RM A55D12a

NACA

RESEARCH MEMORANDUM

THE EFFECTS OF POWERED CONTROLS AND FIRE-CONTROL SYSTEMS ON TRACKING ACCURACY

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

May 26, 1955
Declassified September 14, 1959

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

This report continues an analysis of the relationship between airplane and systems characteristics and tracking accuracy being conducted at the Ames Aeronautical Laboratory by considering the effects of inserting powered flight controls and complex fire-control systems into the pilot-airplane tracking loop. A brief summary of the principal results of the program completed thus far is included.

With regard to powered control systems, it was indicated that various stick-force-feel devices and the static gearing of the control system were not critical in themselves. The only system tested which the pilots could not cope with had a large breakout force which made the stick-force and stick-position response either indeterminate or very small at the actual values of stick force and control-surface position the pilot used in tracking. When the breakout force was reduced the tracking errors were reduced to a satisfactory level.

With regard to fire-control systems, both an optical disturbed-reticle sight and a scope-presentation director system with automatic radar tracking were evaluated. The most significant effect noted was a threefold increase in the gun-line wander when the disturbed-reticle sight was operated with large values of gain of the lead-angle computer. This increase is shown to be associated with the dynamic response of the lead-angle computer.

INTRODUCTION

This report continues the discussion of the airplane and systems characteristics which critically affect tracking accuracy that was initiated in references 1 and 2. The previous papers dealt primarily with the aerodynamic behavior of the airplane; the present paper considers the effects of inserting two additional dynamic elements - powered flight controls and fire-control systems.

The same experimental procedure has again been used, that is, to isolate critical characteristics by comparing the tracking performances with a wide variety of complete systems in the single standard test maneuver shown in figure 1. The maneuver consists of three segments, a steady straight tail chase, an abrupt breakaway turn entry where the target is maneuvering as fast as it can, and a subsequent steady turn at constant normal acceleration. The comparisons to be made herein involve only the two constant g segments. The numerical basis for comparing the tracking will be the standard deviation of the oscillations about the mean aiming point. This will be termed the aim wander. An aim wander of 2 mils implies that the pilot was able to keep the aiming point within 2 mils of its average position approximately 70 percent of the time during the run.

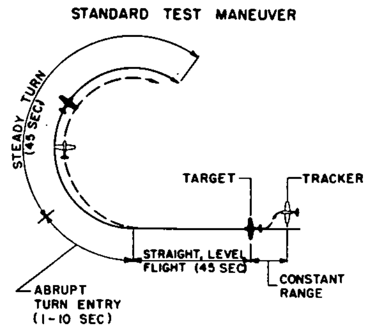

Figure 1

DISCUSSION

Powered Flight Controls

The effects of control-feel characteristics typical of current powered control systems were scrutinized by comparing a large number of contemporary fighters with the World War II F-51H and F8F airplanes with manual control. Figure 2 is a comparison of the fixed-sight aim wanders in pitch plotted as a function of the normal acceleration. The various longitudinal control systems represented include the F-86A (power-boosted elevators with force-feedback plus bob-weight), the F2H-3 and F-84F (irreversible elevators and artificial feel), the F7U-3 (irreversible ailevators), the F-86E (irreversible linked stabilizer and elevator), an early version of the F-86D (irreversible one-piece all-movable tail), and the same F-86D with the present standard service control system. All of the aim wanders are the same order as those of the F-51H and F8F with manual controls (control-surface hinge moments reduced by aerodynamic balance) except the values for the early model F-86D which are as much as four times as large.

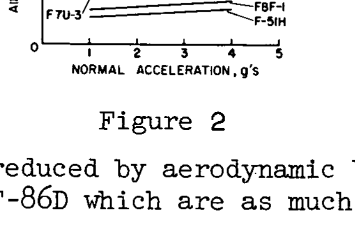

Figure 2

First, consider the group of systems which have reasonably low aim wanders. They include quite a wide variety of artificial-feel devices, such as springs, bobweights, gain changers, q-boxes, and dampers, and include all of the mechanical elements found in the unsatisfactory system; therefore the control-feel devices do not appear to be the critical factor in the tracking problem. Further, the static gearing of the control system in itself does not appear to be critical since the satisfactory systems also encompass the values of stick force per g and stick movement per g encountered on the unsatisfactory system. This underscores a recently published tracking study by Abramovitz and Van Dyke, reference 3, in which these parameters were isolated on a variable-gearing manual-control system with similar results; the pilot was able to track even with control-system gearings which were unsuitable for normal flying.

