Landing Approach Handling Qualities of Transport Aircraft with Relaxed Static Stability

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A flight test program was performed by DFVLR utilizing the HFB 320 in-flight simulator to investigate flying qualities problems associated with the relaxation of natural longitudinal static stability. The main objective of this research program was to investigate the influence of c.g. position on landing approach flying qualities. The static margin was varied from 14 to −10% mean aerodynamic chord (MAC) by rearward translation of the c.g. In addition, the influence of pitch damping and pitch control effectiveness on the flying qualities of an unstable aircraft configuration was studied. Nine configurations were evaluated by four pilots, who flew a total of 181 landing approaches under different natural atmospheric conditions. Cooper-Harper pilot ratings and special effort ratings, as well as statistical values computed from measured performance data of the pilot aircraft system, are presented as a function of the parameters varied and the turbulence intensity.

Introduction

CONVENTIONAL transport aircraft are designed to have good controllability in all degrees of freedom and adequate natural stability in all modes of motion. In order to increase aircraft performance, it is expected that future aircraft will probably have relaxed static stability or static instability. A relaxation of natural longitudinal static stability, however, can lead to flying qualities problems since the pilots are required to pay closer attention to pitch control and airspeed control.

To avoid problems associated with such a degradation in flying qualities, aircraft with relaxed static stability (RSS) in the normal state will be flown either fully automatically or manually with a stability augmentation system (SAS) providing the stability the aircraft inherently lacks. In the event of a failure in the flight augmentation computer (FAC) affecting the components of the stability augmentation system, and particularly in the event of a total failure of the FAC, the aircraft must have minimum (level 3) flying qualities, which ensure that the pilot can safely fulfill his mission.

Purpose of the Flight Test Program

The objectives of this in-flight research program, which utilized the DFVLR HFB 320 in-flight simulator, were to 1) investigate the effect of the relaxation of longitudinal static stability on the landing approach flying qualities by moving the c.g. to the rear, and 2) study the influence of pitch damping and pitch control effectiveness on the landing approach flying qualities for aircraft with static instability.

Experiment Design

Aircraft Model and Configuration Description

A large transport-type aircraft was selected as a reference configuration. To investigate the *influence of stability reduction caused by c.g. translation,* five configurations with c.g. position varying from 35% to 59% MAC were chosen. The neutral point of the selected aircraft was located at 49%, the maneuver point dependent on the c.g. position was located between 60.5% and 61.5% MAC.

The statically unstable configuration with c.g. position located at 55% MAC was taken as the basic configuration for the investigation of the *influence of pitch damping and pitch control effectiveness on flying qualities.* The values under investigation of both parameters were half and double the reference value.

For the investigation the model aircraft was represented by linearized equations of motion in landing approach condition in the onboard computer. The constant longitudinal characteristics, such as reference condition, dimensions, and mass of all configurations are listed in Table 1.

Dynamic Characteristics

Influence of Center-of-Gravity Position

The primary consequence of moving the c.g. to the rear is a destabilization leading to instability in the longitudinal motion if M_α becomes positive. Figure 1 shows the influence of different c.g. positions on the roots of the characteristic motion in the landing approach condition for the selected aircraft.

Starting with the conventional short period and phugoid roots c.g. positions aft of the range that is normally used leads to frequency reductions of both eigenmotions until they change into aperiodic motions. As indicated in the root locus plot, two real roots combine to form a new oscillatory mode for a further rearward shift in c.g. position. For c.g. positions well behind the normally used c.g. range, three poles are in the left half-plane (stable), one of them being on the real axis and two of them characterizing an oscillatory mode, which behaves much like the phugoid mode. However, the fourth pole is located on the real axis in the right half-plane. This positive root characterizes the unstable aperiodic response of such aircraft. Relaxed static stability and static instability affects the response of pitch attitude and speed in particular. The level of instability is mostly measured in terms of the time-to-double amplitude of the aircraft's response (T_2) calculated from the unstable root.

Influence of Pitch Damping and Pitch Control Effectiveness

To investigate the effect of pitch damping and pitch control effectiveness, both parameters, the pitch damping coefficient C_{mq} and the pitch control effectiveness $C_{m\delta es}$, were varied. The values under investigation of both parameters were half and

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double the reference value. The inherent instability of the reference configuration, characterized by the time-to-double amplitude $T_2 = 6.8$ s, remained unchanged throughout the investigation. This was achieved by simultaneously changing the stability parameter $C_{m\alpha}$. In Table 2 the designation and dynamic characteristics are listed for all the selected aircraft configurations.

