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THE DEVELOPMENT OF FLYING QUALITIES FOR LIFTING RE-ENTRY VEHICLES DURING TERMINAL FLIGHT

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FOREWORD

This report on the development of lifting re-entry vehicle flying qualities was prepared by the Cornell Aeronautical Laboratory, Inc., (CAL), Buffalo, New York, in partial fulfillment of USAF Contract F33615-70-C-1755. The contract was performed under Project 680A, "Handling Qualities Requirements for High Speed Military Flight Vehicles", Task No. 680A05.

Prepared under this contract were a preliminary specification for the flying qualities of piloted re-entry vehicles during terminal flight and the flying qualities rationale, backup data, and user's guide to substantiate the requirements.

This work was performed by CAL's Flight Research Department, under the sponsorship of the Air Force Flight Dynamics Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio. Project engineers for the Air Force during the three years of this program were Major William Smith, Mr. James Pruner, and Mr. Terry Neighbor (AFFDL/FGC). Project Engineer for CAL was Mr. D.A. Di Franco. Mr. D. A. Di Franco and Mr. J.F. Mitchell were principal investigators throughout the project. The investigation was conducted under the supervision of Mr. C. R. Chalk.

The Contractor's report number is BM-2995-F-2

This report was submitted by the author on 30 June 1971 and concludes the work on this contract.

This technical report has been reviewed and is approved.

C. B. WESTBROOK
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Flight Control Division
Air Force Flight Dynamics Laboratory

ABSTRACT

This report summarizes a three-year effort which led to the development of a preliminary specification for the flying qualities of piloted re-entry vehicles during terminal flight. Part of this effort was directed at the preparation of the rationale and backup data upon which the flying qualities requirements are based. The effort included support of the FDL-8 lifting body program at the Air Force Flight Dynamics Laboratory from the standpoint of handling qualities. Some effort was also directed at a preliminary examination of lifting re-entry dynamics with time dependent coefficients. Included in this report are recommendations on the handling qualities research programs to improve and extend the handling qualities requirements of lifting re-entry vehicles.

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SECTION I

INTRODUCTION

In January 1968 Cornell Aeronautical Laboratory, Inc. (CAL) was awarded a contract by the Air Force Flight Dynamics Laboratory to conduct a preliminary investigation of the handling qualities requirements for lifting re-entry vehicles. Under this contract some of the important problems associated with an adequate definition of lifting re-entry vehicle handling qualities requirements were investigated. This was followed by a contract in June 1969 to continue the investigation for an additional year. As part of this effort, the in-house design of the FDL-8 high $(L/D)_{max}$ lifting body at the Flight Dynamics Laboratory was supported by CAL from the standpoint of handling qualities. A succeeding contract was awarded to CAL by the Air Force Flight Dynamics Laboratory in June 1970. All of these efforts culminated in the drafting of some preliminary handling qualities requirements for lifting re-entry vehicles during terminal flight (Reference 1). The requirements of Reference 1 include a preliminary draft of a flying qualities specification for piloted re-entry vehicles and the rationale and backup data upon which the flying qualities requirements are based. The results of these efforts are summarized in this report in order to give an overall impression of the present status of lifting re-entry vehicle handling qualities.

Section II consists of an historical presentation of the development of lifting re-entry vehicle handling qualities requirements. Section III summarizes lifting re-entry vehicle handling qualities specifications as they are presented in Reference 1. Section IV is a discussion of efforts on some related items, FDL-7 and FDL-8 handling qualities and some aspects of lifting re-entry dynamics. Suggestions on ground and in-flight handling qualities research programs to improve the specification of lifting re-entry vehicle handling qualities are presented in Section V.

SECTION II

HISTORICAL DEVELOPMENT

In 1959, some preliminary handling qualities requirements were developed for the Air Force Flight Control Laboratory at Wright-Patterson Air Force Base under Contract No. AF33(616)-6240. These preliminary requirements were to be used in the design and development of the X-20 (Dyna-Soar) re-entry vehicle. These requirements were generally based on, and presented in the format of old MIL-F-8785(ASG). Some preliminary requirements on side-arm controllers and reaction controls were also included.

The most recent effort in the development of lifting re-entry vehicle handling qualities began in January 1968. Cornell Aeronautical Laboratory, Inc. (CAL), under Contract AF33(615)-3294, undertook a preliminary investigation of the handling qualities requirements for lifting re-entry vehicles. This work was performed for the U. S. Air Force Flight Dynamics Laboratory at Wright-Patterson Air Force Base.