The remaining consideration is the dynamic response of the control system. Some earlier work by Phillips, Brown, and Matthews (ref. 4) suggested that the dynamic response, specifically the phase angle between the applied stick force and the control-surface response, would be critical, at least in abrupt maneuvers with large control deflections. Therefore the frequency response of several of these systems was measured for control-surface deflections of 0.4° for the airplanes with elevators and 0.2° for the airplanes with all-movable tails. Figure 3 shows the amplitude ratio and phase angle between the stick force and the control-surface position as a function of frequency. The early F-86D system, and the modified system as well, are distinguished from the others by very large phase lags. Since the large phase lags were not reduced in the satisfactory system, they do not appear to have hindered the tracking.

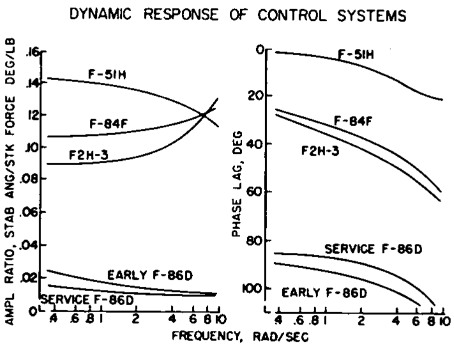

Figure 3

It is apparent that the initial examination of the dynamic response was not adequate. An examination of time histories of the stick-force and control movements during the tracking runs indicates that tracking is essentially a task involving making small corrections to a smooth average fligh path; therefore it involves small control displacements and small stick forces at very low operating frequencies. The difficulty with an analysis such as that in figure 3 is that the response of the control system at the small movements actually involved in tracking is very nonlinear. Figure 4 is a comparison between the responses of the satisfactory and unsatisfactory systems in the same airframe for the ranges of stabilizer position and operating frequencies the pilot actually used in tracking. The increment in the stabilizer position output is shown as a function of the

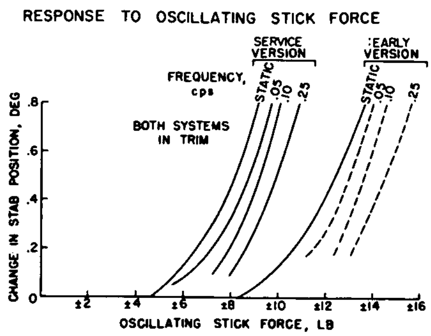

Figure 4

oscillating stick-force input for three frequencies: 0.05, 0.10, and 0.25 cycles per second, with the systems in the trimmed position. The response also varies nonlinearly with the setting of the trimming device. The curves are shown to the lowest values of stabilizer angle and frequency at which a steady response could be measured. The response for the original system is shown dotted for frequencies other than zero because the data had to be obtained on another system of the same type and corrected to the static gearings used in the tracking tests.

The chief difference between these two systems is the sizable reduction in the stick force at which the stabilizer begins to respond. This corresponds to a reduction in the static breakout force from 8 pounds on the unsatisfactory system to 4-1/2 pounds on the satisfactory system. The deadband or region of stick forces wherein there is either no response or a small inconsistent response of the stabilizer has been cut in half, and it is precisely this band within which the pilot desires to operate the system in order to track well. The response to stick force has been shown because the pilot is generally assumed to fly by force feel if he can. The responses to stick position have also been examined and look very much like those shown for the stick force. A deadband in the stick position due to backlash and slop has also been cut in half, from about 0.2° to 0.1°. In essence then the pilot could not track well because at the small stabilizer movements needed to do good tracking, this particular control system had little or no definite response to either stick force or stick position.

Now it would be interesting to compare, say, the specific phase lags and time constants for these two systems to see what values the pilot could cope with. Unfortunately, the actual tracking motions are nearly all within the region where such dynamic response measurements are either unreliable or indeterminate. For this reason, rather than attempting too profound an analysis on the basis of this one unsatisfactory system, we have begun an additional test program wherein an F-86D will be modified to incorporate a variable-response control system in which each of the significant response parameters can be isolated in turn.

Fire-Control Systems

Next the influence of the dynamic response of the fire-control system will be considered. Several systems typical of the different types now in service have each been evaluated when computing a lead-pursuit course, but with the target performing the same standard test maneuver so that the data are directly comparable with the previous fixed-sight results.

