ANALYTICAL INVESTIGATION OF CONTROL REQUIREMENTS FOR HIGH SPEED LOW ALTITUDE PENETRATION

FINAL REPORT BRIEF

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New York; R. P. Quinliven, G. Tye, and H. H. Westerholt, Authors)

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FOREWORD

This report was prepared by the General Electric Company, Light Military Electronics Department, Johnson City, New York, on Air Force Contract No. AF33(657)11318, "Analytical Investigation of Control Requirements for High Speed, Low Altitude Penetration." The contract was initiated under Project 8226, Flight Control System Techniques for Stabilization, Control and Recovery of Advanced Vehicles; Task No. 822601, Advanced Flight Stabilization System Techniques. The work was administered under the direction of the Flight Dynamics Laboratory, Research and Technology Division of the Air Force Systems Command, with Mr. Duane Rubertus as Project Engineer. The investigation was conducted from July 1, 1963 to May 10, 1964.

This report contains unclassified extracts from FDL-TDR-64-99 having the same title.

Principal contributors to this study were Messrs. R. B. Ohnmacht, R. P. Quinlivan, J. D. Snyder, G. Tye, and H. H. Westerholt.

ABSTRACT

The purpose of this work was investigation of control requirements for high speed, low altitude penetration.

The course of action taken made use of a moderately sophisticated simulation of all elements of the automatic control of an aircraft in pitch. The control techniques which were used are a departure in concept from those popularly used to date.

Evaluation of the simulated system performance was the chief means of system analysis. The evaluations were made using four terrain samples, and included seventeen combinations of aircraft configuration and flight conditions, gust disturbances, and radar errors. A limited evaluation of manual control was made.

In the interests of brevity and the desire to keep this "Report Brief" unclassified, specific results have not been included.

It is concluded that the conceptual approach and techniques studied promise to give advanced automatic terrain following systems with superior performance in real environments without adjustment for changes in flight dynamics or terrain characteristics.

This Technical Documentary Report has been reviewed and is approved.

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SYMBOLS

A_D	desired acceleration, ft/sec^2
D/A	indicates a digital to analog conversion function
h	aircraft altitude relative to fixed reference, feet
h_c	aircraft altitude relative to the terrain, feet
h_d	desired trajectory altitude relative to fixed reference, feet (used to designate a function of forward time)
h_T	terrain altitude relative to fixed reference, feet
h_o	minimum clearance altitude command, feet
H_D	desired trajectory altitude, feet (used to designate a function of reverse time)
H_T	terrain altitude relative to fixed reference, feet (used to designate a function of reverse time)
Δh	basic increment of altitude used in digital functions, feet
k_1	computed altitude command for terrain following, feet
K_g	gain of acceleration transfer function
K_1	computed altitude command for terrain following, feet (used to designate a function of reverse time)
K_{11}	
K_{12}	feedback gain terms
K_{13}	
m	control signal, ft/sec^2 or g
n	aircraft normal acceleration, ft/sec^2 or g
s	Laplace transform variable
t	time, seconds

SYMBOLS (Cont'd)

T	time constant, general, seconds
V	aircraft ground velocity, ft/sec
V_D	desired vertical velocity, ft/sec
η	reverse time variable, seconds
μ	future time variable, seconds
τ	fixed interval of time, seconds
φ_g	acceleration error weight factor
φ_h	altitude error weighting factor
$\varphi_{\dot{h}}$	altitude rate error weighting factor
$(\dot{})$	time derivative
$(\ddot{})$	second time derivative
$(\dddot{})$	third time derivative

Section 1

INTRODUCTION

The advantages of low-altitude, high-speed penetration result from the difficulties in detection and short response time imposed on enemy defenses. Previous studies have shown that the vulnerability of a high subsonic or supersonic terrain following aircraft is approximately proportional to average clearance altitude. For any particular pre-planned mission, vulnerability to enemy defenses would therefore be minimized by minimizing average terrain clearance.

Because of the limited capability of equipment such as radars and radio altimeters, a certain minimum clearance, dependent upon the particular sensor accuracies and on the particular terrain following system, is to be maintained in order to have an acceptable probability of avoiding "clobber".

The conflicting requirements of minimum average clearance, subject to an absolute instantaneous clearance, limited vertical acceleration, and limited frequency of vertical acceleration present a tradeoff or "optimization" problem of considerable difficulty.

Because the duration of the terrain following flight might be an hour or more, because the pilot's attention must also include other aspects of the mission, and because of increased performance capability, it is necessary that the terrain following system be automatic for the major portion of the mission It has been argued that a well trained pilot can accomplish better performance than an automatic system. These conclusions are drawn from performance of particular systems, however, and there is no reason why an automatic system cannot provide equal, if not better performance than can be obtained manually if the proper approach to the control problem is taken.

Some form of radar sensor is obviously needed to detect the terrain profile along the projected flight path if acceptable and safe terrain following performance is to be realized under all conditions of weather and over any terrain. A great deal of time and effort has been devoted to this sensor problem.

It has not been apparent, however, how this radar sensor may best be used to control the longitudinal motion of the aircraft through all variations of its dynamics so as to realize a minimum average clearance. It is desirable to accomplish such control within specified limits of stress on the aircraft and crew, within acceptable limits of flight safety, and over all terrain without system modification or adjustment. It is this latter problem to which the effort reported here has been primarily directed.

