LARGE AIRCRAFT HANDLING QUALITIES

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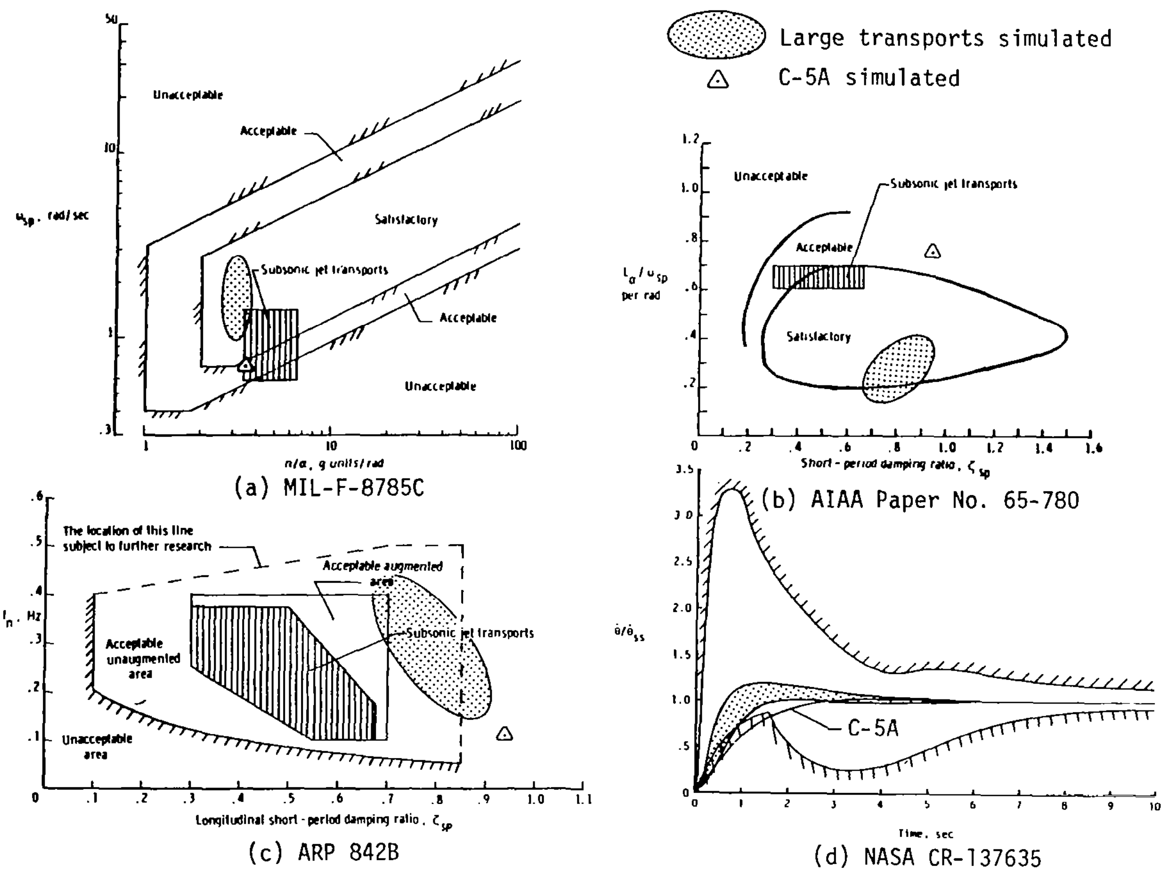
The point to be made here is that some of the present-day longitudinal handling qualities criteria for transport class aircraft do not apply to very large (G.W. ≈ 2,000,000 lbf) transport aircraft. In fact, of the four criteria indicated here, only the short-period frequency requirements of MIL-F-8785C could be said to be in agreement with the present very large aircraft simulation study results. Moreover, if it is conceded that the C-5A has satisfactory longitudinal handling characteristics, then it might be concluded that none of these criteria are applicable to very large aircraft.



(a) MIL-F-8785C

(b) AIAA Paper No. 65-780

(c) ARP 842B

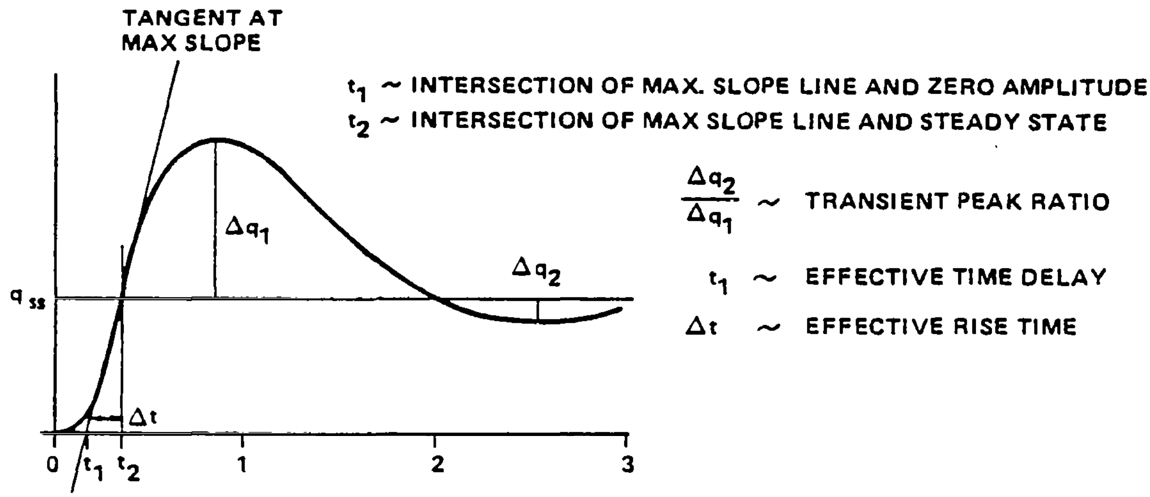
(d) NASA CR-137635

EFFECTIVE TIME DELAY t_1 IN COMMAND PATH
(PILOT ω_{BW} = 1.5 RAD/SEC)

