FLIGHT SIMULATION AND PILOT DESCRIBING FUNCTION TECHNIQUES APPLIED TO THE ANALYSIS OF A PILOT CONTROL SYSTEM FOR A LARGE FLEXIBLE LAUNCH VEHICLE

By Brent Y. Creer, Gordon H. Hardy,
and Dallas G. Denery

Ames Research Center
Moffett Field, Calif., U.S.A.

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SUMMARY

The NASA has completed two phases of a general piloted launch vehicle study. The first phase studied the feasibility of using a pilot to guide and control a vehicle from earth lift-off through insertion into earth orbit. Two different study methods were used. One method was primarily a paper and pencil study, based on servo-analysis theory, wherein a mathematical model was used to describe pilot behavior. The other approach used simulators extensively. The first part of this paper discusses the relative adequacy of these methods. It was concluded that much can be learned by analytical procedures alone, but that assuming a linear pilot model has its pitfalls.

In the second phase of the study, a ground-based flight simulator was used to measure the contribution to mission reliability of allowing the crew to participate actively in guiding and controlling the vehicle if certain primary flight control systems fail. The second part of this paper discusses the methods used in this reliability analysis. It was concluded that this procedure can systematically determine mission success for complex manual control problems.

FIGURE LEGENDS

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Ames Research Center
National Aeronautics and Space Administration
Moffett Field, Calif., USA

1. INTRODUCTION

The NASA is conducting a general research program concerned with pilot control of large, flexible launch vehicles. The launch vehicles being considered are of the Saturn V class, which will be used in the forthcoming manned lunar mission.

This program was motivated by the possibility that the guidance and control system of such a vehicle might be simplified, and the reliability and performance improved if the capabilities of the human pilot were utilized. The research program, to date, has encompassed two major phases. In the initial phase, the feasibility was studied of using a pilot to guide and control from earth lift-off through insertion into an earth orbit. In the second phase, a more sophisticated and refined investigation was conducted wherein a piloted control system was defined as a backup for the primary automatic flight control system. During this phase, the extent to which mission reliability would be increased by allowing the crew to participate actively in guiding and controlling the vehicle in the event of an emergency was measured. The purpose of this paper is to discuss some of the methods used to analyze the pilot-vehicle control system.

A perfectly logical question at this point is "Why discuss well-known techniques for analyzing pilot-vehicle control systems?" First, the project is somewhat unique in that, essentially, two different methods were used to study the feasibility of using a pilot to guide and control the launch vehicle. One method was mainly a paper and pencil study based on servo-analysis theory wherein the pilot-vehicle control system is treated as a closed loop (1-3). The other approach used simulators extensively. In the latter case, the so-called experimental approach was emphasized. Conducting these studies independently and in parallel affords an excellent opportunity to examine the relative merits of these two methods. Therefore, in the first part of this paper, the adequacy of these methods will be discussed. The pilot control systems derived by servo-analysis methods will be compared with systems derived by the more conventional simulator approach. The study of pilot control systems using the servo-analysis approach will be termed "analytical," and the flight simulator approach will be termed "experimental." The experimental method was used by NASA (4,5), while the analytical method was used by Systems Technology Inc. under contract to NASA (6,7).

The second section of this paper will briefly discuss the simulator investigation of the probability of mission success. It is believed that this reliability analysis using piloted simulators is unique. The method, as well as some of the general conclusions regarding the pilot's contribution to mission reliability, should be of general interest to engineers concerned with the interface of a piloted backup system with a primary automatic flight-control system since it is not limited to a specific vehicle.

2. SIMILARITIES BETWEEN LAUNCH VEHICLES AND LARGE WINGED VEHICLES

The methods of studying large flexible boosters should be of value in analyses of pilot control systems for airplane-type transports because boosters and large airplanes (supersonic, hypersonic, large subsonic, etc.) have certain common characteristics. Both have fairly complex control systems, incorporating rate gyros, inertial platforms, signal processing filters, and control-surface power actuators. Both are subject to torque biases when an engine fails. Both tend to be highly flexible with structural mode frequencies approaching control system frequencies. A gross comparison of the approximate "frequency spectrum" for the various degrees of freedom for the two types of vehicles is shown in Fig. 1. It might be noted that external disturbances (wind shears) tend to excite and contribute to the body bending of both classes of vehicles and are a major factor in the vehicle control system design. Finally, in both cases the pilot is located far in front of the vehicle center of gravity; consequently, the attendant cues (i.e., accelerations, etc.) that could influence pilot control are also similar.

From a task standpoint, we can argue that there is a reasonable analogy between the manned boost into orbit and the landing of a large aircraft in zero-zero weather conditions; both are terminal control problems; both are performed on instruments; both involve similar time scales; both primarily involve control of the flight path as the outer loop; and both involve such complex kinematics and guidance programs that successful completion by a completely unaided human pilot is marginal at best. Because of these similarities, some of the techniques used in the subject studies may be applicable to certain winged vehicles.

3. ANALYTICAL AND EXPERIMENTAL METHODS

Figure 2 provides some general information which can be used to determine a method of analysis for a piloted vehicle control system.

The two charts in this figure describe various degrees of system analysis complexity. The upper chart is titled "analytical" and the lower, "experimental." The "experimental" chart was suggested by Cooper and Belsley (8,9), and is based on an examination of various simulator investigations. They concluded that ground-based flight simulators can be classed as rudimentary, basic, or advanced, depending upon their sophistication. This table is to be used as follows: if the application required of the results is known, as well as the type of results desired (qualitative and/or quantitative), the table indicates the type of simulator (rudimentary, basic, or advanced) and task that must be considered to provide a proper evaluation. The more precise and realistic (in a flight sense) the information that is required, the more complete must be the simulation. In the unabridged version of this table (9), the rudimentary, basic, and advanced simulators are defined in terms of the environment which might be impressed upon the pilot (visual, aural, and kinesthetic feedback), the sophistication in the equations of motion, extravehicular disturbances, etc.

A somewhat analogous table can be derived for the analytical approach (10). At least two levels of complexity exist and have been arbitrarily labeled "rudimentary" and "basic." The rudimentary analysis is composed essentially of an open-loop analysis wherein certain vehicle characteristics are computed and compared with preanalyzed and cataloged information on pilot ratings given as functions of vehicle dynamic parameters. The basic analysis is synonymous with closed-loop system analysis techniques using adaptive pilot models. As in the experimental approach, the type and application of the results determine the level of analysis required (Fig. 2). The "basic" analysis and "basic" simulator seem to have approximately the same area of application. The only essential difference, as shown by this table, is that only part task (i.e., essentially continuous tracking) can be considered when the basic analytical method is used. A basic simulator is not so restricted since sequential and decision-making tasks are particularly easy to simulate.

The methods discussed in this paper are shown on Fig. 2. The feasibility studies are classed as basic experimental and basic analytical studies. The reliability analysis studies would have to be classed as advanced experimental. It should be made clear at this point that the analytical and experimental approaches are not competitive methods for the analysis of pilot vehicle control systems. If flight simulators are available, the two techniques should be combined for maximum efficiency. However, for the feasibility studies discussed in this paper, no data on the results of the simulation program were made available to the contractor conducting the analytical study until the end of the program. This severe constraint was deliberately imposed to test the paper and pencil methods (i.e., obtain a calibration). Such a calibration was believed to be useful if flight simulators were not readily available.

Figure 2 suggests then that the design and performance of a piloted control system can be predicted fairly well without resorting to flight simulators for more quantitative information. In fact, it has been suggested that purely analytical processes might be used until it becomes necessary to solve operating problems, define minimum acceptable handling qualities (i.e., failure mode analysis), or define certification problems. Substantial evidence does support this possibility for conventional piloted aircraft (10-13), but more evidence is necessary before one could state this conclusively. In particular, evidence is lacking for the relatively unexplored problem presented by the flexible launch vehicle, which represents a more complex set of dynamics as well as a type of control problem for which there is little previous experience. As illustrated in Fig. 2, the results of these investigations will be presented in such a way as to give the reader an easy insight into the usefulness of the "analytic" technique for a relatively unexplored pilot control system problem without simulation support.

4. TECHNICAL CONSTRAINTS

To interpret the results properly, it is essential to understand the basic technical constraints placed on the experimental and analytical studies (Fig. 3).

