A NEW APPROACH TO QUANTIFICATION OF FLYING QUALITIES EXCELLENCE

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SUMMARY

Flying qualities specifications have been increasing in complexity and in volume of content over the years. However they specify most requirements in terms of open loop criteria when what is desired is achievement of acceptable closed loop flight performance. This results in increased aircraft procurement costs both because of extensive flight testing necessary, and because some very cost effective means of improving closed loop flight characteristics which do not affect open loop characteristics are precluded from use by current ground rules. An example means of putting a lead lag function in series with pilot input is shown to improve the longitudinal handling qualitites of Lockheed's flight research powered sailplane by about three points on the Cooper-Harper scale. It has no effect on the open loop flight characteristics.

Data are presented illustrating a proposed approach to specifying flying qualities criteria in terms of required pilot reserve attention during the accomplishment of specified portions of each aircraft's mission such as landing approach. Required pilot performance at each level of reserve attention is specified in terms of an easily measured parameter such as his RMS altitude variations from the ideal glide path and correlated against critical performance items such as aircraft rate of sink at touchdown. It is shown that it now appears to be possible to specify rational flying qualities criteria in terms of parameters directly related to desired mission performance without constraining the means by which they are met.

INTRODUCTION

Signal Corps Specification No. 486 dated 23 December 1907 for the first heavier-than-air flying machine purchased by the U. S. Government included direct and to the point flying qualities requirements shown in Figure 1. They may be summarized by: "It should be sufficiently simple in its ---- operations to permit an intelligent man to become proficient in its use within a reasonable length of time." A single mission flight demonstration task was specified. In later years after the issuance of this specification, which was written in terms of the true end product desired, attention began to be devoted to defining quantifiable aircraft characteristics which, when attained, would ensure the intent of the 1907 specification. Requirements were developed for airplane control power to allow it to maneuver as desired and for its stability, primarily to minimize the pilot's workload of making continual flight path corrections in response to disturbances, imprecise control, etc. This has been a difficult and continuing task, largely because of the very complex interactions between the many parameters which combine to make up what is called an airplane's "flying qualities" - a loose term in itself. The result has been that over the years these requirements have snowballed into a large volume of generally sufficient but at times, unnecessarily expensive conditions for the attainment of good flying qualities.

Immediately after World War II aircraft were being designed to USAF specification R-1815A which was soon followed by R-1815B. In 1954, the first issue of MIL-F-8785 emerged followed by several amendments, and it was superceded in 1968 by MIL-F-8785A. Only a year later, it too was superceded by MIL-F-8785B and its subsequent amendments. One of the first things that impresses one who compares those documents is that as time goes on, they get thicker. R-1815B has 24 pages; MIL-F-8785B has 88 pages not counting the appendix volume of backup or clarification data. Further examination shows that many specific requirements in MIL-F-8785B demand much more complex analyses and flight testing to demonstrate compliance than do their counterparts in R-1815B or in the initial issue of MIL-F-8785. It is estimated that the cost of analysis and simulation effort against MIL-F-8755B compared to MIL-F-8785 has increased by 40 to 50 percent and that the flight hours required for data acquisition have increased by 25 to 30 percent.

However, significant as is this added expense in aircraft development, it is not the most serious difficulty inherent in MIL-F-8785B. For reasons noted earlier, most of the requirements in the specification are "open loop", i.e., they do not specify what the airplane should be able to do with the pilot guiding it, they specify airplane characteristics without pilot participation that are supposed to cause it to meet his handling qualities desires. In Lockheed's opinion, this feature unnecessarily constrains the designer in his selection of the lowest cost means of providing an air vehicle to the customer which embodies satisfactory handling qualities through use of systems of suitable reliability and maintainability. This point is illustrated by a discussion of a recently developed concept for significant improvement of the flyability of an aircraft without modification of its conventionally defined control, stability, or dynamic characteristics.

CONTROL COMPENSATION

It is believed that future generations of energy efficient aircraft will incorporate relaxed static stability principles to an ever increasing extent, in addition to other CCV concepts. The conventional approach to development of desirable flying qualities in such aircraft is the addition of stability augmentation systems which monitor and modify the aircraft's response to control or external inputs and provide control inputs in parallel with those of the pilot to cause the net aircraft response to be satisfactory to the pilot. An alternative approach to providing improved flying qualities is to add a compensating function in series with the pilot inputs to create the same net airplane response as did the stability augmentation system. This function is carefully chosen to compensate for the difference between the airplane's natural response to a pilot's input and that which research has shown is most pleasing to a pilot. For example, a lead function is used where the aircraft has a large moment of inertia and tends to have a sluggish response. Correspondingly, a lag function may be used where the aircraft's normal response may be too rapid for ease of normal flying such as the case of an RPV or any light, small aircraft. This tailoring of the pilot's input to the aircraft's dynamic characteristics is called "Control Compensation". Figure 2 shows a simple block diagram of a hovering VTOL comparing the mechanization and effect of these two approaches to flying qualities enhancement systems. On the left is shown a simple feedback stability augmentation system which combined with the neutrally stable basic airplane transfer function of the form shown yields the transfer function, θ/δ_c . On the right is shown the equivalent control compensation system which when combined with identical basic airplane characteristics yields the identical net transfer function as does the stability augmentation system. Examination of the control compensation term shows it to be a simple lead control function. Exact duplication of stability augmentation results is not possible for the more complex flight cases where aerodynamic stability and damping are present but a close match is generally possible.

Figure 3 shows the results of a simple three degree of freedom flight simulation exercise. The pilot was presented a displayed attitude command θ_c on a scope. The command varied for each case as shown on the top of the diagram over a period of about one minute. A typical medium transport was being simulated and its damping ratio was varied as shown. Airplane attitude was also displayed to the pilot and his task was to keep the actual airplane attitude consistent with the commanded value. The figure shows that without control compensation, the pilot did very well at the higher values of damping. In the lightly damped case where $\zeta = 0.1$, pilot performance was fair to poor; in the negatively damped case, real control was not achieved. The effect of control compensation is seen to be slight on the cases with adequate damping. In the lightly damped case, the control excursions are markedly diminished and some reasonable measure of control is retained even in the presence of negative damping.

The Control Compensation principle has been evaluated in flight simulations of a number of other Lockheed aircraft. It was also recently flight tested in Lockheed's flight research Caproni jet powered sailplane shown in Figure 4. A sidestick controller was installed and the flying qualities evaluated first with the basic system against those of the unmodified Caproni; then with varying characteristics and extents of control compensation. Figure 5 shows that the flying qualities of the basic unmodified airplane at the aft C.G. limit were rated to be quite poor. This was true both with and without the sidestick controller installation. Note that here the control compensation function is a lead-lag and that its use produced a pilot rating improvement of about three points on the Cooper/Harper scale.

Studies have shown that Control Compensation can be provided to an aircraft at more than an order of magnitude less cost than can stability augmentation and that the resulting system is several orders of magnitude more reliable per channel than is a stability augmentation system. It can be mechanized using either electrical or hydromechanical components hence, has the potential to provide dissimilar redundancy.

While its use may serve as a complete replacement for conventional stability augmentation systems in certain applications, it is not suggested that this is the general case. However, it is believed that the application of this principle in conjunction with other more conventional principles will yield a much less expensive and much more reliable system at no sacrifice at all in system effectiveness. It is again emphasized that Control Compensation affects only pilot-in-the-loop characteristics. Therefore, when flying qualities requirements are specified in terms of airplane characteristics without the pilot-in-the-loop, as do so many of the MIL-F-8785B requirements, the use of this principle is precluded. The Government is thus currently denied the above noted cost and reliability benefits solely because of the manner in which desired flying qualities characteristics are specified.

CLOSED LOOP FLIGHT PERFORMANCE MEASUREMENT

A great deal has been learned about the fundamentals of man/machine interactions and human guidance principles during the years while specifications have continued to identify desired airplane characteristics without human guidance. It is therefore suggested that a totally new approach be considered to the business of specifying flying qualities. Lockheed-Georgia has this year initiated an IRAD Program which has as one of its objectives the evaluation of a concept for specifying flying qualities excellence in terms related only to the pilot's ability to accomplish certain specified tasks. This concept involves the determination of a pilot's performance in accomplishing a task such as landing approach where his performance is measured in terms of quantifiable units such as his RMS deviation from the glideslope. His performance is then measured over a range of percentage time which the pilot must devote to peripheral tasks in order to determine his flying performance variations with his percent reserve attention capability. "Reserve attention" is defined as the percentage of the pilot's time he may safely spend on tasks other than actual flight guidance during the accomplishment of a definable portion of his mission such as landing approach. Implementation of this principle is discussed as follows.