These pitch rate response criteria were developed by Chalk (NASA CR-159236) and address such parameters as "effective time delay (t_1);" "transient peak ratio ($\Delta q_2/\Delta q_1$);" and "effective rise time ($\Delta t = t_2 - t_1$);" and apply to the dynamic response with the pilot in the loop. This table indicates that the effective time delays of the simulated large transports meet the requirements of this reference for pitch, roll, and yaw. Also, although it is not indicated in this chart, the pitch transient peak ratio ($\Delta q_2/\Delta q_1$) requirement was met for all large transports simulated.

None of the large aircraft simulated met the suggested pitch requirements for Δt (effective rise time parameter). This is quite disconcerting since the referenced limits on Δt are derived from or related to the constant limits on $\omega_n{}^2/n/\alpha$ used in MIL-F-8785C, and as shown earlier in the first figure of this presentation, all of the simulated large aircraft met the level 1 requirement for $\omega_n{}^2/n/\alpha$.

It should be noted that NASA CR-159236 lists no requirements for "transient peak ratio" or "effective rise time" for the roll and yaw axes.



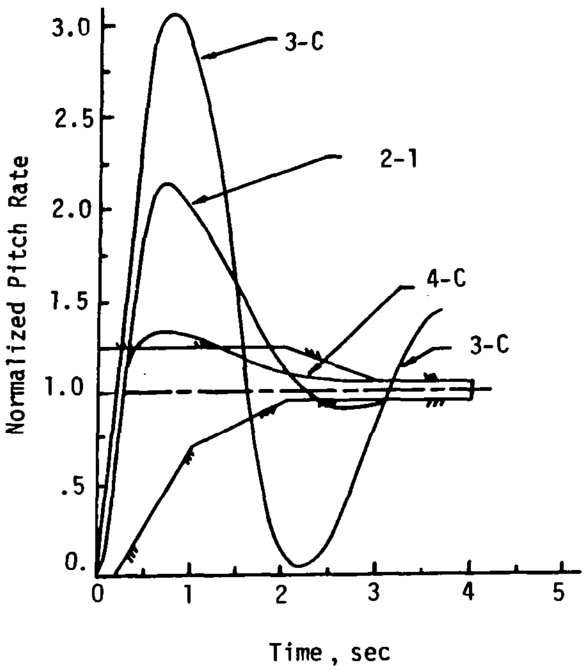
Requirements~NASA CR-159236			Large Aircraft Simulation Results				
				Unaugmented Ave		Augmented Ave	
Level	Pitch	Roll and Yaw	Level	Pitch	Roll	Pitch	Roll
1	≤ .200 sec	≤ .283 sec	1	.053	.103	.120	.133
2	≤ .283 sec	≤ .400 sec	2	✓	✓	✓	✓
3	≤ .350 sec	≤ .467 sec	3	✓	✓	✓	✓

COMPARISON OF SIX LAHOS CONFIGURATIONS TO THE SPACE SHUTTLE SUBSONIC PITCH RATE REQUIREMENTS

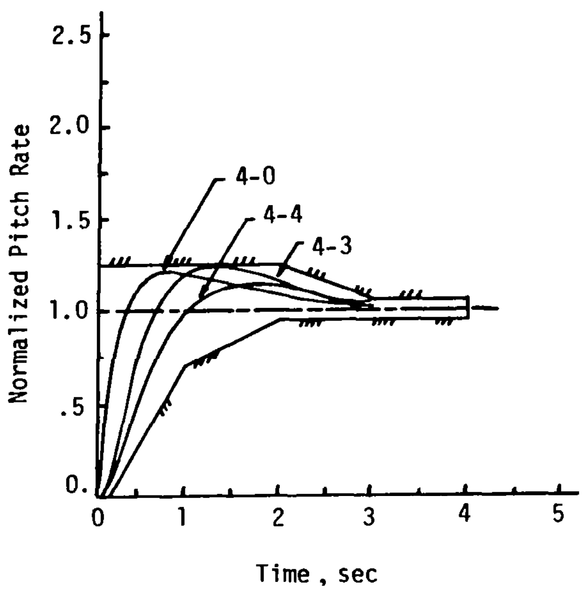
Because the Shuttle is always operated as a closed-loop system, the conventional MIL-F-8785C open-loop aircraft modal format for flying qualities was considered to be inappropriate. Instead, Shuttle pitch axis flying qualities were specified in the time domain by the response boundaries indicated in this chart. However, the Shuttle specification itself does not correlate well with much of the recent flying qualities experimental data. For example, some selected LAHOS configurations (AFFDL-TR-78-122) were compared to the Shuttle criterion. Note that it was possible to select some LAHOS configurations that exceeded the boundaries and yet had good (level 1) flying qualities, while others that met the requirements had poor (level 2) flying qualities. (Similar results were found for correlations of the Neal and Smith data of AFFDL-TR-70-74.)

LAHOS Config.	Pilot Rating	
	Overall	Approach
2-1	Level 1	-
3-C	Level 1	-
4-C	Level 1	Level 1

LAHOS Config.	Pilot Rating	
	Overall	Approach
4-0	Level 2	-
4-3	Level 2	Level 1
4-4	Level 2	Level 2



(a) LAHOS configurations which do not meet the Shuttle pitch-rate requirements.



(b) LAHOS configurations satisfying the Shuttle pitch-rate requirements.