In the experimental program, the rigid body equations of motions simulated were a perturbation set with respect to a reference frame moving along a given nominal trajectory that described the vehicle motion in five degrees of freedom (i.e., three rotational and two translational degrees of freedom). The equations of motion were linearized, and the coefficients were time varying. The first- and second-mode body-bending equations were included in the simulation. The nominal frequency for the first bending mode was ≈ 1 Hz, and for the second, ≈ 2 Hz. Sloshing mass accelerations were computed for the two main propellant tanks in the first stage. The attitude and rate-gyro locations were assumed to be fixed. However, some freedom was allowed in the positioning of the accelerometer used to drive the pilot's display. The wind disturbance was approximated by ramp input building from 0 to 75 m/sec at a rate of about 10 m/sec^2. The direction of the wind was randomly rotated between each piloted simulation run for the data discussed in the first section of the paper. The simulator investigation utilized, for the most part, a fixed cockpit. However, a limited number of piloted launches were simulated with a five-degree-of-freedom centrifuge so that the launch vehicle acceleration could be impressed on the simulator pilot. The changes or sensitivity of system performance to variations in certain vehicle parameters were documented during the simulator runs.

The analytic method was applied only to a fixed (frozen) flight condition, and the maximum dynamic-pressure portion of the flight profile was the key design point. However, the piloted systems evolved were also checked at the lift-off and the first-stage burnout. Fuel sloshing dynamics were not included in the analytic study since it appeared from simulation studies that they did not significantly influence the control-system design; also, their deletion simplified the equations. The remaining technical constraints, Fig. 3, were also applied to the analytic study.

5. RESULTS AND DISCUSSION

5.1 Pilot Vehicle Systems

During these investigations, considerable effort was made to define several competing pilot control systems. These systems were, in essence, "candidate systems" which might warrant a more thorough study. Three that evolved can be distinguished, approximately, on the basis of pilot participation. A brief review of these general forms of pilot-vehicle control systems seems appropriate, if for no other reason than to understand the systems which came under serious consideration and were later defined and analyzed in some detail (Fig. 4). However, all of the systems shown in this figure will not be discussed in detail in this paper.

The fully manual system was considered first. In this case, the pilot observes certain displays that indicate the vehicle's state; he may establish certain feedback paths internal to himself; then he directly controls the servos that swivel the engines in an attempt to control the vehicle's flight path and stabilize certain modes of motion (e.g., rigid body, body bending, etc.).

The second system in this figure is termed "series pilot plus augmented vehicle." The pilot is a principal element in the control system; however, an inner feedback loop is established around the vehicle. This loop augments the vehicle's stability and improves its handling qualities and the overall pilot-vehicle control system performance.

In the third system of Fig. 4, the pilot is shown operating in a parallel or trimmer mode of control wherein he can change the vehicle's flight path by putting in a bias or trimming command to an automatic flight-control system.

Hence, for this specific control problem, whether attacked analytically or experimentally, only the three general forms of vehicle-control system need further consideration and investigation. Incidentally, one might question whether these general system forms were specifically products of the analytic and/or experimental approach or whether they resulted primarily from the respective investigator's experience and general knowledge of pilot-vehicle control systems. This question probably cannot be resolved because the general forms of these systems are quite obvious and have well established precedents in current piloted airplane control systems.

5.2 Pilot Models

Theoretically, if human behavior were exactly predictable in a control task, the same information could be obtained by both flight simulation and analytical techniques. Obviously, at this time, human behavior is not exactly predictable. (This fact gives flight simulation its one primary advantage over analytical techniques for studying piloted control.) Nevertheless, before the analytic study of a closed-loop system can proceed in earnest, suitable approximate mathematical representations must be derived for each element comprising the closed-loop system, including the pilot. In recent years, a great deal of research and study has been directed toward describing human behavior in a control task. Because of mathematical complexities, this research has largely been confined to deriving a "quasi-linear mathematical model" for a pilot while controlling a system described by linearized, constant coefficient equations. Such a pilot model consists of a linear describing function, Y_p, as well as a remnant component. It is sufficient to say that the key to the success or failure of the analytic approach depends upon the validity of approximating the pilot-vehicle control system by a set of linearized, constant coefficient equations plus a stochastic remnant, and upon the adequacy of the derived pilot model. The dynamic characteristics of the human pilot in terms compatible with flight-control engineering practice are summarized in (14). Despite the rather severe limitations on the region and applicability of these data, they have been used very successfully in studying and analyzing the more or less conventional aircraft pilot control problem. The validity, however, of extrapolating these pilot models and associated adaptation rules to controlled elements having higher order dynamics, such as large flexible boosters or large airplane transports, could be questioned. In the following section, a cursory evaluation is made of the validity of extrapolating the pilot model data of (14). The pilot models derived from the data and procedures of (14) are applied to the booster control problem in the analytic study and will be compared with pilot models derived from measurements made with a pilot flying the launch vehicle simulation.

As previously implied, the pilot models are limited to the case of a time invariant controlled element. For the data presented in this section, the controlled element was the unaugmented launch-vehicle dynamics at a discrete time of flight, 77 sec after launch. This is essentially the maximum dynamic pressure flight condition and the point at which the vehicle is most difficult to control. Under these conditions (i.e., unaugmented vehicle and maximum dynamic pressure condition), the prediction of a pilot model is most challenging and seems to represent an "acid" test of the techniques involved.

In discussing pilot-model data, it is well to begin by defining the dynamics of the controlled element. The frequency response of the unaugmented vehicle and its control system as used in the simulator study is compared in Fig. 5 with the controlled element dynamics for the analytic investigation. A slight difference can be seen at both the low and high frequency portions of the spectrum. That at low frequency is due to the assumption that velocity was constant while the equations of motion were analyzed. The high frequency discrepancies are due to slight differences in the engine dynamics and bending frequencies used. The large difference in gain at the first bending mode can be attributed partly to a lower first bending mode natural frequency and partly to a neglect of the second bending mode in the experimental analysis as compared to the analytic study. The main characteristics of the systems are the same, and the effects of the noted discrepancies on the subsequent pilot describing function data should be small.

5.2.1 Analytic pilot describing function

Solely analytical techniques and the controlled element dynamics of Fig. 5 were used to form a pilot describing function for the linear component of the pilot model by the adaptation rules established from existing data. This pilot describing function is as follows:

$$Y_p = \frac{0.5(2j\omega + 1)e^{-0.2j\omega}}{\left(\frac{j\omega}{10}\right)^2 + \frac{2(1)(j\omega)}{10} + 1}$$

The first numerator term (0.5) is the pilot gain in radians of engine angle command per radian of attitude error. The term $(2j\omega + 1)$ is the lead equalization supplied by the pilot to stabilize the vehicle and control the pilot-vehicle system adequately. The exponent $-0.2j\omega$ represents the delay in the pilot's reaction time and the denominator term, $(j\omega/10)^2 + 2(1)(j\omega/10) + 1$, represents his neuromuscular lag.

5.2.2 Measured pilot describing function

As noted previously, pilot describing functions were also measured experimentally with an actual pilot flying the unaugmented vehicle in a fixed-cockpit flight simulator. For these tests, the pilot was given a random appearing attitude tracking task in the pitch plane. The frequency and amplitude of the input were comparable to the input spectrum of the jetstream wind disturbance. The random appearing input signal was characterized by a 2° RMS value with a bandwidth of 0.183 rad/sec. The error signal was displayed to the pilot by a horizontal bar on an oscilloscope. The power spectrum of the input and modified Fourier transform of the idealized wind spike are shown in Fig. 6. The random input signal was composed of eight nonharmonic sine waves, four primary and four secondary. This particular forcing function was used so that a random appearing signal would be obtained in the frequency range of booster task demands, less than 0.2 rad/sec, and still provide energy at higher frequencies without affecting the pilot's low frequency performance. This type of "augmented rectangular input spectrum" has been used successfully in the past and is described more fully in (14). The power spectral characteristics of the wind spike were obtained by defining a "pseudo-autocorrelation function" as $(1/p)\lim T \to \infty \int_{-T}^{T} f(t)f(t+\tau)d\tau$ (15) where p is the interval of wind disturbance. Taking the Fourier transform of this autocorrelation function, we obtain the power spectral characteristics of the wind spike, $(1/p)|c(\omega)|^2$, where $c(\omega)$ is the Fourier transform of the wind spike. This function was then modified to make the amplitudes of this pseudo-continuous spectra compatible with the discrete spectra for comparison purposes. The ordinate in the figure is given in power dB (i.e., $10 \log_{10} \varphi_x^2(\omega_m)$ where $\varphi_x(\omega_m)$ is the amplitude of the input sine wave at frequency ω_m).