Manuscript released by the authors June 1, 1964, for publication as an RTD Technical Documentary Report.

This "Report Brief" is an extraction from the Final Technical Report having the same title. All the details of Simulation and Results have been omitted.

The specific technical effort covered by this report was conducted from 1 July '63 to 10 May '64.

Section 2

THE CONTROL PROBLEM

The basic problem to which this report is addressed is that of controlling the altitude of a high performance aircraft with specified dynamics, and with limited altitude acceleration. It is a particularly difficult control problem in that the vehicle must be continuously maneuvered with relatively large penalties for altitude errors, either positive or negative. In addition to being limited in amplitude, altitude acceleration must be maintained as smooth as practicable in order to minimize pilot fatigue.

Although the preceding statements are essentially axiomatic, they imply a fundamental requirement for this control problem, i.e., that of prediction. If, for instance, unlimited acceleration were available (and permissible), the problem would be primarily one of maximizing the gain-bandwidth of an outer-loop closed on altitude. However, since acceleration is rather severely restricted, a prior knowledge of the altitude objective in considerable detail is an essential requirement of the control system if the desired altitude profile is to be realized with a reasonable degree of accuracy.

Fortunately, in this case, it is possible to acquire a good estimate of a desired altitude trajectory for a substantial time in the future on the basis of measurements obtained by a forward looking radar. Altitude performance depends not only upon the accuracy of the radar measurements, but upon the accuracy to which the vehicle dynamics may be predicted, and upon the accuracy to which the present state (attitude, altitude, etc.) of the vehicle can be measured. It is to be emphasized that altitude performance (accuracy) can be maintained in the presence of significant errors in many of these measurements if sufficient additional acceleration is allowable. No treatment of terrain following performance is therefore, complete with a consideration of an altitude profile alone, but must be considered simultaneously with the resultant acceleration and required measurement accuracies.

Section 3
CONTROL APPROACH

THEORETICAL CONSIDERATIONS

The approach selected for this system is based upon the concept that the determination of a desired altitude trajectory h_d, and the control of the aircraft are separable problems. Although this will not be entirely true in the resultant system, it will be shown to be a good approximation, and permits considerable simplification in the control system synthesis. In addition, this approach permitted the generation of a desired altitude trajectory to be carried out without the complication of simultaneously considering control system stability.

Assume, for the present, that the desired altitude trajectory, $h_d(\mu)$, is known relative to the terrain altitude, $h_T(\mu)$ as shown in Figure 1 . Present absolute (inertial) altitude is denoted by h(t) and present

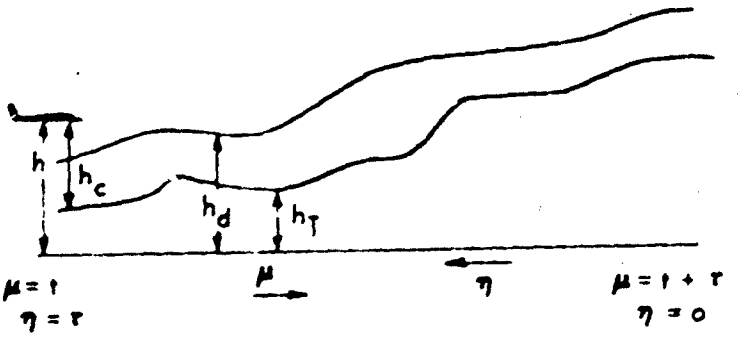

Figure 1. Illustration of Nomenclature

clearance by $h_c(t)$. Independent variables t and μ represent present and future times, respectively, and τ represents a time proportional to maximum range. The symbol (η) is a time variable running from maximum range (time) to zero range (tim

A requirement for the synthesis of the control system is a model of the vehicle dynamics to be controlled. It is assumed that the basic form of the aircraft inner loop dynamics are fixed by other considerations such as pilot handling qualities and that unlimited freedom is not available in the specific form of the inner loop transfer function. It will be shown subsequently that the inner loop may be represented either by a simple pole or a damped-quadratic for the two types of stability augmentation systems considered.

The majority of the results reported are based upon the first order model of the stability augmented aircraft, although a complete derivation for the second-order model was carried out and reported in the 1st Technical Progress Report. Figure 2 depicts the assumed form of dynamics for the subsequent discussion.

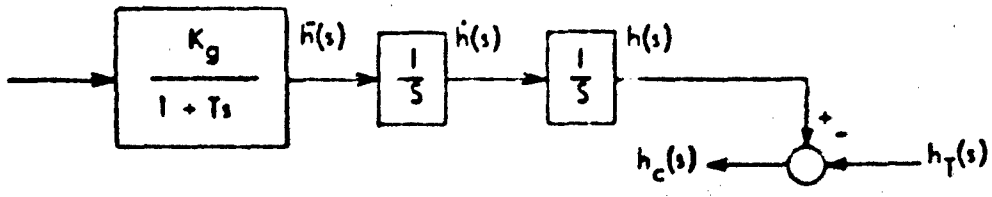

Figure 2. Vehicle Dynamics

The synthesis of an "optimum" control system requires that some index-of-performance to be maximized or minimized be defined. An instantaneous error measure of the form of equation (1) is postulated.

$$H\left[h_c(t),\ \dot{h}(t),\ \ddot{h}(t),\ m(t)\right] = \phi_h \left\{\left[h_d(t) - h_T(t)\right] - h_c(t)\right\}^2 + \phi_{\dot{h}}\left[V_D(t) - \dot{h}(t)\right]^2 + \phi_g\left[A_D(t) - \ddot{h}(t)\right]^2 + \left[m(t)\right]^2 \qquad (1)$$

This form represents the more general control problem where specific vertical velocity ($V_D(t)$) and acceleration ($A_D(t)$) functions are known and included.