COMPARISON OF SIX LAHOS CONFIGURATIONS TO THE SPACE SHUTTLE SUBSONIC PITCH RATE ENVELOPE, BUT USING NORMALIZED α RESPONSE

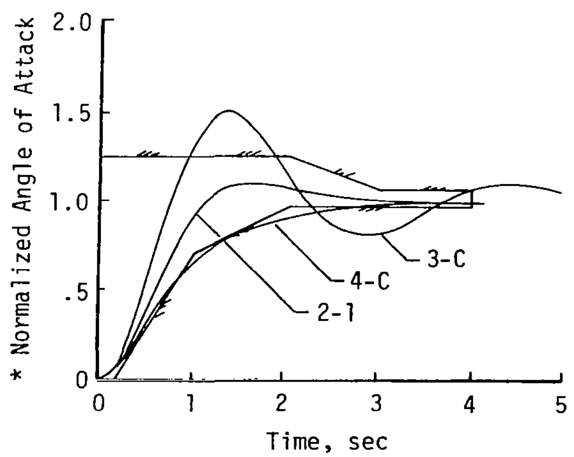
It has been suggested that the original Shuttle time-history envelope was developed for angle of attack instead of pitch rate. The figure on the left of this chart shows the α response of LAHOS configurations 2-1, 4-C, and 3-C plotted in the Shuttle time-history response envelope. The responses now fall approximately within the Shuttle envelope with level 1 flying qualities.

The figure on the right of this chart shows a plot of the α responses of LAHOS configurations 4-0, 4-3, and 4-4 on the same Shuttle time-history envelope, and all three configurations have level 2 flying qualities. Although the pitch rate responses of these three configurations were shown to be within the Shuttle envelope in the previous figure, the angle-of-attack responses shown here indicate a very sluggish, unacceptably responsive vehicle.

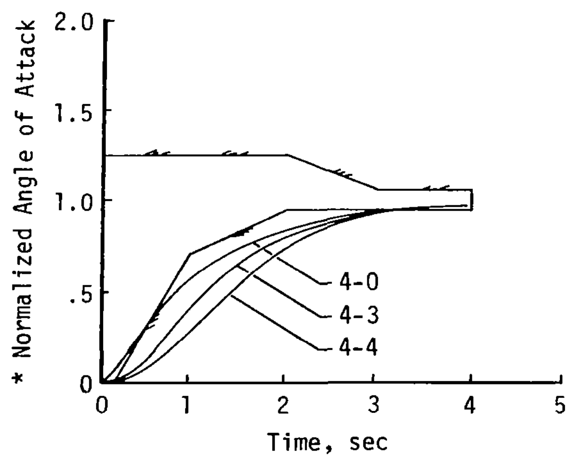
* CALSPAN suggests that normalized α should be used instead of normalized pitch rate.

LAHOS Config.	Pilot Rating	
	Overall	Approach
2-1	Level 1	-
3-C	Level 1	-
4-C	Level 1	Level 1

LAHOS Config.	Pilot Rating	
	Overall	Approach
4-0	Level 2	-
4-3	Level 2	Level 1
4-4	Level 2	Level 2



(a) Configurations which satisfy Shuttle $\dot{\theta}$ envelope when α is used.



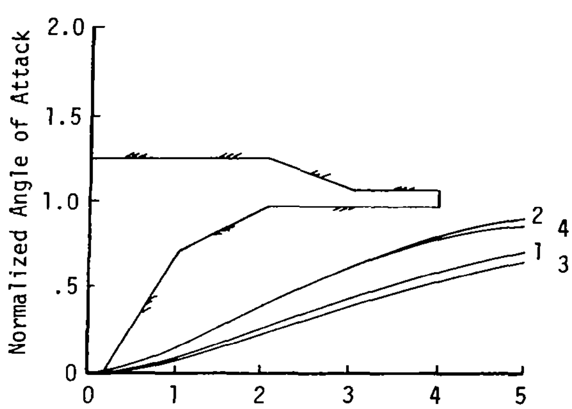
(b) Configurations which do not satisfy Shuttle $\dot{\theta}$ envelope when α is used.

COMPARISON OF LARGE TRANSPORT AIRCRAFT SIMULATED TO SHUTTLE PITCH RATE CRITERION ENVELOPE, BUT USING NORMALIZED α RESPONSE

This chart presents a comparison of the "angle-of-attack" response for the simulated large transport aircraft to the "pitch rate" response criterion developed for the Space Shuttle.

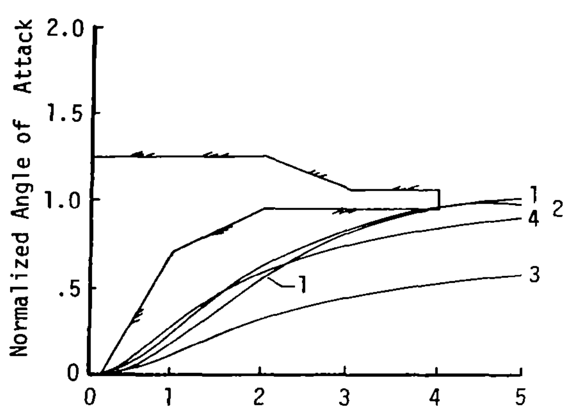
These large aircraft do not correlate well with the Shuttle criterion, even when normalized α is substituted for normalized $\dot{\theta}$. The figure on the right presents the augmented dynamic response for four large aircraft configurations, all of which were assessed by the pilots as having satisfactory (level 1) approach and landing flying qualities. However, when compared to the Shuttle time-history envelope, it would be concluded that these large aircraft had unacceptably sluggish responses, which was not the case.

Large A/C Config.	Pilot Rating, Landing Task
1	Level 2
2	Level 2
3	Level 2
4	Level 1



(a) Unaugmented large transports simulated.