Under this contract some of the important problems associated with an adequate definition of lifting re-entry vehicle handling qualities requirements were considered. Included in the investigation was a survey of the literature, an investigation of lifting re-entry equations of motion suitable for handling qualities interpretation, and recommendations for additional lifting re-entry vehicle handling qualities research. The result of this investigation was a preliminary discussion of the problems associated with a lifting re-entry vehicle handling qualities specification. Although this study left many problems unanswered, a suitable framework was established for more definitive future investigations.

As part of this contract, during October 1968 a series of preliminary meetings was held with a few individual contractors and Government agencies to discuss handling qualities requirements of lifting re-entry vehicles. The discussions were preliminary in nature and all the important contractors and Government agencies engaged in research and design of lifting re-entry vehicles were not represented. The following contractors and Government agencies participated in these meetings:

Air Force Flight Dynamics Laboratory
Cornell Aeronautical Laboratory, Inc.
Air Force Flight Test Center
NASA Flight Research Center
Norair
North American Rockwell, Los Angeles
North American Rockwell, Downey
NASA Ames

The work accomplished under this contract is reported in Reference 2 issued in May 1969.

The above effort was followed by a contract to continue the investigation of lifting re-entry vehicle handling qualities requirements. Contract F33615-69-C-1906 was awarded to CAL by the Air Force Flight Dynamics Laboratory in June 1969. This research effort consisted of a preliminary draft of a handling qualities specification for re-entry vehicles applicable especially to the subsonic glide and landing phase of flight. Recommendations were also made of handling qualities research programs to further define lifting re-entry handling qualities requirements. Part of this investigation was also concerned with the low speed handling qualities requirements of a specific vehicle, the FDL-8 during terminal glide and landing.

This contract was amended in March of 1970. As amended, this research investigation also included an examination of FDL-7 flying qualities and recommendations on ground-based simulation of the FDL-7 lifting re-entry vehicle from the standpoint of acquiring handling qualities data.

The results of this contract were some preliminary handling qualities requirements for the FDL-8 lifting re-entry vehicle issued in October 1969 (Reference 3). These requirements were to apply to the FDL-8 lifting re-entry vehicle during flight at low supersonic, transonic, and subsonic speeds. The requirements consisted primarily of the adaptation of MIL-F-8785(ASG) for application to the FDL-8 vehicle. These requirements were then used to examine unaugmented FDL-8 handling qualities based on the available wind tunnel data and predicted vehicle stability derivatives (Reference 4).

Under this contract as amended, the ground-based simulation of the FDL-7 at the Flight Dynamics Laboratory was supported. Recommendations for ground-based simulation of handling qualities and turbulence are contained in Reference 5. The intent of this support was to identify the important features of the simulation that pertained to handling qualities, and to make recommendations that would enhance the applicability of the information to lifting re-entry vehicle handling qualities requirements.

Lifting re-entry handling qualities are of necessity related to lifting re-entry dynamics. Some of the unique aspects of lifting re-entry dynamics were also investigated under this contract. The purpose was to establish a basis for future expansion of the handling qualities requirements to all the flight phases of lifting re-entry vehicles. The results of this preliminary investigation are reported in Reference 6. Also, the role of lifting re-entry vehicle stability and control and handling qualities in vehicle design was examined in a general way in Reference 7.

The preliminary handling qualities for the FDL-8 presented in Reference 3 were reviewed by the Flight Dynamics Laboratory. These review comments were used in revising and generalizing the requirements of Reference 3 so that they would apply to all medium-to-high maneuverability lifting re-entry vehicles. This preliminary flying qualities specification for piloted re-entry vehicles and the flying qualities rationale upon which the requirements are based is contained in Reference 8.

In July 1970, The Flight Research Department of Cornell Aeronautical Laboratory received Contract F33615-70-C-1755 from the Flight Dynamics Laboratory to continue the work accomplished in the previous two years on lifting re-entry vehicle handling qualities. Work under this contract was completed in June 1971 and terminates the present effort on lifting re-entry vehicle handling qualities.

Under this contract the requirements presented in Reference 8 have been extensively revised and expanded. As part of this effort, copies of the preliminary lifting re-entry handling qualities specification developed the previous year (Reference 8) were sent to a number of contractors and Government agencies for review and comments. These contractors and Government agencies were visited during January 1971 for comments and discussions on lifting re-entry vehicle handling qualities requirements. Those who supplied comments and participated in these discussions are listed below:

Air Force Flight Dynamics Laboratory
Cornell Aeronautical Laboratory, Inc.
NASA - Marshall Space Flight Center
Lockheed Georgia Company
NASA-Manned Spacecraft Center
Martin Marietta Corporation
McDonnell-Douglas Astronautics East
NASA - Ames Research Center
General Dynamics - Convair
North American Rockwell- Los Angeles Division
NASA - Flight Research Center
Air Force Flight Test Center

The comments obtained during these trips were considered in the revision of the lifting re-entry vehicles handling qualities requirements presented in Reference 8. The revised and expanded flying qualities requirements and the rationale and backup data upon which these requirements are based are contained in Reference 1. These revised requirements for lifting re-entry vehicles apply to both large and small vehicles during terminal flight at low supersonic, transonic, and subsonic speeds.