Equation (1) represents only an instantaneous measure of control system error. A more realistic index of performance would be the integral of equation (1) over a period of time. Since the effects of control can only be realized in future time, it is logical to seek that control system which minimizes the integral of equation (1) over all future time for which $h_d(\mu)$ is known, i.e., from present time, t, to $t + \tau$. Thus, in order to determine the "optimum" system, a control signal which is an explicit function of the measurable-state signals and which minimizes the integral of equation (1) is to be obtained. It is essential that the control signal be determined as an explicit function of measurable state signals since a feedback type of control is mandatory.

The minimization of the integral of equation (1) is carried out in Appendix I of the Final Technical Report and leads to a control equation of the form of equation (2).

$$m(t) = k_1(t) - K_{11}\ddot{h}(t) - K_{12}\dot{h}(t) - K_{13}h_c(t) \qquad (2)$$

A block diagram of equation (2) is shown in Figure 3 in a somewhat more conventional form.

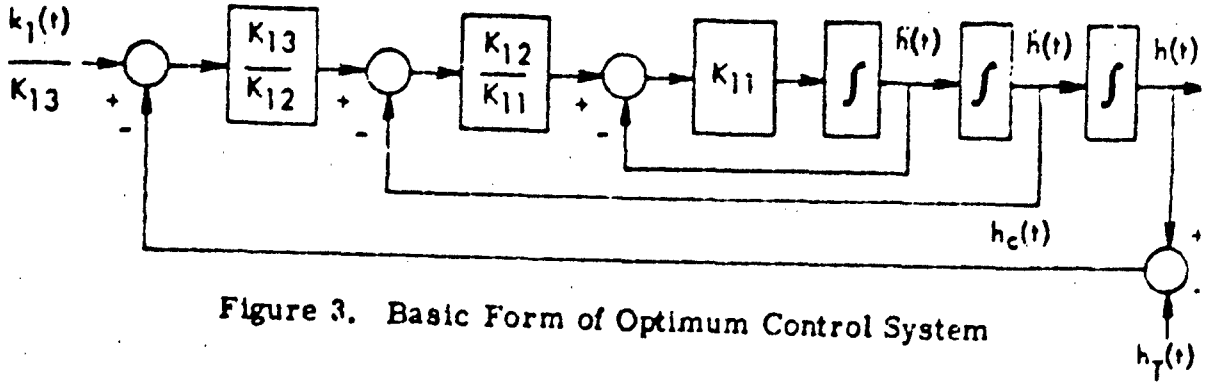

Figure 3. Basic Form of Optimum Control System

The input signal in Figure 3, $\frac{k_1(t)}{K_{13}}$, is a command clearance which is time varying and as shown in Appendix A, is obtained as a solution to equations (3), (4), and (5), where η denotes reverse time and evaluation is required at $\eta = \tau$, or present time.

$$\frac{d}{d\eta}\left[\frac{K_1(\eta)}{K_{13}} + H_T(\eta)\right] = K_{11}\left\{\left[\frac{K_2(\eta)}{K_{11}K_{13}} + H_T(\eta)\right] - \left[\frac{K_1(\eta)}{K_{13}} + H_T(\eta)\right]\right\} \tag{3}$$

$$\frac{d}{d\eta}\left[\frac{K_2(\eta)}{K_{11}K_{13}} + H_T(\eta)\right] = \frac{K_{12}}{K_{11}}\left\{\left[\frac{K_3(\eta)}{K_{12}K_{13}} + H_T(\eta)\right] - \left[\frac{K_1(\eta)}{K_{13}} + H_T(\eta)\right]\right\} \tag{4}$$

$$\frac{d}{d\eta}\left[\frac{K_3(\eta)}{K_{12}K_{13}} + H_T(\eta)\right] = -\frac{K_{13}}{K_{12}}\left\{\left[\frac{K_1(\eta)}{K_{13}} + H_T(\eta)\right] - H_D(\eta)\right\} \tag{5}$$

A block diagram of a system to solve equations (3), (4) and (5) is shown in Figure 4 . Note that these are referred to as K-equations.

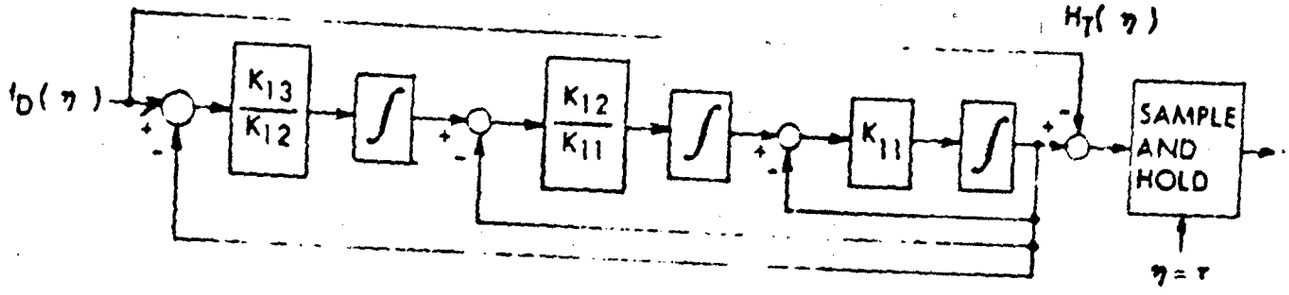

Figure 4. Block Diagram of "K-Equations"

In order that the solution be useful the mechanization must be fast-time scaled. A solution must be obtained before the aircraft's velocity has caused a significant change in its position.