Pilot describing function data were recorded as well as pilot opinion ratings and the integral of the error signal squared.

The pilot describing function Y_p was determined from standard relations for power density spectra in linear systems. These methods are dealt with more thoroughly in (11,16-18). The actual data were analyzed on an analog power spectral analyzer. The pilot describing functions so measured are compared with that predicted in terms of their frequency response in Fig. 7. The predicted pilot describing function is also combined with the Ames tested controlled element Y_c and compared with the experimentally measured Y_pY_c in Fig. 8. These two figures indicate that the predicted Y_p is a fairly accurate description of the pilot describing function in at least the low frequency range. The equalization characteristics are in very close agreement. There does, however, appear to be a slight difference in the phase. A low frequency phase droop is predictable from previous human response data but this was intentionally omitted from the predicted Y_p in the analytic study because of its negligible effect on the system analysis. Unfortunately, the high frequency characteristics of the predicted describing function are not as easily verified for this control task. If the predicted high-frequency neuromuscular characteristics are assumed, the experimentally obtained Y_p can best be described by

$$Y_p = \frac{0.47(1.7j\omega + 1)e^{-[0.25j\omega+(0.1/j\omega+0.2)]}}{[(j\omega/10)^2 + 2(1)(j\omega/10) + 1]}$$

Thus far, only the pilot describing function portion of the "quasi-linear mathematical model" has been considered. However, the model is not complete without the remnant component. Before a completely valid comparison can be made of an actual pilot's performance with that of a quasi-linear mathematical model, the remnant term must be specified as well as the pilot describing function. Unfortunately, the remnant component has not been investigated so well as the pilot describing function and it was only briefly considered during the early analytical studies discussed in this report. Likewise, at this time, the remnant portion from the flight simulator experimental data has not been analyzed. However, even without a direct description of the remnant, several different sets of data were obtained during this study that indirectly show the strong influence of the remnant in this particular pilot booster control problem.

A rough idea of the importance of the remnant term can be obtained from Figs. 9 and 10. Previously, it was noted that these pilot describing functions were measured while the pilot was performing a random appearing attitude tracking task in the pitch plane. During the tests, the ratio of the mean error signal squared to the mean input signal squared for the system when controlled by the pilot describing function and when controlled by two research pilots was measured and is presented in Fig. 9. In addition, Fig. 10 shows the time history of the transverse accelerations that occur at the vehicle nose position while the vehicle is controlled by an actual pilot or by the predicted pilot describing function. These transverse accelerations are due to the first bending mode. Both figures indicate that something besides the given pilot describing function is necessary to describe the actual pilot performance adequately. It is suspected that these discrepancies are the result of not including the pilot remnant in the pilot model.

During this evaluation of the pilot describing function, the analytic pilot describing function model was switched on and assumed control of the simulated vehicle without the actual pilot's knowledge. It was reasoned that if the pilot failed to realize the switch, the mathematical model used was adequate to a first approximation. The time traces of this experiment are shown in Fig. 11. Even though Figs. 9 and 10 show that the pilot's output is not completely described by a describing function, the actual pilot continued to control the vehicle for intervals of time exceeding a minute before he realized that he was no longer in control of the vehicle. It is also interesting that about a minute after the switch, the pilot's control characteristics changed considerably (Fig. 11). The most obvious change is the seemingly higher gain technique used.

This brief evaluation of the "derived" and "measured" pilot describing function data indicates that the available pilot describing function data are partially valid in the low frequency regions, up to unity gain crossover of $Y_p Y_c$, for the relatively unexplored problem discussed herein. However, preliminary results indicate that for the control problem considered in this paper, the remnant term is of great importance and must be included in the analysis before a complete system analysis can be made. The effect of pilot remnant will be discussed later.

5.3 Control Loop Structure

The next step is to show some examples of the specific pilot-vehicle control systems that resulted from the experimental and analytical studies. The control systems presented are for the pitch plane of motion and for the series pilot plus augmented vehicle. At this point, it may appear inconsistent that the pilot describing function data were presented for the unaugmented vehicle, whereas the control system data are presented for the series pilot plus augmented vehicle. However, these various sets of data were selected for discussion because they best illustrate the capabilities of the various techniques involved. The derivation of a pilot describing function is most challenging for a marginally stable controlled element (unaugmented vehicle). On the other hand, the real worth of the analytical techniques is demonstrated by their ability to define and predict the performance of an augmented-vehicle control system that has good performance and handling qualities, etc. The specific pilot-vehicle control systems that resulted from the experimental and analytical studies are shown in block diagram form in Fig. 12.

The flight-simulator derived system, in the upper part of the figure, is composed of an inner feedback loop which augments the vehicle stability. By means of an outer loop, certain vehicle state variables are displayed to the pilot and provide him with the necessary information to perform assigned tasks (such as, to reduce the structural loads, to stabilize and control vehicle attitude, etc.). There are two filters in the loops. The filter in the rate augmentation loop stabilizes the body bending or elastic modes of motion. The design procedure was typical of that used by an automatic flight-control system engineer, i.e., finding a filter that would attenuate and/or shift the phase of the body-bending content of the feedback signal so that the stability margins would be adequate without significantly altering the rigid-body content of the signal. A second-order passive filter, immediately downstream from the pilot, smooths the output of the pilot's controller at the elastic bending frequencies. This filter, in conjunction with the rate augmentation filter, stabilizes and reduces the magnitude of the elastic-structural excitation to an acceptable level.

Now let us examine the pilot control system loops which resulted from the analytic approach. The equalization filter, selected to adequately augment the rigid mode stability and attenuate the bending modes, was placed in the forward path, as shown. The block diagram in Fig. 12 is determined by the analytical procedures with no remnant effect applied.

To understand the outside feedback loop, one must appreciate the pilot task involved. At lift-off, the pilot's task is to stabilize and control the vehicle attitude. As the region of maximum dynamic pressure is approached and as the wind disturbance is encountered, the pilot's primary task becomes one of reducing the structural load (termed load relief) on the vehicle by minimizing the body-bending moments, with secondary emphasis on attitude control. When the attitude-stabilization task was analyzed, the outer loop was closed by transmitting the vehicle pitch angle φ to the loop element representing the pilot $(K_p(t))$. Similarly, when the load-relief task was analyzed, the vehicle transverse acceleration A_z formed the outside loop closure, since the pilot uses the transverse acceleration to help reduce the structural loads. A switch has been placed in the outside loop to indicate that the analytic method admits to a single "error" quantity (i.e., attitude or acceleration) being fed into the pilot describing function box. The K/S terms shown will be discussed later.

Some appreciation for the similarities between these two systems can be gained from a brief qualitative comparison of these loop structures. The system block diagram in the lower portion of Fig. 12 has been recast into a completely equivalent block diagram and is shown in Fig. 13.

Fig. 13 shows that the analytical and experimental systems are similar in that rate-feedback and rate-augmentation filters are present in both systems. From a frequency-response standpoint, these two filters are nearly equivalent. One dissimilarity in the two systems is apparent in that the analytic investigation indicated that vehicle static stability is required for a good pilot rating. This was achieved by the inner-loop feedback of vehicle pitch attitude. However, this feedback does not represent a strong dissimilarity with the experimentally derived system, inasmuch as it only changes the vehicle's static stability from slightly negative to slightly positive. A major difference between these two control systems is the pilot's stick filter. An adequate description of the dynamics of the actual nonlinear time varying human pilot requires a describing function plus a remnant. Because of the lack of suitable remnant data, no quantitative design of the pilot's stick filter using purely analytical techniques was attempted. However, it was predicted, qualitatively, that a pilot's stick filter might be required to reduce the vibratory excitation (6). The foregoing emphasis of differences in the pilot's stick filter may be confusing in view of the equalizing element that appears immediately downstream from the pilot. However, it should be recalled from the earlier discussion of this system, as shown in Fig. 12, that the lag elements were a direct result of stabilizing the bending modes and were not based on preventing the excitation of body bending caused by the pilot's controller output, per se.

