1239

SPACE SHUTTLE ORBITER HANDLING QUALITY CRITERIA APPLICABLE TO TERMINAL AREA, APPROACH, AND LANDING

By

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INTRODUCTION

(Figure 1)

The requirement for satisfactory handling qualities of the space shuttle vehicle (SSV) may have a major impact on the vehicle and control system configuration. The present military specification for the flying qualities of piloted airplanes (MIL-F-8785B) has been developed to specify the requirements for satisfactory handling qualities for piloted military aircraft. While much of this specification for piloted aircraft is applicable to the SSV during terminal area, approach, and landing, there are some aspects of the SSV that are not satisfactorily covered (e.g., unpowered approach and landing).

Consequently, the NASA Ames Research Center (ARC) contracted (Contract NAS2-6057) with Systems Technology, Incorporated, to derive handling qualities criteria for the SSV orbiter during the terminal phases of flight using MIL-F-8785B as a point of departure. The study combined the results of an analytical pilot-vehicle systems analysis with the results of an extensive simulation conducted simultaneously at ARC. The purpose of this paper is to present some results of this study. The complete results will be reported in a low number NASA contractor report in the near future.

Several areas of MIL-F-8785B were initially identified as needing additional or modified criteria. These are listed in figure 1. Each of these areas will be discussed and criteria recommended. Two problem areas were also identified and are listed in figure 1. They will also be discussed.

SPACE SHUTTLE ORBITER HANDLING QUALITY CRITERIA APPLICABLE TO TERMINAL AREA, APPROACH, AND LANDING

- AREAS OF MIL-F-8785 B IDENTIFIED AS NEEDING ADDITIONAL OR MODIFIED CRITERIA
  - FLIGHT-PATH STABILITY AND CONTROL
  - PITCH ATTITUDE CONTROL
  - HEADING CONTROL
  - LONGITUDINAL PILOT INDUCED OSCILLATIONS
  - MISCELLANEOUS TOPICS
- PROBLEM AREAS IDENTIFIED
  - PITCH TRIM CHANGES DURING FINAL APPROACH
  - LATERAL RIDE QUALITY PROBLEM DURING FINAL APPROACH

Figure 1

UNPOWERED APPROACH AND LANDING TRAJECTORY
(Figure 2)

Before getting into the specific problem areas, a look at the various phases of an unpowered approach and landing trajectory is desirable. Figure 2 depicts a trajectory for that portion of the SSV trajectory considered in the present study. There are three fairly separate phases.

The high altitude maneuvering phase of flight extends from end of reentry (assumed for the study to be 30,000 m altitude and Mach = 3) down to capturing the initial approach path (3000 - 6000 meters). It is characterized by flight near maximum L/D using roll maneuvers for energy management. While most current SSV configurations have quite poor HQ characteristics (caused by high α, supersonic-transonic aerodynamics, etc.) the HQ requirements during this phase are quite low since precise maneuvering is not required.

The straight-in, constant flight path angle (10-20 degrees), initial approach phase usually starts at about 3000 - 6000 meters and extends down to the initial flare (200 - 600 m). Flight during this phase is characterized by fairly precise maneuvering. The vehicle is usually flown at a fairly constant equivalent speed (subsonic) 20-50% in excess of that for maximum L/D.

The constant flight path angle (about 3°) final approach extends from the initial flare down to final flare and touchdown. This phase of flight is one of the most critical for the SSV, requiring very precise maneuvering. The vehicle is decellerating from the equilibrium speed of the initial approach down to touchdown near the speed for maximum L/D.

