Flight Test of Stick Force Stability in Attitude-Stabilized Aircraft

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Longitudinal flight control systems based upon pitch-rate-command/attitude-hold (PRC/AH) are being developed without positive stick force stability, as required in contemporary airworthiness criteria. The need for (artificially generated) positive stick force stability in such systems has been investigated in two flight test programs using a Beechcraft Queen Air-80 and a Fokker F-28/Mk6000. Based upon statistical analysis of performance measures and "effort ratings" of 120 approaches, it is concluded that the positive stick force stability system implemented in this study reduces airspeed deviations from the reference speed at the cost of increased glide path deviations and increased pilot effort. Only for relatively small levels of positive stick force stability was a modest reduction of airspeed deviation obtained, while not significantly degrading glide path tracking and pilot effort, as compared to the case of neutral stick force stability. Since aircraft with electrical flight control systems will most probably be controlled by sidesticks with various force-deflection relationships, pitch rate per unit airspeed deviation is a better parameter than stick force per unit airspeed deviation to indicate the level of stick force stability for PRC/AH flight control systems.

I. Introduction

AIRCRAFT of the so-called control configured vehicle (CCV) type are characterized by the use of flight critical electrical command and stability augmentation systems. For longitudinal control, pitch-rate-command/attitude-hold (PRC/AH) is considered one of the possible control types to be used in future CCV transport aircraft (particularly for landing approach). Longitudinal maneuvering characteristics and, more specifically, short-period response characteristics of aircraft fitted with PRC/AH flight control systems have been under study at the National Aerospace Laboratory for several years. Results of the investigations to date are presented in Refs. 1 and 2.

A feature of a flight control system based on attitude stabilization is the lack of a stable stick force versus airspeed relationship. However, positive stick force stability (PSFS) is required by contemporary civil airworthiness standards or military specifications. It is of great interest to aircraft flight control system designers, as well as to regulatory agencies, to establish the relevance of such a requirement for the future aircraft types just mentioned. The investigation described in this paper was aimed at the establishment of a possible need for a criterion on the level of artificial stick force stability during the landing approach of pitch attitude stabilized jet transport aircraft.

II. Theory

A. The Landing Approach Piloting Task

Landing approaches are usually flown using the "stabilized approach" technique. This implies that during the execution of the approach the deviations of the aircraft position relative to an earth-fixed path, as well as the speed deviations from the selected approach speed, are kept within tight tolerances. It is generally assumed that a relation exists between the amount of stick force stability required and the drag characteristics (thrust required vs airspeed) around the approach speed in order to obtain favorable handling characteristics in the case of manual thrust control. A conceptional picture presenting the thrust required vs airspeed relationship and associated information such as stall speed, speed for minimum drag, and approach speed is given in Fig. 1.

Two situations can be distinguished:

1) The approach speed is lower than the speed for minimum drag. If the flight path angle is kept constant, a decrease in airspeed results in an increase of the angle of attack and angle of pitch and a further reduction of the airspeed. If the aircraft possesses positive angle-of-attack stability and positive stick force stability, the pilot has to pull the elevator which triggers his attention, due to the need for a steadily increasing force on the longitudinal controller.

If, however, neutral stick force stability exists, as is the case for the basic form of the control system under consideration here (PRC/AH), the "warning" cue is not present in this form (although inputs to rotate the aircraft to increase angle of attack will be made). Moreover, the tendency to "dropping the nose" during moments of unattended pitch control is also absent, since pitch attitude is kept constant automatically.