Under this contract the investigation of lifting re-entry vehicle dynamics with time dependent coefficients continued and the results are presented in Reference 9.

SECTION III

LIFTING RE-ENTRY VEHICLE HANDLING QUALITIES SPECIFICATION

Reference 1 presents the handling qualities requirements for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. The requirements apply to both large and small vehicles and vehicles from low to high cross-range based on hypersonic $(L/D)_{max}$ and normal load factors.

One unique aspect of the specification contained in Reference 1 is that requirements are written for operational as well as experimental lifting re-entry vehicles. Experimental lifting re-entry vehicles are generally flown by skilled and highly trained experimental test pilots. The flight envelopes of these vehicles are restricted and the vehicles are flown under what are considered ideal flight conditions. Since experimental lifting re-entry vehicles are likely to be the rule rather than the exception for some time to come, writing requirements for experimental as well as operational vehicles was considered advisable. In general, minimum acceptable handling qualities for an experimental vehicle performing an experimental mission are inadequate for the same vehicle under operational conditions, although some requirements are the same for operational and experimental vehicles.

Handling qualities requirements for military aircraft are generally specified in terms of "open-loop" parameters for the vehicle that result in a certain level of handling qualities. This same approach is used in specifying handling qualities requirements for re-entry vehicles in Reference 1. Since the open-loop parameters used in most cases are those of MIL-F-8785B(ASG), it is assumed that the vehicle is sustained in flight by primarily aerodynamic forces and controlled primarily by aerodynamic controls. It is also assumed that the essential aspects of the vehicle dynamics can be adequately defined by a set of linear differential equations with constant coefficients, and that the longitudinal and lateral-directional motions can be considered uncoupled, or only slightly coupled. An additional basic assumption made in the requirements as presented is that the important modal parameters from the point of view of handling qualities are the same for augmented as well as unaugmented vehicles. It is assumed that primary and secondary flight control system requirements from the point of view of handling qualities can be stated separately.

The requirements specified in Reference 1 are not applicable to lifting re-entry vehicle flight phases when the dynamic pressure is much below that necessary to develop lift equal to the weight of the vehicle. The requirements do not apply when the effects of time dependent coefficient dynamics are significant. Significant nonlinearities in stability derivatives, such as nonlinearities with angles of attack and angle of sideslip, are also not adequately covered by the requirements in Reference 1.

The format used in presenting the flying qualities requirements for piloted lifting re-entry vehicles is identical to that for piloted airplanes. This method appears to be most suitable at the present time during terminal flight in the lower atmosphere. The format is that of MIL-F-8785B(ASG).

In Reference 1, the rationale and available data used in arriving at the re-entry vehicle handling qualities requirements are presented. Only brief comments are made when the rationale and data available for particular requirements are the same or similar to those used in establishing requirements for airplanes as presented in MIL-F-8785B(ASG). When the rationale is different and the requirements are new and based on new data, these requirements are discussed in detail and the new data are presented.

All handling qualities specifications have [illegible], and this is especially true of a lifting re-entry vehicle specification. [illegible]tions for ground and in-flight handling qualities research pr[illegible] contained in Section V.

SECTION IV

ITEMS RELATED TO RE-ENTRY HANDLING QUALITIES

A number of corollary items were investigated that are related to lifting re-entry handling qualities requirements and these items are discussed briefly in this section.

4.1 Support of the FDL-8 and FDL-7 Programs

One of the primary reasons for developing handling qualities requirements for piloted re-entry vehicles is to use them in establishing the design requirements of the basic vehicle and the flight control system. The requirements of Reference 3 were in fact developed for this very purpose in connection with the Flight Dynamics Laboratory's development of the FDL-8, a small lifting re-entry vehicle configuration with high hypersonic $(L/D)_{max}$ (2.5 to 3.0) and high cross-range.

The vehicle under development at the Flight Dynamics Laboratory is a research vehicle that will be used to investigate the flight characteristics and handling qualities during terminal flight of a hypersonic high $(L/D)_{max}$ configuration.

In support of this program some preliminary checks of FDL-8 handling qualities were made based primarily on static stability and control characteristics obtained from low speed wind tunnel test ($M \approx 0.2$). Low speed dynamic stability and control derivatives used in the analysis were estimated by personnel at the Flight Dynamics Laboratory. The results of this analysis are presented in Reference 4. Since no information was available on the flight control system design, the handling qualities of the augmented vehicle were not considered.