The foregoing discussion again points out one important aspect of the remnant or, really, the current dearth of suitable remnant data from which a good analysis can be made. Another aspect of this remnant problem is associated with the placement of the K/S in the acceleration feedback loop (Figs. 12 and 13). The K/S term was included mainly to improve the dynamic response of the vehicle at low frequencies. In a quasi-linear analysis that did not consider pilot remnant, it is not critical whether this term was placed in front of the pilot or downstream from him; but, when the system performance was checked on a flight simulator with an actual (noisy) pilot in control, it was found to depend strongly upon the position of this term. Consequently, pilot remnant was concluded to be a dominant factor in system performance. It should be noted that pilot comments indicated the system performance was influenced to a certain extent by the pilot's difficulty in interpreting the displayed control variables that had been filtered by the K/S term. Some performance figures showing the marked effect of pilot remnant (i.e., position of the K/S term) on pilot-vehicle system performance will be discussed later.

The analytic and experimental derived systems were compared briefly, on the basis of the control loop structure. Perhaps the best way to compare two piloted control systems is on the basis of their performance. Accordingly, some quantitative as well as subjective performance measurements were made for the systems just discussed and these measures are shown in Fig. 14. These data are for the case in which the K/S term is placed downstream from the pilot. As noted previously, we will also present data for the case in which the K/S term is in front of the pilot. The performance measures are pilot rating, pilot opinion, M/M_D, and N_Z. The ratio M/M_D is the maximum vehicle structural bending moment encountered as the vehicle penetrates the wind-shear region divided by the design bending moment. An M/M_D value of 1 or greater indicates structural failure. Any M/M_D value less than 1 is safe from a structural-load standpoint. It should be noted that the motions experienced by the pilot of a flexible launch vehicle are somewhat similar to those that would be experienced by a pilot situated on the end of a long, flexing pole. The resulting oscillatory transverse accelerations, N_Z, are measures of the body bending. It was anticipated that large values of N_Z may be undesirable since they may be detrimental to pilot control. It should be emphasized at this point that these performance measures were obtained by programming each system on the fixed-cockpit flight simulator.

Figure 14 indicates that the performance of the two systems is almost identical with the exception of some minor differences in pilot comments on the handling qualities. Since certain factors (i.e., pilot stick filter design and perhaps other pilot remnant effects) were not considered in the derivation of the analytic system, it is somewhat surprising that the two systems are so similar in their performance capability. However, after a moment's reflection, it becomes clear that the main benefit derived from the placement of the K/S term after the pilot is, essentially, that it acted as a pilot's stick filter; consequently, the performance of the analytical and experimental derived systems were nearly the same. From a slightly different point of view, it appears that the K/S term modified the dynamics of the system so that the remnant portion of the pilot model was no longer an important element in the system analysis.

5.4 Effects of Remnant Term on System Performance

It was indicated earlier that the performance of the analytical derived system in a flight simulator was markedly influenced by shifting the K/S term from forward of the pilot to behind him. The performance data obtained were both objective and subjective; they point out the strong influence of the pilot remnant term in this particular pilot-vehicle control system. The results of this phase of the program are shown on Fig. 15. The data for the K/S filter after the pilot are presented in the lower part of the figure. Pilot ratings, pilot comments, and certain measures of pilot-vehicle system performance are given. Pilot ratings from 3 to 3-1/2 indicate a satisfactory system. Pilots' comments were "acceptable with mildly unpleasant characteristics" and "requires smooth control to prevent excitation of the body-bending motions." Values of M/M_D from 0.45 to 0.5 were measured with the pilot attempting to fly the vehicle so as to minimize the structural loading as the wind shear was penetrated. Values of the transverse accelerations at the pilot's position were from 0.05 to 0.1 g.

Shifting the K/S term ahead of the pilot caused a marked deterioration in the system performance and acceptability. The pilot rating deteriorated from satisfactory to unsatisfactory with handling qualities acceptable for emergency conditions only (rating of 6-1/2). Pilot comments were "very difficult to interpret correct control action from the displays, etc." The values of M/M_D were doubled as a result of shifting the K/S term; the transverse accelerations experienced at the spacecraft cockpit were four times the previous level.

5.5 Predicted and Measured Performance

A pertinent question at this point is "How well can objective measures of system performance, such as pilot's opinion and pilot's numerical ratings of the vehicle control system handling qualities be predicted by closed-loop system analysis techniques?" Reference (6) states that making these predictions with the analytic method is "a difficult and highly artistic enterprise." Figure 16 shows the pilot comments and pilot ratings of vehicle handling qualities predicted from the analytic investigation as well as those gathered, for the same systems, from flight simulator runs. In this case, data are given for two different systems, namely, the fully manual system (or unaugmented vehicle case) and the series pilot plus augmented vehicle control system. The pilot opinions and ratings measured from the flight simulator are shown along the lower portion of the figure and the predicted values are shown along the upper part. For the unaugmented vehicle the predicted and measured ratings agree substantially. The best numerical ratings by the participating pilots was 5, which is identical to the predicted value. The upper level of the predicted ratings was 9, which was substantially worse than the ratings which would be confirmed by flight simulator runs (i.e., 7). Perhaps the most noteworthy point from these data is the close agreement between the pilot's predicted and actual comments. The major difference in pilot comments was the prediction that with appropriate displays, the pilot could fly the unaugmented vehicle about two axes. The pilot's actual comments indicated that it was possible to control the unaugmented vehicle about one axis only. In subsequent questioning, the pilots indicated that, in their opinion, this latter statement was true regardless of the displays. It was also predicted that the accuracy in tracking pitch guidance commands would be poor. This prediction stemmed from the droop of the frequency-response curve in the lower frequency range of the spectra for the controlled element in the analytic investigation (Fig. 5). As noted previously, the controlled element, as investigated on the flight simulator, did not exhibit this characteristic and hence this latter predicted pilot comment was never verified.

Now consider the augmented vehicle. Only one set of flight simulator data is shown, i.e., for the K/S term behind the pilot. These data are presented, since the previous discussions indicate this is the particular case for which the "analytic techniques" might predict pilot ratings and pilot opinions.

For the augmented vehicle, the flight simulator derived ratings ranged from 3 to 3-1/2. It was predicted that the ratings would range from 3 to 6, which is a rather imprecise prediction of pilot rating although it does bracket the measured pilot-rating data. Pilots comments are in fair agreement, but the predicted comments lead one to believe that excitation of body-bending motion is no problem. Actual pilot comments, however, indicate that smooth control inputs are necessary to prevent such excitation.

6. DISCUSSION OF A TECHNIQUE FOR RELIABILITY ANALYSIS

The conclusion reached from the studies discussed in the first part of this paper was that piloted control of a large flexible launch vehicle is feasible. Thus it would be expected that the "probability of mission success" would be increased if a manual control system were added to back up the vehicle's automatic flight control system. An analysis was made to determine whether the probability of mission success could be increased by incorporating the proposed piloted backup control system. The technique for measuring the reliability contribution of a piloted backup system is the subject of this section of the paper.

The technique is similar to one that has been used for the automatic system. It is also similar to the "Pilot-Controller Integration for Emergency Conditions" concept (19) which was refined and applied to the X-22A V/STOL vehicle (20).

The seven steps inherent in the technique are shown in Fig. 17 and are discussed below.

1. Define system: Collect the necessary information on the vehicle, systems, trajectory, mission, etc., to enable a simulation to be conducted. Define manual system.

2. Define major failure modes: Predict major failure modes (as opposed to component failure modes). Define failure dynamics and obtain necessary information to simulate failure modes. Obtain unreliability number (probability of occurrence) for each major failure mode.

3. Simulate system and failure modes: Use the data gathered in steps 1 and 2 and appropriate mathematical models to develop a real-time piloted flight simulation of the vehicle and its major failure modes.

4. Define pilot procedures: Use the flight simulation developed in step 3, conduct a systematic investigation wherein the failure modes investigated are made to occur at various times of flight with the pilot in control of the simulated vehicle. From this investigation, develop background information from which the crew can learn to detect and correctly identify each failure as well as to follow the correct pilot procedure in the event of a failure. (Most of the emergency section of the pilot's handbook is written during this study phase. Also, at this time, preliminary changes to the proposed manual system can be made.)

5. Conduct simulation with random failures: Using several subjects and a large number of simulated flights with random failures, determine the probability of mission failure (effectivity) for each of the major failure modes.

6. Determine probability of mission failure: Using the unreliability numbers from step 2 and the effectivity numbers from step 5, calculate the failure mode criticality (effect of failure on probability of mission failure).

7. Modify system and procedures as necessary: Analyze the results of step 6 to determine those failure modes having the greatest influence on mission failure. Redesign the system or modify the procedures developed in step 4 as necessary to reach a suitable level of "probability of mission success."

The application of these seven steps to the subject vehicle will now be discussed.