2) The approach speed is equal to or higher than the speed for minimum drag. In this situation, the merits of a requirement on positive stick force stability in relation to the execution of the landing approach are less obvious than for the preceding situation. From the discussion in the next section, it appears, however, that positive stick force stability

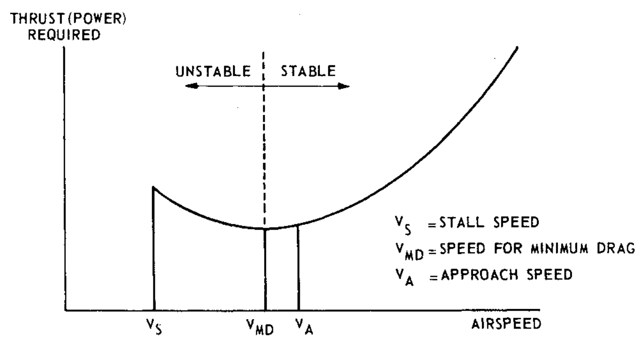

Fig. 1 Qualitative static thrust stability.

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for unaugmented aircraft is closely related to static longitudinal stability, which is considered a favorable feature for transport aircraft in the landing approach.

Most reports in the literature presenting analytical approaches to the stability aspects of the landing approach piloting task are based on the assumption of the continuous attention of the pilot to his glide path and speed control task. In operational practice, however, the pilot's attention is distributed over several subtasks, which limits the validity of the analytical approach.

B. Static Longitudinal Stability

When flight phases are considered for which speed must be kept constant and the flight path rectilinear (ILS/VASIS approach), static longitudinal stability, in a somewhat wider context than static angle-of-attack stability, has to be considered.[3] It can be shown that for aircraft with a PRC/AH flight control system "static angle-of-pitch stability" can replace static angle-of-attack stability as one of the required features to obtain static longitudinal stability. Beside pitch damping and static Mach or speed stability (pitching moment due to speed variation), "static thrust stability" is the other important feature, the level of which determines the existence of static longitudinal stability.

C. Contemporary Criteria

Flying qualities criteria which have a direct bearing on the main objective of the flight test experiment discussed in this paper will be considered.

1. Stick Force Stability

An inspection of contemporary criteria in the form of civil airworthiness standards and requirements or military specifications[4-7] indicates that they all require a positive slope of the stick force vs airspeed curve, but that only the Federal Aircraft Regulation (FAR)[4] presents a quantitative criterion of 1 lb per 6 knots.

2. Static Thrust Stability

From Refs. 4-7, only Refs. 6 and 7 specify quantitative requirements for manual throttle control in the form of the local gradient of flight path angle vs true airspeed at the approach speed ($\partial\gamma/\partial V$). The most stringent requirement of the two is the one proposed in Ref. 7. For satisfactory (Level 1) handling, it is required that $\partial\gamma/\partial V \leq 0$. This limiting case is in accordance with the opinion presented in another treatment of static thrust stability related to transport aircraft.[8]

3. Long-Period Mode

References 6 and 7 require the following:

$\zeta_p \geq 0.04$ Satisfactory (Level 1)

$\zeta_p \geq 0$ Acceptable (Level 2)

Reference 3 states: "Phugoid characteristics should be such that for oscillations with relatively short period the motion is neutrally stable (or convergent) and for oscillations with relatively long periods the motion may be slightly unstable (or divergent)."

III. Experiments

A. Aircraft and Systems

Two flight test programs, described in Refs. 9 and 10, have been performed with different aircraft types, both fitted with a "model-following" flight control system featuring PRC/AH characteristics augmented with a system to generate positive stick force stability and controlled through a sidestick controller. It was intended to use a National Aerospace Laboratory developed deflection-type sidestick controller in the first program. However, it was impossible to install this sidestick in the Queen Air cockpit due to space limitations, so a less space-consuming force-type sidestick was selected. In the second program, the controller just mentioned was used. The main characteristics of the entire program are indicated in Table 1, although only phase 2 will be discussed in any detail.

For the Fokker F-28/Mk6000 (Fig. 2) an approach configuration described by extended slats, a flap angle of 25 deg, gear down, and speed brakes "in" was selected; the approach speed was varied with aircraft weight so that neutral static thrust stability existed for each approach.

The system for pitch attitude control was mechanized according to the "model-following" principle (see Fig. 3). An electronic "model" calculates the pitch attitude θ_c in relation to the pilot input s_e (deg stick deflection). The signal θ_c is entered into the attitude stabilization loop of the F-28 autopilot in such a way that the actual pitch attitude θ follows the commanded pitch attitude closely. The various selectable parameters were set during initial flight testing.