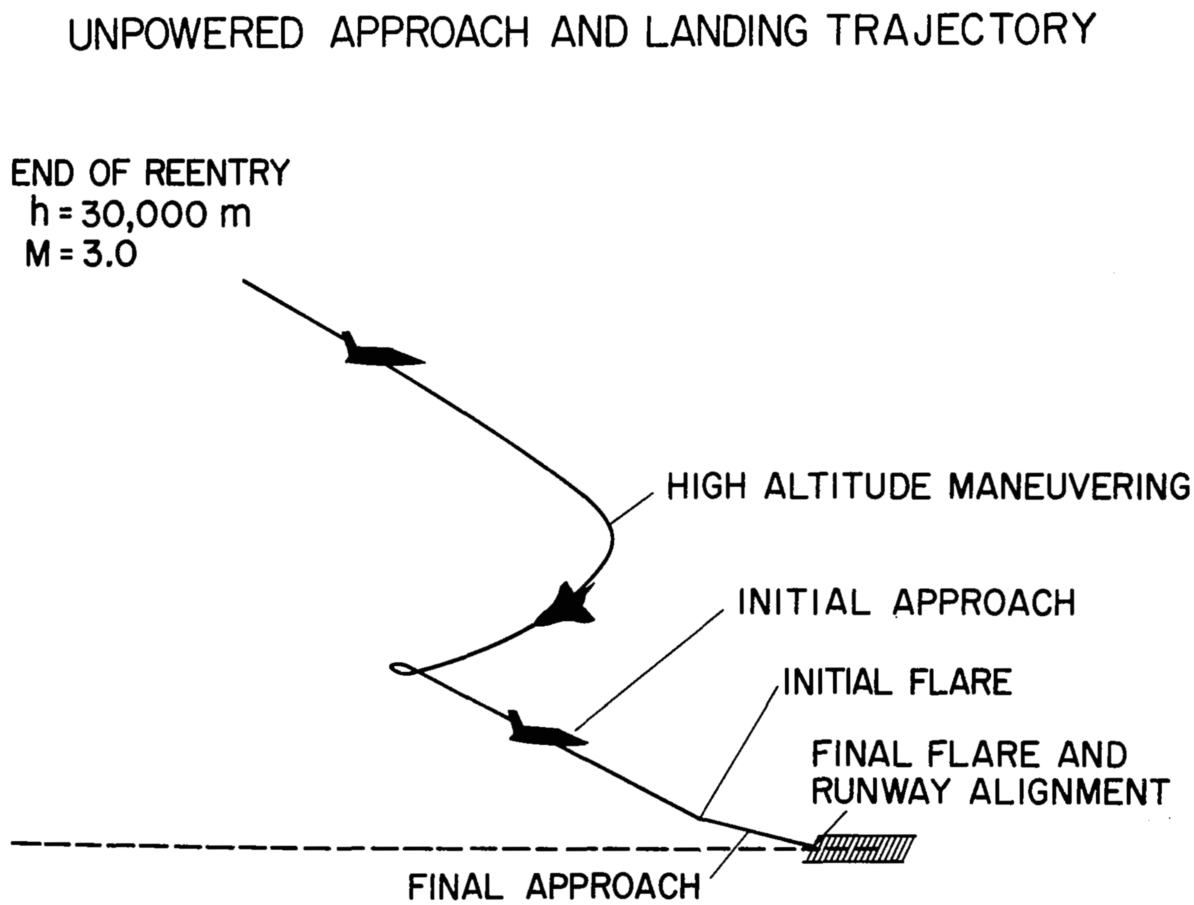
UNPOWERED APPROACH AND LANDING TRAJECTORY
END OF REENTRY
h = 30,000 m
M = 3.0
HIGH ALTITUDE MANEUVERING
INITIAL APPROACH
INITIAL FLARE
FINAL FLARE AND
RUNWAY ALIGNMENT
FINAL APPROACH

Figure 2

FLIGHT PATH STABILITY AND CONTROL FOR AN UNPOWERED APPROACH AND LANDING
(Figure 3)

Flight path stability and control is a measure of the vehicles capability to be controlled to the desired flight path assuming satisfactory attitude control. The main difference for flight in the approach and landing phase between a conventional airplane and the SSV is, of course, that the SSV may be unpowered. For a conventional powered approach, the present study recommends using the criteria of MIL-F-8785B. For an unpowered approach, new criteria are needed.

As mentioned earlier, the initial approach is made at essentially a constant flight path angle and equivalent airspeed. This phase should be made on the frontside of the drag curve (i.e., at speeds greater than that for maximum L/D). The problem was to define how far on the frontside was necessary. A considerable amount of effort was unsuccessfully spent attempting to define such a criteria. There appeared to be no handling quality problem per se as long as the approach was on the frontside of the drag curve. The only problems were of a performance nature, that is whether or not the pilot had sufficient maneuver capability to compensate for initial errors and winds. The pilots did object if the initial approach was too steep because of the high decent rates and large flight path angle change required during initial flare.

During the final approach phase, very precise flight path control is necessary. To ensure this a limit value on the flight path time constant, T_{θ_2}, was selected. T_{θ_2} is the time constant in the response of flight path to a pitch attitude change.

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FLIGHT PATH STABILITY AND CONTROL

- RECOMMENDED REQUIREMENTS
  - INITIAL APPROACH ANGLE $\leq 20°$
  - FLIGHT PATH TIME CONSTANT, T_{θ_2}, ≤ 2.5 sec
  - FINAL APPROACH FLOAT TIME $\geq 6\ T_{\theta_2}$

- TYPICAL SSV CHARACTERISTICS

CONFIGURATION	T_{θ_2}, sec
MDAC HCR	2.0
040 A	1.9

- IMPACT ON VEHICLE CONFIGURATION

$$T_{\theta_2} \doteq \frac{-1}{Z_w} = \frac{-1}{\dfrac{C_{Z_\alpha} S\bar{q}}{2mV}}$$

Figure 3

FLIGHT PATH TIME CONSTANT

(Figure 4)

(Continued from previous page.)

Figure 4 shows a typical variation of pilot rating (Cooper-Harper) for different values of T_{Θ_2} during the final approach. From data of this type, it is recommended that the maximum value of T_{Θ_2} up until the runway threshold be limited to 2.5 seconds. Since the magnitude of T_{Θ_2} is approximately inversely proportional to $Z\omega$, the rate of change of normal force with plunge velocity, it can be seen that this criteria can have a significant effect on the air frame configuration. Values for two candidate SSV configurations are shown in figure 3 and are seen to be satisfactory.