Test Description

Evaluation Task

The piloting task was to execute landing approaches in normal air traffic control (ATC) conditions and during natural atmospheric disturbances of crosswinds, shear, and turbulence. The evaluation task consisted of precision tracking of the instrument landing system (ILS) beam, preceded by a glideslope intercept at an altitude of 2500 ft. The evaluation pilot had to perform a level-off followed by a go-around at 500 ft above the ground.

The evaluation pilots were instructed to fly both glidepath and airspeed as accurately as possible. The ILS signals displayed on the evaluation pilot's instruments were changed by onboard computation in such a way that the pilot, in performing a level-off at 500 ft above the ground, obtained the information he normally receives only from flare-out to touchdown.

Pilot Briefing and Comment

Four evaluation pilots participated in this flying-qualities investigation. Each evaluation pilot was given a pre-evaluation flight of about two hours to become familiar with the reference model configuration. A total of 44 evaluation missions with 181 landing approaches were performed during the flight test program. The pilots received a written briefing guide and rating information. Before flying they were briefed orally on the general experiment purposes and simulation procedures. The evaluation pilots were given no information about the configuration flown. The complete mission consisted of five approaches.

During the flight, pilot ratings and commentary were recorded on a tape recorder. After each approach, pilots were asked to assign "effort ratings" for a number of subtasks. A Cooper-Harper rating was given after the last approach of one mission for both longitudinal and lateral-directional dynamics. At the end of the evaluation flight, the pilot gave his formal commentary using a comment card.

Data Recording

A 120-channel digital recorder was used for onboard recording. All signals of interest were recorded at 10 sample/s:

1) Tracking deviations
2) Pilot activities
3) Control surface motions
4) Aircraft states—model and HFB 320
5) Control system signals.

In addition, pilot ratings (PR) and comments were recorded on a separate voice recorder.

Experiment Mechanization

HFB 320 Aircraft

The DFVLR HFB 320 in-flight simulator was used as the test vehicle in this flight test program (Fig. 2). The DFVLR

Table 1 Constant model aircraft characteristics

True airspeed	$V = 64$ m/s	Wing area	$S = 260.0$ m^2
Altitude	$h = 762$ m	MAC	$\bar{c} = 6.6$m
Flight path angle	$\gamma = -3$ deg	Mass	$m = 100{,}000$ kg
Moment of inertia about pitching axis			$I_y = 11{,}190{,}000$ kgm^2

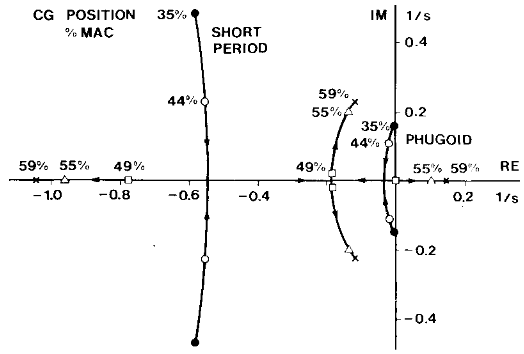

Fig. 1 Influence of c.g. position on the roots of characteristic motion.

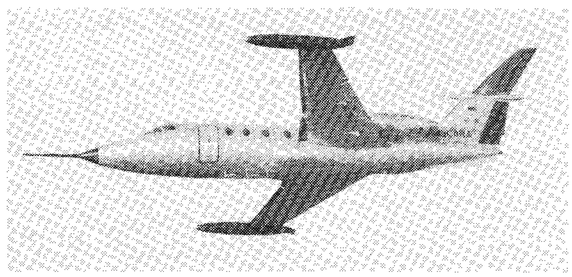

Fig. 2 DFVLR HFB 320 in-flight simulator.