A pilot's duty environment may be represented by a diagram as shown in Figure 6. Beginning at the 12:00 position and proceeding counterclockwise, the first segment indicates those tasks associated with basic flight guidance. If the percentage of his time required to accomplish these tasks does not exceed some value which still allows a fairly large percentage reserve attention capacity, and time to accomplish the other tasks noted, the aircraft exhibits Level One flying qualities. While this definition is not an exact paraphrase of that in MIL-F-8785B, it is certainly consistent with it. Now is for some reason the percentage of the pilot's attention capacity required for the accomplishment of his flight guidance tasks grows until it uses up most or all of his reserve attention and perhaps diminishes the attention he can provide to peripheral tasks such as outside visual checks, one may consider the aircraft to be exhibiting Level 2 flying qualities. Similarly, Level 3 flying qualities involves near total pilot effort in pure flight guidance leaving only minimal capability for other essentials such as crew communication.

Pursuing this approach, flight simulation studies were initiated to measure in definable units the effect of pilot workload on glideslope tracking performance. A typical Lockheed advanced transport aircraft was simulated and its flying qualities were progressively degraded by reducing its effective tail area and by moving its C.G. aft. Thus several different airplane configurations were defined which exhibited Cooper ratings covering virtually the complete scale of flying qualities from excellent to catastrophic. As each configuration at its specific Cooper rating was flown on successive approaches, varying amounts of the pilot's attention were directed away from the flight guidance task. These diversions were set up as percentages of a series of eight second cycles during each run. For example, at 50% reserve attention, the pilot would "fly" for four seconds, look away for four seconds, return his attention to flight guidance for another four seconds, etc. All runs began at 1,000 feet altitude above the airfield using a straight in approach. Light turbulence was included, i.e., 1/2 the MIL-F-8785B specified value. Measurements were taken of the actual glide path achieved compared to the ideal intended path and an RMS altitude deviation determined for each run. It thus became possible to plot RMS altitude deviation observed as a function of the percentage of time the pilot's attention is demanded elsewhere; i.e., his reserve attention capacity. Such a plot is shown in Figure 7 with curves for each of several flying qualities levels, or Cooper ratings. Each point shown is the average of a series of five runs. The standard deviation value of the data scatter within each five run series was about a quarter to half the altitude deviation values shown. As would be expected, a rather consistent deterioration in glidepath altitude tracking performance is shown with increasing pilot reserve attention (or percentage distraction) and with progressively poor pilot rating. The curves appear to be roughly parallel at the lower values of pilot reserve attention and the airplane is seen to "get away from" the pilot at progressively lower values of pilot reserve attention as pilot Cooper ratings are degraded. During the one part of the process of data acquisition, the pilot became much more fatigued than anyone realized. Only later when the data were extended (and didn't correlate) was the earlier fatigue situation recognized. Some of the "tired pilot" points are shown by flagged symbols on Figure 7; considerable performance degradation is evident.

The real concern related to glidepath deviation, of course, is not with the deviation itself, but in its influence on probable touchdown rate of sink or touchdown position on the runway compared to that intended. For purposes of this analysis, the former was chosen. Figure 8 presents a plot of the maximum touchdown rate of sink achieved in each set of five runs versus the average RMS glidepath deviation. The philosophy is that what is being sought is a measure or indicator of the poorest probable landing for each condition investigated. It is seen that for the P.R. = 2.5 aircraft, no definable trend of touchdown rate of sink with altitude deviation appears to exist, whereas for the poorer pilot ratings, a very clear trend is evident. This may be partially due to the fact that the particular configuration simulated exhibited a strong positive ground effect. Hence the stable configurations tended to a natural flare on landing. The P.R. = 2.5 aircraft showed essentially the same touchdown sink rate hands off as it did in the poorer of the piloted landing cases. Since most transport aircraft are designed for a limit touchdown rate of sink of 9 feet per second, the minimum level of RMS deviation which yields 9 fps touchdown sink rate has been chosen as the outer value of a Level 3 flying qualities band. Similarly, a desirable rate of sink is 2-3 fps, however, the pilot was unable to achieve this value consistently with even the best of the configurations flown. Hence, the lowest RMS deviation on the scatter-band which yields a 4 fps touchdown rate has been selected as the maximum acceptable for Level 1 flying qualities. The boundary for Level 2 flying qualities has for purposes of this plot been arbitrarily located halfway between the Level 1 and the Level 2 boundaries. This plot has now defined limit values of RMS glideslope deviations for each flying qualities level.

By noting the RMS altitude deviation values included in each flying qualities level band for each pilot rating, the previous two plots may now be combined to yield Figure 9. This plot is in a form suitable for inclusion in a specification. It specifies readily determinable airplane performance against a specific task and the requirements for each flying qualities level are clearly identified. It is seen that the distinction between the flying qualities levels in terms of altitude deviation becomes vanishingly small at the higher levels of pilot inattention (highest reserve attention). While this is perhaps logical, it is also possible that the shape of these boundaries has been inadvertently perturbed by the aforementioned favorable ground effect which should not be the case for general specifications. Further, it is emphasized that this figure is intended to convey criteria related to only one performance parameter desired, i.e., a reliably safe touchdown. Lockheed expects to expand this investigation during the balance of the year by adding further degrees of freedom/constraints to the basic task such as going to the full six degrees of flight freedom and directing the pilot to attempt each touchdown on a specific point on the runway.

Another critically important measure of a pilot's flight performance on the glide path, significant to longitudinal guidance, is airspeed control. This is important both to maintain adequate stall margin for maneuvering and to accommodate reasonable levels of near ground wind variations, as well as to ensure against exceeding a touchdown airspeed consistent with runway length limitations. To develop this means of performance criteria measurement, data are also taken during the above discussed simulation runs of RMS airspeed error during the landing approach and this is plotted versus pilot reserve attention in Figure 10. Once again, very little difference is observed in pilot performance between the P.R. = 2.5 and the P.R. = 4 aircraft. Although very little difference due to pilot fatigue is noted on the P.R. = 4 points, a drastic change is seen in the P.R. = 6 data. The effect on airspeed deviation in going from P.R. = 4 to P.R. = 6 was considerably less than anticipated for the unfatigued pilot which may be partially due to the simplistic 3 degree of simulation used. Believing that the fatigued pilot data may be more representative of the general case, it will be used at this time until more comprehensive data are run later in the year.

Records are also made of the airspeed at touchdown and of the minimum airspeed encountered during landing approach. A plot is then made as seen in Figure 11 of touchdown airspeed versus RMS airspeed error. Only those airspeed points are plotted where the landing was made at above the desired airspeed. From a performance viewpoint, touchdowns at below the desired airspeed have no adverse significance. Somewhat surprisingly, relatively few data points are available because in these simulations, by far the greatest preponderance of cases yielded a touchdown airspeed that was below rather than above the target value. Also plotted are the points indicating the minimum airspeed encountered in any of each of the five runs made, showing the nearest proximity to stall occurring during the approach to the 50 ft. height. The selection of criteria to be used in establishing the limits of airspeed deviations acceptable within each flying qualities level could be a study in itself and should certainly be specified by the customer. For illustration purposes, the Level 3 boundary was selected to be that point on the minimum airspeed line where stall warning at 1.07 V_S was barely avoided while maneuvering the airplane in a 20 degree banked turn--approximately 1.1 V_S. Landing distance varies approximately as the touchdown velocity squared and all flight handbook values are expected to be accurate within 5%. Therefore, the maximum RMS deviation allowable for Level 1 flying qualities has been specified to be at the point where the maximum touchdown airspeed on the scatterband exceeds the desired by 2 1/2%. Since the target airspeed is held constant during the latter portion of the landing approach to the onset of landing flare, for convenience the airspeed actually shown for this criteria is that encountered at the 50 ft. height. Lastly, as before, the Level 2 boundary is shown halfway between Levels 1 and 3. This figure thus establishes the values of RMS airspeed error at the boundaries of the flying qualities levels.

