Manual Terrain-Following System Development for a Supersonic Fighter Aircraft

Robert L. Kisslinger* and George J. Vetsch†
McDonnell Aircraft Corporation, St. Louis, Mo.

The requirements for a low-level, high-speed penetration to a target are briefly reviewed. The design constraints on the pitch command system are then evolved, and the effects of load factor, flight path angle, and type of command display on system design and performance are presented. During the incorporation of manual terrain-following systems into two different versions of the F-4 airplane, fixed base flight simulators were utilized to optimize system design as well as to finalize system parameters. As a result of these studies, each system was modified to provide improved performance and to obtain a command display acceptable to the pilot. A scoring technique that allows optimization of the system parameters without tailoring the system to a particular terrain type was developed. An ideal profile is generated for the terrain being used, and the actual flight path is compared to the ideal. Therefore, comparison will show how well the system allowed the pilot to follow the terrain within the design constraints and will indicate the type of system deficiency which must be removed in order to bring the flight path closer to the optimum.

I. Requirements

OVER the past decade, it has become increasingly obvious that survival of an attack vehicle will depend upon remaining undetected by enemy defenses. Defense systems have improved to the point that detection and kill are virtually synonymous. One of the best known ways of avoiding detection is to remain in the shadow of another object. This obviously leads to manned flight at altitudes below the peaks of the terrain. There is a limit, however, to how long a man can fly safely without some form of assistance in deciding the proper maneuver to execute to remain above the terrain but not too far above it. This minimum altitude increases rapidly with an increase in true air speed. We thus arrive at the first tradeoff that must be made in the design of a terrain-following system. Considering reaction time, speed, and range of the most probable defense that we must penetrate, we can decide upon the optimum speed and altitude at which we must fly to obtain acceptable probability of survival from enemy action. This decision will result in a choice of set clearance, which is the radar altitude at which we wish to crest peaks, as well as that altitude we wish to maintain over flat or gently sloping land. It is then the task of the system designer to evolve a terrain-following command system that will provide the terrain-following capability with essentially zero probability of ground impact.

One of the limiting factors in the design of the command system arises from a consideration of human physical capability and fatigue susceptibility. Perfect terrain-following would require an infinite load factor capacity in the aircraft to reproduce the high-frequency changes in terrain slope. Allowing the aircraft to operate at its structural limits whenever a change in flight path angle is required would produce following close enough to satisfy the operations analyst. Even these load factor capabilities would be far above the loads that a human pilot could tolerate for any appreciable time. Many studies have investigated human tolerance to acceleration, and the concensus is that limits of $+2.0\ g$ and $-0.5\ g$ incremental acceleration are the most that the average pilot can withstand at the frequency encountered during terrain-following flight. It is the writers' opinion, which has been corroborated by flight testing, that these should be considered the hard limits for optimization and that $+1.0$ and $-0.25\ g$ should be used as the command levels for normal maneuvering. However, the system must be capable of generating normal acceleration commands as great as the vehicle's limit load factor should system performance or pilot error place the aircraft in an otherwise untenable position.

Following the choice of load factor limits, the next parameter limits to be established are the maximum flight path angles. Pushing over past the peak of a hill is performed generally in an attitude during which the forward-looking radar has no terrain video within control range. This condition, of course, results in a maximum pushover command. If this signal is not limited, the pilot would be commanded to hold negative acceleration until his flight path was so steep as to require excessive positive accelerations to prevent ground impact. The flight path angle limits set for any particular vehicle are based upon the maximum speed programed for usage. These limits may be set symmetrically in the order of $\pm 10°$ for ease of mechanization, since early pullups are required to prevent ballooning past the peak.

Having established the maneuvering limits for the system, we can now focus our attention on the command system itself. The basic maneuvering of an airplane in the longitudinal axis is accomplished by control of pitch rate and/or normal load factor, depending upon the speed range under discussion. Since we are attempting to design a tactical system, we must consider airspeeds from the minimum safe speed at the heaviest airplane gross weight to the maximum speed available at the lightest gross weight. It is thus most desirable to use a control system that has in its inner loop a blend of pitch rate and normal acceleration feedbacks. Attempts have been made in the past to use an inner loop that controls flight path angle. This type of control results is a "situation" display similar to the command system for an instrument landing system. The fallacy in this approach is the fact that we are not in a static environment. By the time the pilot has maneuvered his vehicle to satisfy the present situation, the situation itself will have changed. We must therefore use a "command" display signal to allow the pilot to anticipate his maneuvering requirements.