Table 2 Characteristics of selected configurations

Configuration	A1	A2	A3	A4	A5	B1	B2	C1	C2
C.g. location, % MAC	35	44	49	55	59	—	—	55	55
Static margin; % MAC	14	5	≈0	−6	−10	—	—	−6	−6
$C_{m\alpha}$	−0.923	−0.410	−0.124	0.218	0.440	0.100	0.440	0.218	0.218
Short period root									
ω_{nsp}, rad/s	0.75	0.60	—	—	—	—	—	—	—
ζ_{sp}	0.77	0.92	—	—	—	—	—	—	—
Phugoid root									
ω_{np}, rad/s	0.15	0.11	—	—	—	—	—	—	—
ζ_p	0.03	0.11	—	—	—	—	—	—	—
New oscillatory root									
ω_n, rad/s	—	—	0.18	0.24	0.25	0.22	0.26	0.24	0.24
ζ	—	—	0.99	0.57	0.47	0.51	0.65	0.57	0.57
Aperiodic roots									
Time constant τ_1, s	—	—	1.28	1.04	0.96	1.265	0.75	1.04	1.04
Time constant τ_2, s			−457.6	−9.75	−6.88	−9.91	−9.77	−9.75	−9.75
Time-to-double T_2, s			317.1	6.76	4.77	6.87	6.77	6.76	6.76

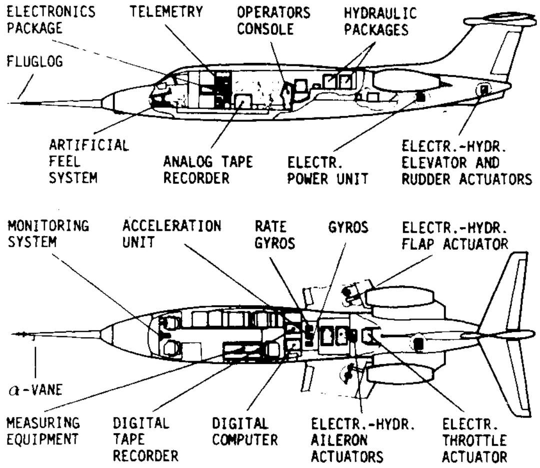

Fig. 3 In-flight simulator equipment.

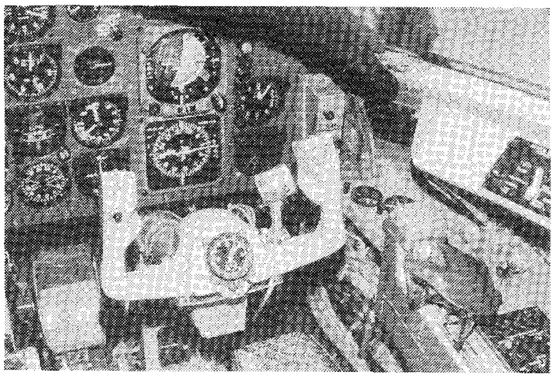

Fig. 4 Evaluation pilot's cockpit instrumentation.

HFB 320 is a five-degree-of-freedom simulator with a digital model-following control system.[1]

Figure 3 shows the in-flight simulation equipment. Conventional controls (wheel, column, and pedals) were used. The cockpit instruments for the evaluation pilot are shown in Fig. 4. The primary instruments on the panel were standard instruments.

Simulation Verification

The verification of the model-following control system was done on the ground, using a complete aircraft-system real-time simulation, and also in flight. The simulation accuracy demonstration in flight was made by using step and doublet inputs and by comparing model and actual aircraft responses. Samples of model-following responses are shown for configuration A4 (c.g. position at 55% MAC) in Fig. 5. In this figure the dashed lines show the time histories of selected parameters of the model, and the continuous lines show the time histories of the respective parameters of the in-flight simulator. The HFB 320 motion system was configured to reproduce the motion of the model at the pilot's seat.

Experiment Results and Analysis

Introduction

In this section the main results of the flight test program are presented. More detailed information is given in Refs. 2 and 3. The data obtained from the experiment are in the following form:

1) Pilot Cooper-Harper ratings (longitudinal and lateral).
2) Pilot effort ratings using the pilot questionnaire for a number of subtasks and the total task.
3) Pilot commentaries using the pilot comment card.