It is of interest to note that the dynamics depicted in Figure 4 are the same, except for a difference in form, as those of the altitude loop shown in Figure 3 . Obtaining a solution to equations (3) through (5) is thus equivalent to flying a model of the dynamics in Figure 3 backwards over the desired altitude trajectory. The difference between the solution to equations (3) through (5) and the terrain-altitude, $H_T(\eta)$ is then a command clearance which lags the required clearance in reverse time, and therefore leads the required clearance in forward time. Moreover, the time varying solution is not only valid for present time, but for a distance into the future consistent with the accuracy of the radar-measured terrain. This latter conclusion is particularly significant in that it is possible to obtain a continuous command input even though the basic information (forward terrain) is sampled periodically (at radar frame time).

An additional necessary condition for the minimization of the integral of equation (1) is that the following set of algebraic equations be satisfied (Appendix A):

$$\phi_g + 2K_{12} - K_{11}^2 = 0 \tag{6}$$

$$\phi_{\dot{h}} + 2K_{11}K_{12} - K_{12}^2 = 0 \tag{7}$$

$$\phi_h - K_{13}^2 = 0 \tag{8}$$

These equations permit the gains, K_{11}, K_{12}, and K_{13}, in Figure 3 to be determined in terms of the weighting factors (tradeoff consideration), ϕ_h, $\phi_{\dot{h}}$, and ϕ_g. It is apparent that specification of the inner loop time constant, T, from other considerations does not allow complete freedom of choice in these weighting factors. In fact, the gain K_{11} may be determined by inspection of Figures 2 and 3 to be 1/T. Since altitude rate is not of direct concern dynamically, a logical choice for $\phi_{\dot{h}}$ is zero. The remaining degree of freedom allows either ϕ_h or ϕ_g, or a functional relationship between ϕ_h and ϕ_g to be chosen. Since the basic tradeoff is altitude error for vertical acceleration, the ratio of ϕ_g to ϕ_h is a logical choice. The ratio chosen for the majority of the simulation results was

$$\frac{\phi_g}{\phi_h} = \left(\frac{113 \text{ ft}}{32.2 \text{ ft/sec}^2} \right)^2 = 12.3 \tag{9}$$

Gains in the altitude loop (and in equations 3, 4, 5) are, for the choice of equation (9),

$$\left.\begin{aligned} K_{11} &= 2 \text{ radians/sec} \\ \frac{K_{12}}{K_{11}} &= 0.6 \text{ ft/sec}^2/\text{ft/sec} \\ \frac{K_{13}}{K_{12}} &= 0.3 \text{ ft/sec/ft.} \end{aligned}\right\} \tag{10}$$

The selection of $K_{11} = 2$ rad/sec, represents a median of all the flight conditions and aircraft configurations with the self-adaptive stability augmentation assumed.

GENERATION OF DESIRED ALTITUDE TRAJECTORY

Generation of the desired altitude trajectory, (h_d), is the most significant remaining area where performance can be greatly affected, and which is critical in determining ultimate complexity. This area is discussed in detail below.

The generation of certain portions of an acceleration-limited trajectory is relatively straight forward. Consider the terrain depicted in Figure 5 . Henceforth, the offset clearance, h_o,

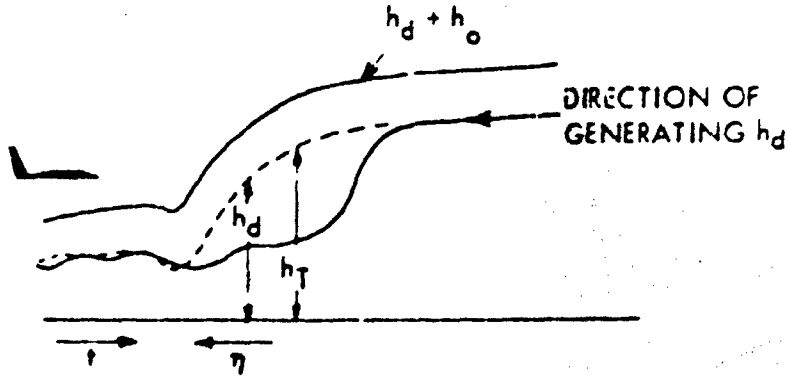

Figure 5. h_d Generation, Front Side

will be disregarded since this constant can be introduced again at any time. The only problem of concern here is the time-varying(or distance-varying) component of h_d relative to h_T. The terrain profile, H_T, is scanned in time sequence from maximum range down to zero range. Certainly near the tops of hills (as shown in Figure 5) the desired altitude trajectory is simply the acceleration limited profile (dotted line). This portion of H_d is generated by simply imposing a hard limit on negative acceleration in a wide-bandwidth, second-order tracker which otherwise follows H_T with negligible errors. The hard limit on negative acceleration is imposed only when the slope of $H_T(\eta)$ is less than or equal to zero.