Assuming the flight path time constant is satisfactory, the pilot still needs a certain minimum time to settle down on the shallow glide slope and get set up for final flare and touchdown. The recommended value for float time (measured from completion of initial flare to runway threshold) is 6 times the flight path time constant or about 12 seconds for the particular SSV configurations noted.

The requirement for being on the front side of the drag curve during initial approach is not necessary for the final approach.

It should be noted that during the simulation studies to develop the present criteria, part of the final approach and the landing was done VFR, but the cockpit display also included raw ILS data. The limiting values of $1/T_{\Theta_2}$ and final approach float time may change for different display conditions. The requirements for IFR may be more stringent; and use of a flight director display might ease the requirements. There were also some indications of a possible effect of L/D on the criteria; however, the effect cannot be defined from the current data.

EFFECT OF FLIGHT PATH TIME CONSTANT

FLOAT PHASE $V_{L/D_{MAX}}$ = 220 knots T_{FLOAT} = 30 sec

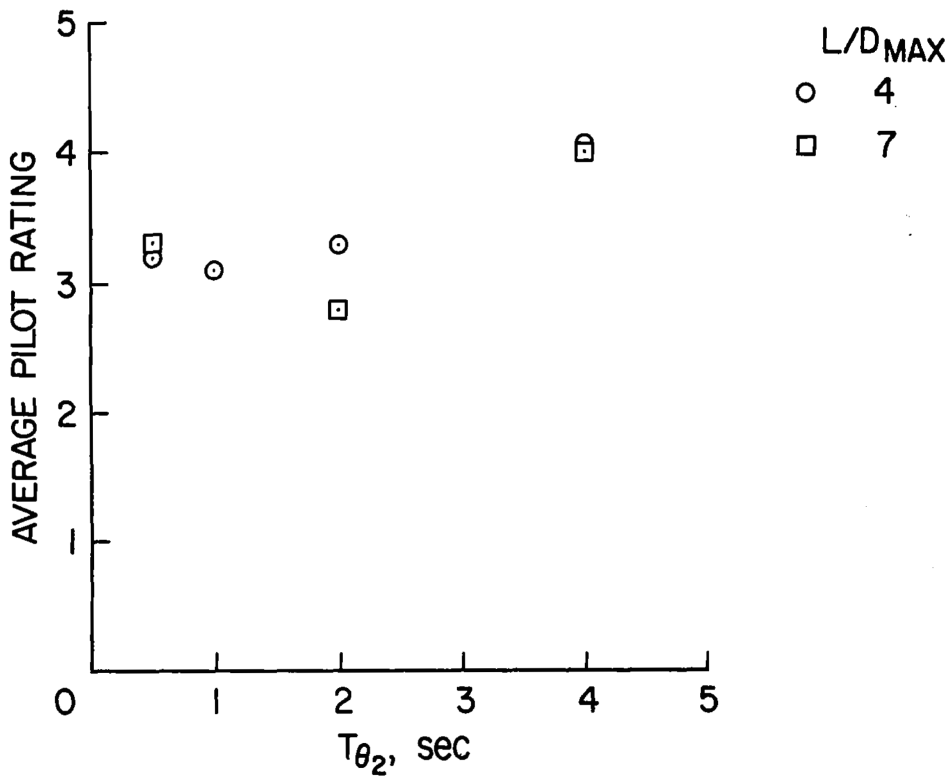

Figure 4

1247

FINAL APPROACH AND LANDING PITCH ATTITUDE CONTROL

(Figure 5)

The recommended criteria for the SSV for pitch attitude control during final approach and landing is based on an earlier study by Systems Technology, Incorporated, sponsored by the Air Force (STI TR-189-1).

Figure 5 shows the MIL-F-8785B criteria and that recommended for the SSV for a typical flight condition during the final approach. The abscissa is the equivalent pitch short period damping, $2\zeta_{SP}\ \omega_{SP}$, while the ordinate is the equivalent short period natural frequency, ω_{SP}. The Level 1 and 3 flying qualities boundaries are shown. Insufficient data existed to adequately define the lower left corner of the recommended SSV Level 3 criteria. Level 1 corresponds to clearly adequate flying qualities (Cooper-Harper pilot rating < 3-1/2) while Level 3 corresponds to flying qualities such that the vehicle can be controlled safely, but pilot workload is excessive (Cooper-Harper pilot rating < 6-1/2). Characteristics for two typical unaugmented SSV's are shown, the McDonnel/Douglas HCR Phase B configuration (model 050B) and the NASA 040A configuration (from a Lockheed Missiles and Space Company report, LMSC EM L4-02-01-M7-3, based on a September 1971 data package). The 040A configuration is shown at two angles of attack as there was a break in the static stability curve near the trim condition chosen.

For Level 1 flying qualities, the MIL-F-8785B criteria for piloted airplanes and the criteria recommended for the SSV are quite similar while for Level 3, the SSV criteria is much less restrictive.

If it is desired to fly the SSV unaugmented or with minimum augmentation, this new Level 3 criteria may be significant.