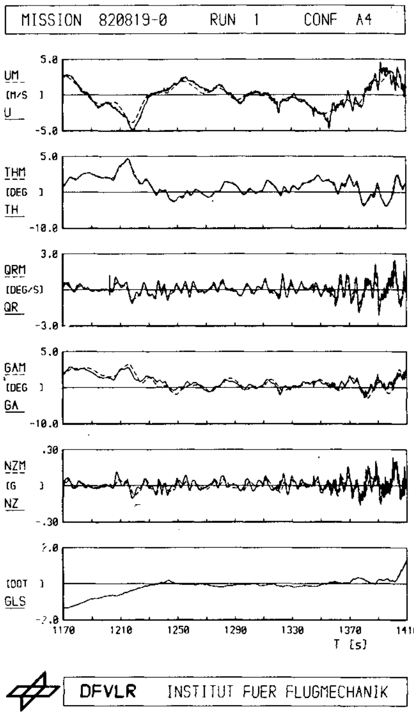

Fig. 5 Sample of model-following responses.

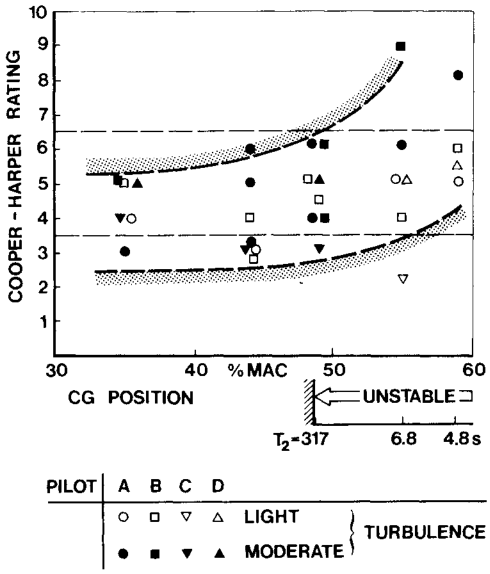

Fig. 6 Cooper-Harper pilot ratings vs c.g. position.

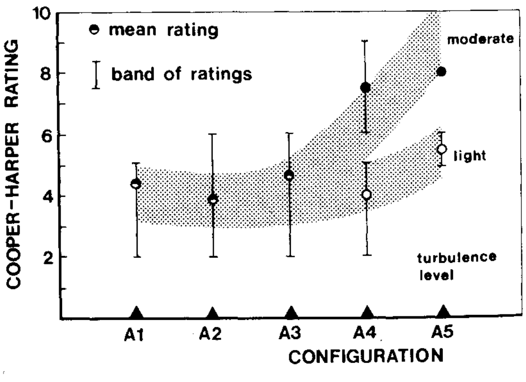

Fig. 7 Mean Cooper-Harper pilot ratings.

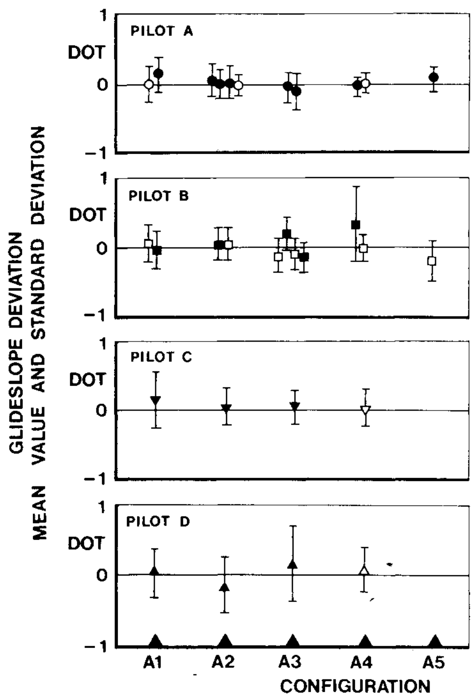

Fig. 8 Glideslope tracking performance.

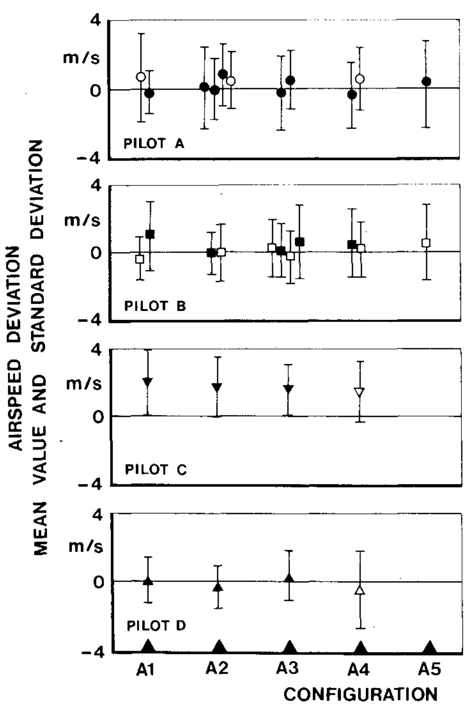

Fig. 9 Airspeed tracking performance.