The optimization of the terrain-following system entails choice of system gains and compensation networks that will

Presented at the AIAA/ION Guidance and Control Conference, Minneapolis, Minn., August 16–18, 1965 (no preprint number; published in bound volume of preprints of the meeting); submitted September 16, 1965; revision received January 3, 1966.

* Senior Group Engineer, Guidance and Control Mechanics.
† Senior Engineer, Guidance and Control Mechanics.

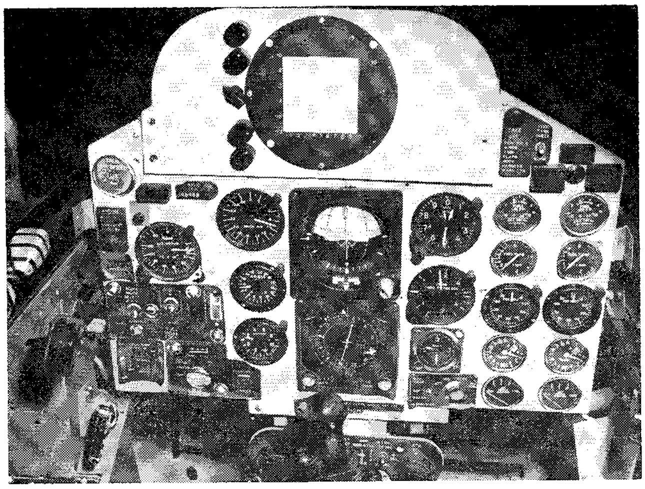

Fig. 1 Flight simulator instrument panel.

produce safe flight at the minimum average clearance altitude within the constraints just discussed. In the following sections of this paper, the method used to optimize two such systems, as well as some of the problems encountered during this optimization, are discussed, followed by a discourse on the scoring technique that has evolved to aid in the development and evaluation of the systems.

II. Development of Command Signals

1. General

The McDonnell Aircraft Corp. (MAC) effort to develop manual terrain-following systems for application in strike and reconnaissance aircraft has been directed to the obtaining of readily flyable pitch command signals with systems that provide maximum terrain screening from ground-based detection. In each case, the operational concepts and preliminary system parameters have been defined by the radar system contractor. However, the parameters have not been directly applicable for implementation of a manual terrain-following mode in the F-4 airplane. The differences, in most cases, have been the result of an attempt to provide the desired manual terrain-following capability with systems designed for automatic terrain-following, slower aircraft, or excessively smooth terrain.

In order to evaluate the original designs and optimize the systems for manual terrain-following in the F-4 aircraft, an analog simulation was established. A fixed-base flight simulator was included in the test setup to enable test pilots

Fig. 2 Flight simulator exterior.

to "fly" simulated terrain-following missions and thus obtain pilot opinion of system performance and flyability. A brief description of the major components of the simulation is presented in the following paragraphs to illustrate the approach taken to optimize terrain-following performance and develop a usable pitch command signal.

1.1 *Airframe and flight simulator*

A set of six-degree-of-freedom nonlinear equations of motion was mechanized on the analog computer to simulate the airframe. The coefficients of these equations were computed continuously from the product of the aerodynamic derivatives, variable dynamic pressure, and dimensionalizing constants. The aerodynamic derivatives were mechanized on nonlinear function-generating equipment. The equations used in the MAC simulation are

$$\dot{V} = (T/m) + g\,(\alpha \cos\theta \cos\phi - \sin\theta) + (\bar{q}SC_x/m)$$

$$\dot{\alpha} = \frac{-T\alpha}{mV} + \frac{g}{V}\,(\alpha \sin\theta + \cos\theta \cos\phi) + \frac{T(0.0916)}{mV} - p\beta + q + \frac{\bar{q}SC_z}{mV}$$