When a fire-control computer is inserted in the pilot-control-system-airplane tracking combination, some new geometry must be considered. Figure 5 illustrates some significant terms. The line of sight L is the true line in space from the tracking airplane to the target. It is measured from a reference axis fixed in space. The gun line or armament reference line is the longitudinal axis of the tracking airplane. It must lead the line of sight by a certain angle in order to score a hit. This required position of the gun line is indicated to the pilot by means of the tracking line which is an apparent line in space the pilot sees when he looks through the gunsight reticle. The reticle is mechanically offset from the gun line by the computed lead angle P furnished by the fire-control system, thus when the pilot maneuvers the airplane so that the reticle is exactly on the target the gun line has the desired lead angle with respect to the line of sight. A small error in tracking has been shown for clarity. With a fixed sight the tracking line is rigidly attached to the gun line at an arbitrary angle and their motions are identical. With a computing sight their relative motions depend on the dynamic response of the computer and will be an important concern in the rest of the report.

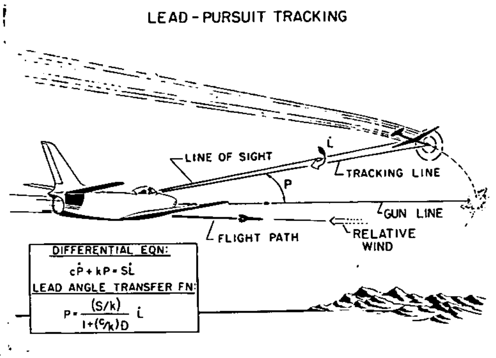

Figure 5

The gun-line motions are pertinent to projectiles which are not significantly affected by the relative wind, such as cannon shells or spin-stabilized rockets. For projectiles which "jump" or aline themselves with the relative wind, such as conventional rockets with fins, the flight path must be considered rather than the gun line. The flight path differs from the gun line by an amount depending on the angle of attack and the pitching velocity.

Figure 5 has illustrated a system where the tracking information and the target are directly visible to the pilot. There are other systems where the target is not visible and the desired gun-line position is represented on the face of an oscilloscope. These will be discussed as the test results are presented.

Since it is desired to compare the effects of changing the dynamic response for several types of fire-control system, the first problem is to select some common numerical basis to describe the responses of widely different systems. Not only are the individual inputs and outputs physically different, but there are both electrical and mechanical analog computers with completely different physical constants. Something fundamental is required, and for this purpose the differential equation involving the lead angle, the basic building block in all of the computers, will be examined as indicated in figure 5. The resulting open-loop lead-angle transfer function relating the lead angle P to the angular velocity of the line of sight $\dot{L}$ contains a gain and a first-order time constant which are to be found in some form in any system.

The term, gain, which will be the primary test variable, is the required constant of proportionality between the basic computer input, the angular velocity of the line of sight, and the computer output, the lead angle. The numerical value of the gain depends on ballistics, such as the velocity of the projectile, and on the flight conditions, such as the range. In this case, the test maneuver holds enough quantities constant so that the gain can be expressed physically by the projectile flight time in seconds. The time constant is a lag term which is introduced by the necessary filtering in an electrical analog or damping in a mechanical analog computer. The numerical value is usually a simple constant in an electrical analog; in a mechanical analog it is the ratio of the damping coefficient to the gain as shown in the equation in figure 5.

The individual systems tested as implied vary in a number of details. For simplicity only two will be described: the actual computer inputs used to represent the line-of-sight rate, and the actual outputs used to indicate the desired lead angle to the pilot. The block diagrams and transfer functions of the individual systems are presented in figure 6 for reference; however, the tracking performances will be plotted as functions of the gain and time constant so that direct comparisons between systems can be made.

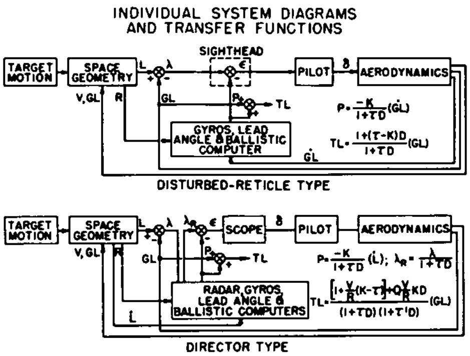

Figure 6

Disturbed-reticle system.- The first system considered, the A-1 sight in the F-86A airplane, is classified as a disturbed reticle system. The actual input to the computer is the angular velocity of the gun line, rather than that of the line of sight, which is called for in the lead-angle equation. This substitution is made to eliminate the need to provide equipment to measure the true line of sight. The result of this substitution is the distinctive feature of this system as far as tracking is concerned - a change in the computed lead angle must be generated by a motion of the tracking airplane, that is, by the pilot disturbing the gun line. The actual output of the system is the position of the tracking line which is presented to the pilot on the windshield for direct visual comparison with the real line of sight, the particular system illustrated in figure 5.