This preliminary examination of the unaugmented FDL-8 indicated that the vehicle was deficient in damping about all three axes and would require damping augmentation to meet Level 1 requirements. The vehicle appeared to be spirally stable and had no coupled roll-spiral mode for the cases investigated. Most of the cases investigated indicated that the vehicle did not meet Level 1 lateral-directional requirements for Flight Phase Category C. A more detailed investigation with Mach number and flight control system characteristics included will be required before definitive statements can be made concerning FDL-8 handling qualities.

The AFFDL simulation of the FDL-7 lifting body was supported in April and May of 1970. Features of the simulation that pertain to handling qualities were identified and recommendations were made for enhancing the applicability of information obtained from the simulation to lifting body handling qualities technology.

To improve handling qualities information obtained from the simulation, specific recommendations were made on task definition, configuration identification, and pilot evaluation comments and ratings. Since atmospheric turbulence is a problem of considerable significance in the evaluation of handling qualities of re-entry vehicles, specific recommendations were also made on the simulation of turbulence. All of these recommendations are contained in Reference 5. Many of the recommendations were considered in the ground-based simulation of the FDL-7 during April and May of 1970.

4.2 Aspects of Re-Entry Dynamics

The handling qualities requirements of Reference 1 apply during terminal flight at low supersonic, transonic, and subsonic speeds. If these requirements are to be extended to other flight phases of lifting re-entry vehicles, a knowledge of the salient aspects of vehicle dynamics during these flight phases is essential.

A preliminary investigation of the dynamics of lifting re-entry vehicles with time dependent coefficients in the equations of motion was undertaken. In the analysis of Reference 6 only longitudinal short period dynamics were investigated. The relationship between the vehicle trajectory conditions and the degree of time dependency in the equations was established. Computer results were obtained and a reasonably simple analytic approach was devised to explain the results. It was established that the time-dependent effects are related to the trajectory conditions and the constant coefficient dynamic solution. The results showed that response characteristics such as frequency and damping ratio are functions of time in the time-dependent cases. Some of the responses can be divergent while others are convergent for the same flight condition.

From the analysis of Reference 6, it was found that the time-dependent coefficient problems considered could be reduced to a one-degree-of-freedom problem. This work was continued in Reference 7. Using the same analytic approach presented in Reference 7, the analysis was extended to additional responses and response derivatives. It was also demonstrated, that with some complication in the approach, the analysis could be extended to two and three degrees of freedom and even to lateral-directional motions.

This work should be useful in the future when the lifting re-entry vehicle handling qualities requirements of Reference 1 are extended to other flight phases.

SECTION V

SUGGESTED GROUND AND IN-FLIGHT HANDLING QUALITIES PROGRAMS

Reference 1 contains a preliminary flying qualities specification for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. Included are the rationale and backup data upon which these requirements are based. An examination of Reference 1 makes it readily apparent that it was difficult to establish quantitative requirements in many instances, simply because no data or inadequate handling qualities data exists. Although this is especially true of many of the requirements that are unique to lifting re-entry vehicles, it is also true of some requirements that are expected to be common to lifting re-entry vehicles and conventional aircraft. In large part, the deficiencies in the requirements can only be overcome by well planned handling qualities research programs. Some of the important programs that will aid in eliminating many of the flying qualities specification deficiencies are presented and discussed in this section.

The fact that the programs must be well planned cannot be overemphasized. The research programs must be tailored to both the potential and limitations of the simulation facility, which can vary from simple fixed-base ground simulators, moving-base ground simulators, and total in-flight simulators. When moving visual scene displays and proprioceptive cues are expected to be important to the handling qualities results, such cues must be adequately included in the simulation program or the results must be considered preliminary and subject to future verification. Based on recent comparisons of ground and in-flight simulations, such as Reference 10, it is not necessarily a valid assumption that fixed-base ground simulators give conservative results, i.e., the simulated vehicle characteristics would be rated better in actual flight. Strong consideration should be given to an adequate simulation of atmospheric turbulence when evaluating the characteristics of lifting re-entry vehicles and airplanes. Reference 11 indicates to what extent some lifting re-entry vehicle characteristics can be downgraded in the presence of turbulence.

In the gathering of handling qualities data through simulation, it is important that the vehicle mission and tasks are clearly understood by the evaluation pilots and good pilot comment data and rating data are obtained. Such data can then be used to establish quantitative handling qualities requirements where deficiencies in the present specification exist.

What kind of simulation facility, ground-based, or in-flight, should be used for each of the programs discussed is not indicated. This will depend on many details of the simulation facility and the research program. Ground and in-flight simulations are often looked upon as complementary. A simplified ground-based simulation program is the basis for a detailed and more realistic in-flight simulation program.