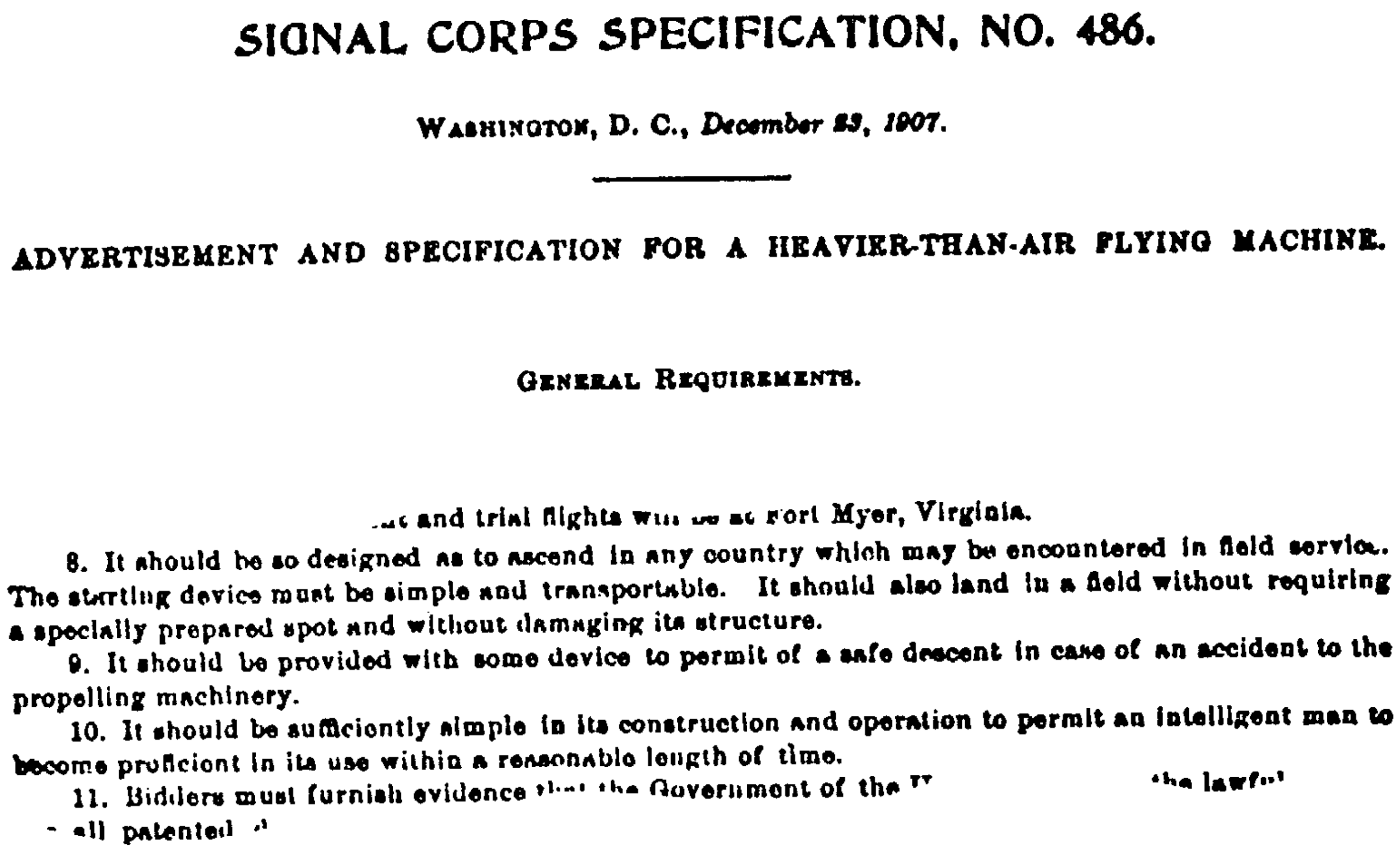
Figure 12 may now be prepared using the boundary curves from Figure 10, the cutoff values of V_{eRMS} from Figure 11, and by fairing an upper boundary curve. This plot, together with that of Figure 9 are presented as illustrative of an approach towards establishment of sufficient flying qualities criteria for any transport aircraft in the landing approach flight regime. The performance criteria chosen to deliniate flying qualities levels have yielded a surprisingly and perhaps unrealisticly large range of level 1 performance. Based on these data, it would appear that the actual capability of a skilled pilot to accomplish critical tasks is not appreciably affected by flying qualities in the upper four levels of pilot rating and only modestly so through a rating of 6. It is suspected that the difficulty of the flying task used for criteria establishment should be increased, since it appears that flight safety is a significant function of flying qualities only in those cases where piloting skill is taxed by environmental circumstances such as severe turbulence, wind shear, engine failure, obstacle clearance, or by pilot fatigue. As noted earlier, these considerations will be addressed later this year in the Lockheed simulations.

Obviously this approach can be extended to defining piloting tasks for other parts of an airplane's mission profile. Some of these are indicated in Figure 13. It is noted that the principle embodied in specifying flying qualities in the above noted fashion is not new. It is in fact quite consistent with the flight performance specifications provided by the Air Force for automatic flight control systems such as those shown in Figure 13. In each case rational criteria are presented which are directly related to desired mission performance requirements without constraining the means by which they are met.

PERSPECTIVE

It is worth a few moments to consider those factors which contribute to pilot control of flight. Some of these are shown in Figure 14. In years past, only the first two items indicated were of particular significance and the pilot's inherent capabilities and limitations were very imperfectly understood. Hence, flying qualities requirements were specified in terms of airframe parameters based on entirely empirical data concerning pilot desirements. The idea was to provide the pilot with whatever appeared to make him comfortable in the belief that in so doing flight safety and mission effectivity were being maximized. However, in later years, two very significant developments have occurred and are progressing. (1) First, as everyone knows, automatic flight control systems came on the scene and introduced a whole new dimension of design options not only to obtain completely automated flight, but also to provide virtually any level of flying qualities largely independent of basic airframe characteristics. (2) Secondly, a much deeper understanding of the human pilot's functional capabilities is being achieved in AFCS terms. It is thus possible to mathematically model the pilot, as well as the airframe and the flight control system elements, and then to directly solve for the effect of variations in the characteristics of any element in the total system on the effectivity of the total system. That is why it is now possible to greatly improve the flyability of an airframe with otherwise poor flying qualities by tailoring--making compatible--the pilot's control inputs to the inherent airframe characteristics with simple mechanisms rather than multi-channel AFCS systems.

It is incumbent, therefore, on those who write the specifications against which future USAF aircraft will be procured to be sure that the truly desired airplane characteristics, those which determine the aircraft's ability to perform its mission, are accurately and completely specified in terms of the desired features. Recognition must be maintained that all those design features shown in Figure 14 work together and must be accounted for in the determination of what constitutes suitable flight handling performance. Any other approach is certain to have the dual disadvantages of incompletely assuring attainment of desired performance and of precluding use of the most cost effective design approaches to developing needed vehicle systems.



SIGNAL CORPS SPECIFICATION, NO. 486.

WASHINGTON, D. C., *December 23, 1907.*

ADVERTISEMENT AND SPECIFICATION FOR A HEAVIER-THAN-AIR FLYING MACHINE.

GENERAL REQUIREMENTS.

...t and trial flights will be at Fort Myer, Virginia.

8. It should be so designed as to ascend in any country which may be encountered in field service. The starting device must be simple and transportable. It should also land in a field without requiring a specially prepared spot and without damaging its structure.

9. It should be provided with some device to permit of a safe descent in case of an accident to the propelling machinery.

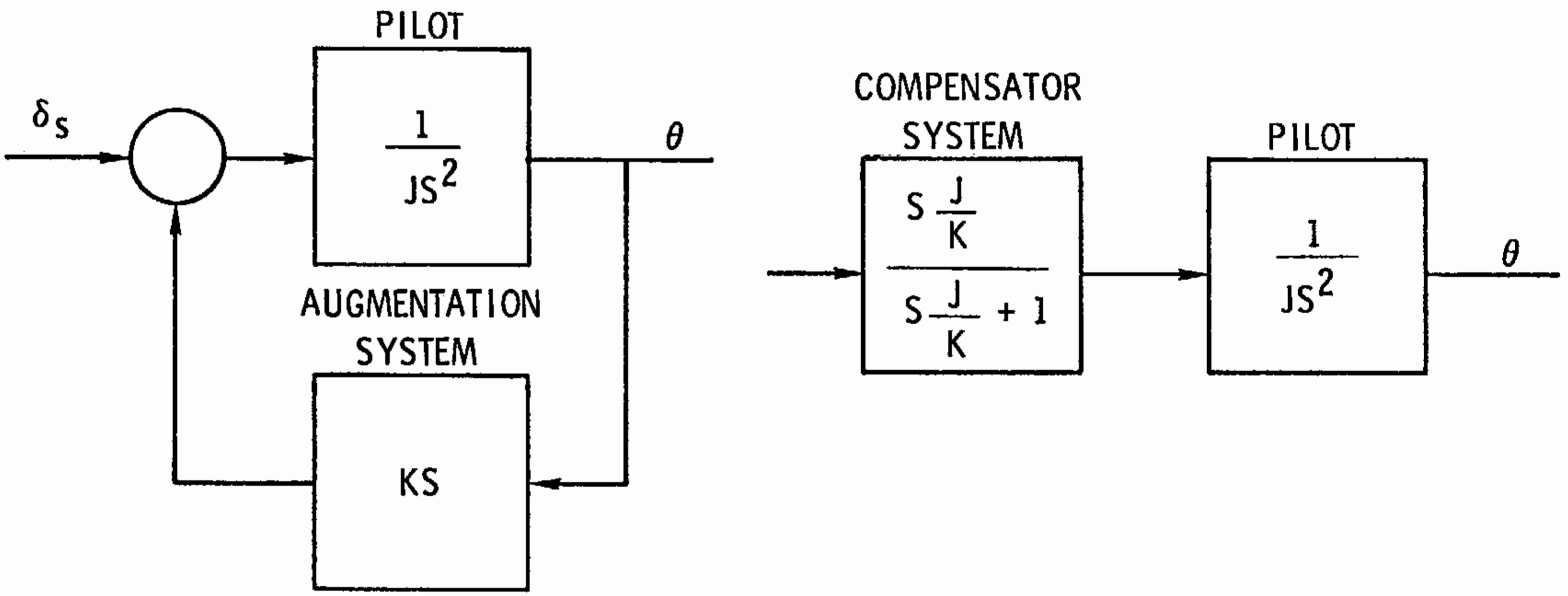
10. It should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time.