Figure 7 shows the effect of changing the gain of the lead-angle computer (expressed as projectile flight time) upon the three significant wanders: tracking line, gun line, and flight path. The shaded regions are the envelopes of all of the test points. The lowest value of gain corresponds to a short range, 800 feet, and high altitude, 35,000 feet; the highest corresponds to a long range, 3,000 feet, and low altitude, 10,000 feet. At each test value of gain the time constant was varied within the limits shown by changing the damping in the computer mechanism. The average fixed-sight aim wander in the same airplane is shown for comparison.

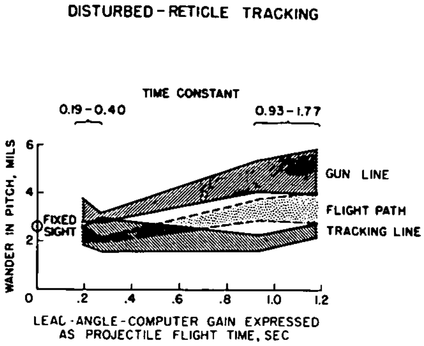

Figure 7

The tracking-line wanders are not significantly affected by any of the changes in the system response. It is apparent that the pilot was able to cope with all of these changes and track as accurately as he could with a fixed sight. This also implies that fixed-sight aim wanders are a good indication of the tracking wanders to be expected when a disturbed-reticle system is added to the tracking loop.

The gun-line wanders, however, which are a measure of the dispersion imposed on small jump-angle projectiles, increase proportionally with gain to about three times the tracking-line wanders, or to the order of 6 mils. This increase is readily explained. It is associated with the changes in the frequency response of the lead-angle computer which are illustrated in figure 8. The amplitude ratio, or ratio of gun-line input to tracking-line output, is shown as a function of frequency at the lowest and the highest values of gain tested. At the low gain, short range, where the lead required is small, the ratio of gun line to tracking line is nearly 1 at normal operating frequencies - the two are closely coupled and, in effect, approach a fixed sight. At high gain, long range, or long flight times, where the lead required is large, the amplitude ratio increases significantly at operating frequencies, and a larger motion of the gun line is required to generate the required lead angle. Thus, the increase in the gun-line wanders observed in the flight tests is inherent in the lead computation and is associated with the principle of using the gun line as the input to generate the lead angle.

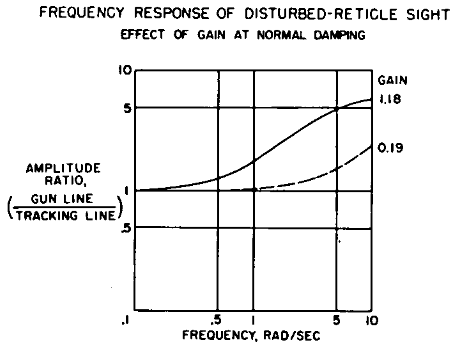

Figure 8

The flight-path wanders, of course, show the same tendency to increase as the gun-line wanders; however, the numerical values are smaller, of the order of 3 mils, and do not appear to be significant since they apply only to projectiles with large jump angles, such as conventional rockets, which inherently have comparatively large dispersion angles.

The effects of changing the system damping coefficient, which is the ratio of the time constant to the gain, are worthy of separate note. The test points corresponding to the different time constants showed the same two trends at each value of gain. There were no significant variations with time constant, but there was a large random scatter of the amount indicated by the envelope on figure 7. Both of these observations have been explained by studying the changes in the pilot's behavior corresponding to the changes in the system damping, particularly the frequency content of his tracking motions.