Most of the programs discussed are directly applicable to the flying qualities specification of Reference 1 during the terminal flight of lifting re-entry vehicles at low supersonic, transonic, and subsonic speeds. A few of the programs are directed at a preliminary investigation into other areas, i.e., the possible extension of the flying qualities requirements to other than terminal flight phases of re-entry.

5.1 Programs on Flight-Path Stability

The proposed requirements specify that the flight-path angle versus airspeed ($d\gamma/du$) must be stable for all speeds during the flare and float to touchdown for unpowered vehicles. This requires that the touchdown speed be higher than the speed for $(L/D)_{max}$. There is some indication that "frontside" operation can be relaxed, at least during the float and some "backside" operation may be allowable, especially if the vehicle has speed brakes. In addition, no data presently exists for determining the degree of flight path stability ($d\gamma/du$)required for unpowered landings with steep glide path angles.

One or more research programs should be conducted to measure the degree of flight path instability allowable or the degree of stability required, both during the flare and the float, to meet various handling qualities Levels during unpowered landings. The investigation should consider variations in $d\gamma/du$, speed brake effectiveness, and the ratio of flare altitude to flare time (h_f/t_f) or $(L/D)_{max}$. Variations in short-period dynamics may also be a consideration.

5.2 Programs on Longitudinal Short-Period Dynamics

Certain requirements in MIL-F-8785B(ASG) (Reference 12, paragraph 3.2.2.2.2) are stated such that they require the unaugmented airplane to be statically stable. Specific requirements for unaugmented vehicle static stability have been eliminated from the lifting re-entry specification. It is only required that any deficiencies in the unaugmented vehicle be corrected through an augmentation system with adequate reliability.

Some more recent in-flight simulation programs, as well as some past programs, indicate that short-period requirements in both frequency and damping can be more lenient than those specified for airplanes in MIL-F-8785B(ASG). In fact, these recent programs indicate that for Category B Flight Phases, negative damping may be acceptable (PR < 6.5). Unfortunately, these experiments were conducted in smooth air under VFR conditions. In fact, the damping requirements in MIL-F-8785B(ASG) are higher than data indicate simply to compensate for more realistic levels of turbulence under operational conditions.

A need obviously exists to conduct simulation programs for various Flight Phases and Classes of lifting re-entry on minimum longitudinal short-period requirements for various handling qualities Levels, especially degraded Levels. The parameters to be varied are $\omega_{n_{sp}}$, ζ_{sp} , n/α , and possibly L_α . It is, of course, important that these experiments be conducted with an adequate simulation of turbulence in order that realistic minimum short-period requirements can be established. These experiments may indicate that short-period requirements can be relaxed for some Flight Phases.

Lower limits on $\omega_{n_{sp}}$ are a result of a degradation in the precision of control of the vehicle or its sluggish response. Lower limits on n/α or L_α are associated with a decrease in vehicle responsiveness in terms of flight path angle changes. For the unpowered landings of Class III vehicles, there is also some indication that the sluggish response will make it difficult to obtain adequate flight-path changes without the pilot overdriving the vehicle, which can lead to closed-loop difficulties in flight path control. Lower limits on $\omega_{n_{sp}}$, n/α and L_α, and their interrelationship, are difficult to establish based on available data. The limits on these parameters in the specification are somewhat arbitrary. These limits are especially important to Class III lifting re-entry vehicles in the landing approach since such vehicles will tend to have low values of $\omega_{n_{sp}}$ and n/α or L_α in this Flight Phase.

Handling qualities research programs should be conducted for both powered and unpowered lifting re-entry configurations in the landing approach to establish more definitive requirements on the lower limits of $\omega_{n_{sp}}$, n/α, and L_α and their interrelationship. These requirements will be of special importance to Class III vehicles such as the Space Shuttle Vehicle Booster and Orbiter.

5.3 Programs on Control Requirements in Maneuvering Flight

Present maneuver force requirements for airplanes are in terms of maneuver force gradients (F_s/n). For lifting re-entry vehicles, the maneuver requirement in Reference 1 has been cast in the same way. The parameter F_s/n is not very meaningful for a statically unstable vehicle. It also becomes less meaningful as n/α is reduced when the dynamic pressure decreases below that required to develop lift equal to the weight of the vehicle. For a vehicle flying at zero dynamic pressure, F_s/n is quite meaningless. There is reason to believe, that under conditions where F_s/n becomes less important, the pilot is concerned with the control of vehicle attitude as described by F_s/α or F_s/θ. If future research does establish that a statically unstable vehicle is acceptable for degraded Levels, Levels 2 and 3, then Reference 13 suggests that $\ddot{\theta}/F_s$ may be an important feel parameter. What parameter is important is also related to the Flight Phase, the piloting tasks, and the vehicle dynamics. At zero dynamic pressure, during orbital flight, experience with Mercury, Gemini, and Apollo should give a great deal of insight into the problem. For flight at low dynamic pressure, such as high altitude flights of the X-15 using reaction controls, attitude command or hold control was considered most satisfactory. Attitude rate command was rated next best, followed by acceleration command. Rate command was preferred in pitch and attitude command was preferred in roll and yaw.