11. Bidders must furnish evidence that the Government of the U the lawful

all patented

FIGURE 1

FLYING QUALITIES ENHANCEMENT SYSTEMS



STABILITY
AUGMENTATION

$$\frac{\theta}{\delta_s} = \frac{1}{KS(S\frac{J}{K} + 1)}$$

CONTROL
COMPENSATION

$$\frac{\theta}{\delta_s} = \frac{1}{KS(S\frac{J}{K} + 1)}$$

FIGURE 2

LONGITUDINAL TRACKING RESPONSE

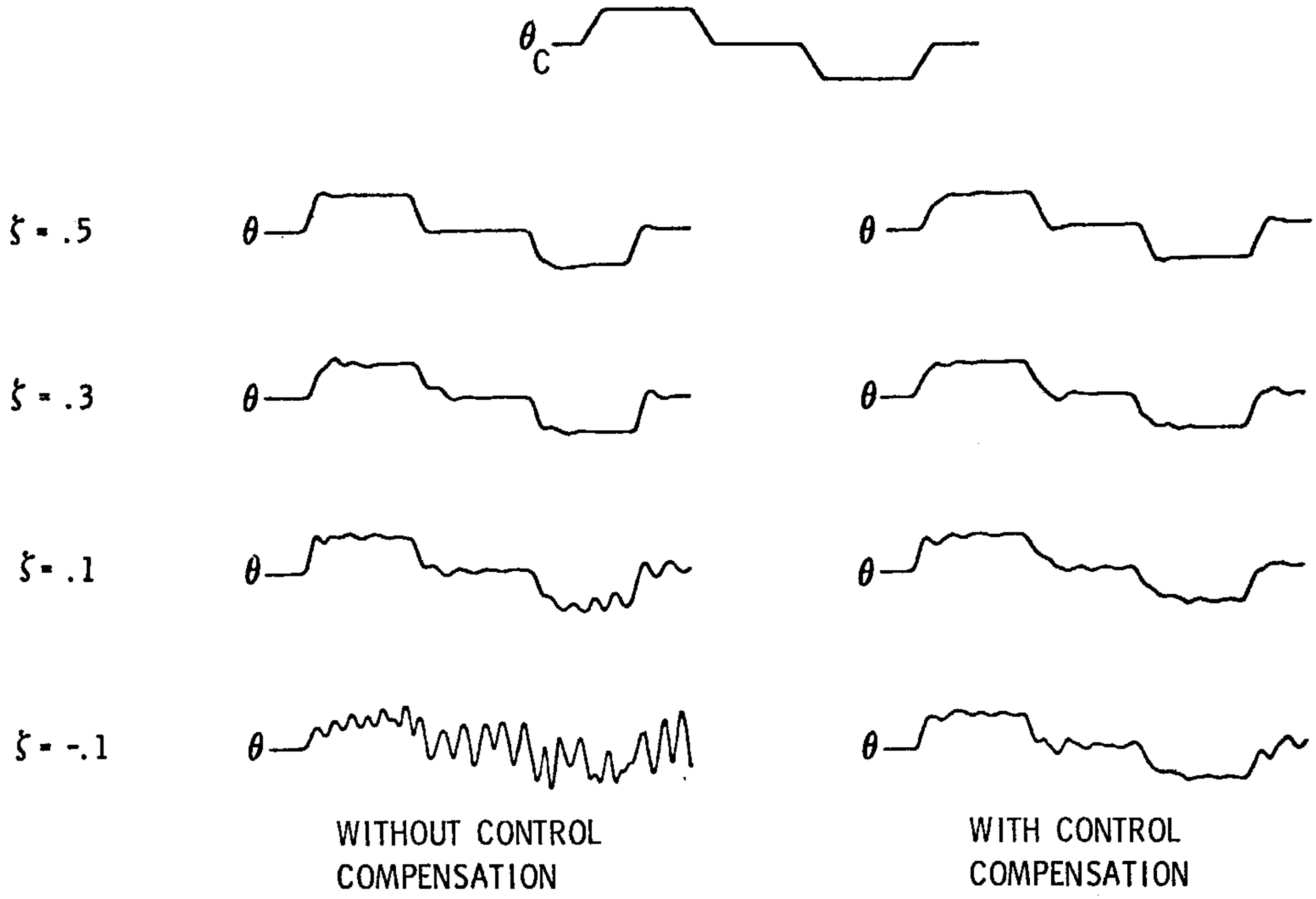


FIGURE 3

LOCKHEED FLIGHT RESEARCH AIRCRAFT

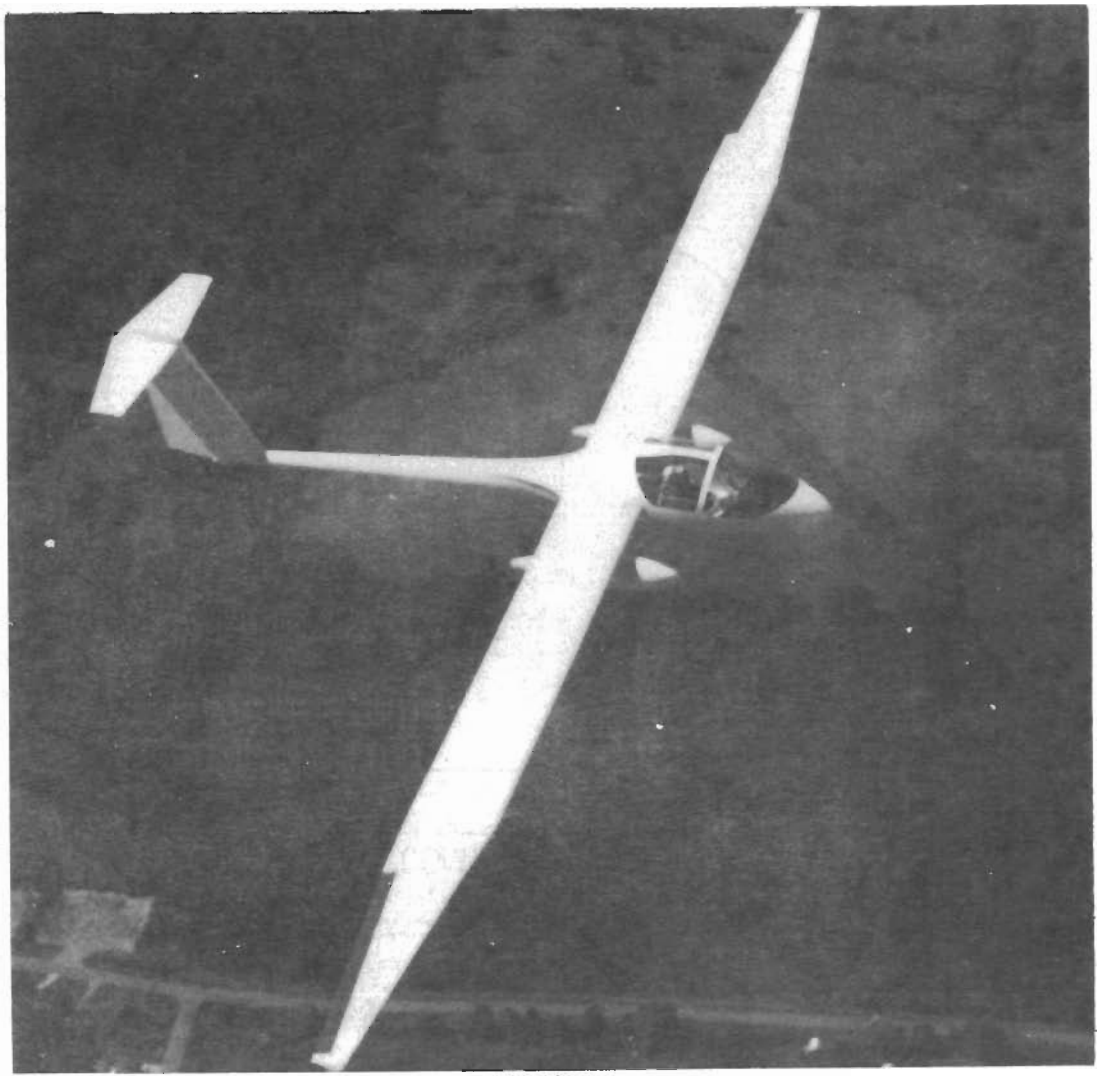


FIGURE 4

EFFECT OF CONTROL COMPENSATION ON CAPRONI FLYING QUALITIES

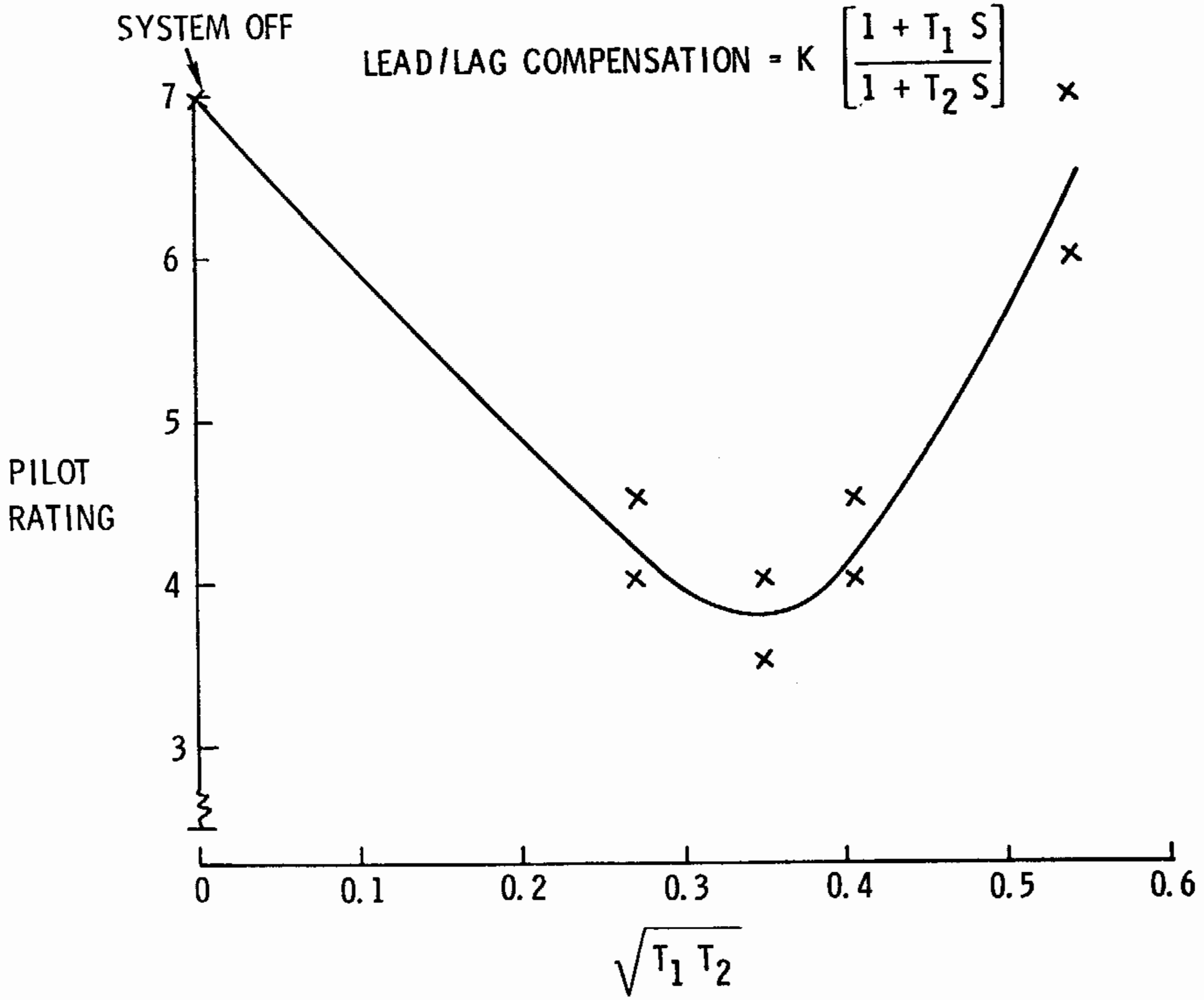


FIGURE 5

TOTAL PILOT WORKLOAD

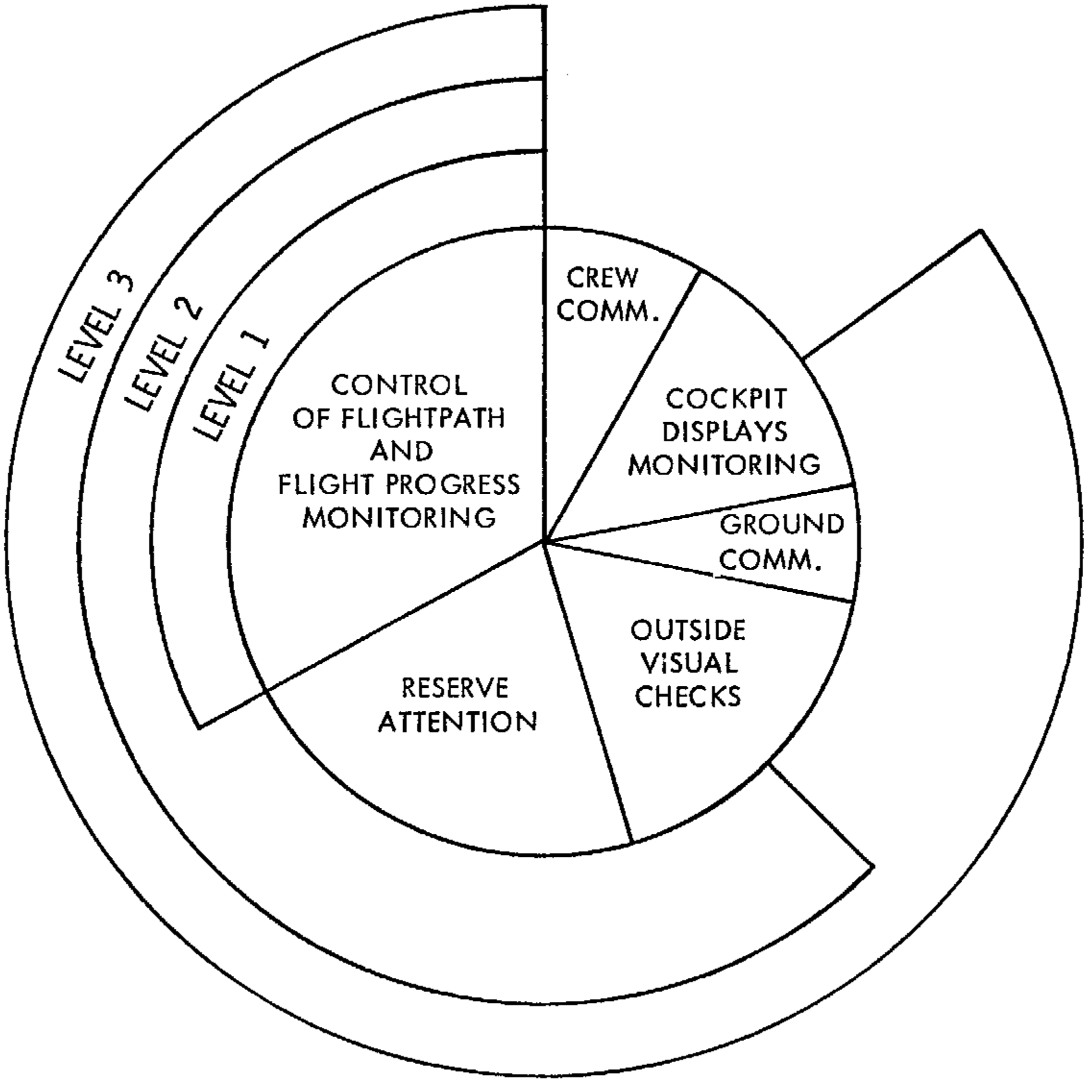


FIGURE 6

EFFECT OF PILOT WORKLOAD ON ALTITUDE CONTROL

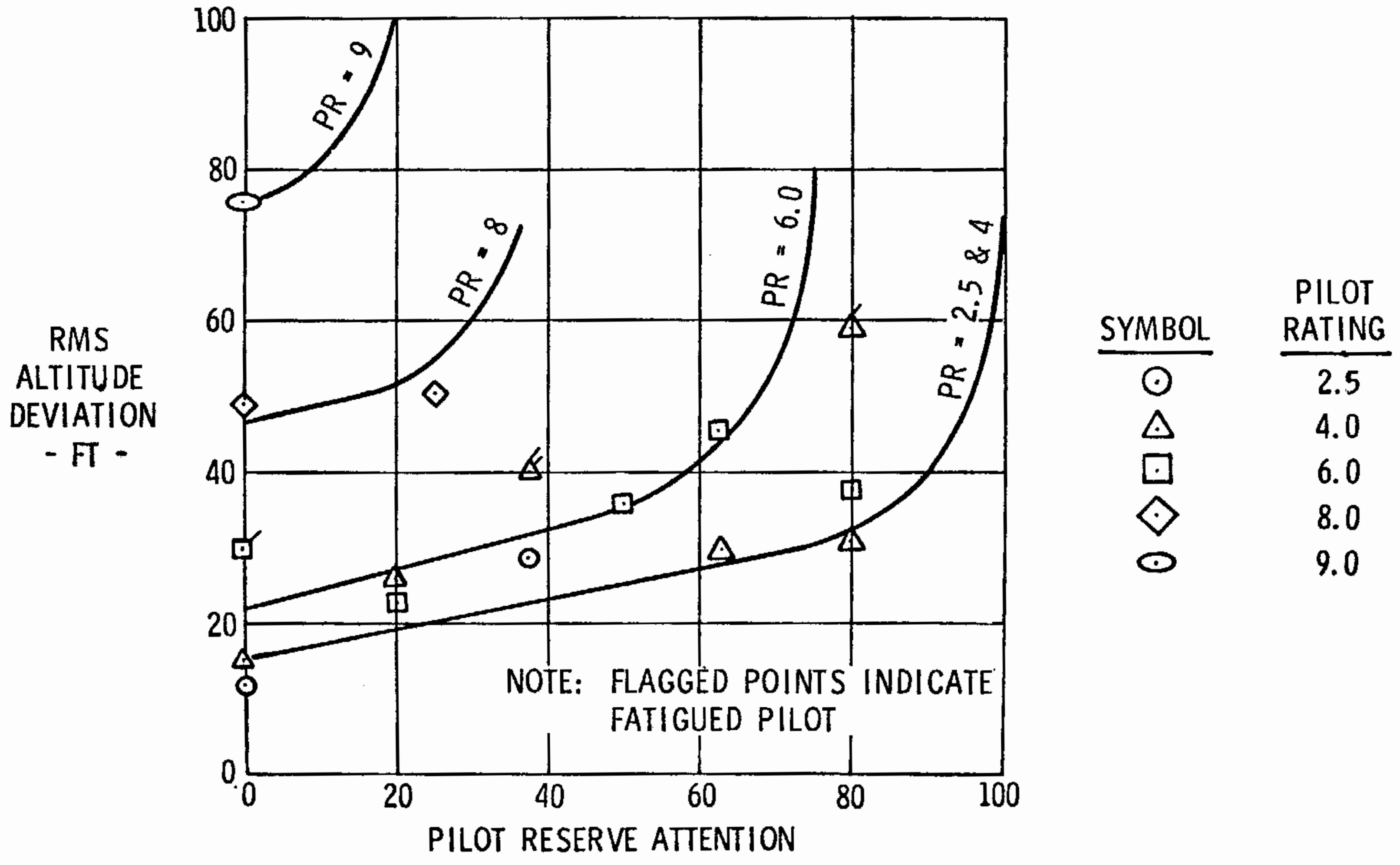