4) Onboard recorded data of tracking deviations, pilot activity, control surface deflections, model and aircraft state variables.

The pilots were instructed to characterize the turbulence intensity encountered during the landing approaches by classifying turbulence at one of three levels of intensity: smooth, light, or moderate. In the evaluation the standard deviation of vertical gust intensity was calculated from onboard measured values and correlated with pilot comments on the turbulence levels. The calculated values, together with pilot comments, were used to determine the following boundaries of turbulence intensity:

light: $\sigma_{wg} < 1.00$ m/s

moderate: 1 m/s $\leq \sigma_{wg} \leq 1.75$ m/s

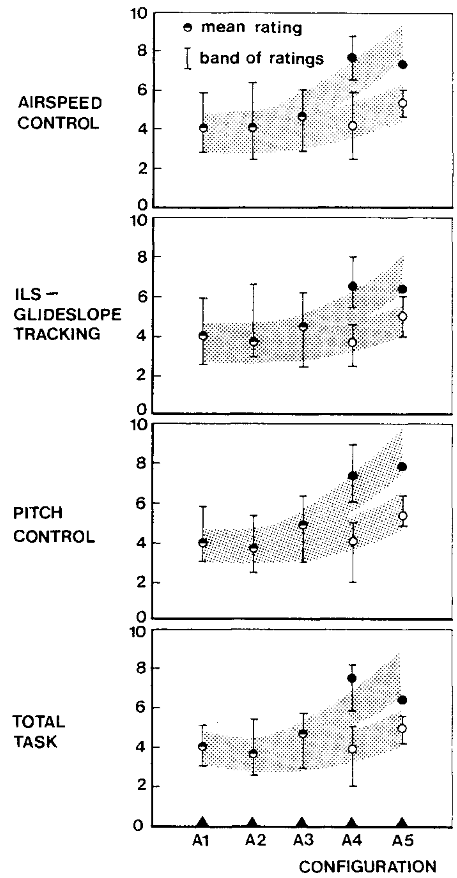

Fig. 10 Pilot effort ratings.

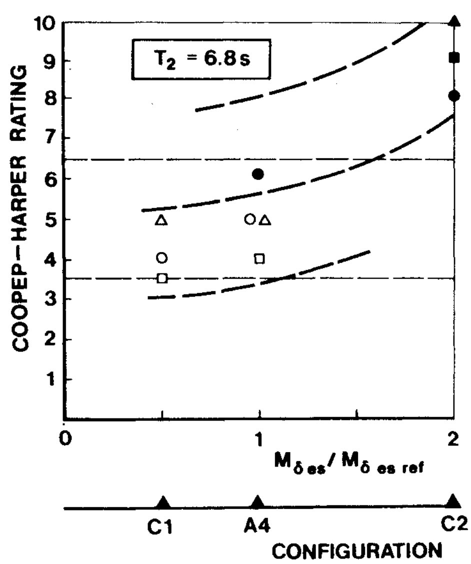

Fig. 11 Cooper-Harper pilot ratings vs pitch control effectiveness.

In the following figures, open symbols indicate light turbulence intensity, and full symbols indicate moderate turbulence intensity.

Each landing approach was documented by time history plots. For each mission (five approaches), statistical data (mean value, standard deviation) were computed from different variables of approach.

Results

Influence of Center-of-Gravity Position

In Fig. 6 the influence of c.g. position translation on Cooper-Harper ratings is presented for all missions in-

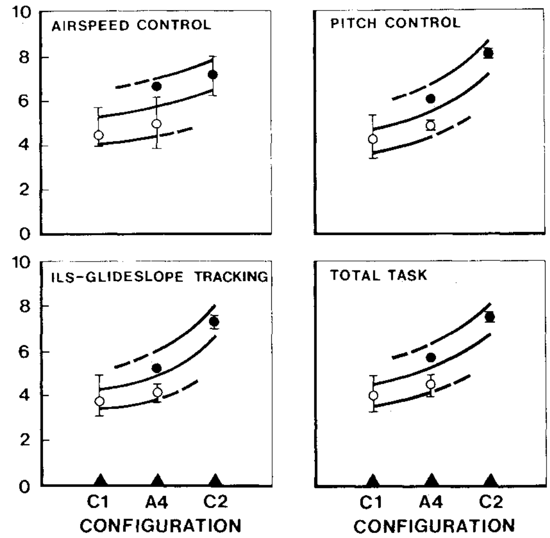

Fig. 12 Pilot effort ratings (○ = mean rating, ⊕ = band of ratings).