This is obviously an important and fertile area for handling qualities research to establish control requirements for lifting re-entry vehicles based on their Flight Phases, piloting tasks, and vehicle dynamics. Research in this area should also make it possible to extend lifting re-entry vehicle requirements to Flight Phases other than those during terminal flight at low supersonic, transonic, and subsonic speeds. Much of the preliminary research in this area can be done in ground-based simulators.

The present requirements on the ratio of elevator control force to control travel are not based on handling qualities data. Work in this area can be combined with other work on control requirements.

5.4 Programs on Pilot-Induced Oscillations

It has not been possible to establish quantitative requirements that will eliminate PIO's in airplanes or lifting re-entry vehicles. This is a complex problem associated with the interrelationship of control system and vehicle dynamics and piloting tasks. Both analytic and experimental work in this area should continue. Either moving-base or in-flight simulation will probably be essential because of the importance of proprioceptive cues in PIO's.

5.5 Programs on Requirements for Unpowered Landings

An analysis and examination of available data has been conducted, and preliminary requirements have been established, for the flare and float of lifting re-entry vehicles during unpowered landings. The important parameter for establishing flare requirements is the ratio of flare altitude to flare time (h_f/t_f). The important parameter during the float appears to be simply float time (t_{FL}). Unfortunately, little comment data and no pilot rating data exist with which to establish handling qualities Level boundaries as a function of h_f/t_f and t_{FL} . Based on the available data, and discussions with personnel at NASA FRC and AFFTC at Edwards Air Force Base, some tentative handling qualities requirements have been established for experimental Class III and IV lifting re-entry vehicles.

More ground and in-flight handling qualities research programs should be conducted to confirm or modify the tentative handling qualities Level boundaries based on the parameters h_f/t_f during the flare and t_{FL} during the float. Similar boundaries should also be established for operational lifting re-entry vehicles. The simulation should be concerned with both Classes of lifting re-entry vehicles. The flare parameter (h_f/t_f) should be varied primarily through a variation in the unpowered $(L/D)_{max}$. The time for float (t_{FL}) will be varied primarily through changes in flare initiation velocity. Increases in flare velocity will increase the excess kinetic energy that must be dissipated during the float. The g's pulled during the flare should be varied to establish its importance to the flare maneuver. The use of speed brakes for flight path and velocity modulation will be an important consideration in the simulation. Turbulence and IFR flight conditions are essential simulation requirements for operational lifting re-entry vehicles. Attempts should be made to establish both maximum and minimum boundaries on flare altitudes for various Levels. It is essential that good pilot comment data are obtained on both the flare and float conditions simulated.

5.6 Programs on Adverse Elevator Lift in the Landing Approach

There are some indications, based on published reports, that adverse lift, due to a pitch control aft of the c.g., can lead to piloting difficulties in the landing approach. The adverse lift results in closed-loop problems associated with flight path control. The data on this subject that presently exist are insufficient and often confusing when interpreted in terms of handling qualities. Although $M_{\delta_e}\delta_e$ and $n_{\delta_e}\delta_e$ are suggested as important parameters in some reports, short period dynamics must also play an important role. It has also been suggested that the delay in the flight path response in the desired direction may also be an important parameter.

Any ground or in-flight simulation program conducted to investigate this problem from the point of view of handling qualities should consider new parameters as well as those that have been suggested. The problem should be viewed as closed-loop in order to establish parameters of importance to handling qualities specifications. The parameters $M_{\delta_e}\delta_e$ and $n_{\delta_e}\delta_e$, as they are presently considered, are more open-loop and total control power parameters. The adverse effects of elevator lift in the landing approach are expected to be of greatest concern to slow responding (Class III) lifting re-entry vehicles. Moving-base ground simulation may be an important consideration for valid results.

5.7 Programs on Lateral-Directional Response with Atmospheric Disturbances

Present requirements on the lateral-directional response characteristics in atmospheric turbulence are qualitative, yet indications are that the response and control of lifting re-entry vehicles in turbulence is likely to be one of their most critical handling qualities aspects, particularly during the terminal Flight Phases. Consideration of the following factors should confirm this conclusion:

1. Lifting re-entry vehicles are likely to have large rolling moments due to sideslip (L'_β), low roll damping, high $|\phi/\beta|_d$, and significant control coupling in terms of yawing moments due to ailerons (N'_{δ_a})and rolling moments due to rudder (L'_{δ_r}). All of these factors are likely to put the vehicle near the limits of the handling qualities Level boundaries even though the vehicle is augmented.