6.1 Definition of Launch Vehicle and Systems

The example boost vehicle carries the second stage, third stage, and the spacecraft from the launch pad through the high dynamic-pressure region to staging at an altitude of about 66,000 m. The flight lasts about 2-1/2 minutes and stages at about 2,400 m/sec. The control problem is complicated by wind and gusts, as well as by flexible-body and fuel-sloshing dynamics with frequencies approaching control frequencies.

The control system selected for this portion of the study is based on earlier feasibility studies (Fig. 18). The upper half of the figure shows (solid lines) the automatic system as implemented in this study. The engine actuator command signals are attitude rate and attitude error summed, gained, and filtered in the control computer. The vehicle has five thrust engines, four of which are control engines. This provides some redundancy in the event of thrust losses or actuator failures. The lower half shows (solid lines) the spacecraft control system. The dashed lines indicate the items added for the proposed manual backup system. The pilot's display included attitude error, from the launch-vehicle guidance system, as well as the outputs from body-mounted accelerometers in the launch vehicle. The display included altitude, velocity, flight-path angle, etc., of the spacecraft. The output of the pilot controller was passively filtered (low pass to attenuate output at flexible body frequencies) and summed with the output of the automatic system at the control computer. This system allowed the pilot to form an adaptive-parallel control loop which is activated when failures occur in the primary system.

6.2 Definition of Major Failure Modes

The launch-vehicle major failure modes can be divided into three categories: (1) control-system hardware failures (gyros, wiring, etc.),

(2) engine actuator failures (hard over, null, oscillating), and (3) thrust failures. The first ten failures in Fig. 2 are the launch vehicle major failure modes considered in order of their assumed unreliabilities (probability of occurrence). The unreliability for each failure mode is shown relative to the most probable failure mode (one engine actuator hard over). Failure modes 11 through 19 of Fig. 19 are associated with the hardware added as a result of the piloted backup system. The unreliability data for the pilot's displays are not shown since no mission failures were caused by a display failure.

6.3 Simulation System and Failure Modes

A detailed and comprehensive fixed-cab simulation was set up. It included fuel sloshing, engine, and flexible-body dynamics as well as six-degree-of-freedom rigid-body dynamics.

6.4 Definition of Pilot Procedures

The pilot's primary task before a system failed was to monitor the displays. His only control inputs were those necessary for load relief in the event of large wind-induced aerodynamic loads. He reduced the loads by closing the piloted parallel loop using the displayed output signals of the body-mounted accelerometers. Reducing these aerodynamic loads gives the vehicle a greater margin of safety in the event of a system failure.

In the event of a launch-vehicle system failure (i.e., failures 1 through 10), the "overriding" pilot's procedure was to "keep the attitude of the vehicle at the nominal value." He did this by operating as an adaptive element in the loop that paralleled the automatic flight-control system. For hardware failures in the launch-vehicle control system (i.e., loss of platform, attitude rate, attitude signal, etc.), the pilot used information displayed from sensors located in the spacecraft to stabilize and control the vehicle attitude. Specifically, if the launch vehicle attitude-rate loop malfunctions (i.e., failure 6 or 10) and the vehicle motions become unstable, the pilot, using the displayed-rate information (which is sensed from gyros located in the spacecraft), takes over and stabilizes the vehicle motions. When an engine actuator fails, the vehicle develops asymmetric rotational moments. In this case, the pilot acts as an integration type element in that he injects trimming or bias commands to null the unbalanced or asymmetric rotational moments. In the case of a single display failure, the information displayed was sufficiently redundant that by a quick cross-check the pilot was able to detect which instrument had failed and continue to fly the vehicle using the remaining sources of displayed information.

6.5 Simulation With Random Failures

It should be pointed out that in this study we were concerned principally with the question "Is the automatic flight-control system plus a piloted backup system more or less reliable than the automatic flight-control system taken alone?" The reliability level of the automatic flight-control system forms the reference condition, thus making it necessary to measure the reliability of the automatic system using the same flight simulation setup, same flight conditions, etc., that were used for the piloted system.

There were several variables to consider in the simulation: the number of pilots (3 used) and failures (19 for piloted system and 10 for the automatic), the wind magnitude (2 used), the time of failure (3 major divisions; before, at, and after high q), and the wind direction (i.e., for some failures the vehicle turns into or away from wind). From these variables it was determined that there were 176 basic failure situations per pilot for the piloted system and 116 for the automatic. To make the number of failures approximately proportional to probability of occurrence, 79 additional situations were added making a total of 255 situations per pilot for the manual system and 195 for the automatic system. These situations were then presented to the pilot in a random order with one failure for each simulated flight. The automatic system data were obtained at the same time the simulation was set up for the manual flights. The probability of mission failure for a major failure mode (effectivity number) was calculated from these data. The criteria for a successful or unsuccessful flight were vehicle structural loading and guidance considerations.

6.6 Determination of the Probability of Mission Failure

The major failure mode effectivity numbers as determined by the simulation are tabulated in Fig. 20. The data are shown for one wind magnitude only. The failure mode criticality (probability of mission failure) shown in Fig. 20 is the product of the failure mode unreliability and effectivity numbers. Since the unreliability numbers were normalized to the most probable failure mode, the criticality numbers also have only relative significance. The overall mission criticality, shown at the bottom of Fig. 20, is obtained by summing the criticality numbers for the appropriate failure modes. The results indicate that including the pilot in a backup control system for the first stage reduces mission criticality by a factor of 2.

7. DISCUSSION

Some results obtained in the present study are applicable to certain other vehicles. Consider the question of what is the optimum pilot control mode for the all-weather landing of large transport aircraft. The trend has favored a fully automatic system with pilot monitor and backup. This is precisely the mode of control used for the present study. A significant question concerning this mode of control is "Can the pilot adapt to the failure dynamics fast enough in the event of a failure?"

The present study shows that, with sufficient recent practice, the pilot could adapt to the failure dynamics from a monitor mode as fast as from a primary control mode.

The pilot's ability to recognize display failures was another significant result of the study. As seen in Fig. 20, no mission failures were attributable to display failures (zero effectivity). Inadvertent takeovers were eliminated by the ground rule that two separate indications of a failure were necessary before a pilot could take over.

A third significant result of the study was the pilot's ability to act as a highly effective frequency selective filter. In the backup mode of operation considered, the pilot was required to act as an adaptive parallel loop to the automatic system. Depending on the failure mode, he was required to close attitude, attitude rate, and/or accelerometer load-relief loops. By observing his display panel, the pilot quite easily separated out and disregarded the flexible body content of these sensor signals; in most instances, this allowed the pilot to control rigid-body motions more effectively than an automatic system utilizing passive filtering of the flexible-body signals.

8. CONCLUDING REMARKS

The technique described above allows mission success to be systematically determined for a complex manual system. The technique further indicates those systems or procedures requiring further development. In addition, several specific results applicable to other large vehicles resulted from the study.

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ITEM	LAUNCH VEHICLE	AIR-TRANSPORT
BENDING FREQUENCY, Hz	1 TO 2	$1\frac{3}{4}$
FUEL SLOSH FREQUENCY, Hz	$\frac{1}{2}$	$\frac{1}{2}$ TO 1
RIGID BODY FREQUENCY, Hz	≈ 0	.1
PILOT-TO-CG POSITION, m	60	33
DISTURBANCES	WIND SHEAR	WIND GUST
TASK	GUIDANCE INTO ORBIT	IFR APPROACH AND LANDING

Fig. 1.- Gross similarities in launch vehicle and air transport control.

ANALYTICAL

FIDELITY \ CLASS	RUDIMENTARY	BASIC	— — —
APPLICATION	FEASIBILITY OF CONTROL PREDICTION OF PROBLEM AREAS	DEFINITION OF CONTROL SYSTEM & PERFORMANCE HANDLING QUALITY ESTIMATE SENSITIVITY DISPLAY REQUIREMENTS	AD HOC ANALYSIS OF DATA TO GENERALIZE EXPERIMENTAL FINDINGS
RESULTS	QUALITATIVE	QUALITATIVE-QUANTITATIVE	— — —
TASK	— — —	PART TASK (TRACKING)	
METHOD OF EVALUATION	OPEN-LOOP STABILITY ANALYSIS & CORRELATION WITH HANDLING QUALITY SPECIFICATIONS	CLOSED-LOOP ANALYSIS USING PILOT DESCRIBING FUNCTIONS + REMNANT	

EXPERIMENTAL

FIDELITY \ CLASS	RUDIMENTARY	BASIC	ADVANCED
APPLICATION	FEASIBILITY OF CONTROL PREDICTION OF PROBLEM AREAS	DEFINITION OF CONTROL SYSTEM & SYSTEM BEHAVIOR HANDLING QUALITY TRENDS DISPLAY DEVELOPMENT	SOLUTION OF OPERATING PROBS MIN. ACCEPTABLE HANDLING QUALITIES CERTIFICATION PROB DEF. DISPLAY AIDS ANALYSIS
RESULTS	QUALITATIVE	QUANTITATIVE	DIRECTLY APPLICABLE TO FLIGHT
TASK	PART TASK	PART ⟶ WHOLE TASK	WHOLE TASK
METHOD OF EVALUATION	PILOT OPINION	PILOT OPINION + PERFORMANCE MEASURES	MEASURED TASK PERFORMANCE + PILOT OPINION

MINOR ⟶ INCREASING TO ⟶ MAX FEASIBLE
SOPHISTICATION

Fig. 2.- Pilot control system analysis.