$$\dot{\beta} = (g/V) \cos\theta \sin\phi + (\bar{q}SC_y/mV) + p\alpha - r$$

$$\dot{p} = \frac{I_y - I_z}{I_x}\,qr + \frac{I_{xz}}{I_x}\,(\dot{r} + pq) + \frac{\bar{q}Sb}{I_x}\,(C_1 - C_N\alpha)$$

$$\dot{q} = \frac{I_z - I_x}{I_y}\,rp - \frac{I_{xz}}{I_y}\,p^2 + \frac{\bar{q}ScC_M}{I_y}$$

$$\dot{r} = \frac{I_x - I_y}{I_z}\,pq + \frac{I_{xz}}{I_z}\,\dot{p} + \frac{\bar{q}Sb}{I_z}\,(C_1\alpha + C_N)$$

$$\dot{\theta} = q \cos\phi - r \sin\phi$$

$$\dot{\phi} = p + \tan\theta\,(r \cos\phi + q \sin\phi) = p + \dot{\psi} \sin\theta$$

$$\dot{\psi} = (1/\cos\theta)\,(r \cos\phi + q \sin\phi)$$

$$V_N = V[\cos\theta \cos\psi + \alpha(\sin\phi \sin\psi + \cos\phi \sin\theta \cos\psi)]$$

$$V_E = V[\cos\theta \sin\psi + \alpha(-\sin\phi \cos\psi + \cos\phi \sin\theta \sin\psi)]$$

$$\gamma = \theta - \alpha \cos\phi$$

$$\dot{h} = V \sin\gamma$$

$$h = h_0 + \int \dot{h}$$

$$h_{\text{barometric altitude}} = h_0 + [1/(S + 1)]\int \dot{h}$$

$$h_{\text{radar altitude}} = h - h_{\text{terrain}}$$

$$\bar{q} = \tfrac{1}{2}\rho V^2$$

$$\rho = 2.377 \times 10^{-3} - 6.918 \times 10^{-8}h + 6.845 \times 10^{-13}\,h^2$$

$$M = V/49.1\,(518.7 - 0.003565h)^{1/2}$$

$$N_z = +\,[T(0.0916)/mg] - \cos\theta \cos\phi - (\bar{q}\,SC_z/mg)$$

$$N_y = \bar{q}\,SC_y/mg$$

$$F_{\text{stick}} = 0.41\bar{q}\,(0.014 - 0.252\,\delta_{ST} - 0.088Y_t) + 26 - 17.3\,\delta_{ST} - 6.4Y_t + 35.5\,\dot{\delta}_{ST} + 5N_z + 5.95\dot{q}$$

A modified mockup of an F-4 front cockpit was used as a fixed-base flight simulator. The solutions of the equations of motion and coordinate transformation equations were presented on a flight director attitude indicator, Mach meter, barometric and radar altimeters, rate-of-climb indicator, normal accelerometer, angle-of-attack indicator, and engine tachometers. This group of instruments presented all necessary information for the control of attitude, angular rates, and velocities. The cockpit canopy was covered with an opaque material, and instrument lighting was provided so that instrument flight conditions could be simulated with the canopy lowered. Photographs of the instrument panel and the exterior of the flight simulator are presented in Figs. 1 and 2.

Artificial feel systems were installed in the flight simulator to provide realistic forces in response to control deflections. An electrohydraulic device simulated the pitch control axis bobweight and bellows system forces of the F-4 airplane. Aileron and rudder forces were provided by self-centering spring cartridges with force gradients matching those of the airplane. Pilot inputs to the flight simulator controls were sensed with potentiometers, and the voltages thus generated were used as inputs to the equations of motion.

A three-axis stability augmentation system with dynamics matching the aircraft automatic flight control system was mechanized on the analog computer. Rate damping signals that were provided by these loops were summed with the manual command signals to improve airplane handling qualities. This system was used during all terrain-following flights.

1.2 Radar simulator

A radar simulator was designed and constructed at MAC for the simulation of terrain-following systems. This simulator utilizes an electronic terrain map, pickoff head, sampler, and command computer. Sufficient flexibility was provided in the design to permit the evaluation of a variety of command systems.