It should be noted that some difficulty was experienced in verifying the recommended criteria of figure 5 on the NASA ARC SSV simulation. It was concluded that most of the problem could be attributed to a longitudinal trim problem associated with the particular side arm controller used (discussed later) and that while the recommended criteria was primarily based on piloted aircraft results, it was probably applicable to the SSV.

FINAL APPROACH AND LANDING PITCH ATTITUDE CONTROL

V_e = 180 knots $n/\alpha \doteq 5.0$ g'S / rad $1/T_{\theta_2} \doteq 0.53\ sec^{-1}$

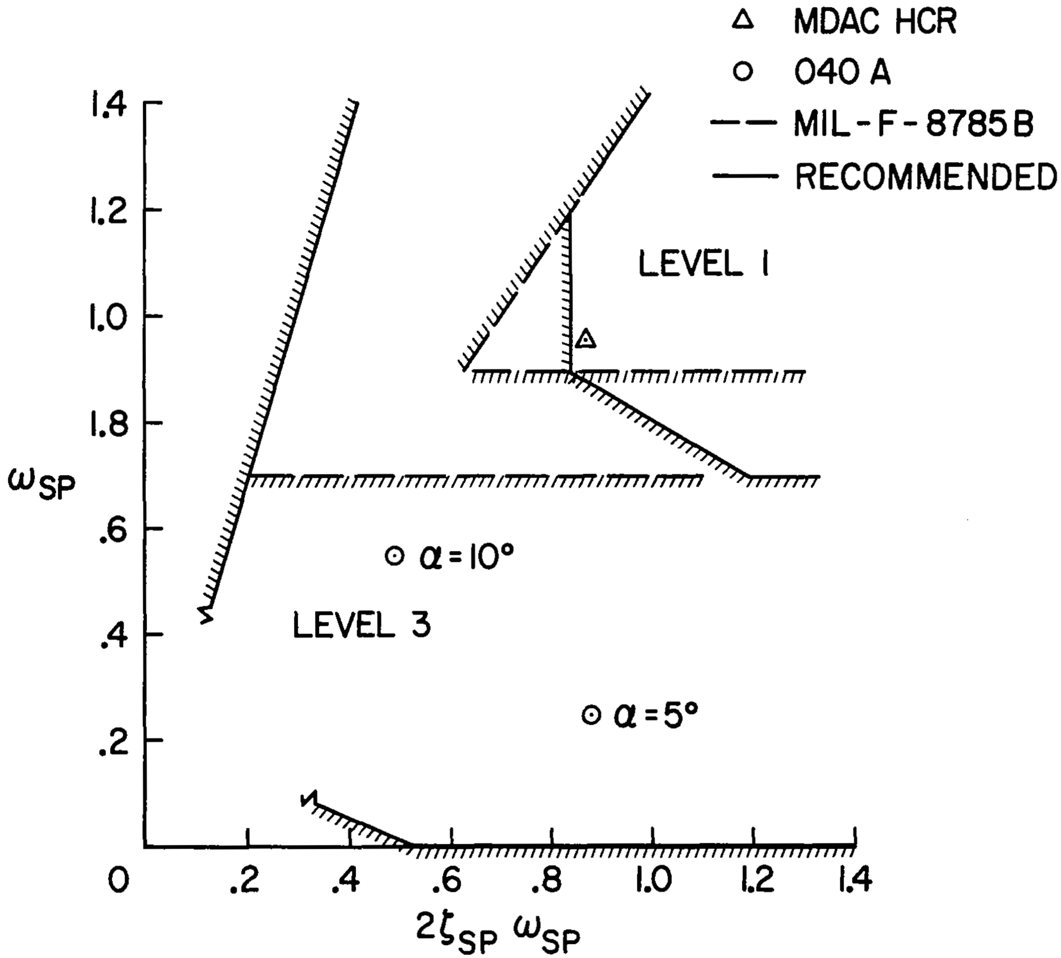

Figure 5

HEADING CONTROL
(Figure 6)

The military flying quality specification for piloted aircraft, MIL-F-8785B, has no direct criteria on heading control. It attempts to insure adequate heading control by restricting the amount of sideslip in aileron-alone turns. Because of the importance of adequate heading control in the final approach, the present study attempted to develop a heading control criterion.

The recommended criterion is based on the aileron-to-rudder crossfeed which would be required to coordinate turns, i.e., keep sideslip equal to zero. The criterion involves two parameters and is shown in figure 6. One is the ratio of yaw acceleration to roll acceleration due to aileron, $N'_{\delta_a}/L'_{\delta_a}$, measured in stability axes, divided by dutch roll frequency squared. The second parameter, μ, defines the shape of the required crossfeed in the frequency domain. This parameter is computed as follows:

- Compute the ideal rudder/aileron crossfeed, Y_{cf}, required to keep zero sideslip. This computation can be based on the measured or estimated sideslip/stick and sideslip/rudder pedal frequency responses, i.e.,

  $$Y_{cf} = -\frac{\text{sideslip/stick frequency response}}{\text{sideslip/rudder pedal frequency response}}$$

  where the frequency responses are those of the airplane plus appropriate augmentation systems.