2. The requirements on "weathercock" stability for an unaugmented airplane in MIL-F-8785B(ASG) have been deleted from the proposed lifting re-entry vehicle requirements. This has been done in order not to restrict vehicle design when adequate stability can be obtained through augmentation. In addition, strong arguments and some data are presented that indicate that consideration should be given to allowing some static instability for degraded Levels of handling qualities. Yet the data often do not adequately consider the effects of atmospheric turbulence.

3. The minimum Dutch roll damping requirements are not particularly high, yet a concern for turbulence response is one of the reasons that the total damping ($\zeta_d \omega_d$) is increased when $\omega_{n_d}^2 |\phi/\beta|_d$ exceeds particular values. Yet this requirement is not well substantiated by data.

All of these factors and others indicate that an evaluation of many of the lateral-directional requirements of lifting re-entry vehicles in the presence of atmospheric turbulence is extremely important. This simulation can be conducted in ground simulators, but in-flight simulation is desirable. When simulated turbulence is used, strong consideration should be given to realistic levels and models for atmospheric turbulence, such as non-Gaussian models. The simulation programs should consider values of handling qualities parameters such as ω_{n_d}, ζ_d, $\zeta_d \omega_d$, $\omega_{n_d}^2 |\phi/\beta|_d$, p_{osc}/p_{AV}, $\Delta\beta_{max}$, that are near the Level 1, Level 2, and Level 3 boundaries when such boundaries have been specified. It should then be possible to assess the validity of the requirements with the presence of atmospheric turbulence. These investigations will indicate the degree to which certain requirements, such as $\zeta_d \omega_d$ as a function of $\omega_{n_d}^2 |\phi/\beta|_d$, may be relaxed or must be tightened.

5.8 Programs on Coupled Roll-Spiral Oscillations

The requirements for airplanes in MIL-F-8785B(ASG) and the proposed lifting re-entry vehicle specification do not permit a coupled roll-spiral (lateral-directional phugoid). Reference 14 indicates that both the M2-F2 and the X-22A lifting bodies have coupled roll-spirals under some flight conditions. When this mode is lightly damped or undamped, serious handling qualities problems may result. There is some indication, however, that if the roll-spiral is reasonably well damped, some roll-spiral coupling can be allowed, at least for the degraded handling qualities levels. A conservative approach was taken in the specification because of the possible strong effects of turbulence (Reference 11). Since roll-spiral coupling may be a "fact of life" for some lifting re-entry vehicles under certain flight conditions, a further investigation of this problem seems advisable.

An evaluation of roll-spiral coupling in a moving-base or in-flight simulator seems advisable because of the importance of proprioceptive cues. Roll-spiral damping $(\zeta\omega_n)_{RS}$ and frequency $(\omega_n)_{RS}$ will be important variables as well as the location of the Dutch roll poles and numerator zeros.

It is strongly recommended that in this investigation turbulence be adequately simulated because of the possible strong effects of turbulence on the handling qualities results.

5.9 Programs on Roll Control Effectiveness Requirements

Roll control effectiveness requirements for lifting re-entry vehicles have been "derived" from those of conventional airplanes as discussed in Reference 1. In deriving these requirements, consideration has been given to the differences as well as the similarities in roll requirements during the various Flight Phases of airplanes and lifting re-entry vehicles. Consideration has also been given to the fact that lifting re-entry vehicles in all probability will be much more sensitive to atmospheric turbulence, especially in roll. The roll effectiveness requirements of lifting re-entry vehicles are likely to be determined largely by lateral-directional characteristics of the vehicles combined with the effects of turbulence. The ability to obtain large roll angles rapidly or large roll rate performance is not likely to be a requirement, at least during terminal flight at low supersonic, transonic, and subsonic speeds.

The "derived" roll performance requirements for lifting re-entry vehicles should be checked through simulation, especially for the landing approach. It is essential in the simulation that the pilot have appropriate tasks, including roll and turn coordination, for each of the Flight Phases evaluated. It is essential in this simulation that the pilots assess the roll effectiveness in the presence of turbulence. Some of the other lateral-directional characteristics of lifting re-entry vehicles that hamper roll performance, require rudder coordination, and generally degrade handling qualities should also be considered in the simulation to properly assess roll effectiveness requirements for both Class III and Class IV vehicles.

5.10 Programs on Reaction Controls and Reaction Augmentation Systems

Reaction controls and reaction augmentation systems are not generally expected to be a requirement for lifting re-entry vehicles during terminal flight at low supersonic, transonic, and subsonic speeds. However, for some special flight conditions, such as flight at large angles of attack, reaction controls may be required if aerodynamic controls are ineffective.