The system for artificial stick force stability was based on feedback of a signal proportional to airspeed deviation from a trim value (Fig. 3). This mechanization tends to produce an effective M_u stability derivative, which is more negative than that which exists in the absence of artificial stick force stability. As will be seen, this can destabilize the aircraft's long-period dynamics. To prevent pitch attitude excitation as a result of turbulence, a threshold in the speed error signal was mechanized.

The most important characteristics of the system were:

Model-form

$$\frac{\theta_c}{s_e} = \frac{K_s(s+1/\tau_m)}{s(s^2+2\zeta_m\omega_m s+\omega_m^2)}$$

$$K_s = 1.43\ \mathrm{s}^{-2} \qquad 1/\tau_m = 1.79\ \mathrm{s}^{-1}$$

$$\omega_m = 2.10\ \mathrm{rad\ s}^{-1} \qquad \zeta_m = 0.7$$

Pitch control gain

$$(K_s/\tau_m\omega_m^2) = 0.58\ \mathrm{s}^{-1}$$

The following three stick force stability gradients were tested:

Configuration I	:0	No PSFS
Configuration II	:0.9 N/knot	Medium PSFS
Configuration III	:2.2 N/knot	High PSFS

Table 1 Program characteristics

	Aircraft, powerplant	Approach type, speed	Pilots × runs × configurations
Phase 1[9]	Beechcraft Model 80, two reciprocating engines	ILS, 105 knots	4×5×3
Phase 2[10]	Fokker F-28/Mk6000, two jet engines	ILS/VASIS, 125-115 knots	3×6×3

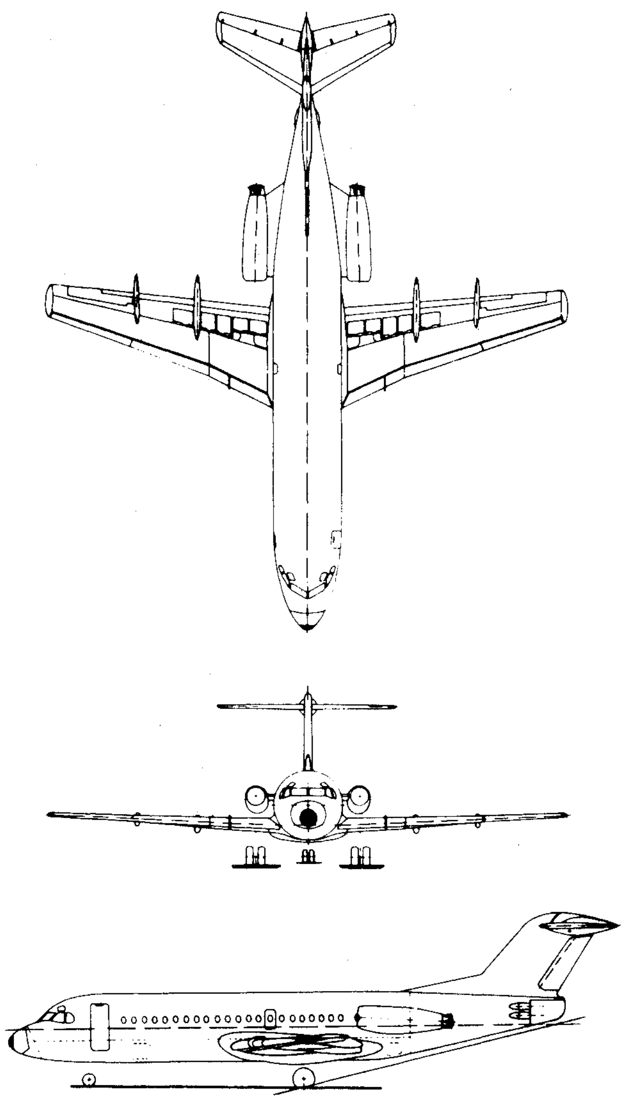

Fig. 2 Three-view drawing of the Fokker F-28/Mk6000.