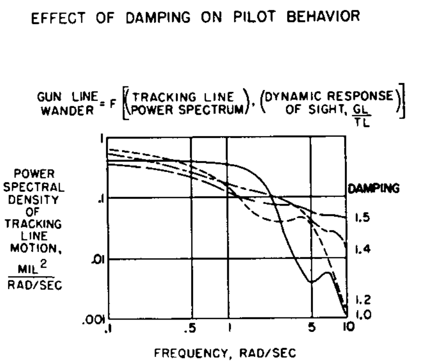

Figure 9

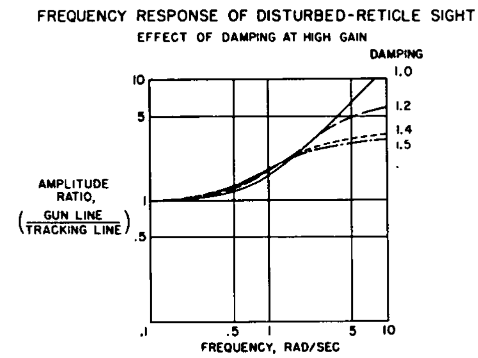

Figure 10

Figure 9 shows the relative amount of the tracking-line motion as a function of the frequency of the motion at four different values of damping. When the system is well damped, the pilot still makes rapid high-frequency corrective motions. When the system is poorly damped, the pilot moves the system primarily at low frequencies, that is, slowly and smoothly. By referring to the frequency response of the sight at the same four values of damping, figure 10, it can be seen that, in effect, the pilot is confining the frequencies at which he operates the system to those frequencies below the frequency (about 4 radians per second) at which the system response begins to change significantly with damping. Thus, this compensation by the pilot is the reason that there was no consistent variation of gun-line wander with damping or the time constant. The second observation, the amount of scatter, is due to the fact that the pilot, being human, is inconsistent. The test results indicate considerable random variation in the pilot behavior from the average values shown in figure 9, even under identical test conditions.

The reason the pilot behavior has been stressed is that it must be considered when attempting to predict the gun-line wander with a new fire-control system or a different airplane. As indicated by the general relationship at the top of figure 9, the gun-line wander can be predicted by applying the known transfer functions of the new system to existing tracking-line or fixed-sight aim-wander data. However, it has been found that a variation of the tracking-line power spectrum with damping must be included. In order to get some idea of how general the empirical averaged variations shown in figure 9 might be, these data have been used to predict the gun-line behavior of the Navy Mark 16 sight in the FJ-2 airplane with good accuracy; however, the variations in the sight mechanics and certainly the airframe in this case may not be large enough to be a significant test. A more complete discussion of these disturbed-reticle-system tracking tests has been published in reference 5.

Director system.- The next type of system considered, a modified E-4 in the early F-86D, is classified as a director system. The actual input to the computer is the angular velocity of the line of sight as measured by an automatic tracking radar. The distinctive feature of this system, therefore, is that a motion of the tracking airplane or gun line is not required to generate the lead angle. There is a complication, however, in the fact that the line-of-sight measurement is noisy. The actual output varies considerably from the tracking-line concept in the previous system. Since this system must operate where the target is not visible, the tracking output is presented to the pilot as a displacement between two dots on an oscilloscope. This displacement is an arbitrary function of the error in the gun-line position, which the pilot is supposed to reduce to zero.

In comparing this system with the previous one, therefore, both the principle of the lead computer and the presentation to the pilot have been changed. The effects of the computer response will be considered first.

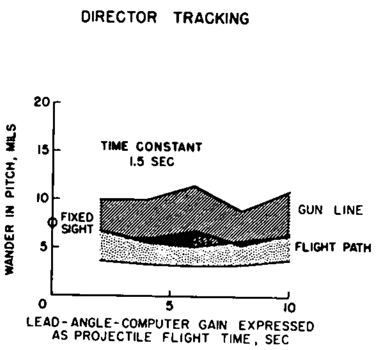

Figure 11

Figure 11 again shows the variation of the gun-line and flight-path wanders with gain at the normal computer time constant. Note that the range of gain covered is considerably larger than for the disturbed-reticle sight, 10 seconds compared to 1.2, to account for long-range rockets or very low-speed projectiles such as bombs. There are two significant observations with regard to the gun-line behavior, which was the chief item of interest in the disturbed-reticle system. First, the gun-line wanders with this system in the tracking loop are no larger than the fixed-sight aim wanders in the same airplane. (Remember that this evaluation was made in the early unmodified F-86D with the poor control response.) Second, in contrast to the disturbed-reticle system, they are not affected by the gain or lead angle. This would be expected since the gun-line motions simply are not involved in the lead computation unless there is an unwanted coupling between the motions of the airplane and the tracking radar antenna. The corresponding flight-path wanders are of the order of 5 mils, again probably insignificant in comparison with the dispersion of likely projectiles.