- Over the frequency range 0.2-5 rad/sec, approximate the ideal crossfeed by a filter of the form

  $$\frac{-N_{\delta_a}}{N'_{\delta_a}}\frac{(s + z)}{(s + p)}$$

- μ is given by

  $$\mu = \frac{z}{p} - 1$$

The value of μ and $N'_{\delta_a}/L'_{\delta_a}\omega_d^2$ should then fall within the contours shown in figure 8.

(Continued on next page.)

(Figure 6)

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For $\mu = 0$ the ideal crossfeed would be a pure gain; rudder into the turn for adverse yaw and rudder opposite to the turn for proverse yaw. For $\mu = -1$ the ideal crossfeed low frequency characteristics or D.C. gain would equal zero with the high frequency crossfeed characteristics still requiring rudder into or opposite to the turn for adverse or proverse yaw respectively. For values of $\mu < -1$ the ideal crossfeed required rudder reversals while for $\mu > 0$ large amounts of D.C. gain are required.

The MDAC HCR vehicle is shown for several subsonic flight conditions (no calculations made for the NASA 040A configuration).

It was found that the above criteria is not appropriate if the magnitude of aileron-yaw becomes quite small. Then the yaw due to roll rate is the critical parameter. It is, therefore, recommended that if $|N'_{\delta_a}/L'_{\delta_a}| \leq 0.04$, the following be used instead of figure 7 (N'_p also measured in stability axes):

$$-0.25 < N'_p - \frac{g}{U_o} < 0.15 \text{ sec}^{-1}$$

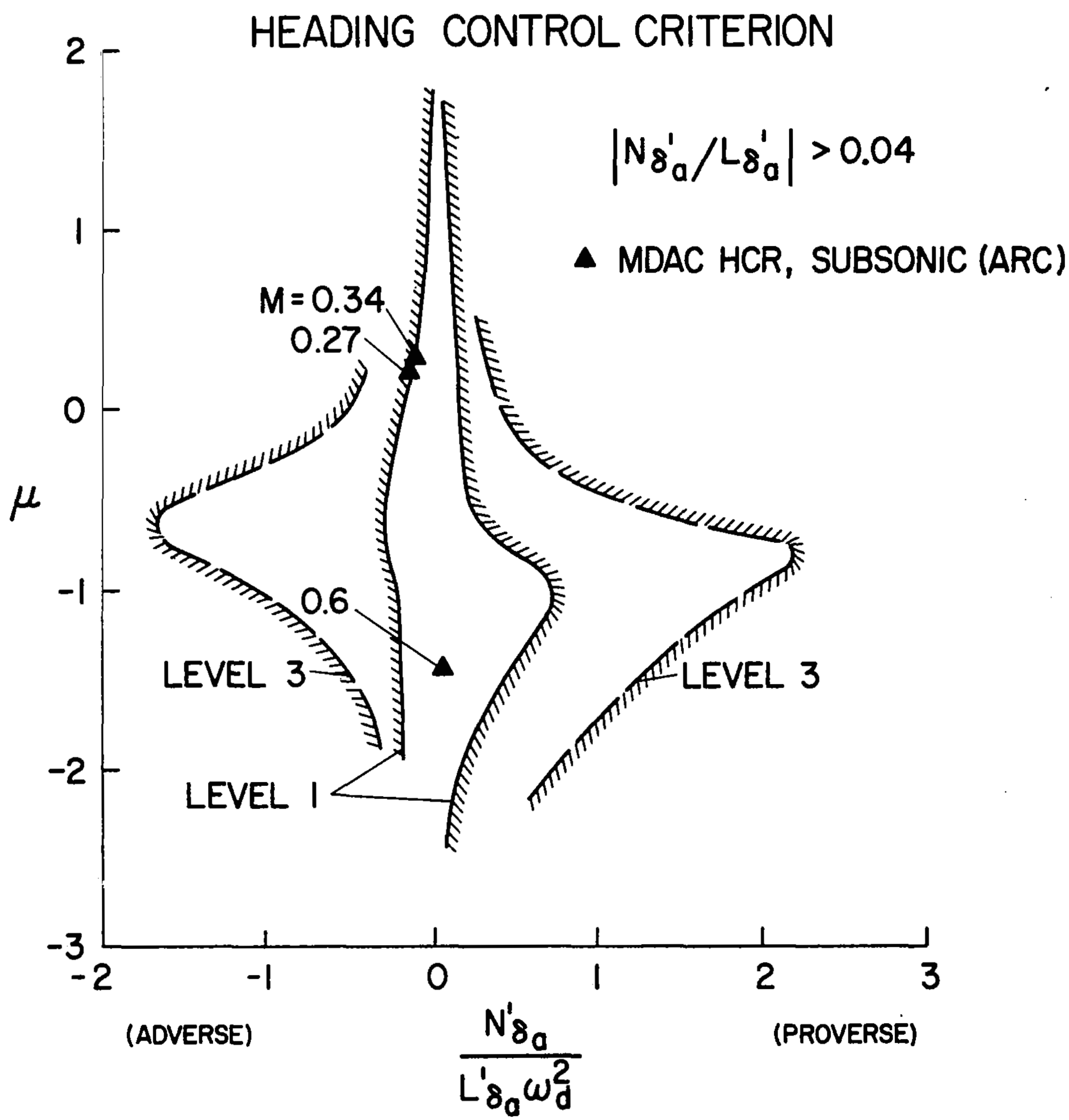
HEADING CONTROL CRITERION
$|N'_{\delta_a}/L'_{\delta_a}| > 0.04$
▲ MDAC HCR, SUBSONIC (ARC)
M = 0.34
0.27
0.6
LEVEL 3
LEVEL 3
LEVEL 1
μ
2
1
0
-1
-2
-3
-2
-1
0
1
2
3
(ADVERSE)
$\frac{N'_{\delta_a}}{L'_{\delta_a}\omega_d^2}$
(PROVERSE)