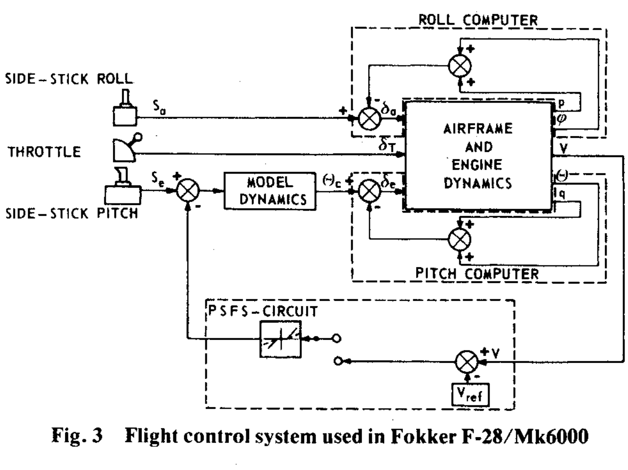

Fig. 3 Flight control system used in Fokker F-28/Mk6000

Speed error threshold $= +2 \rightarrow -2$ knots

Force/deflection of the sidestick controller = 3 N/deg

Long-period dynamics:

No PSFS – no oscillatory mode

Medium PSFS – stable oscillatory mode; undamped natural frequency 0.19 rad/s; damping ratio 0.12

High PSFS – unstable oscillatory mode; undamped natural frequency 0.29 rad/s; damping ratio 0.05.

The highest stick force stability gradient (configuration III) was selected to be comparable to the gradient (2 N/knot) tested in phase 1 of the experiment. Due to the pronounced difference in stick force per g (and stick force per unit of rotational acceleration) selected for the different type of sidestick controllers used in the two experiments, the required feedback gain for the airspeed deviation resulted in a mildly unstable long-period oscillation when the aircraft was disturbed in such a way that the airspeed deviation exceeded the value of the speed error threshold. On board the test aircraft, all relevant data were sampled at a suitable frequency and recorded digitally.

B. Experimental Design

For the benefit of a statistical comparison of the various configurations, every evaluation pilot had to carry out six approaches per configuration, which amounted to a total of eighteen approaches per pilot. It was possible to carry out ten approaches per flight, so two flights per pilot were necessary, including one familiarization run in each flight. The configurations were presented in "pseudorandom" order. Three experienced test pilots took part in the evaluation. Before the flight experiments started, the pilots were briefed by means of comprehensive written instructions. One aspect that should be mentioned is that an ILS/VASIS approach had to be carried out. The transition to the VASIS was attempted as early as possible (a range of heights of 500-900 ft for the transition resulted).

The two important questions that had to be answered on the basis of in-flight recorded information were:

1) In what way does positive stick force stability influence the pilot-aircraft performance?

Regarding this question, the variables considered were ILS glide slope and localizer deviation, airspeed error, and pitch attitude.

2) Does positive stick force stability influence the effort that is required to achieve this performance?

Regarding this question, a distinction has been made between physical and mental effort. For the first, the following objective measures were considered: stick deflection in pitch and roll as well as throttle deflection. For the second, subjective pilot ratings and comments have been used. To make the ratings amenable to statistical treatment, so-called effort rating on a 10-point (nonadjectival) rating scale[11] were obtained on glide slope control, localizer control, airspeed control, and the approach as a whole.

C. Data Reduction

The period from ILS glide slope acquisition to initiation of overshoot is the flight phase considered. The following characteristics of the variables mentioned in the preceding section were computed: 1) the minimum value that occurred (min.); 2) the maximum value that occurred (max.); 3) the mean value (mean); and 4) the root mean square value (rms). For pitch attitude and throttle deflection, the standard deviation (st. dev.) was used instead of the rms value.