Large A/C Config.	Pilot Rating, Landing Task
1	Level 1
2	Level 1
3	Level 1
4	Level 1



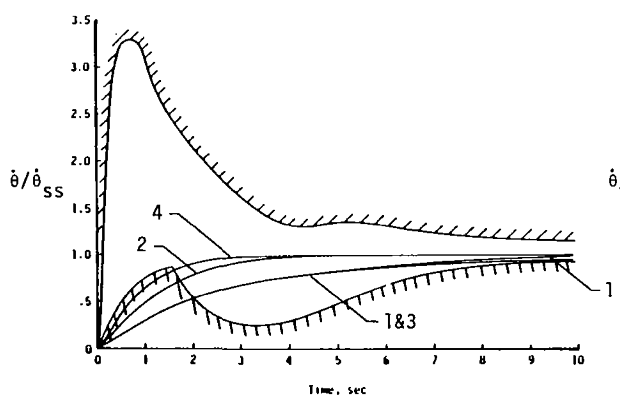
(b) Augmented large transports simulated.

COMPARISON OF LARGE TRANSPORT SIMULATED AIRCRAFT TO BOEING PITCH RATE REQUIREMENTS

The low-speed pitch rate response criterion indicated in this chart and reported in NASA CR-137635 was developed by the Boeing Company for application to the handling qualities requirements for supersonic transports. It should be noted that this Boeing criterion differs from the Shuttle pitch rate response criterion presented earlier in that this Boeing criterion allows for much more pitch rate overshoot, and allows for much less initial pitch rate delay.

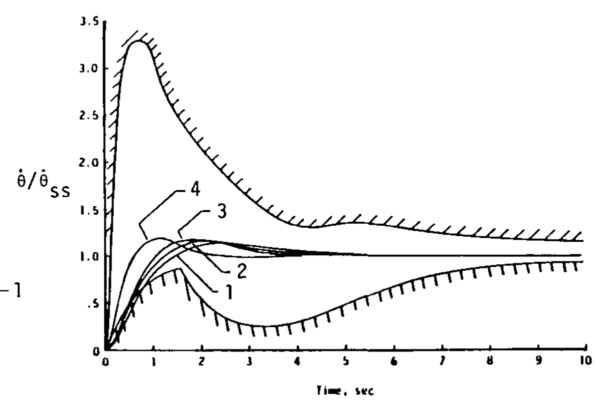
Upon comparing this pitch rate response and pilot opinion of the very large "subsonic" jet transport of the present ground-based simulation study, it can be seen that the simulated large aircraft results agree reasonably well with the Boeing-developed SST landing approach criterion. Indications are, however, that the minimum satisfactory level of "initial" pitch rate response allowed by this criterion could probably be relaxed for very large (G.W. ≈ 2,000,000 lbf) transport aircraft.

Large A/C Config.	Pilot Rating, Landing Task
1	Level 2
2	Level 2
3	Level 2
4	Level 1



(a) Unaugmented large transports simulated.

Large A/C Config.	Pilot Rating, Landing Task
1	Level 1
2	Level 1
3	Level 1
4	Level 1



(b) Augmented large transports simulated.

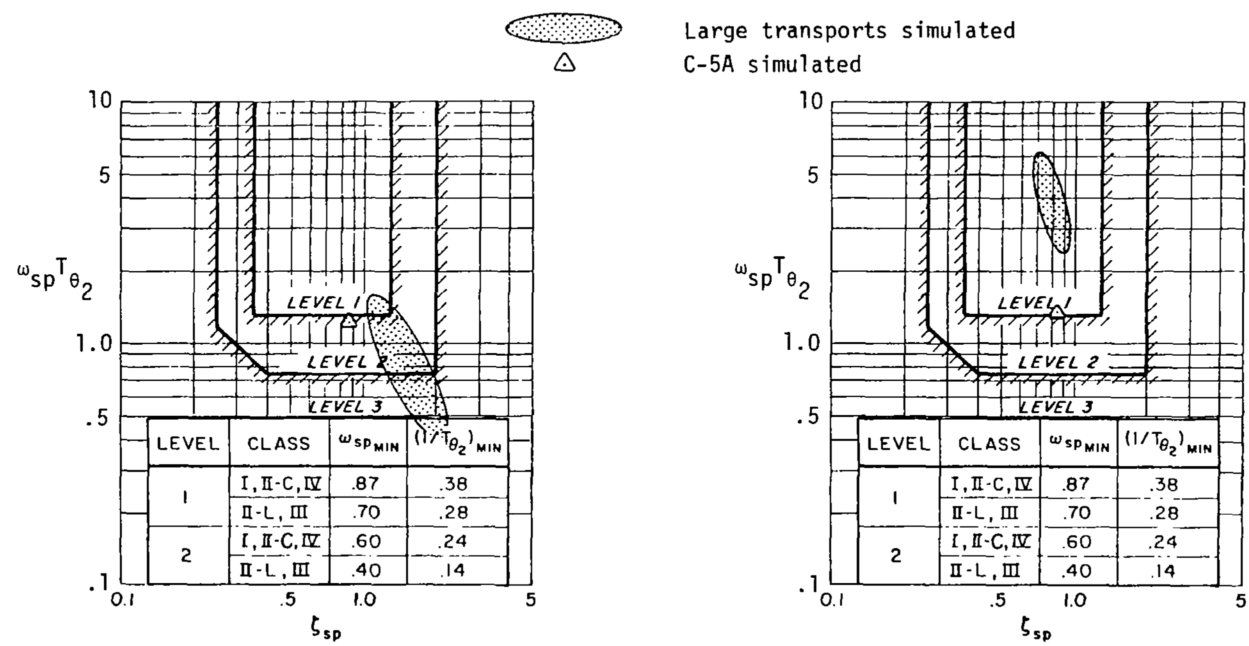
COMPARISON OF SHORT-TERM PITCH RESPONSE OF SIMULATED LARGE TRANSPORT AIRCRAFT WITH CATEGORY C REQUIREMENTS OF PROPOSED MIL HANDBOOK

The short-period frequency requirement of 8785C was based upon the premise that the normal acceleration response to attitude changes is a primary factor affecting the pilot's perception of the minimum allowable ω_{sp} [that is, limits are placed on $\omega_{sp}^2/(n/\alpha)$]. Likewise, the physical interpretation of the so-called "control anticipation parameter" [CAP = $\omega_{sp}^2/(n/\alpha)$] assumes that the dominant concern for a pilot pitch control input is normal acceleration response.