Figure 6

LONGITUDINAL PILOT-INDUCED OSCILLATIONS
(Figure 7)

MIL-F-8785B merely prohibits pilot-induced oscillations (PIOs) without providing any quantitative guidance. For the orbiter, the recommended criteria is based on STI TR 189-1. This criteria applies only for tasks which require tight attitude control.

Figure 7 shows the pilot/vehicle model of the pitch attitude loop used for analysis and the resulting root locus. The system elements are the pilot, the effective control system, and the effective air frame. Each of these components are represented by an appropriate simple transfer function form which identifies the key factors contributing to the closed-loop stability of the system. These are the pilot gain, K_P, the control system lag, τ_C; and the effective airframe dynamics, ζ'_P ω'_{S_P}, and $1/T_{\theta_2}$.

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LONGITUDINAL PILOT - INDUCED OSCILLATIONS

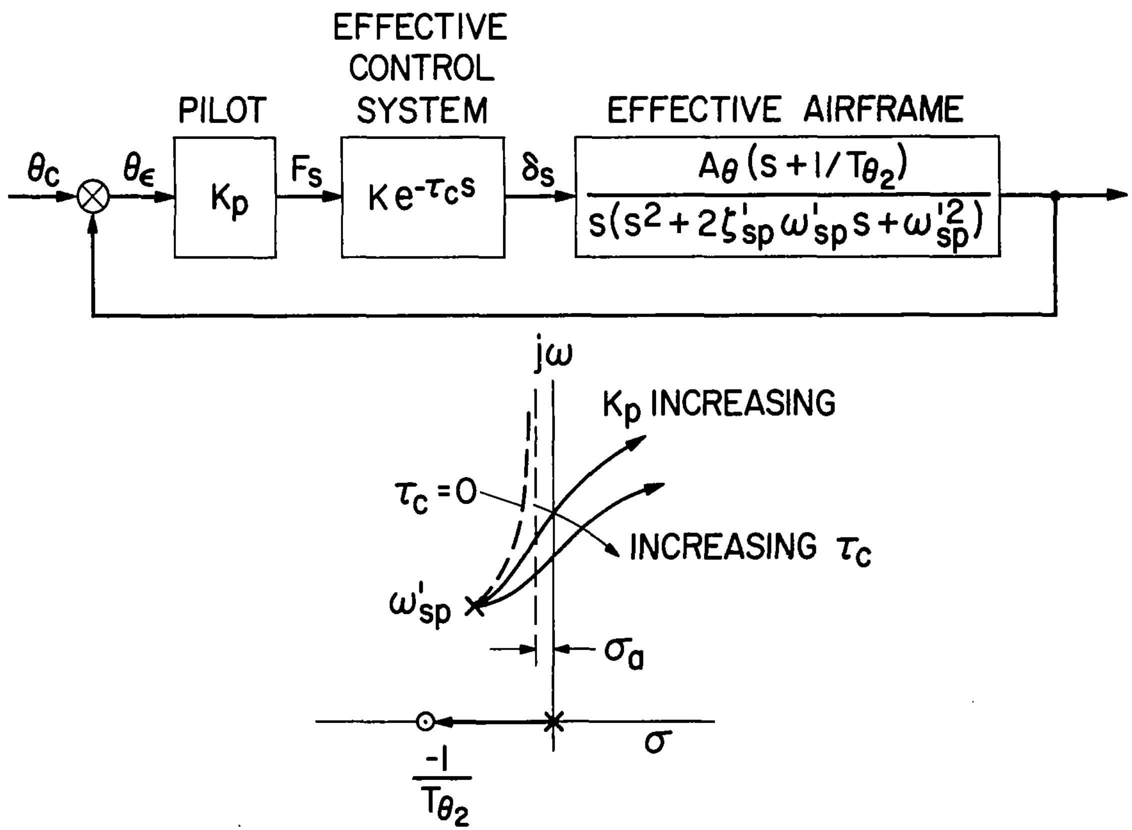

Figure 7

REQUIREMENT FOR AVOIDANCE OF LONGITUDINAL PILOT-INDUCED OSCILLATIONS
(Figure 8)

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The PIO criteria shown in figure 8 is expressed in terms which are related to these factors. The abscissa of figure 8 is based on the root locus high gain asymptote parameter, σ_a, which is functionally related to the factors of figure 7 (i.e., $\sigma_a = 2\zeta'_{SP}\,\omega'_{SP} - 1/2\ 1/T_{\theta_2}$). The ordinate represents the effective control system lag contribution to the phase angle measured at the effective airframe short-period frequency (i.e., $\phi \doteq \tau_C\,\omega_{SP}$).