It is necessary to apply a statistical test to be able to say whether the differences that occur in the derived quantities for the various configurations are significant rather than the result of mere chance. Because of the relative small number of samples, nonparametric tests were used.[12] Furthermore, tests for "matched pairs" were used. The "matched pairs" are considered to be two configurations with the same sequence number in the test (e.g., the nth run with configuration I and the nth run with configuration II are a matched pair). In this way, the best chance is created that runs under the same atmospheric conditions are compared with each other. Since the data are measured on an interval scale, the "randomization" test for matched pairs could be used. For large samples, however, the randomization test is not practical because of the tedious computations involved; for these cases, the "Wilcoxon Matched Pairs Signed Ranks" test was selected.

IV. Results

A. Results Obtained During Phase 1

A comparison is made of results obtained for a configuration with neutral stick force stability and a configuration with positive stick force stability with a gradient of 2 N/knot (no speed error threshold).

The significant results based on nonparametric statistics, obtained with the aircraft operating in a regime of positive static thrust stability, can be summarized as follows: a reduced maximum airspeed deviation (excess speed), a reduced rms airspeed deviation, a reduced (subjective) pilot effort in airspeed holding, and an increased rms stick force in pitch.

B. Results Obtained During Phase 2

Of the two experiments, phase 2 is considered the most important (jet transport, flight condition for neutral static thrust stability). Therefore, the results of this phase will be given in a more detailed form.

1. Derived Quantities

Differences occurring in the derived quantities (min., max., mean, rms, st. dev.) for all runs performed with each configuration were tested for their significance with the "Wilcoxon Matched Pairs Signed Ranks" test. For those derived quantities for which significant differences were observed with this test, the randomization test for matched pairs was applied to the derived quantities per pilot (six matched pairs). The average values per pilot and for all pilots together are plotted in Fig. 4.

Some observations can be expressed as follows:

1) The rms glide slope deviations are larger and the maximum deviations on the low side are larger with positive stick force stability.

2) The rms airspeed error shows significant improvement only when comparing configurations I and II. The maximum airspeed error shows a highly significant reduction when comparing configuration I with either configurations II or III.

3) The pitch attitude standard deviation increases approximately 50% when comparing configurations I and II with configuration III.

4) Stick deflections in pitch are larger with positive stick force stability. It is interesting to observe that a nonzero mean value of stick deflection in pitch for configurations II and III exists, corresponding to an average speed in excess of the reference speed.

5) The statistical tests did not indicate significant differences in the derived quantities for throttle deflection.

2. Pilot Ratings and Commentary

A questionnaire was used to obtain pilot effort ratings on several items. These ratings were transformed to standard normal form (zero mean, unity variance) for each pilot to account for different pilot rating styles. In all respects, the configuration with high positive stick force stability (configuration III) is more difficult than the configurations without or with medium-positive stick force stability (configurations I and II).

Moreover, questions were asked to evoke pilot commentary on specific characteristics.

On Glide Path Control: In general, the pilots felt that it was not too difficult to keep the aircraft on the glide slope, although turbulence and windshear introduced some problems. There were complaints about "sloppy" response in pitch as well as "pitch overshoot" which, especially in tur-