The electronic terrain map used with the simulator consisted of a printed circuit board on which thin conductive strips were deposited across the width of the board. These conductive strips are placed at 0.1-in. intervals along the length of the board. Conductive paint was applied to the surface of the board, providing a linear variation in resistance between lines. Provisions were made to apply d.c. voltages proportional to terrain height to each line on the map individually. By establishing a map range scale factor and applying accurate voltages to each line, any section of actual terrain could be simulated.

An electrical pickoff head was provided to sample terrain height at various ranges ahead of the aircraft. The pickoff head was constructed on a fiberglass base with 61 accurately spaced holes drilled through this base for mounting the pickoff contacts. Each contact was individually spring-loaded to assure good electrical contact with the electronic map on which the head rested. By assigning the aircraft location to the first pickoff point, the output of this point could be used to obtain terrain altitude directly below the aircraft, and each following contact point could be used to obtain terrain height at a known range ahead of the aircraft. A photograph of the electronic map and pickoff head is shown in Fig. 3.

Two types of sampling systems have been used to sample the output of each contact point on the pickoff head. The first system used in the MAC studies employed 61 cathode follower amplifiers to sample the voltages. The cathode followers were consecutively sampled beginning at the aircraft and ending at the maximum range point at a rate such that a complete sweep of all amplifiers was accomplished in half the vertical sweep period of the radar antenna being simulated. Thus, a complete description of the terrain ahead of the aircraft was obtained during each sweep.

The second sampling system was designed to facilitate a much higher sampling rate to enable the inclusion of actual radar hardware in the real time problem. In this system, the output of each pickoff point was connected to a field effects transistor. A master trigger or radar transmitter pulse was simulated utilizing a digital clock operating at the

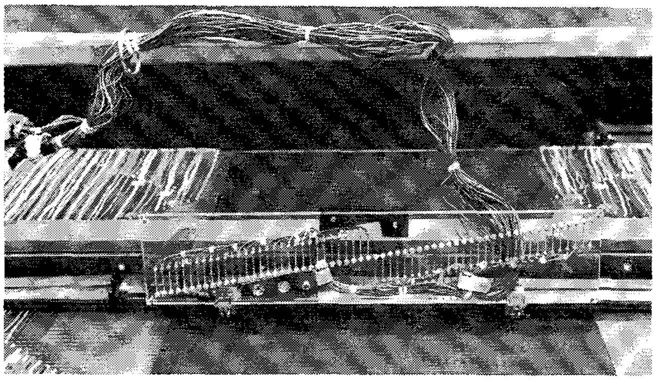

Fig. 3 Radar simulator pickoff head.

radar pulse rate frequency. Following each simulated transmitter pulse, each field effects transistor was gated on in turn, beginning at the aircraft location and continuing sequentially through the remaining 60 pickoff point amplifiers. Each field effects transistor was gated on for a period of 2 μsec. By placing the pickoff points at an effective 1000-ft interval and sampling at a rate of 2 μsec/pickoff point, the 492 ft/μsec radar pulse transmission speed was closely approximated.

A geometric equation was solved continuously as the altitude at each pickoff point was sampled to detect boresight intersection with the terrain. When an intersection of the boresight line with terrain was detected, following a master trigger pulse, a video pulse was generated. If no boresight intersection was detected, because of antenna scan angle or aircraft altitude, no video pulse was generated. This method of simulation provided realistic master trigger and video pulses that were, in turn, applied to the radar computer hardware for further processing.

Two basic types of terrain-following computer mechanizations, which are classified in accordance with the method used to generate a command signal, have been optimized and evaluated using the simulations just described. A general discussion of the operational principles of the two system types and the modifications found necessary during the MAC simulations is presented in the following paragraphs.

2. Relative Range Command System

The relative range command system operates by comparing the measured range to the terrain to a reference range and generating an error signal in proportion to this difference within a linear command zone. The maximum error signal that is generated during each half-cycle of the antenna's vertical sweep is used as the basic command signal. The command signal is updated at the end of each half-cycle of the antenna's sweep if the over-all level is increasing or at the end of each complete sweep cycle if the level is decreasing. Thus, a sampled data command results, with the sampling frequency alternating between 3 and 6 cps.