It is, of course, also true that the pitch attitude response to pitch control inputs is of paramount importance, and, whether the appropriate correlating parameter is n/α or $1/T_{\theta_2}$ is a moot point in that data that correlate with $1/T_{\theta_2}$ generally also correlate with n/α. However, it was observed in AIAA Paper No. 69-898 that the product $\omega_{sp}T_{\theta_2}$ provided a slightly better correlation than CAP. (Physically, $\omega_{sp}T_{\theta_2}$ represents the separation in phase between aircraft response in path and pitch attitude.)

Thus, the $\omega_{sp}T_{\theta_2}$, in combination with ζ_{sp}, criterion of AFWAL-TR-82-3081 is presented in this chart along with the characteristics of the simulated very large aircraft of the present study. And, since the pilots' opinion of these configurations during approach and landing were, in general, level 2 when unaugmented and level 1 when augmented, it is concluded that the results of the present 6-DOF ground-based simulator results are in good agreement with this $\omega_{sp}T_{\theta_2}$ vs. ζ_{sp} criterion.

NOTE: $1/T_{\theta_2} \doteq n_\alpha(g/V)$ IN THIS INSTANCE



LEVEL	CLASS	$\omega_{sp_{MIN}}$	$(1/T_{\theta_2})_{MIN}$
1	I, II-C, IV	.87	.38
	II-L, III	.70	.28
2	I, II-C, IV	.60	.24
	II-L, III	.40	.14

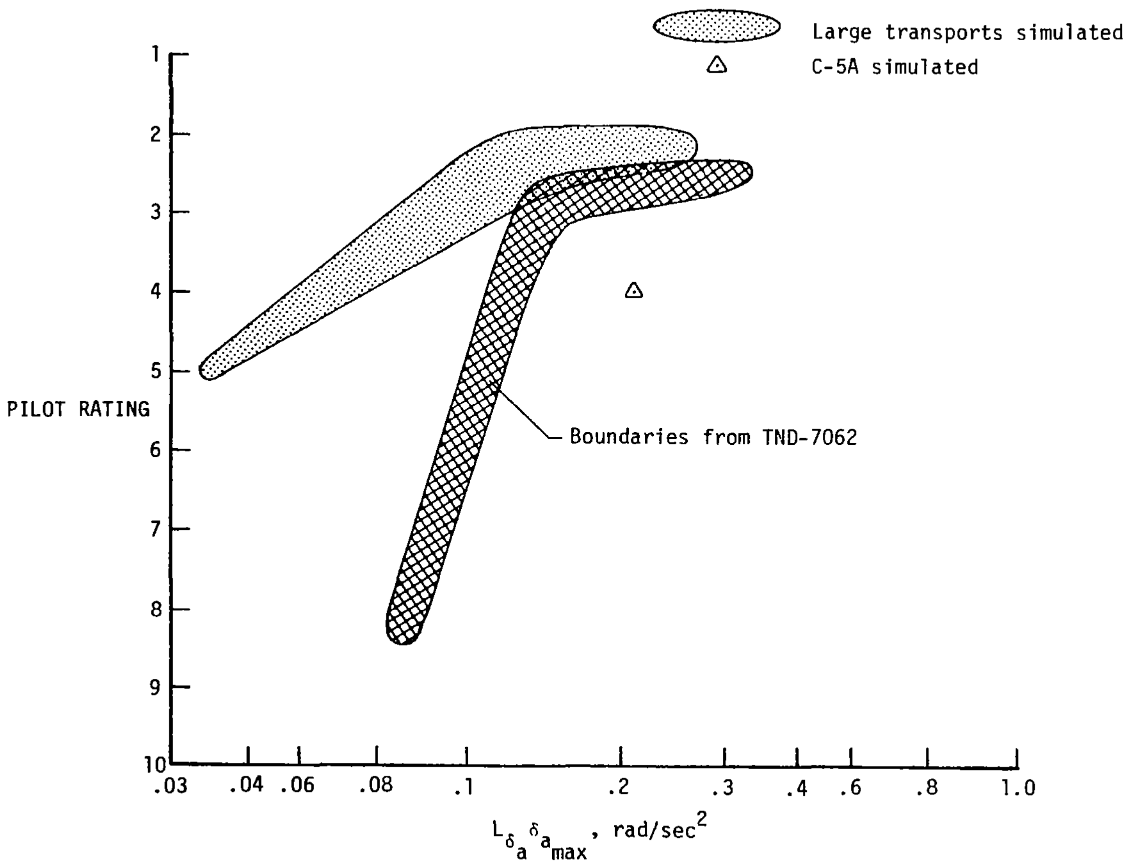
(a) Large aircraft, unaugmented. (b) Large aircraft, augmented.