FIGURE 7

CORRELATION OF RMS ALTITUDE DEVIATION WITH LANDING R/S

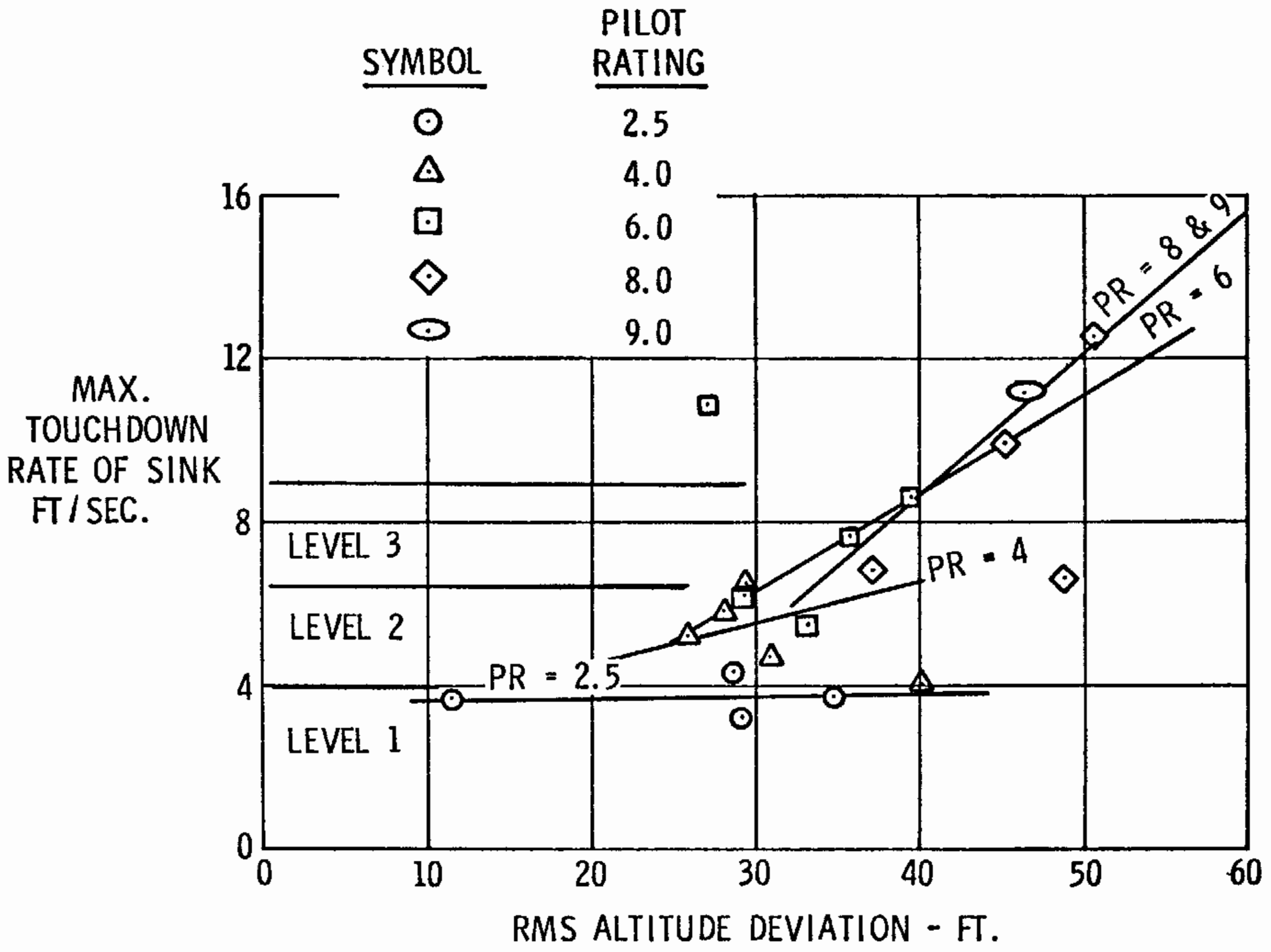


FIGURE 8

DETERMINATION OF FLYING QUALITIES LEVEL THROUGH MEASUREMENT OF ALTITUDE DEVIATIONS

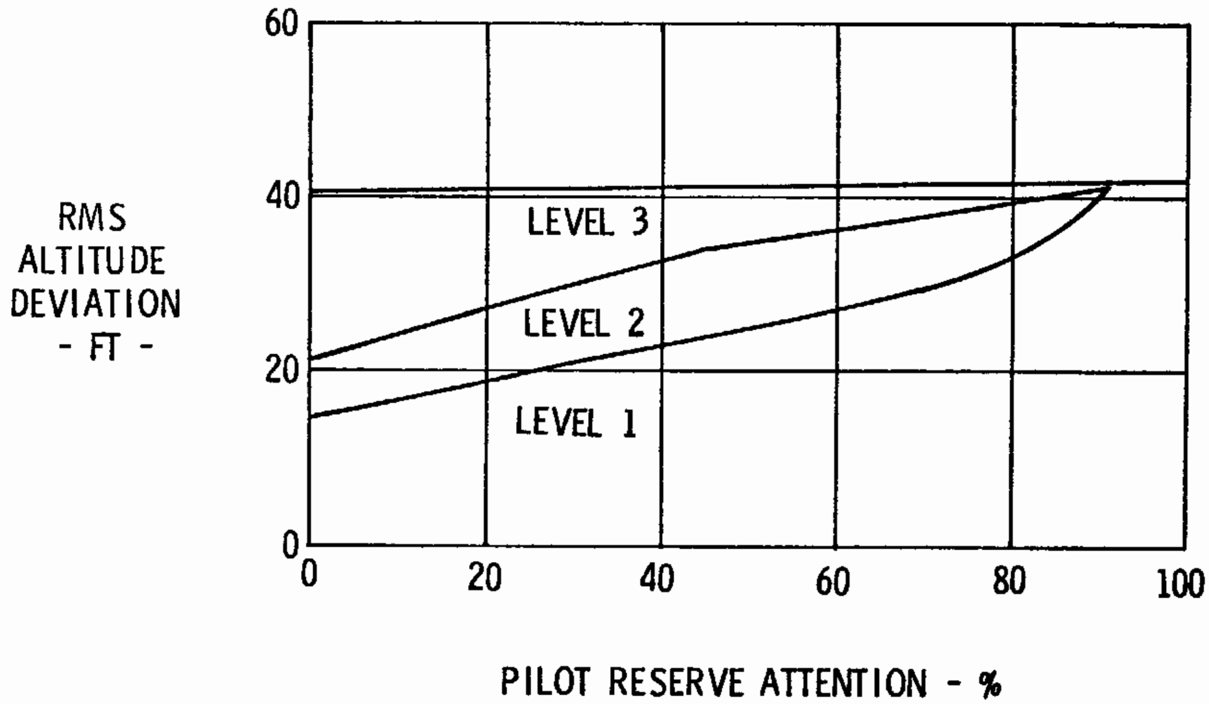


FIGURE 9

EFFECT OF PILOT WORKLOAD ON AIRSPEED CONTROL

NOTE: FLAGGED POINTS INCLUDE EFFECTS OF PILOT FATIGUE

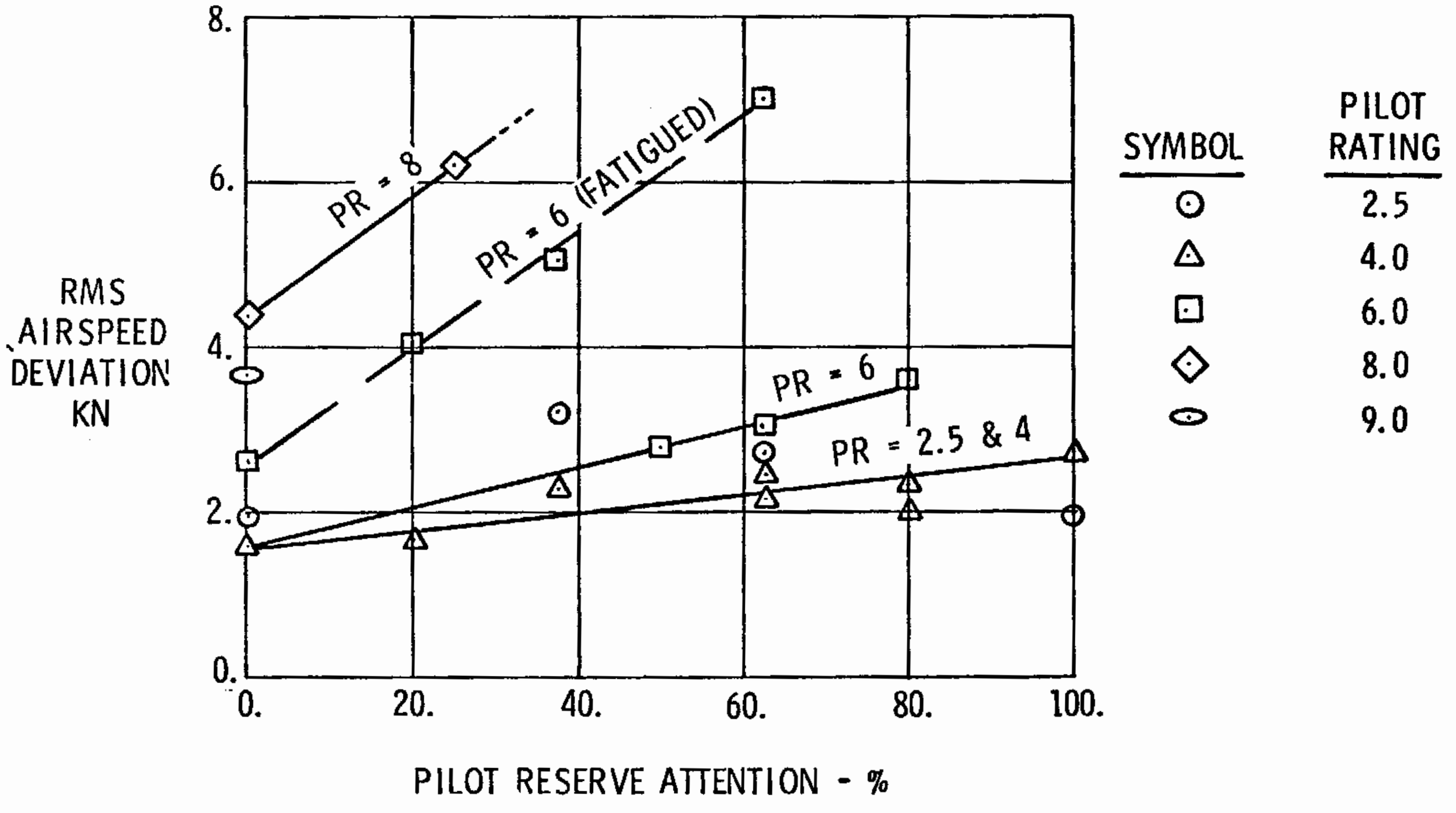


FIGURE 10

GLIDESLOPE AIRSPEED CONTROL

OPEN SYMBOLS ARE MINIMUM AIRSPEED ENCOUNTERED
CLOSED SYMBOLS ARE AIRSPEED AT FLARE INITIATION

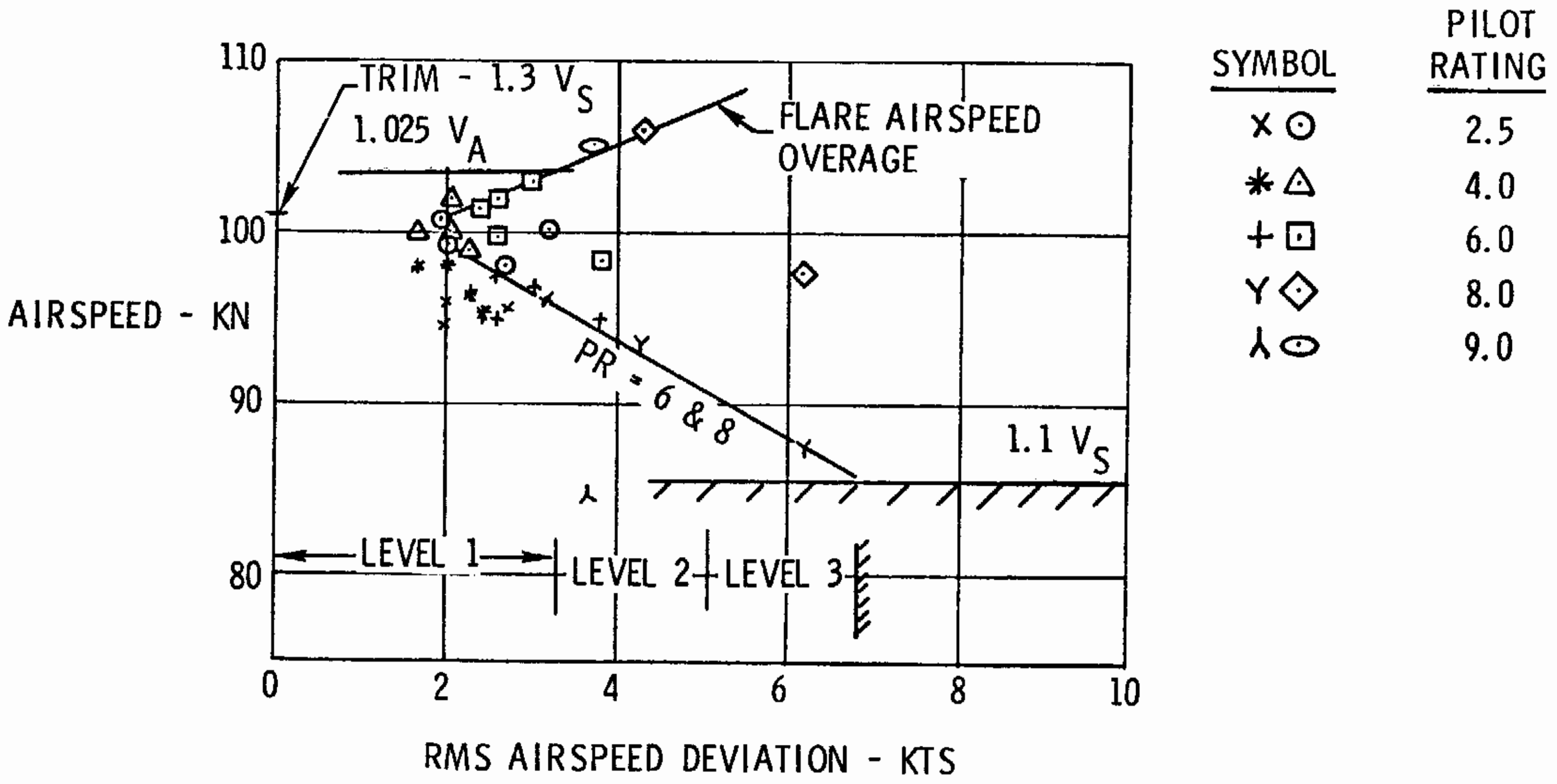


FIGURE 11

DETERMINATION OF FLYING QUALITIES LEVEL THROUGH MEASUREMENT OF AIRSPEED DEVIATIONS

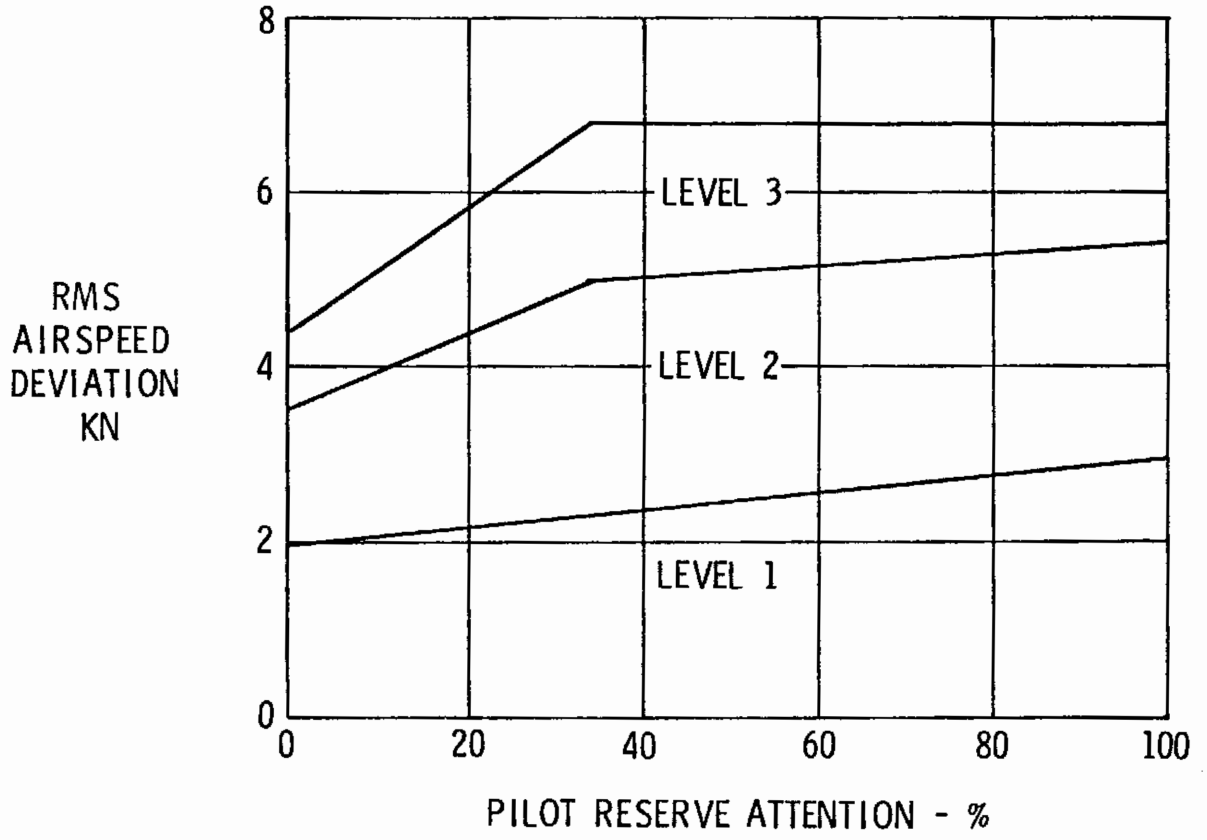


FIGURE 12

TASK ORIENTED APPROACH TO CRITERIA SPECIFICATION