The reference range used in this system is defined as a template, which is illustrated in Fig. 4. The bottom and front faces of the template are nominally the locus of points that could be cleared at a desired height using a two-incremental g pullup at 0.9 Mach number. The template faces also take into account pilot and aircraft response times.

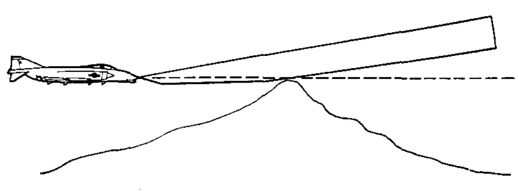

Fig. 4 Relative range command system template.

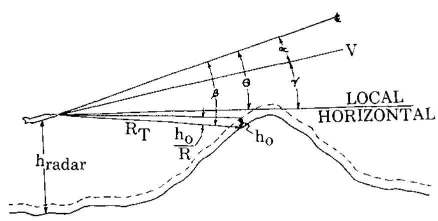

Fig. 5 Angle system geometry.

"Climb-high" (the ability to anticipate peaks so that they are cleared with a zero flight path angle) is achieved in the relative range system by the method used to stabilize the vertical sweep of the antenna. By summing aircraft pitch attitude with the antenna's vertical sweep signal, the sweep reference or zero gimbal line is held horizontal during a climb. This effectively maintains the template in a horizontal position and results in sufficiently early climbs to permit the aircraft to crest mountains in level flight.

Considerable simulation effort was applied to the optimization of the relative range system. The MAC analog simulation was coordinated closely with digital simulations performed by the radar system contractor. Significant time was saved by utilizing parameter definitions supplied by the digital simulations as initial values for the analog simulation. The parameters associated with the development of the template penetration signal which were optimized included bottom and front face slopes, distance to the template along the zero gimbal line, and linear command zone width.

The parameter that was found to have the most pronounced effect on pilot opinion of system operation and flyability was the slope of the bottom face of the template. It was found that bottom face slopes that were too low caused severe pitch oscillations as a result of the large effective gain for small vertical penetrations of the template. Excessively large bottom face slopes resulted in undershooting the clearance plane as mountains and ridges were crested. The other parameters affecting the development of the template penetration signal required minor modifications to account for differences in response of the nonlinear airframe and actual pilot response time.

The template penetration signal is essentially an indication of the instantaneous geometrical situation and is not directly usable as a pitch command signal. Pitch attitude and rate feedback loops were provided in the original system design to generate a command or "zero reader" display. During the MAC simulation, it was found that flight path angle and differentiated pitch attitude provided the most desirable characteristics for this purpose. The gains and time constants used in these loops were determined from considerations of the maximum dive angle and accelerations desired, system stability, and pilot opinion. It was found that a simple lag filter provided adequate smoothing of the output signal to the display.

The relative range system has the advantages of relatively simple feedback loops and output filter and a readily flyable pitch command signal. Disadvantages include an inherent characteristic to undershoot the commanded clearance altitude and critical template shape. In addition, performance can be near optimum at only one speed, with degradation occurring both above and below the design speed because of the fixed template shape.

3. Angle System

The angle system functions by comparing the angle to the offset terrain with the aircraft flight path angle in order to obtain a basic command signal. The offset terrain is a line drawn parallel to the terrain at the desired clearance altitude. The angle to the offset terrain is obtained by summing antenna position, pitch attitude, and a signal proportional to the ratio of the set clearance altitude to the range to the terrain. A diagram defining these angles is presented in Fig. 5.

In order to avoid excessively early climbs due to the detection of terrain at long ranges, a shaped function is subtracted from the angle to the terrain signal. The shaped function is varied as a function of aircraft velocity to provide less attenuation as speed increases. Computation of the shaped function in this manner provides average deviations from the clearance plane which vary with speed, thus providing maximum utilization of terrain shielding within the normal acceleration constraints imposed.

The composite angle to the terrain and shaped function signal is peak detected over a complete vertical scan of the antenna. The peak detector is sampled at the end of each complete scan, and the maximum value is used as the basic command signal until the next scan is completed. Data rates in this system are near 1 cps at the output of the peak detector.