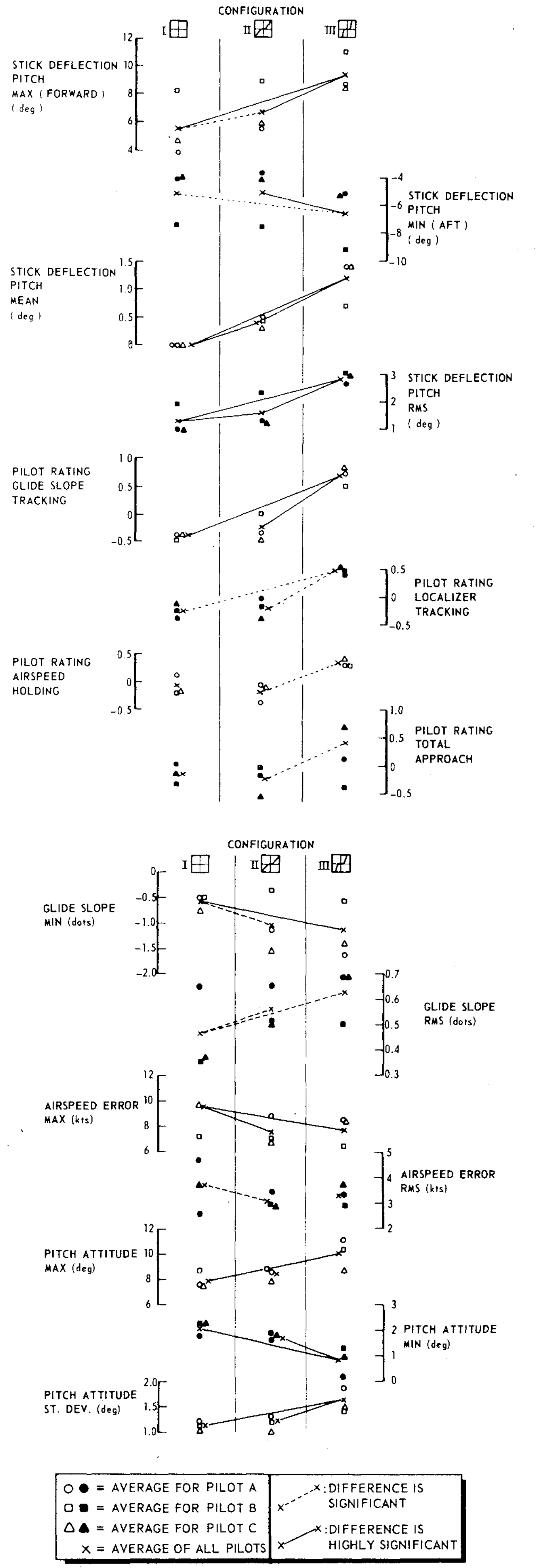

Fig. 4 Derived quantities for which significant differences occurred.

bulence, could lead to unsteadiness in the glide path control. These comments were related to some characteristics of the attitude stabilization loop of the autopilot which was not optimized for maneuvering. A comment made by all pilots was that the high PSFS gradient tended to upset glide path control (see pitch attitude st. dev. in Fig. 4). One pilot mentioned that he had the impression that someone else was controlling the aircraft in the high PSFS case.

On Airspeed Control: Because of the existing neutral static thrust stability, large thrust corrections were required to maintain the reference airspeed. According to all pilots, it was, for all configurations, difficult to restore the reference speed when the speed was too high. They observed that positive stick force stability improved airspeed control, but that this occurred at the cost of a reduction of the quality of glide path control, especially for the high PSFS gradient (configuration III). The general opinion was that positive stick force stability helps to indicate an off-speed condition when no turbulence, or a very light level of it, exists, but that in higher levels of turbulence the warning is masked and the glide path performance is seriously degraded, especially when the PSFS gradient is too high.

C. Discussion of Results

As the preceding sections indicate, there is a good correlation between the results obtained with the positive stick force stability of phase 1 and those with the medium PSFS of phase 2, although the gradient evaluated in phase 1 is closer to the gradient for high PSFS of phase 2.

The PSFS gradient evaluated in phase 1[9] and the gradient evaluated in phase 2[10] were 2 N/knot (no airspeed threshold) and 0.9 and 2.2 N/knot (airspeed threshold 2 knots), respectively. The different type of sidesticks and associated gains used must be regarded as the prime factor for this discrepancy, although differences in the characteristics of the pitch attitude flight control system, the level of static thrust stability, and the form of guidance used during the approach may have had influence. In phase 1, the pilot-selected gain led to values for stick force per *g* and stick force per unit of rotational acceleration which are much higher than those for phase 2. This was caused by the fact that pilots prefer relatively small sidestick deflections during approach flying with a deflection-type sidestick (also observed in tests described in Ref. 1), which is accompanied by small stick forces for this particular sidestick. Selecting "hands-off" pitch rate per unit of speed error as a parameter (instead of stick force per unit of error) is one way to exclude typical manipulator characteristics. The relation between pitch rate and airspeed error for the configurations tested in phases 1 and 2 are presented in Fig. 5. As is evident from this figure, there is reasonable agreement between the level of the commanded pitch rate evaluated in phase 1 and the level for medium PSFS of phase 2 for values of airspeed error of 4-6 knots.