COMPARISON OF SIMULATED LARGE TRANSPORT AIRCRAFT TO LOCKHEED C-5A AND BOUNDARIES FROM FLIGHT TEST

The boundary indicated as taken from TN D-7062 was derived using a general purpose airborne simulator (Lockheed Jetstar) with a model-controlled, variable-stability system installed to provide simulation capability. This boundary presents the pilot ratings (PR) for the maximum "roll acceleration" commanded by the pilots for the various roll time constants investigated. The boundary indicates that a roll acceleration capability of approximately 0.12 rad/sec^2 or greater was considered to be satisfactory (PR $<$ 3.5) by the pilots; and that the pilot ratings rapidly became unacceptable (PR $>$ 6.5) when the roll acceleration capability was decreased below 0.10 rad/sec^2.

The boundary indicated for the large transports (G.W. ≈ 2,000,000 lbf) simulated in the present study (on a 6-DOF ground-based simulator) indicates that a roll acceleration capability as low as 0.09 rad/sec^2 was evaluated as being satisfactory (PR $<$ 3.5). Similar piloting tasks were used in both studies.

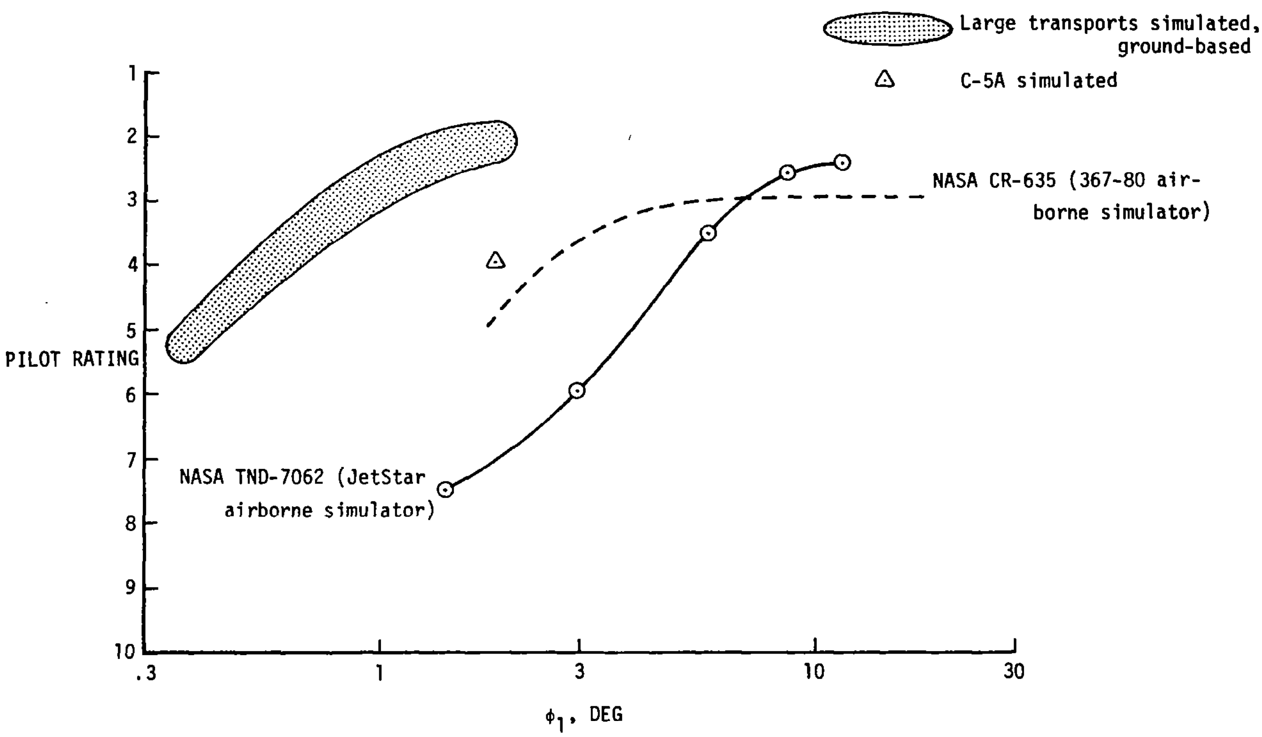
Note that the C-5A ground-based simulation results indicate a pilot rating of 4.0 (level 2) for the lateral-directional handling qualities and yet the roll acceleration capability was greater than 0.2 rad/sec^2, indicating that the roll control power was not the reason for the level 2 lateral-directional pilot rating.



COMPARISON OF RESULTS FROM LARGE AIRCRAFT SIMULATIONS WITH REFERENCED RESULTS

This chart relates pilot opinion of an aircraft's roll response to the parameter ϕ_1. (The term ϕ_1 is defined as the maximum bank angle that can be achieved in one second.) The results of the present large aircraft simulation study (6-DOF ground-based simulator) are compared to the results of TN D-7062 and CR-635 (both reporting results obtained from airborne simulators).