It is obviously not possible for the aircraft to fly a trajectory whose first derivative is discontinuous as is the case where $H_d(\eta)$ intersects $H_T(\eta)$ near the bottom of the hill. However, the dynamic prediction will smooth this "corner" in H_d by giving up positive altitude error. Thus, even though the portion of the desired altitude trajectory which requires positive acceleration is not generated, the system tends to fill in this part in a safe manner. In order to restrict the positive acceleration to a reasonable value, however, it is necessary to limit the maximum negative slope of $H_d(\eta)$ as well. The specific limit depends upon the choice of weighting factors $(\frac{\phi_g}{\phi_h})$ and for those chosen, (12.3), the limiting rate on $H_d(\eta)$ is approximately 100 fps, independent of speed.

When the terrain is sloping downward, as depicted in Figure 6 , the desired altitude trajectory is initially a negative acceleration-limited

trajectory similar to that shown in Figure 5 . The generation of this portion of h_d requires that h_T be read out in forward time sequence.

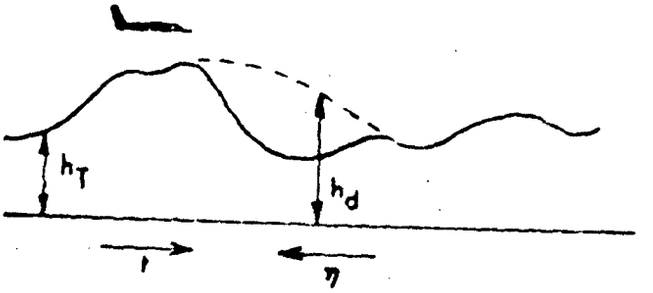

Figure 6. h_d Generation, Back Side

To accomplish this would require additional storage. A simpler approach is obtained by observing that this is precisely the path (initially) that the aircraft would fly if h_d were made equal to h_T in this region and a negative acceleration limit were imposed upon the control. In the vicinity of the point where the aircraft approaches the terrain (rather h_o feet above the terrain) the altitude loop comes out of saturation and settles out as it normally would in response to an altitude error. It is also necessary, in this latter case, to limit the command altitude rate in order to restrict the maximum positive acceleration in the pull-out. Again, for the ratio of ϕ_g/ϕ_h chosen, the limiting altitude rate is approximately 100 FPS, independent of speed.

Although the introduction of negative acceleration and decent rate limits in the altitude loop permit a more simple generation of h_d, this simplification leads to a difficulty. Since $H_d(\eta)$ and $H_T(\eta)$ are identical when $\dot{h}_T(\eta) \geq o$ (consideration of h_o notwithstanding), the relatively large change in $\dot{H}_d(\eta)$ near the top of a hill cannot be followed by the altitude loop and is smoothed in much the same manner as the pull-up corner (Figure 5), except that this smoothing leads to a negative clearance error which can be in the order of 100 feet depending upon the lower scan-limit of the radar. The lower scan-limit is representative of a worse case terrain-decent rate since terrain slopes greater than this limit can not be seen. To remove this negative clearance error without resorting to additional complexity in generating h_d, the gains of the K-equations (3), (4), (5)) were increased by an order of magnitude whenever $H_T(\eta)$ is increasing (back sides of hills) so as to prevent the co mmand clearance from ever becoming negative. The manner in which this is accomplished is discussed later. This technique

prevents the system from undercutting the desired altitude trajectory by any significant amount, but at the expense of removing prediction on downward sloping terrain. Such an approach is safe from the standpoint of clobber, but suffers in that mean clearance must necessarily increase.

The introduction of the non-linearities just discussed are not fundamental to the basic approach, but were included rather than resort to additional complexity at this stage of the system development. Although the additional complexity required to generate a more realistic desired altitude trajectory is not large in terms of additional equipment, the time schedule did not permit the incorporation of a forward-time readout in the simulation facility. As a consequence, the results reported are those obtained with non-linear K-equations, and with negative acceleration and decent-rate limits in the altitude loop.

Section 4

SIMULATION FACILITY

The simulation facility used for this study was composed of a combination of special purpose digital equipment, a standard analog computer, and some interface equipment.

The forward-looking radar, radio altimeter, and part of the command generation were constructed from digital building blocks. The remainder of the command-generation was done with 2 Philbrick operational manifolds which included a total of 17 operational amplifiers. The aircraft was simulated on an Electronics Associates Model 31-R analog computer. Figure 7 is a block diagram of this facility.

The portions of the simulator other than the analog computer were housed in 2 standard instrument racks. The digital equipment included 14 glass delay lines for memory, and approximately 350 logic modules. Each logic module contains either one flip flop or two NOR circuits. The Philbric manifolds were also mounted in these racks. See Figure 8.