At the outset of the MAC analog simulation, "climb-high" was provided by amplifying the angle to the offset terrain if the offset terrain was detected at a positive angle relative to the horizontal at the aircraft location. During the simulation, it was found that the nonlinear gain zone that resulted from the "climb-high" amplification resulted in a command signal that was very difficult to fly at altitudes near the set clearance altitude. In order to avoid this difficulty, a bias was added to the "climb-high" switching circuitry, and this resulted in delaying the application of the "climb-high" gain until the offset terrain appeared at a preset positive angle above the horizontal. This modification eliminated the nonlinear gain zone for near-level flight which was initially encountered.

In the original system design, the peak-detected angle to the offset terrain was compared to the aircraft flight path angle and amplified to obtain a load factor command signal. A combination of load factor and Euler angle pitch rate feedback was summed with the load factor command to obtain an error signal. This error signal was applied to the pitch command display through a lead-integrator output stage.

The original system design had evolved from studies of automatic terrain-following using the relatively low-amplitude terrain of Southern Pennsylvania. When attempts were made to perform simulated manual flights over the more severe course 10 of the China Lake area in Southern California, several deficiencies were found to exist. Since "climb-high" was applied only in those situations where terrain appeared above the horizontal at the aircraft's position, insufficient climb commands were presented to the pilot to permit safe recoveries from steep dive angles that occurred between mountains. When the system gain was increased in an attempt to relieve this situation, the pilots found the pitch command signal intolerably difficult to fly because of the increased needle sensitivity. Therefore, methods of increasing system gain only during the potentially hazardous situation just described were evaluated, and a method was found to provide satisfactory performance.

When manual terrain-following was attempted with the angle system, which was originally designed for automatic flight, a requirement for modifications of the output filter stage became readily apparent. After considerable experimentation with feedback and forward loop filters and gains, an adaptive output filter stage was developed. This stage

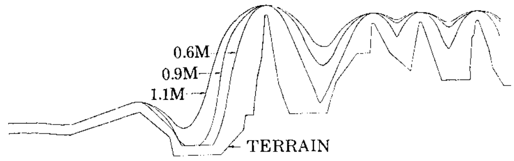

Fig. 6 Ideal profiles.

operated as an integrator for low-amplitude error outputs, as a lead-lag filter for intermediate level outputs, and as a simple lag for large output signals.

The main advantages of the angle system is its ease in being tailored to the flight characteristics of the particular vehicle in which it is being installed. The variation in performance with speed is easily compensated also with both the feedback gains and the shaped function. The angle system also had the advantages of a readily flyable pitch command signal and little or no undershooting of the set clearance altitude. In addition, appreciable errors in the forward or feedback loop signals do not alter significantly the terrain performance obtained. The system has the disadvantage of being more complicated, and more care in design must be taken to achieve the required level of reliability. The use of inflight built-in test equipment is also more difficult.

III. Scoring Techniques

At the initiation of work in the terrain-following area, it was assumed that the optimum system would maintain the minimum terrain clearance. As a result, it became common to use the term "set clearance" synonymously with "average clearance." This assumption regarding these terms would be true if the flight plan could always be such as to traverse only flat or gently sloping land. Unfortunately, the natural environment on the earth's surface presents some rather abruptly changing sections of terrain. As stated previously, accelerations must be limited to pilot-acceptable levels. As a result, the climb over a peak is initiated early enough to stay within maneuvering limits, and the pushover is terminated so as to meet the same requirements. This means that over rough terrain a large portion of the flight will be at a height considerably above the desired clearance altitude. If we use as our method of measuring excellence of performance the integral of the difference between the actual flight path and the set clearance, a significant change in actual performance could be masked by the fact that the roughness of the terrain results in a large value for the integral regardless of the job performed. The result might be that the system is optimized for the particular terrain being used during the development. To prevent this, a method that will properly indicate improvement or degradation of performance as parameters are varied, with no biasing of the data as a function of terrain roughness, must be used to score each run. Several investigators have independently arrived at similar scoring techniques; the one used at McDonnell is termed the "ideal profile" method of scoring.