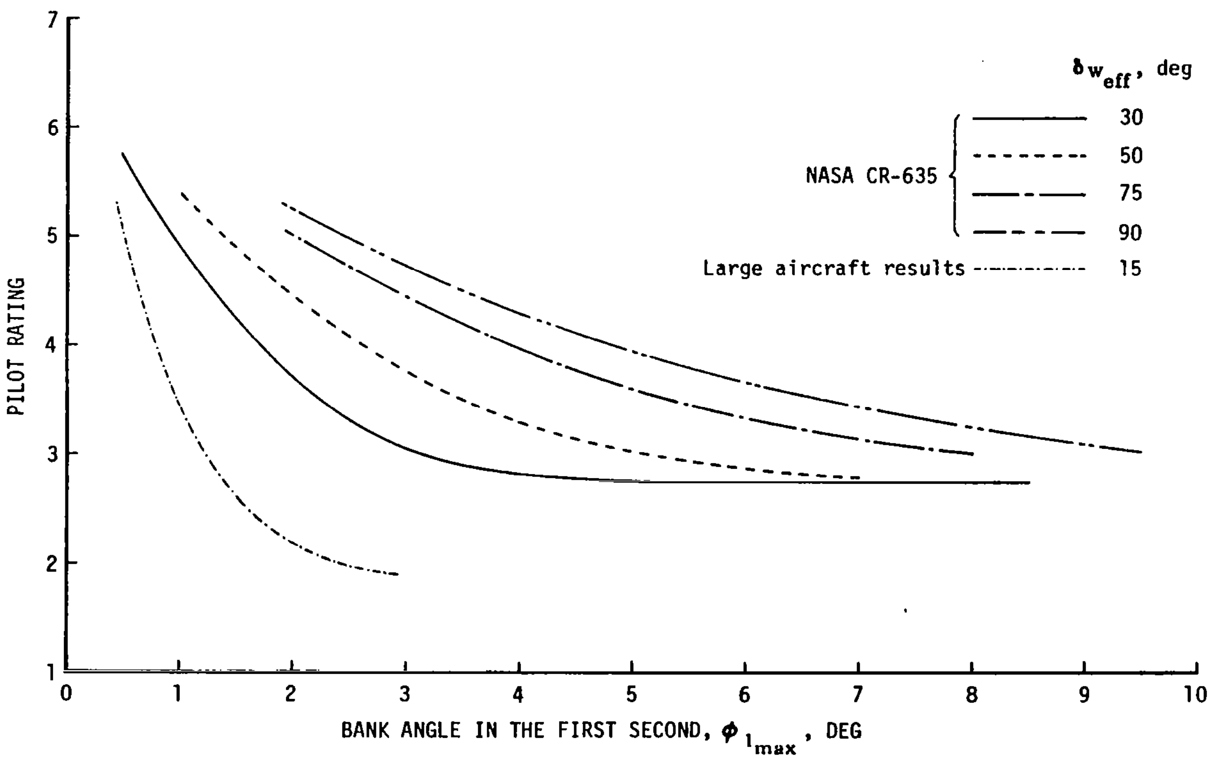
None of these simulation results agrees as to the minimum satisfactory level (PR < 3.5) of ϕ_1. The results from TN D-7062 indicate that ϕ_1 must be greater than approximately 6° for level 1 roll response; the results of CR-635 indicate that ϕ_1 must be greater than approximately 3° for level 1 roll response; and the results from the present ground-based simulation study indicate that the ϕ_1 for very large transport aircraft could be as low as approximately 1° and still be considered to have satisfactory (level 1) roll response.



VARIATION OF PILOT RATING WITH BANK ANGLE ATTAINED IN THE FIRST SECOND

Maximum bank angle in the first second after initiation of wheel deflection ($\phi_{1_{max}}$) has been suggested as a figure of merit for roll control systems. The variation of pilot rating with $\phi_{1_{max}}$ for the ground-based simulator results reported in CR-635 are indicated in this chart to be a function of effective wheel angle, $\delta_{w_{eff}}$. (The term $\delta_{w_{eff}}$ is defined as the wheel angle for maximum rolling moment.)

These indicated lines of constant effective wheel angle suggest that the pilot is rating the bank angle per wheel deflection or roll response sensitivity, more so, or instead of, the parameter $\phi_{1_{max}}$. Another interesting point to be seen from this chart is that a constant pilot rating of 3 (level 1) was obtained at the constant value of $\phi_{1_{max}}/\delta_\omega = 0.1$, while $\phi_{1_{max}}$ varied from 3° ($\delta_{w_{eff}} = 30°$) to 9° ($\delta_{w_{eff}} = 90°$). Note also the results of the present large aircraft simulation study. Although values of $\phi_{1_{max}}$ of these large aircraft configurations were much smaller than those of the referenced data, the large aircraft $\delta_{w_{eff}}$ was also smaller and the overall results were the same; a pilot rating of 3 was obtained when $\phi_1/\delta_w = 0.1$ ($\phi_{1_{max}} \approx 1.5°$ for $\delta_{w_{eff}} \approx 15°$).

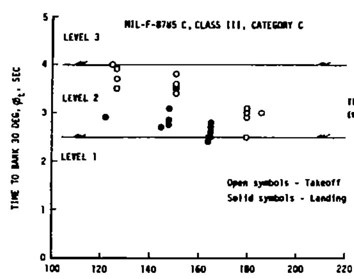


COMPARISON OF ROLL PERFORMANCE FROM LARGE AIRCRAFT SIMULATED WITH REFERENCED RESULTS

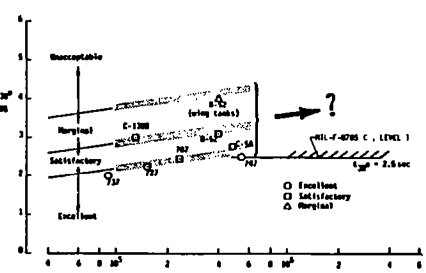
An inadequate "large aircraft data base" has led to handling qualities specification problems, and, as a result, there is a risk that future aircraft will be overdesigned, unnecessarily expensive, or possibly inadequate to perform the design mission. For example, considerable effort and expense were initially expended on the C-5A in an attempt to meet a requirement for rolling to an 8° bank angle in one second. It was later determined from flight tests that the handling qualities of the C-5A were totally acceptable with less than one-half such roll capability.

All four of the figures on this chart relate pilot opinion to the time required to bank 30° ($t_{\phi=30°}$). Figure (a) shows C-5A roll performance compared to the 8785C requirement. Although this aircraft is considered to have satisfactory roll performance, it would be evaluated as less than satisfactory by the military specification criterion. Boeing suggested a few years ago that the $t_{\phi=30°}$ criterion should be a function of aircraft landing weight (fig. (b)). Several aircraft in service today meet this criteria but do not meet the MIL-SPEC criteria. Extrapolation of the Boeing criteria indicates that the $t_{\phi=30°}$ requirement should be relaxed for heavier Class III aircraft.