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- THREE AXES, FIVE DEGREES OF FREEDOM
- LINEARIZED EQUATIONS OF MOTION WITH TIME VARYING COEFFICIENTS
- TWO FUEL TANKS
- TWO BENDING MODES
- DISPLAY ACCELEROMETER LOCATION VARIABLE
- 75 mps WIND SPIKE FOR DISTURBANCE
- FIXED COCKPIT AND CENTRIFUGE
- PARAMETER VARIATIONS

Fig. 3.- Technical constraints.

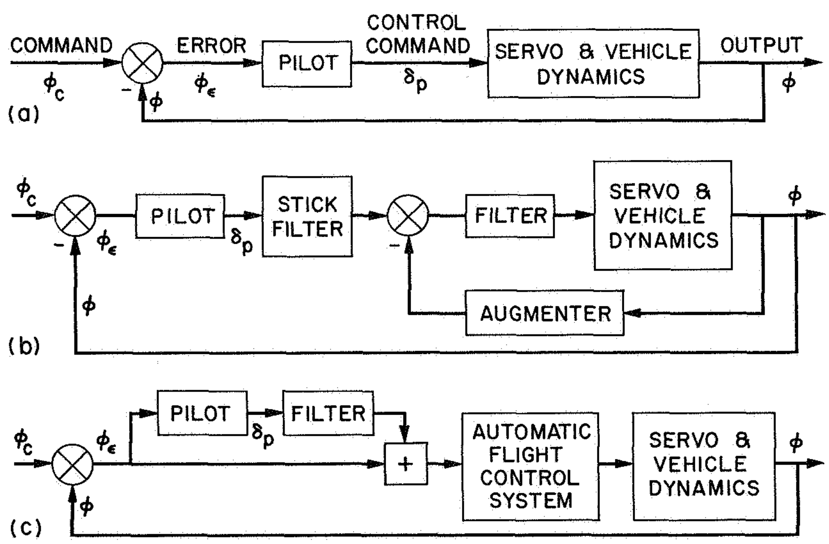

Fig. 4.- Pilot-vehicle control systems.

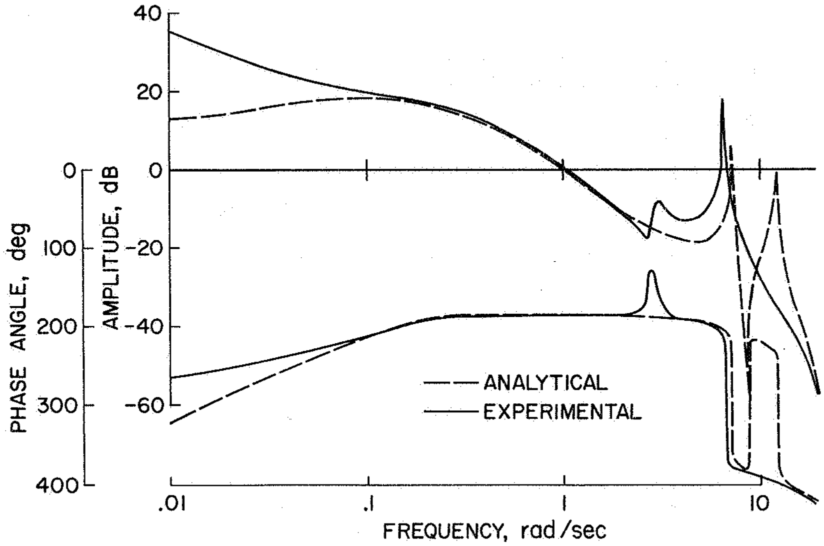

Fig. 5.- Controlled element-full manual.

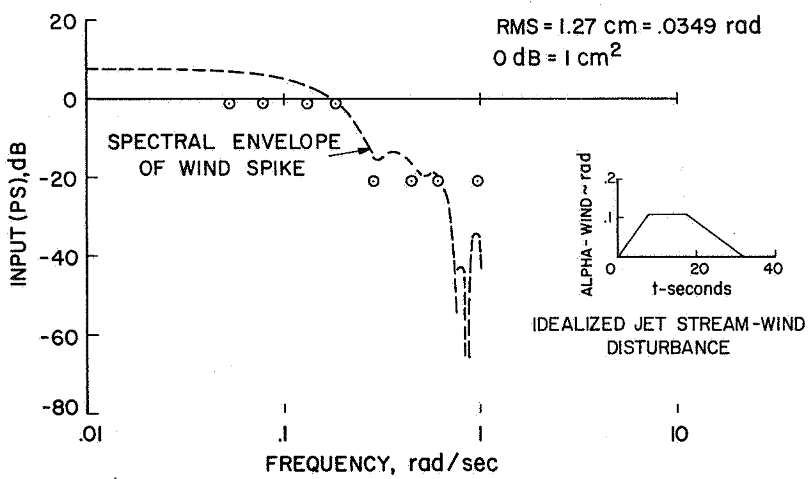

Fig. 6.- Input power spectrum.

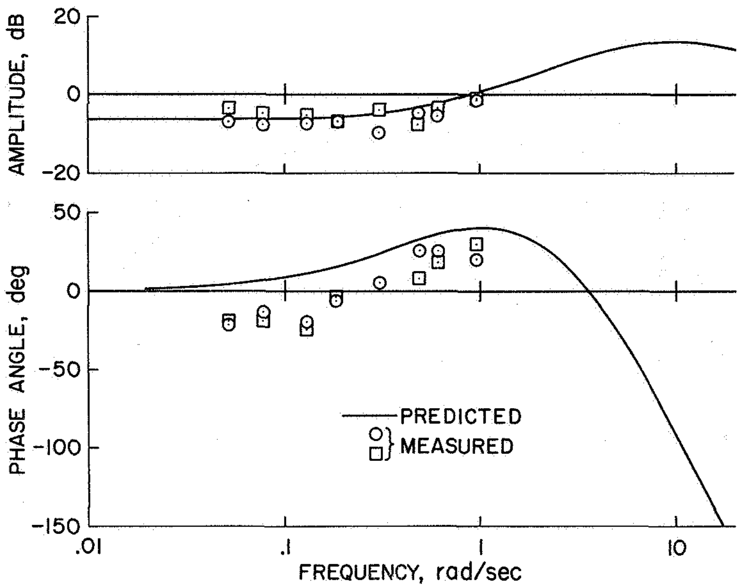

Fig. 7.- Comparison of measured and predicted pilot describing functions.

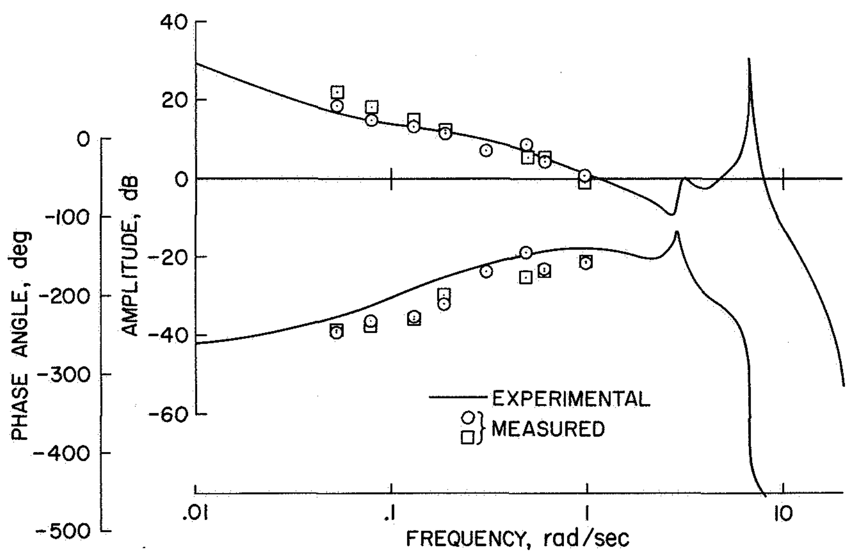

Fig. 8.- Combined pilot-vehicle open-loop frequency response.