(CLOSED LOOP ~ PILOT, AIRFRAME, DISPLAYS, MANUAL CONTROLLERS)

- BREAK DOWN EXISTING FLIGHT PHASE FORMAT INTO THE VARIOUS PILOTING TASKS CONTAINED WITHIN A GIVEN MISSION PROFILE.
  - TAKE-OFF
  - LANDING
  - AERIAL REFUELING
  - TARGET TRACKING
  - AIR-GROUND ATTACK
  - AIRLIFT ASSAULT LANDING
- SPECIFY PILOT-IN-THE-LOOP FLYING QUALITIES SIMILAR TO APPROACH FOR SPECIFYING PERFORMANCE OF AUTOMATIC FLIGHT CONTROL SYSTEMS:
  - ALL-WEATHER LANDING SYSTEM
  - AUTO-PILOT
  - TERRAIN FOLLOWING
  - TASK ORIENTED CONTROL SYSTEMS
  - FUSELAGE AIMING

FIGURE 13

FACTORS CONTRIBUTING TO PILOT CONTROL OF FLIGHT

- PILOT SKILL AND TRAINING
- AIRFRAME
- FLIGHT CONTROL SYSTEM
  - AUTOMATIC
  - PRIMARY
  - SECONDARY
- FLIGHT PATH DISPLAYS

FIGURE 14