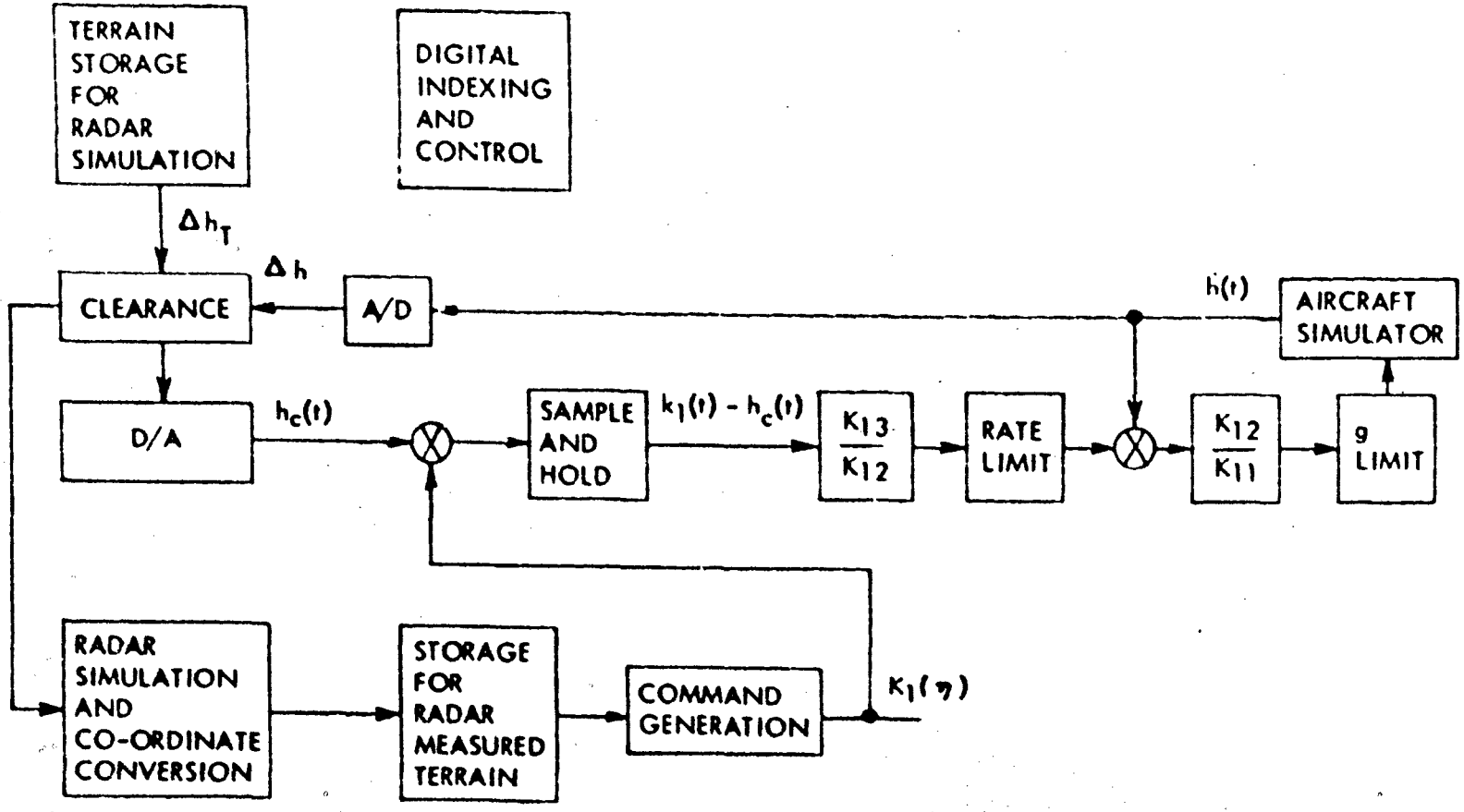

Figure 7. Simulation Block Diagram

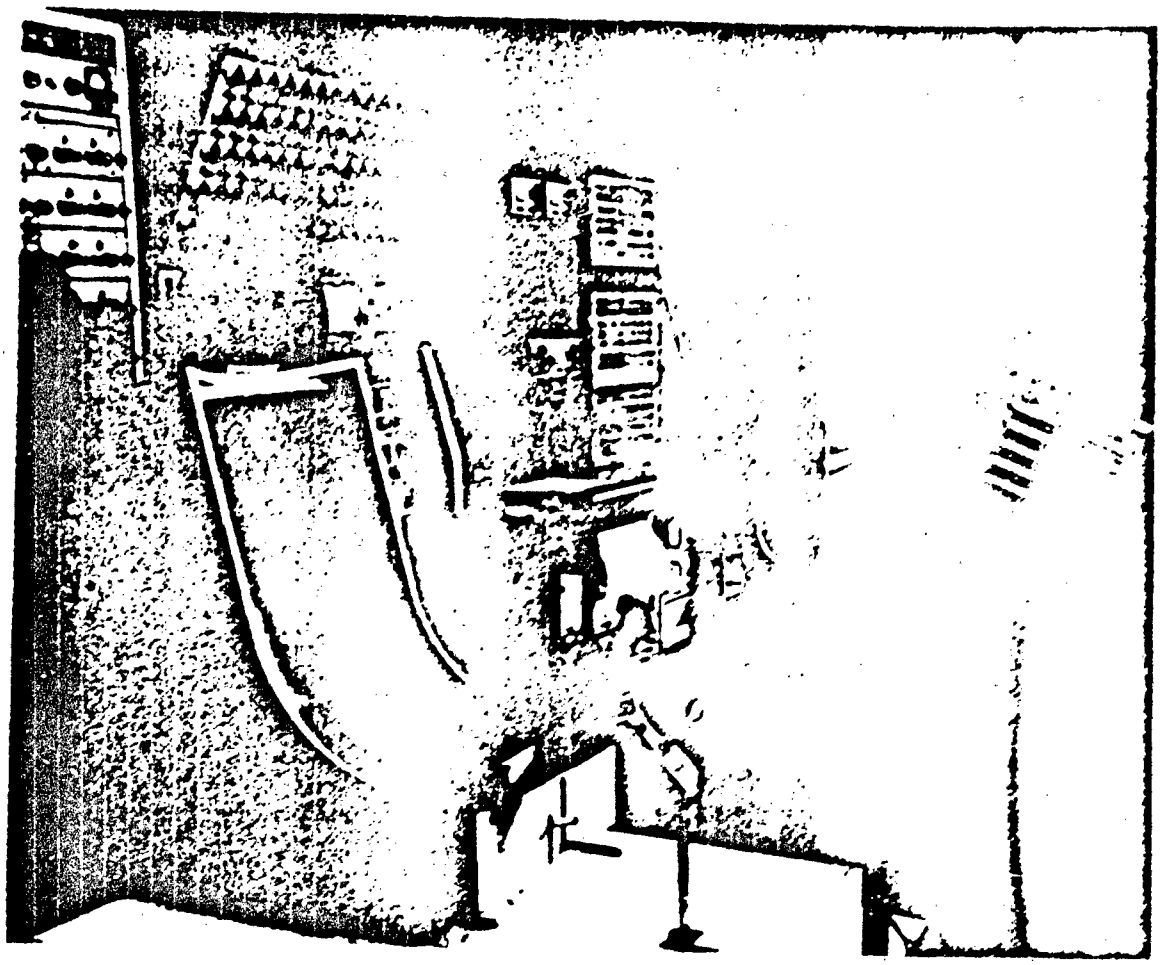

Figure 8. Simulation Facility

Section 5

SIMULATION RESULTS

INTRODUCTION

The physical forms of the actual data obtained from the simulation were of two kinds. The first and largest quantity was taken by conventional traces of system variables on an eight channel, Model, Mark 200 Brush Recorder. The second class of data was taken in digital form with special equipment; which is a part of the computer laboratory facility. This equipment works in conjunction with an IBM 1620 computer to make an analog-to-digital conversion and punches the data on standard cards. The data taken were: aircraft clearance altitude, normal acceleration at the center-of-gravity and normal acceleration at the pilot's location.

The digital data taken were used with the IBM 1620 computer to make the following reductions.

A. Minimum Clearance
B. Maximum Acceleration at pilot
C. Root mean square acceleration at pilot
D. Root mean square acceleration at c.g.
E. Average Clearance
F. Cumulative Distribution Clearance
G. Cumulative Distribution Acceleration at pilot
H. Auto Correlation Function of Acceleration at pilot

PERFORMANCE MEASURES

Terrain following performance can be quantitatively measured in a number of ways, but no generally accepted standard of total system performance exists at the present time. Most performance measures that have been suggested are useful primarily in evaluating the effects of variations in system parameters or in comparing the performance of one approach vs. another. The format of the data presented in the final report is not intended to suggest any universal performance measure, but to describe the pertinent results in a reasonably concise manner.

The two most significant measurements used to describe system behavior are clearance altitude and normal (approximately vertical) acceleration. Average clearance altitude is quite generally accepted as a measure of vulnerability at a specific speed over a specific terrain. A measure of the likelihood of collision with the terrain is obtained from the distribution of the lower clearance altitudes. Probability-of-clobber, as obtained from

the cumulative distribution of clearance assumes that the distribution of clearances, as extrapolated below the least measured clearance altitude is gaussian. For the system investigated, a specific minimum clearance for the worst case condition can be found in the absence of system malfunctions, or random sensor errors. As an absolute number, probability-of-clobber has no real significance in such a case. As a relative number, for the purpose of examining the effects of parameter variations, however; probability-of-clobber is a useful measure. For evaluation of flight safety as it is effected by stochastic error sources, such as those of the radar, altimeter, gyros, accelerometers, or as effected by equipment reliability, probability-of-clobber has significance in an absolute sense.