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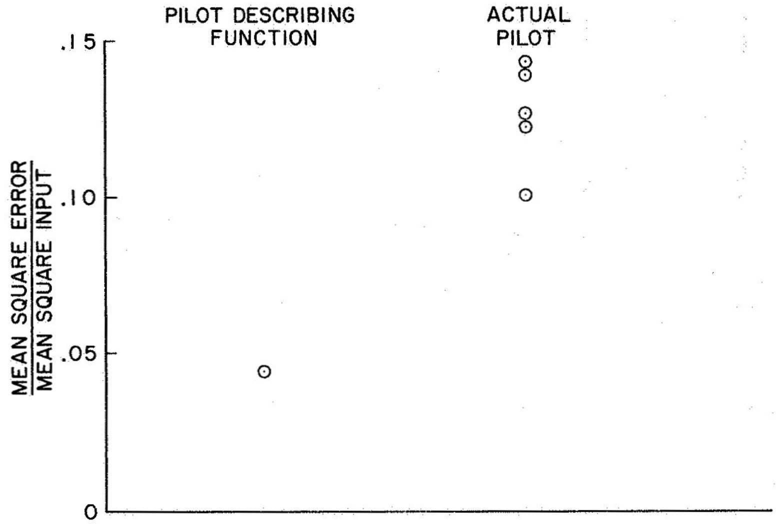

Fig. 9.- Comparison of pilot and pilot describing function performance.

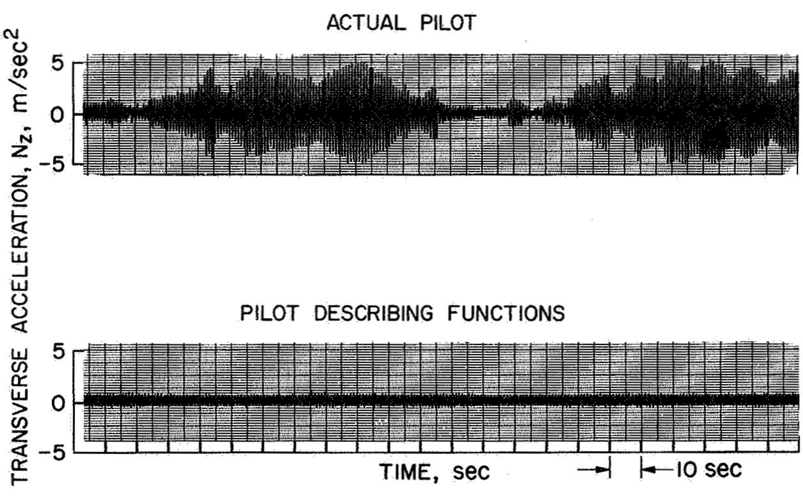

Fig. 10.- Body bending with vehicle controlled by pilot and by pilot describing function.

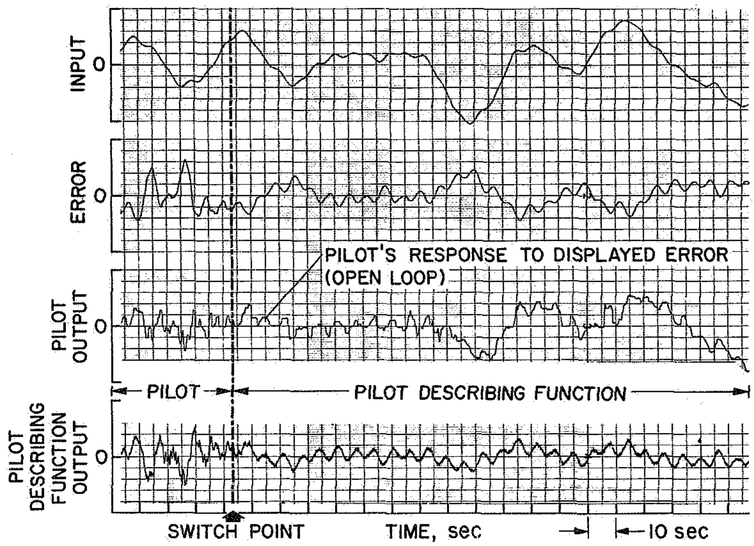

Fig. 11.- Time history of pilot and pilot describing function controlling vehicle.

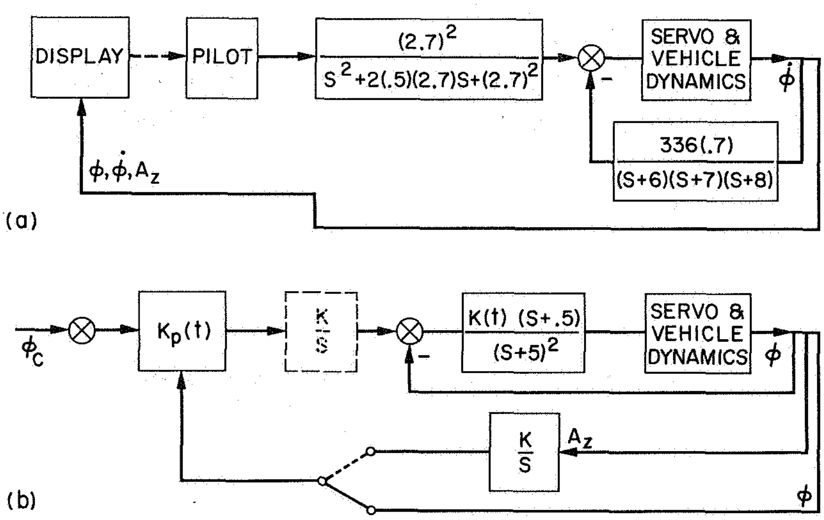

Fig. 12.- Series pilot plus augmented vehicle control system.

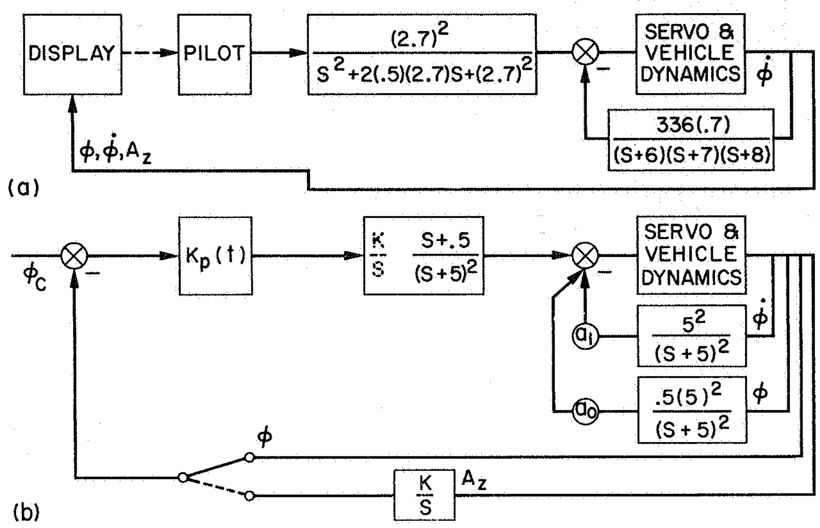

Fig. 13.- Series pilot plus augmented vehicle control system.

INDICES / PILOTED SYSTEM	PILOT RATING	PILOT COMMENTS	M/M_D	n,g
EXPERIMENTAL	$2\frac{1}{2}$ TO 4	EASY TO FLY IF CONTROL TASK IS GIVEN UNDIVIDED ATTENTION EXCITATION OF BODY BENDING RELATIVELY INSENSITIVE TO PILOT CONTROLLER INPUTS	.35 TO .5	.03 TO .07
ANALYTIC	3 TO $3\frac{1}{2}$	ACCEPTABLE, MILDLY UNPLEASANT CHARACTERISTICS REQUIRES SMOOTH CONTROL INPUTS TO PREVENT EXCITATION OF BODY BENDING MOTIONS	.45 TO .55	.05 TO .1

Fig. 14.- Performance comparison.