The unaugmented vehicle dependent characteristic, σ_a, for the two SSV configurations discussed previously, is also shown on figure 8 for a typical landing approach condition (Category C). It can be seen that even with no control system lag, the unaugmented vehicle may be marginal for Level 1 flying qualities but will probably be acceptable for Level 3. This result was generally verified on the NASA ARC simulation of the MDAC HCR vehicle where pilot comments indicated that the vehicle seemed lightly damped but no PIO problem per se.

REQUIREMENTS FOR AVOIDANCE OF PILOT-INDUCED OSCILLATIONS

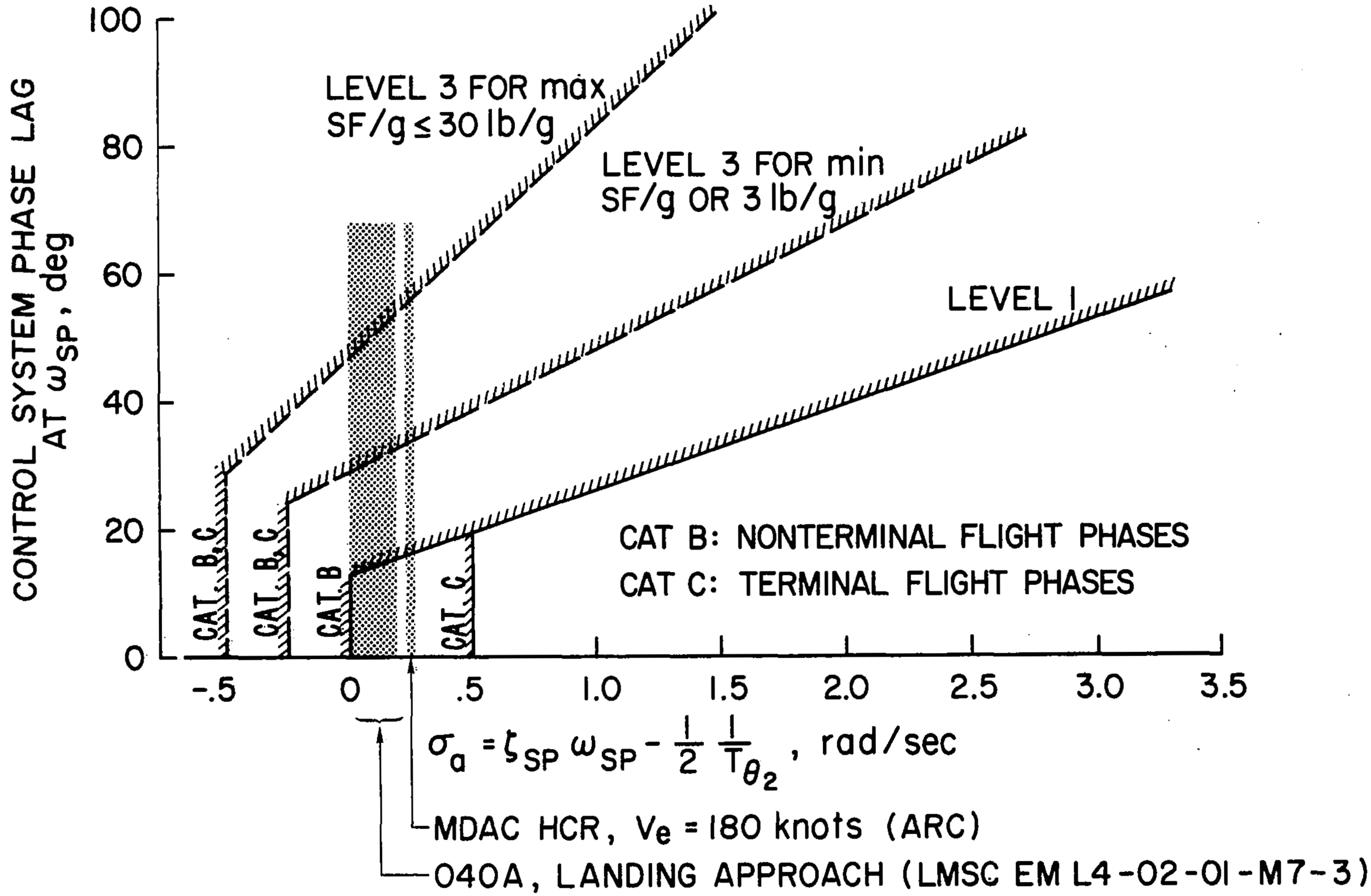

Figure 8

1257

MISCELLANEOUS TOPICS

(Figure 9)

Three additional areas will be discussed briefly.