V. Conclusions

The conclusion, mainly based on phase 2 (jet aircraft), is that for aircraft equipped with pitch-rate-command/attitude-hold flight control systems in the landing approach, the positive stick force stability (PSFS) system discussed here reduces airspeed deviations from the reference speed at the cost of increased glide slope deviations and increased pilot stick deflections. This result is obtained with an aircraft with neutral static thrust stability. For relatively small PSFS gradients associated with stable long-period dynamics, the airspeed reduction is modest and the glide slope deviations and pilot stick deflections are not very much increased as compared to the case of neutral stick force stability. For higher gradients and slightly unstable long-period dynamics, the increment is more pronounced. Therefore, great care is needed in selecting an upper limit for the level of artificial stick force stability, especially as regards the damping of the long-period dynamics.

The influence of turbulence with a higher intensity than encountered during the flight tests and pronounced wind-shears has to be established. In addition, the flare and touchdown maneuver has to be considered. Investigations will be continued in this direction using a moving base simulator with outside view display.

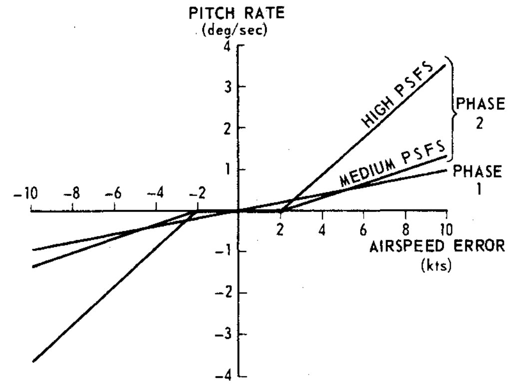

Fig. 5 The relation between pitch rate and airspeed error.

References

[1] Mooij, H.A., "Handling Quality Criteria Development for Transport Aircraft with Fly-by-Wire Primary Flight Control Systems," NLR TR 74141 U, 1976.

[2] van Gool, M.F.C. and Mooij, H.A., "Human Pilot Describing Function Remnant and Associated Information for Pitch Attitude Control: Results from In-Flight and Ground-Based Tracking Experiments," NLR TR 75062 U, 1975.

[3] *ICAO Airworthiness Technical Manual, Section 2, Flying Qualities,"* 1st edition, 1974.

[4] "Airworthiness Standards. Transport Category Airplanes," FAR, Vol. III, Pt. 25, 1965, 1970.

[5] "British Civil Airworthiness Requirements, Chapter D2-10, Handling-Stability," Air Registration Board, 1971.

[6] "Military Specification Flying Qualities of Piloted Airplanes," MIL-F-8785 B (ASG), Aug. 1969.

[7] "Flying Qualities Requirements," second report of Subcommittee No. 73 JAC 925, 1975.

[8] Davies, D.P., *Handling the Big Jets,"* Civil Aviation Authority, 3rd edition, 1971.

[9] Mooij, H.A. and van Gool, M.F.C., "The Need of Stick Force Stability for Attitude-Stabilized Aircraft. Part 1," NLR TR 76125 U, 1976.

[10] Mooij, H.A. and van Gool, M.F.C., "The Need of Stick Force Stability for Attitude-Stabilized Aircraft. Part II," NLR TR 77027 U, 1977.

[11] Hess, R.A., "Non-Adjectival Rating Scales in Human Response Experiments," *Human Factors,* Vol. 15 (3), 1973, pp. 275-280.

[12] Siegel, S., *Non-Parametric Statistics for the Behavioral Sciences,* McGraw Hill, New York, 1956.