The principal purpose in recording vertical acceleration is to obtain a measure of pilot comfort (or discomfort). A great deal of study has been conducted by a number of investigators to obtain a standard of riding quality for the low altitude mission. Although no one number is a sufficient index for a particular run, many studies apparently agree that both magnitude and spectral characteristics of the acceleration, as well as duration of exposure, are required to obtain an adequate measure of the ride.

Since the pilot is not only sensitive to magnitude (and direction) of acceleration but the frequency at which the various levels of acceleration occur, a histogram of acceleration for several representative runs have been included in the final report. Digital data recording and processing time would have been prohibitive to obtain this data on all runs.

A most informative data on acceleration appears to be the auto correlation function since this presents not only the mean-square acceleration, but a measure of the high frequency content of the forces acting on the pilot. Although the power spectral density is perhaps a more common measure, the auto correlation function was simpler to obtain from the digital data and contains the same intrinsic information. Here again this measure has not attained the stature of a standard and is therefore useful only for comparative evaluation.

EXTENT OF RESULTS OBTAINED

The full report includes data as a result of study into the following areas of terrain following (T. F.):

1. Effects of flight conditions upon T. F. performance
2. Effects of wind gust upon T. F. performance
3. Effects of radar errors upon T. F. performance
4. Effects of minimum clearance setting upon T. F. performance
5. Effects of radar frame time upon T. F. performance

6. Performance over various terrain samples
7. Actuator behavior during T. F. operation
8. Pilot integration into an automatic T. F. system

Section 6

CONCLUSIONS

A new and different concept of control for terrain following has been demonstrated to be feasible, through simulation. Although the program objective was not to obtain the best possible performance, results indicate that performance obtained during the initial phase is equal to or better than state-of-the-art. If a desired altitude trajectory which is essentially the theoretical limit of performance can be generated with practical equipment, the form of control system simulated will permit the realization of that trajectory by the aircraft.