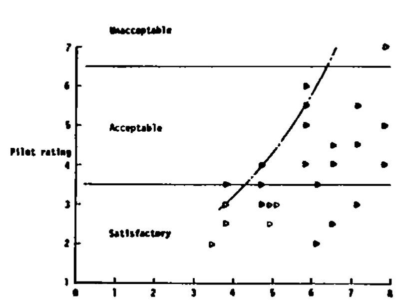
Current results of the ongoing large aircraft simulation study are summarized in figures (c) and (d). Results shown in figure (c) indicate that a $t_{\phi=30°}$ of less than 6 sec should result in "acceptable" roll response characteristics, and that a $t_{\phi=30°}$ of less than 4.0 sec results in "satisfactory" roll response. Figure (d) indicates that the present large aircraft ground-based simulation results are in good agreement with the airborne simulation results of TN D-7062, wherein smaller Class III aircraft were simulated.



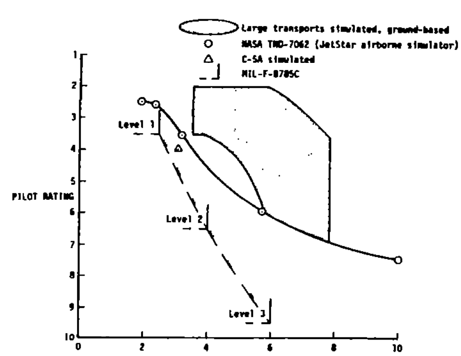
(a) C-5A roll performance (PR=3.5).



(b) Roll performance of various aircraft at landing approach.



(c) Large aircraft simulated roll performance for landing task.



(d) Large aircraft simulated roll performance compared to other results and MIL-F-8785C.

SUMMARY

- The short-period frequency requirements of MIL-F-8785C are applicable to the very large transport aircraft simulated.

- The large aircraft simulated in this study meet the requirements of NASA CR-159236 for effective time delay and pitch transient peak ratio. However, the requirements of this reference for the effective rise time parameter are believed to be too conservative for very large transport aircraft.

- These large aircraft simulation results are in very good agreement with the $\omega_{sp}T_{\theta_2}$ vs. ζ_{sp} criterion of AFWAL-TR-82-3081.

- A value of the parameter $L_{\delta_A}\delta_{A_{max}}$, which is an indication of the roll accleration capability, as low as 0.09 rad/sec^2 was considered to be satisfactory for the very large transports simulated. This compares to a value of approximately 0.12 rad/sec^2 desired for smaller transports.

- A minimum satisfactory level of the parameter ϕ_1 was determined to be much lower for the large aircraft simulated in this study compared to the values determined in previous studies for smaller transport aircraft. However, the magnitude of ϕ_1/δ_w required for these large transports was determined to be the same as that required for smaller transports; thus, $\phi_1/\delta_w \approx 0.1$ produces satisfactory roll characteristics.

- Data obtained to date as well as other data indicate that MIL-SPEC requirements for the parameter $t_{\phi=30°}$ are too conservative for very large transport aircraft. The results of the present study indicate that a $t_{\phi=30°}$ of less than 6 sec should result in "acceptable" roll response characteristics, and a $t_{\phi=30°}$ of less than 4.0 sec should result in "satisfactory" roll response.

BIBLIOGRAPHY

1. Military Specification Flying Qualities of Piloted Airplanes, MIL-F-8785C, Nov. 1980.

2. Shomber, H. A.; and Gertsen, W. M.: Longitudinal Handling Qualities Criteria: An Evaluation. AIAA Paper No. 65-780, Nov. 1965.

3. Aerospace Recommended Practice: Design Objectives for Flying Qualities of Civil Transport Aircraft. ARP 842B, Soc. Automat. Eng., Aug. 1, 1964. Revised Nov. 30, 1970.

4. Sudderth, Robert W.; Bohn, Jeff G.; Caniff, Martin A.; and Bennett, Gregory R.: Development of Longitudinal Handling Qualities Criteria for Large Advanced Supersonic Aircraft. NASA CR-137635, March 1975.

5. Chalk, C. R.: Recommendations for SCR Flying Qualities Design Criteria. NASA CR-159236, April 1980.

6. Smith, Rogers E.: Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities. AFFDL-TR-78-122, vol. 1, March 1978.

7. Neal, T. Peter; and Smith, Rogers E.: An In-Flight Investigation to Develop Control System Design Criteria for Fighter Airplanes. AFFDL-TR-70-74, vol. 1, Dec. 1970.

8. Ashkenas, I. L.: Summary and Interpretation of Recent Longitudinal Flying Qualities Results. AIAA Paper No. 69-898, Aug. 1969.

9. Hoh, Roger H.; Mitchell, David G.; Ashkenas, Irving L.; Klein, Richard H.; Heffley, Robert K.; and Hodgkinson, John: Proposed MIL Standard and Handbook - Flying Qualities of Air Vehicles, vol. 2: Proposed MIL Handbook. AFWAL-TR-82-3081, vol. 2, Nov. 1982.

10. Holleman, Euclid C.; and Powers, Bruce G.: Flight Investigation of the Roll Requirements for Transport Airplanes in the Landing Approach. NASA TN D-7062, Oct. 1972.

11. Condit, Philip M.; Kimbrel, Laddie G.; and Root, Robert G.: Inflight and Ground-Based Simulation of Handling Qualities of Very Large Airplanes in Landing Approach. NASA CR-635, Oct. 1966.