The ideal profile is defined as the flight path that would be followed if the terrain sensor had foreknowledge of the total path to be flown and could operate at the design limits with no lag for the maneuvers. Using the constraints developed earlier of $+2\ g$, $-0.5\ g$, $\pm 10°$, and adding the additional constraint of level flight at the set clearance at peaks, we may construct this profile for any terrain. Since the pullups and pushovers are constant g maneuvers, the radius of curvature will vary with airspeed. Sample ideal profiles for three speeds are presented in Fig. 6.

The scoring method used to determine performance excellence employs a comparison of the actual flight path with that of the ideal profile. The deviation then is analyzed statistically to establish the probability of occurrence of errors from the ideal, and the results are used to indicate how well the system allowed the pilot to fly the desired track. This information, coupled with pilot opinion of the ease of following the command display, allows a rapid optimization of the system which minimizes the probability of designing the system to a particular terrain type. During the evaluation of the two systems mentioned previously, the section of terrain which was shown with the ideal profiles of Fig. 6 was used for the majority of the flights. This terrain can be broken into four sections for analysis. These sections are long enough to eliminate the effect of different entry conditions and sufficiently different to produce the desired effects. The first section is almost flat, with only gently changing slopes. The second section is an isolated peak, with the letdown into rough terrain. The third section is a series of closely spaced hills of significant height. The final section is a peak of extreme height, with a flat plain on the back side and several minor shelves on the way down. This last feature is the one that has been shown to be the most serious threat to a terrain-following system.

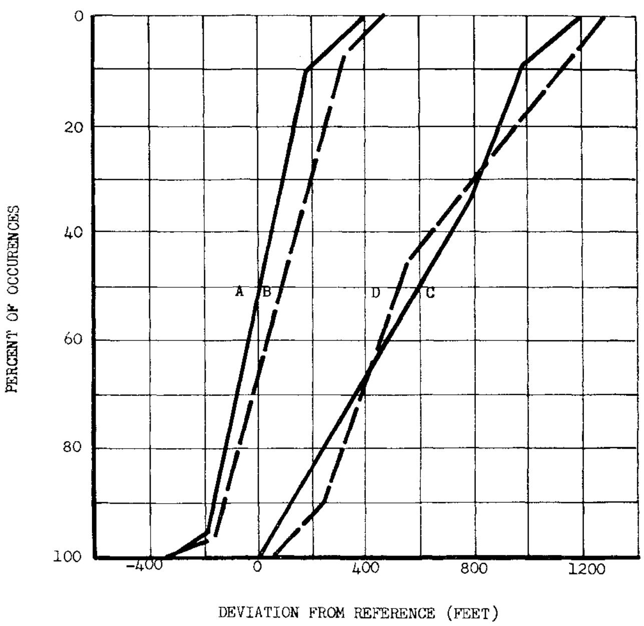

Fig. 7 Scoring system comparison (A, B = ideal profile; C, D = offset terrain).

A typical example of the difference in scoring shown by the use of the ideal profile, as compared to the offset terrain, is shown in Fig. 7. Curves A and B represent the probability of occurrence of errors from the ideal, whereas curves C and D represent the errors from the offset terrain. The change between the two curves in each set was caused by a change in one of the system parameters. Curve A shows a definite improvement over curve B for all altitudes, whereas it is difficult to draw a conclusion as to whether curve C or D represents better performance. A digital program is being established presently which will take flight test data, terrain height, and terrain clearance and then compute the ideal profile for the actual terrain flown plus the errors from this ideal. This program will facilitate flight test development and evaluation of any terrain-following system.

IV. Conclusions

As a result of the studies just discussed, the following conclusions can be drawn:

1) Manual terrain-following system for supersonic fighter aircraft using low set clearances presently are feasible.

2) The preflight development of a manual terrain-following system must be performed using a flight simulator that includes a realistic representation of the radar, display, and aircraft dynamics and utilizes a human operator to fly the test missions.

3) Evaluation of system performance should be accomplished using a scoring system that isolates changes in performance caused by parameter variations from changes in performance resulting from flight over a difficult terrain.