Seventeen different combinations of speed, weight, center-of-gravity, and external configuration (wing tanks) of the F-105 were investigated to determine the effects of aircraft dynamics on the automatic terrain following control problem. It was determined that an altitude loop having adequate bandwidth for terrain following could not be obtained using a stability augmentation system such as that presently on the F-105 without significant modification. An adequate altitude loop over a sufficiently wide range of flight conditions and aircraft configurations can be synthesized using presently available self-adaptive techniques for stability augmentation.

The effects of vertical wind gusts upon terrain clearance can be made negligible with a properly designed altitude loop closed on a high-gain stability augmentation system. The use of a high-gain stability augmentation system, however, leads to continuous high-amplitude, high-frequency motion of the series and power actuators. Sufficient experience with such high-gain systems is not available to conclude that actuator reliability will not be compromised.

The basic control approach is not unduly sensitive to random errors of the magnitude to be expected from a vertically-scanning, on-boresight radar presently available. The required period between successive vertical radar-scans can be as high as 6 seconds at aircraft speeds up to Mach 1.2 without seriously compromising performance. Frame time of the radar has no effect upon control stability.

A manual mode of control which permits performance essentially equal to that obtained by the automatic system was simulated. However, the percentage of the pilot's attention that would be necessary to achieve these results was considered to be excessively high. No difficulty occured in entering manual from automatic control or in entering automatic from manual control.

It is estimated that the performance indicated by simulation results can readily be achieved with a size, weight, cost, and reliability of equipment which is consistent with tactical aircraft requirements.

Section 7

RECOMMENDATIONS

A significant reduction in average clearance can be achieved within the same acceleration limits (magnitude) by a better estimate of the desired altitude trajectory. It has been demonstrated that this problem can be attacked without a simultaneous consideration of control system stability. If the two-point boundary value problem can be solved with a practical mechanization, then the "ideal profile" suggested by CAL should be obtainable over any terrain at any speed. It is recommended that a primary effort be applied to a practical solution of this latter problem for the terrain following application.

The simulation should be extended to include continuous velocity scaling. No particular problems are foreseen for the most likely range of flight conditions. At very low speeds, however, the relatively large variations in speed, without throttle control, could present some difficulties that have not been sufficiently explored.

A great deal of information on the future behavior of the system, such as predicted altitude, is potentially available and should be of considerable value as a "confidence" form of display. Similarly, for manual operation, it is possible to display not only the present, but the future command in continuous form. A study of the specific information of a predictive character and the form that it should take in order to best utilize the capabilities of the pilot is recommended.

System operation without the use of a radar altimeter should be explored in more detail. For the same level of performance, a more accurate radar may be required, but the smoother ride that results from omission of the altimeter in the control loop may have substantial advantage.

A specific form of failure detection should be simulated in detail. The amount of decision time available to the pilot should be determined, and consideration given to an alternate-mode decision process.

A potential problem has been reported with regard to the behavior of the stabilator actuators. It is recommended that further study be made with the purpose of determining a specific solution. This should be conducted with a damping sensor-gain changer operating as a part of the self-adaptive control simulation. Further study is recommended in the areas of power actuator dynamic variations and control deadband.

It is recommended that plans be made to carry out a flight test to further the development of an advance control system with capabilities demonstrated

by this effort. Such flight test could be made in a manner to by-pass the need for a forward-looking-radar and a "highly reliable" flight control. By planning this flight test to parallel further simulation study, a methodical step can be made to a complete flight test in an expeditious manner and bring such a systen to an operational phase efficiently.

REFERENCES

1. Pelton, F. M., Second Annual Report-Advance Concepts for Terrain Avoidance, Cornell Aeronautical Laboratory, Inc. Report No. IH-1224-P-8, 31 January 1960

2. Snyder, J. D. and Westerholt, H. H., Analytical Investigation of Flight Control Requirements for Terrain Following - Technical Progress Report II, General Electric Company, 30 March 1964

3. Hart, J. E. et al., Stochastic Disturbance Data for Flight Control System Analysis, Lockheed-Georgia Company, No. ASD-TDR-62-347, September 1962

4. Studies and Simulation of Terrain Avoidance Problems (AD CON II), Cornell Aeronautical Laboratory, Inc., Report No. IH-1705-E-2, February 1963

5. Pelton, F. M., Ninth Quarterly Progress Report - Advance Concepts for Terrain Avoidance, Cornell Aeronautical Laboratory, Inc., Report No. IH-1224-P-9, 15 November 1960

6. Rawson, H. E., Flight Simulator Study of Human Performance During Low-Altitude, High-Speed Flight, Trecom Technical Report 63-52, November 1963

7. Merriam III, C. W., An Optimization Theory for Feedback Control System Design, General Electric Co., March 1960

8. Ellert, F. J., and Merrian III, C. W., Synthesis of Feedback Control Using Optimization Theory - An Example, General Electric Co., 1962

9. A'Harrah, R C., Low Altitude, High Speed Handling and Riding Qualities, North American Aviation Inc., 1963

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