on a plane of equivalent roll mode time constant τ_R' vs equivalent time delay T_p in Fig. 14 and the C-H = 3.5 boundary based on the regression equation is shown.

At this point it should be stressed that this result is applicable only for the experiments as described here. The expression does not apply to different types of flight control systems, and it is even questionable if ratings can be predicted outside the range of variables applied in the present experiments.

V. Conclusions

Two simulator programs have been carried out in which aircraft equipped with rate-command/attitude-hold flight control systems, controlled by side stick controller, were investigated in the landing approach and touchdown flight phase.

The results have been compared with handling qualities criteria mentioned in the literature. These are formulated for aircraft equipped with conventional flight control systems, using several parameters to indicate the quickness and the magnitude of the roll response.

It is suggested by the pilot ratings that for aircraft with advanced flight control systems resulting in increased precision and ease of bank angle control, the "internal standard," according to which the pilots judge the flying qualities, will increase as well. This implies that advanced flight control systems will have to comply with requirements that are stricter than the comtemporary ones.

Acknowledgments

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