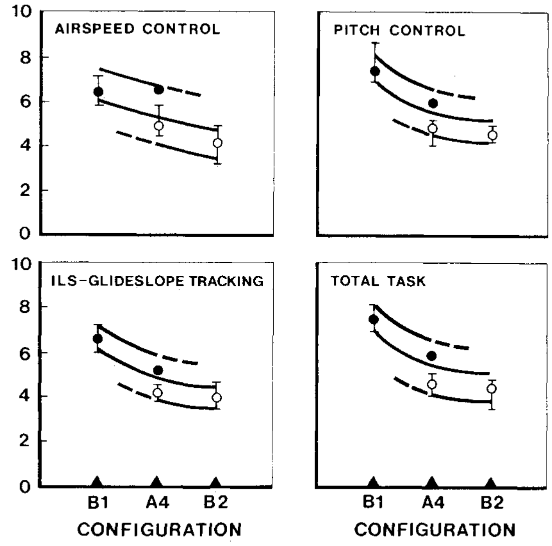

Fig. 14 Pilot effort ratings (○ = mean rating, ⊕ = band of ratings).

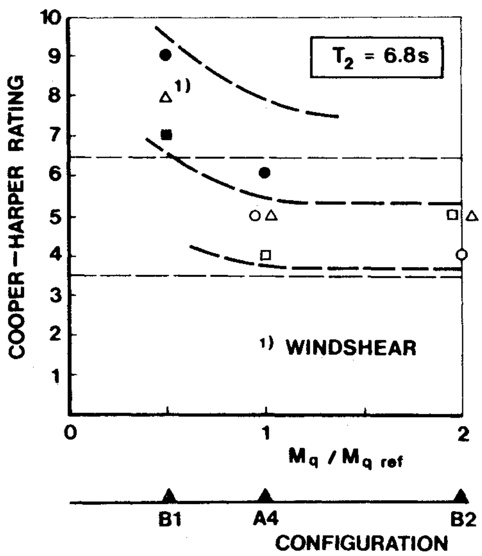

Fig. 13 Cooper-Harper pilot ratings vs pitch damping.

vestigated in this part of the flight test program. In addition, turbulence intensity, as characterized by the boundaries given in the previous section, is indicated. In this figure no clear tendency can be detected until the time-to-double amplitude reaches 6.8 s. All ratings are within a specific band of ratings; moreover, turbulence seems not to be a major factor. It is remarkable only in that, for a great number of approaches, pilots rated configuration A2 the best of all configurations.

A deterioration in flying qualities, however, can be detected for configurations with a time-to-double amplitude of less than about 6 s (c.g. position 55% MAC). In these cases, pilot ratings are clearly influenced by turbulence intensity. This is shown in Fig. 7, which presents for each configuration both the mean values of the Cooper-Harper ratings of all pilots and the corresponding bands of pilot ratings. From this figure an improvement in Cooper-Harper ratings from configuration A1 to configuration A2 can be identified. This confirms the tendency mentioned above that configuration A2, with a c.g. position at 44% MAC, was rated best in comparison with all other configurations. A further translation of the c.g. position to the rear, however, leads to an almost constant deterioration in mean pilot ratings. The gradient of the deterioration depends on the turbulence intensity.

To characterize the achieved performance of the pilot-aircraft system, measured performance data (mean value and standard deviation) of glideslope and airspeed are plotted in Figs. 8 and 9 for each pilot. As can be seen from both figures, the deviations lie mostly within a band of ±0.5 DOT in glideslope and ±3 m/s (± 5.8 knots) in true airspeed. This shows that all pilots tried to fulfill the task, but only pilot C accepted a higher landing approach speed.