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INDICES / PILOTED SYSTEM	PILOT RATING	PILOT COMMENTS	M/M_D	n,g
K/S BEFORE PILOT	5 TO $6\frac{1}{2}$	VERY DIFFICULT TO INTERPRET CORRECT CONTROL ACTION FROM DISPLAYS LITTLE FEEDBACK OF ELASTIC MOTIONS TO PILOT THROUGH ACCELERATION DISPLAY YET SMOOTH CONTROL INPUTS ARE NECESSARY TO PREVENT LARGE EXCITATION OF ELASTIC MOTIONS	.85 TO 1.15	.11 TO .49
K/S AFTER PILOT	3 TO $3\frac{1}{2}$	ACCEPTABLE, MILDLY UNPLEASANT CHARACTERISTICS REQUIRES SMOOTH CONTROL INPUTS TO PREVENT EXCITATION OF BODY BENDING MOTIONS	.45 TO .55	.05 TO .1

Fig. 15.- Influence of pilot remnant.

	FULL MANUAL		SERIES PILOT + AUGMENTED VEHICLE	
INDICES	PILOT RATING	PILOT COMMENT	PILOT RATING	PILOT COMMENT
PREDICTED	5 TO 9 (ONE AXIS)	EXTREMELY DIFFICULT TO CONTROL IN THE PRESENCE OF ANY DISTURBANCES PILOT WILL BE NEAR LIMITS OF CONTROL HANDLING QUALITIES POOR PILOT CAN FLY TWO AXES WITH PROPER DISPLAYS ACCURACY IN TRACKING PITCH GUIDANCE COMMANDS IS POOR	3 TO 6	HANDLING QUALITIES SHOULD BE APPRECIABLY BETTER THAN FOR FULL MANUAL SYSTEM GOOD TRACKING ACCURACY AND MINIMIZATION OF INTERNAL SYSTEM DISTURBANCES
MEASURED FROM SIMULATOR	5 TO 7	VERY DIFFICULT TO FLY REQUIRES CONSTANT ATTENTION TO PREVENT LOSS OF CONTROL POSSIBLE TO CONTROL ABOUT 1-AXIS ONLY	3 TO $3\frac{1}{2}$	ACCEPTABLE, MILDLY UNPLEASANT CHARACTERISTICS REQUIRES SMOOTH CONTROL INPUTS TO PREVENT EXCITATION OF BODY BENDING MOTIONS

Fig. 16.- Comparison of predicted and measured performance.

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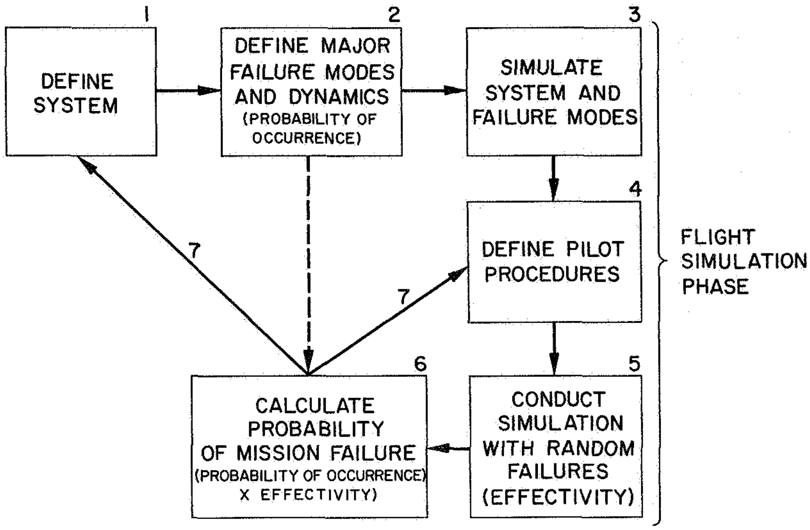

Fig. 17.- Technique for measuring probability of mission success.

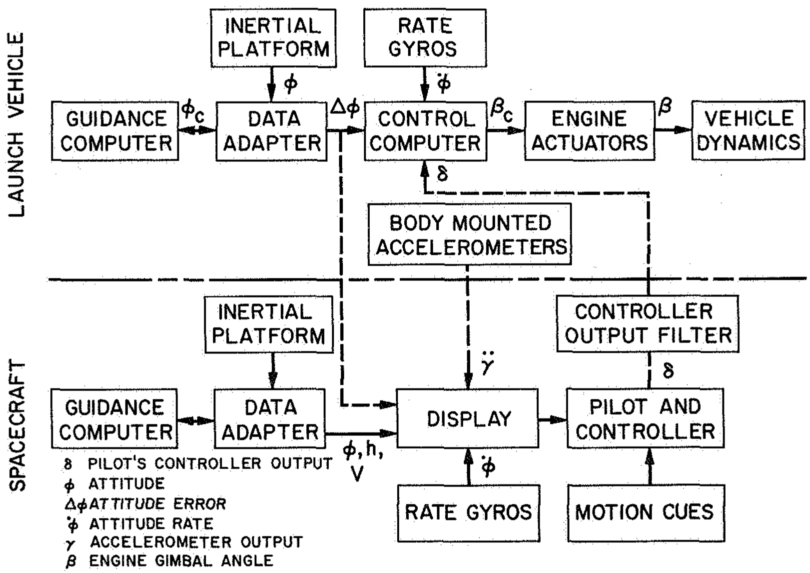

Fig. 18.- Launch vehicle backup guidance and control system.

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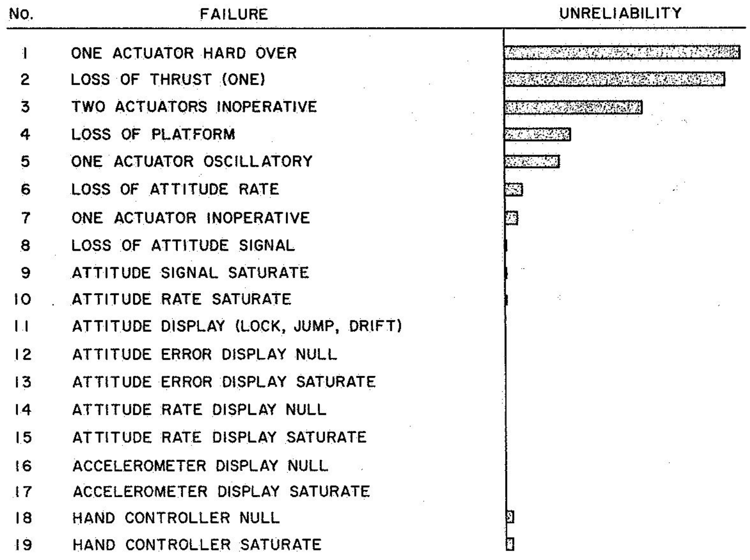

Fig. 19.- Failures considered.

No.	FAILURE	UNRELIABILITY	SYSTEM	EFFEC-TIVITY	CRITICALITY
1	ONE ACTUATOR HARD OVER		MANUAL AUTO	.045 .488	
2	LOSS OF THRUST (ONE)			.439 .450	
3	TWO ACTUATORS INOPERATIVE			.011 .392	
4	LOSS OF PLATFORM			.044 .666	
5	ONE ACTUATOR OSCILLATORY			.577 .400	
6	LOSS OF ATTITUDE RATE			.090 .801	
7	ONE ACTUATOR INOPERATIVE			0 .401	
8	LOSS OF ATTITUDE SIGNAL			0 .578	
9	ATTITUDE SIGNAL SATURATE			.444 .667	
10	ATTITUDE RATE SATURATE			.785 1.000	
11	ATTITUDE DISPLAY (LOCK, JUMP, DRIFT)			0 N.A.	
12	ATTITUDE ERROR DISPLAY NULL			0 N.A.	
13	ATTITUDE ERROR DISPLAY SATURATE			0 N.A.	
14	ATTITUDE RATE DISPLAY NULL			0 N.A.	
15	ATTITUDE RATE DISPLAY SATURATE			0 N.A.	
16	ACCELEROMETER DISPLAY NULL			0 N.A.	
17	ACCELEROMETER DISPLAY SATURATE			0 N.A.	
18	HAND CONTROLLER NULL			0 N.A.	
19	HAND CONTROLLER SATURATE		MANUAL AUTO	.440 N.A.	
		TOTAL CRITICALITY	MAN. AUTO.		

Fig. 20.- Criticality study, maximum wind condition.

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