Jerry Lockenour, Northrop: How did you control the pilot attention?

Answer: We required the pilot to look away to another area when a red light came on. When a green light then came on, he resumed his flight task.

Capt Martin, AFFTC: How do you propose to quantify pilot reserve attention safely in flight test?

Answer: Experimentally, obviously in a safe environment such as doing a landing approach to a predetermined altitude at 10,000 ft say.

John Hodgkinson, MACAIR: How do you predict pilot attention analytically?

Answer: We don't. That's part of the experimental objective.

Bill Levison, BBN: There are a variety of models to predict attention. Doesn't % attention depend on cycle time?

Answer: Probably. We tried two different cycle times and settled on 8 seconds, the lesser of the ones used. In the real case, of course, cycle times would vary quite widely.

Jerry, Lockenour, Northrop: The pilot compensation would allow an electric backup control system.

Answer: It could. Even better, it can be mechanized entirely hydraulically which improves its reliability per channel by more than two orders of magnitude, and provides dissimilar redundancy.

Representative from 6570 AMRL: Pursuant to the question from Capt Martin AFFTC, we here at AMRL have a number of nonintrusive procedures for assessing percent of available attention and workload by psychological methods. These involve secondary task, time estimation, and psychophysiological methods. We would be happy to discuss these at length any time.