The effort ratings shown in Fig. 10 correlate well with the Cooper-Harper ratings in Fig. 7. The effort rated by the pilots for performing the pitch control subtask and the total task decreases when changing from configuration A1 to configuration A2. Effort ratings for the airspeed control and ILS-glideslope tracking subtasks remain nearly constant. This confirms the overall tendency for a translation of the c.g. position from 35% MAC to 44% MAC to lead to a slight improvement in flying qualities. A further translation of c.g. position to the rear, however, results in a deterioration in flying qualities that can be identified in an increase in effort ratings for the individual subtasks, combined with an increase in the overall Cooper-Harper ratings.

Influence of Pitch Control Effectiveness

The results presented in Fig. 11 show a remarkable influence of pitch control effectiveness on the Cooper-Harper pilot ratings obtained. The level of unacceptable flying qualities ($PR > 6.5$) is reached for configuration C2, which was flown in moderate turbulence by all pilots.

Compared to the reference configuration A4, configuration C2, with twice the control effectiveness, was rated worse and the aircraft configuration C1, with half the control effectiveness of configuration A4, was rated slightly better. Although configuration C2 was flown in turbulence only, a deterioration in flying qualities of configuration C2 compared to configuration A4 probably exists in the absence of turbulence, too, as indicate by the dashed lines. The high control effectiveness configuration was characterized as "oversensitive and dangerous" by the pilots. They run into difficulties because they continuously overcontrolled the airplane. On the basis of pilot comments, the airplane would not be flyable to touchdown in turbulence. A lower boundary where the airplane's response becomes too sluggish was not achieved in these investigations.

Figure 12 presents for each configuration both the mean values of the effort ratings of all pilots and the corresponding bands of ratings. The effort ratings shown in this figure correlate well with Cooper-Harper pilot ratings. The effort needed by the pilots to perform the total task and all subtasks

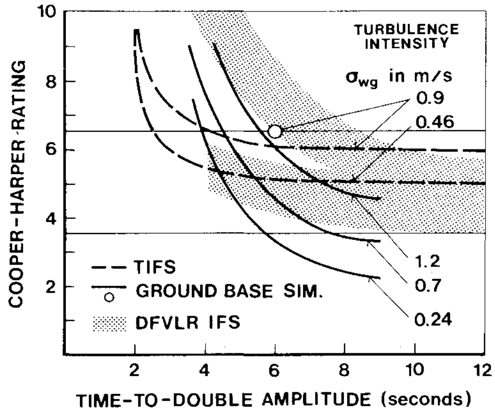

Fig. 15 Comparison of results (SST landing approach).

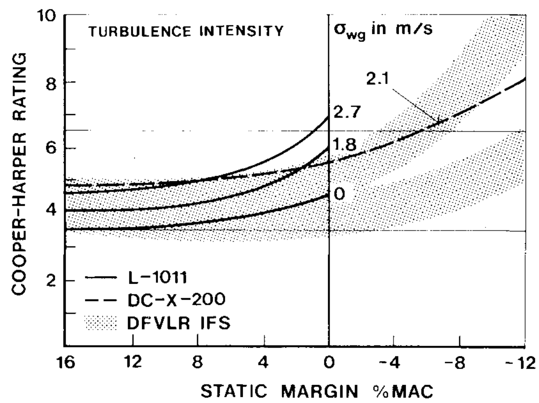

Fig. 16 Comparison of results (wide-body transport).

increases when changing from the reference configuration to configuration C2 and decreases with the reduction in pitch control effectiveness.

Influence of Pitch Damping

In Fig. 13 the Cooper-Harper ratings for configuration B1 ($M_q = 0.5M_{qref}$) and configuration B2 ($M_q = 2.0M_{qref}$) are presented.

Again, one configuration (B1) was flown in moderate turbulence by all pilots. Although the turbulence intensity was only light during the mission of pilot D, the presence of wind shear made the accomplishment of his task more difficult.

Changing from the reference configuration to configuration B1 leads to a remarkable deterioration in pilot ratings. This effect is caused by both the reduction in pitch damping and the increase in turbulence intensity. Decreasing the pitch damping in combination with a constant amount of instability (time-to-double amplitude) causes difficulties for the pilots. Configuration B1, which had half the level of pitch damping of the reference aircraft, was extremely difficult to fly in turbulence and wind-shear conditions. For the pilots participating in the in-flight simulations, it was not possible to acquire or to maintain a given pitch attitude.