The first deals with the dynamics of the primary flight control system. MIL-F-8785B specifies the allowable control system lag from cockpit control force input to control surface motions. Based on STI TR 189-1, it is recommended for the SSV Level 1 requirement that the total phase lag from cockpit control force or displacement to vehicle attitude be specified as less than 135 degrees, at 1 rad/sec.

MIL-F-8785B limits rudder pedal forces for zero side slip in rolls. It is felt that this is overly restrictive and a SSV HQ criteria should limit rudder pedal forces to keep sideslip less than some finite value.

The only MIL-F-8785B criterion for rudder power is to ensure adequate rudder power for steady sideslips in crosswind approaches. It is recommended that adequate rudder power be provided the SSV to rapidly decrab the vehicle for runway alignment at touchdown.

MISCELLANEOUS TOPICS

- PRIMARY FLIGHT CONTROL SYSTEM DYNAMICS
  - MIL-F-8785 B SPECIFIES ALLOWABLE PHASE LAG IN CONTROL SYSTEM
  - PRESENT STUDY SPECIFIES TOTAL PHASE LAG FROM COCKPIT TO VEHICLE ATTITUDE
  - RECOMMENDED LEVEL I CRITERIA: 135° AT 1 rad/sec
- RUDDER PEDAL FORCES DURING ROLLS
  - MIL-F-8785 B LIMITS FORCES FOR ZERO SIDESLIP IN ROLLS
  - PRESENT STUDY RECOMMENDS LIMITING FORCES FOR FINITE VALUES OF SIDESLIP
- RUDDER POWER FOR DECRAB
  - MIL-F-8785 B SPECIFIES RUDDER POWER FOR STEADY SIDESLIP DURING CROSSWIND APPROACH
  - PRESENT STUDY RECOMMENDS ADDITIONAL CRITERIA FOR DECRAB NEEDED

Figure 9

PROBLEM AREAS

(Figure 10)

While much additional work needs to be done on the areas of research considered, two new problem areas developed during the course of the study. Because of time limitations, the present study didn't fully resolve these.

The first problem area encountered was trouble with longitudinal trim during the final approach with the particular side arm controller and trim system used in the NASA ARC simulation. As mentioned earlier, the final approach is characterized by a constant flight path angle and constantly decreasing equivalent airspeed. The decreasing airspeed requires that the vehicle be constantly retrimmed. The side arm controller used has a very light force gradient and a series trim wheel. Several symptoms were noted: (1) because of the light force gradient, it was possible to forget to trim resulting in inadequate elevator for flare; (2) it was difficult to coordinate stick motion while retrimming; and, (3) it was difficult to get full required elevator and still maintain the trim sensitivity at a reasonably low value. Based on the experience obtained, it appears that a comprehensive investigation needs to be conducted before a specification can be made for side arm controllers.

The other problem relates more to ride, rather than handling qualities. It was experienced during the simulation runs in support of the heading control work discussed earlier. With a large aircraft approaching at high angles of attach the pilot can be situated several feet above the stability axes. If the aircraft is coordinated, it will roll about the velocity vector or stability X axis. This can produce highly objectionable side accelerations at the cockpit, especially if the aileron roll acceleration is high. The only solutions are to reduce the aileron power below what is normally considered desirable or to degrade the degree of coordination. Both have deleterious effects so a design compromise must be made. The outcome of the proper compromises needs further investigation and definition.

PROBLEM AREAS

- PITCH TRIM CHANGES DURING FINAL APPROACH DICTATES A GOOD PITCH TRIM SYSTEM

- LATERAL RIDE QUALITY PROBLEM DURING FINAL APPROACH – CAUSED BY HIGH α AND HIGH ROLL POWER

Figure 10

AREAS NEEDING FURTHER RESEARCH
(Figure 11)

Further research is also needed in several of the areas investigated.

Additional research in the area of flight path control criteria is considered essential because of the potential impact of the criteria on basic vehicle parameters and trajectory limitations. If an unpowered Orbiter is selected, the criteria proposed here need to be extended. The effects of IFR flight and the effects of adding a flight director display should be assessed. The potential influence on the criteria of variations in L/D also needs further investigation. If a powered Orbiter is selected, a better flight path control criterion than that of 8785B may be desirable.

Further verification of the recommended pitch attitude control criteria is needed. The proposed criteria is mainly based on results from conventional aircraft. Because of the longitudinal trim problem discussed earlier, it was not possible to conclusively verify the proposed criteria for the SSV on an unpowered trajectory. This was especially true for the Level 3 flying quality boundary.

Further research on heading control criteria is also considered important but of lower priority than the subjects noted above. The criterion proposed appears to be a significant advancement, but additional verification, and possible refinement, is highly desirable.

FURTHER RESEARCH NEEDED

- PITCH FLIGHT PATH CONTROL
    - UNPOWERED
    - POWERED
- PITCH ATTITUDE CONTROL
- HEADING CONTROL

Figure 11