The role of reaction controls and reaction control augmentation systems will be greatest for those vehicle Flight Phases at zero or low dynamic pressure, of the order of 10 to 25 pounds per square foot or less. How high the dynamic pressure must be before aerodynamic controls are sufficiently effective for control and augmentation is a function of the vehicle mission and piloting tasks.

Pilot control requirements using reaction controls are a function of the effectiveness of the aerodynamic controls, when both controls are used simultaneously. The requirements are also related to the vehicle dynamics and the piloting tasks. The vehicle dynamics at zero dynamic pressure can be supplemented through a reaction control augmentation. The degree of augmentation involved will be determined by the tasks and the piloting problems in performing the tasks. A simple acceleration command may be acceptable, or a rate, or position command control may be required. The type of command desired may also be a function of whether the control is used in roll, pitch, or yaw.

At zero dynamic pressure the reaction control requirements and the reaction augmentation system requirements of lifting re-entry vehicles can probably be based on experience with Mercury, Gemini, and Apollo. To the extent that the Flight Phases and tasks are similar, the control requirements of these essentially ballistic vehicles and lifting re-entry vehicles should also be similar. Operational experience with the X-15 reaction control and reaction augmentation system should shed some light on reaction control and augmentation requirements when the dynamic pressure is low and the tasks are difference (Reference 15). The X-15 experience indicated that a maximum reaction control power of approximately 2.0 deg/sec^2 in pitch and yaw and 5.8 deg/sec^2 in roll are acceptable. Using the two systems in each axis the control power could be doubled and the pilots liked the more rapid maneuver capability. Generally, position command was rated most acceptable in pitch and yaw and rate command in roll, although acceleration commands were often considered acceptable about all axes. The acceptability of the various control modes is of course task dependent and generalizations are not easy to make. See, for example, Reference 16. It is interesting to note, that based on X-15 experience, aerodynamic coupling between roll and yaw, as the dynamic pressure increased, complicated considerably the control task with an acceleration command system.

A series of simulation programs should be undertaken to investigate reaction control power and reaction control mode requirements for a number of Flight Phases of lifting re-entry vehicles where the dynamic pressures are low or zero. These investigations will establish the reaction control augmentation that is required to obtain acceptable control modes. Based on an examination of vehicle Flight Phases, a number of typical piloting tasks should be determined for pitch control, roll control, and coordinated turns during boost, coast, and re-entry. For these Flight Phases, typical longitudinal and lateral-directional dynamic characteristics should be determined. The dynamics will vary from that of an unaugmented vehicle to that of a vehicle that is highly augmented both through aerodynamic and reaction controls. Emphasis should be put on the minimum augmentation that is acceptable by the pilot to perform the tasks. When time dependent coefficient dynamics is likely to be important, it should be included in the simulation of vehicle motions.

Based on such simulation experiments, the relationship between command modes, piloting tasks, and vehicle dynamics can be established. It should then be possible to obtain some insight into the nature of handling qualities criteria for lifting re-entry vehicles during Flight Phases at zero and low dynamic pressures. These handling qualities criteria can be used to extend handling qualities requirements to these same Flight Phases.

5.11 Programs on Side Stick Controllers

It is expected that single or dual side stick controllers will be used on future lifting re-entry vehicles. Although side stick controllers have been proposed and evaluated in the past, insufficient data exists with which to propose side stick controller requirements for lifting re-entry vehicles. The characteristics of the X-20, X-15, and other side stick controllers should be examined to determine some of the tentative characteristics that should be considered in any side stick controller research program.

Breakout torques, torque gradients, total angular deflections, and controller dynamics should be variables in the investigation. The compatibility of a given set of side stick characteristics to flight at zero and low dynamic pressures and during atmospheric flight should also be assessed. Consideration should also be given to the blending of aerodynamic and reaction controls in the same controller, and how this blending should be accomplished. In the X-15, reaction controls and aerodynamic controls were operated through separate side stick controllers on each side of the cockpit. Many of the details that should be considered in the design of a good side stick controller from the handling qualities point of view will only be discovered through an adequate set of ground and in-flight simulation programs.

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13. ABSTRACT

This report summarizes a three-year effort which led to the development of a preliminary specification for the flying qualities of piloted re-entry vehicles during terminal flight. Part of this effort was directed at the preparation of the rationale and backup data upon which the flying qualities requirements are based. The effort included support of the FDL-8 lifting body program at the Air Force Flight Dynamics Laboratory from the standpoint of handling qualities. Some effort was also directed at a preliminary examination of lifting re-entry dynamics with time dependent coefficients. Included in this report are recommendations on the handling qualities research programs to improve and extend the handling qualities requirements of lifting re-entry vehicles.

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