No clear tendency in pilot ratings as a result of doubling the pitch damping is identifiable in Fig. 13, if only the pilot ratings for the flights with the same turbulence conditions are considered. The pilot effort ratings presented in Fig. 14 show the same tendencies as the Cooper-Harper pilot ratings. The effort needed by the pilots increases with decreasing pitch damping and remains nearly constant if the pitch damping is doubled.

Comparison of Results with Data from Similar Investigations

In the following section the results obtained in this investigation will be compared with data from similar experiments. The investigation of the flying qualities of relaxed stable and unstable transport aircraft configurations was intensified in 1972 in order to investigate the low-speed landing approach flying qualities of super sonic transport (SST) configurations. The time-to-double amplitude of the aircraft's unstable response in pitch attitude or angle of attack to elevator inputs was found to be the most important parameter for the definition of minimum flying qualities. Figure 15 presents a comparison of the results given in Refs. 4–6 concerning the landing approach flying qualities of SST configurations, with the DFVLR results.

From this comparison a similar trend in pilot rating can be identified as a function of time-to-double amplitude. All data indicate a lack of sensitivity of pilot rating with time-to-double amplitude if T_2 is greater than about 6 s. The Cooper-Harper ratings for the SST experiments show a remarkable deterioration for times-to-double amplitude of less than 6 s in one case of less than 3 s in the other. They are strongly influenced by the turbulence intensity. The results obtained from the DFVLR in-flight investigations fit the given curves well. They confirm that the flying qualities of *slightly* unstable aircraft are highly affected by turbulence and are independent of time-to-double amplitude up to a certain level of instability.

Since 1977 new flying-qualities investigations of transport aircraft configurations with relaxed static stability have been conducted. The most varied parameter with those experiments was the c.g. position or static margin. Figure 16 represents the Cooper-Harper pilot ratings resulting from two simulator experiments[7,8] investigating the influence of static margin on pilot acceptability of minimum longitudinal stability for the landing approach task and the results from the DFVLR in-flight simulation program.

The aircraft models used in the simulator investigations were the Douglas DC-X-200 and the Lockheed L-1011. In general, the DFVLR results fit the given curves well; however, they show no deterioration in pilot ratings for small values of static margin, i.e., near the stability boundary the aircraft configurations investigated in-flight by DFVLR are rated better than the L-1011 configurations. For greater negative values of static margin (i.e., for higher levels of instability) the pilot ratings obtained from the DFVLR flight tests performed in moderate turbulence are worse than the ratings given for the DC-X-200 configuration investigated under comparable turbulence conditions.

Conclusions

The DFVLR in-flight simulator was used to investigate the influence of stability reduction on the landing approach flying qualities of transport aircraft. In this flight test program the static margin was varied from 14% to −10% MAC by rearward c.g. translation. In addition the values of pitch damping and pitch control effectiveness were changed in combination with a constant amount of instability. The pilot ratings and comment data obtained in this experiment suggest the following conclusions.

Influence of Center-of-Gravity Position

1) No clear tendency of Cooper-Harper pilot ratings to deteriorate with decreasing stability is detectable until inherent instability corresponding to 6 s time-to-double amplitude is reached.

2) Cooper-Harper ratings for all pilots show a slight improvement when the static margin is changed from 14 to 5% MAC.

3) Pilot ratings deteriorate for configurations with a time-to-double amplitude of their unstable motion of less than 6 s.

4) The effect of turbulence on the pilot ratings is relatively low until time-to-double amplitude reaches about 6 s. For configurations with a time-to-double amplitude of less than this value, however, the influence of turbulence becomes greater and the intensity determines the gradient of deterioration.

5) Both pilot effort ratings and comments confirm the Cooper-Harper rating tendency. After an initial drop, their effort to fulfill the task with the same accuracy in all cases increases with increasing instability.

6) Compared with the results of former investigations concerning the landing approach flying qualities of relaxed stable transport aircraft configurations, the results of the DFVLR inflight experiments show a similar trend in pilot rating as a function of time-to-double amplitude or static margin.

Influence of Pitch Damping and Pitch Control Effectiveness

1) The flying qualities of the evaluated aircraft configurations are strongly affected by both pitch damping and pitch control effectiveness.

2) Decreasing the pitch damping in combination with an unchanged amount of instability leads to unacceptable flying qualities owing to extreme difficulties with pitch attitude tracking.

3) High values of pitch control effectiveness tend to make the aircraft oversensitive and are not acceptable to the pilots.

4) The pilot ratings are influenced by the encountered turbulence.

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