Due to the many independent variables which affect the oscilloscope presentation of the tracking error to the pilot, no data analogous to the tracking-line wanders are shown on figure 11, although it can be deduced from the gun-line wanders that the pilot was able to track satisfactorily with this particular presentation. The more important of these variables, which require separate evaluation, include the amount of information presented as compared with a visual tracking situation, the noise in the error signal or the amount of filtering applied to it, and the scope sensitivity, that is, the particular ratio between the dot motion and the gun-line error.

Tests have been conducted at the Langley Aeronautical Laboratory to isolate the effects of the lack of target information, that is, angle of bank or attitude, in the various segments of the test maneuver. A noise-free scope presentation was simulated by tracking a very bright light in a target airplane at night. The aim wanders presented in the following table show that tracking in the steady-g portions of the test maneuver which have been considered in this report was not affected by this factor.

Target attitude information	Portion of test maneuver	Aim wander in mils	
		Pitch	Yaw
Complete, visual	Steady 1 g flight	1.2	2.1
	Steady turns	2.4	4.0
Simulated scope presentation	Steady 1 g flight	2.1	2.7
	Steady turns	3.2	5.9

The effects of noise in the tracking-error signal have also been isolated at Langley. An APQ-35 radar in an F3D airplane was used with the lead computer and filtering disconnected so that the pilot when looking at the scope simply saw the position of his own gun line with respect to a noisy representation of the target position. Figure 12 shows the wander of the gun line as a function of the noise apparent to the pilot as represented by the root-mean-square difference between the true target position and the position indicated on the scope. The noise-free point again was obtained by the technique of visually tracking a very bright light in the tail of the target airplane at night. This point, as would be expected, coincides with fixed-sight aim wanders on the same airplane. Starting from the noise-free point, there is a very significant increase in the gun-line wander as the noise in the presentation apparent to the pilot increases.

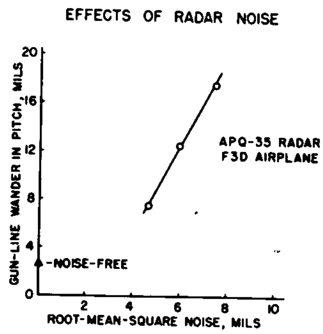

Figure 12

In the E-4 system tests discussed previously, sufficient filtering was applied to reduce the noise level in the tests to roughly 4 mils rms, therefore this factor should not affect the previous results.

A test program to study the effects of the sensitivity of the tracking-error signal, the other important variable in the scope presentation, is just getting under way and no results are available as yet. Since the gun-line wanders are already equal to the fixed-sight wanders, no significant improvement is expected, but the critical range of acceptable sensitivity should be defined.

Before leaving the subject of director systems, reference should be made to tracking data of an optical director system. Particularly in air-to-ground use, the presence of clutter and noise often makes the use of radar tracking impractical, as figure 12 suggested. In such cases it may be desirable to consider a director system with the pilot operating an optical tracking device to furnish the line-of-sight rate input. In reference 6 Turner, Triplett, and White have shown that very low tracking-line wanders of the order of 1 mil or less can be achieved with such a system even in the presence of the motions of the tracking airplane.

CONCLUSIONS

Figure 13 summarizes some of the results of the NACA tracking research. The left-hand side of the figure shows the four major dynamic elements that comprise a tracking system: the pilot, the aerodynamics, the control system, and the fire-control system. The center section lists the more important changes in these elements which have been evaluated. The right-hand side shows the relative increases in aim wander as these changes are introduced. The shaded bar, the initial data in each case, represents an experienced pilot in a normal F-51H with manual controls and a fixed sight.

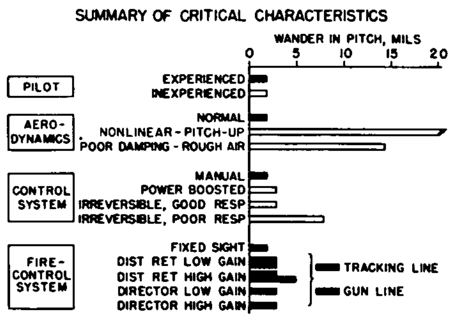

Figure 13

There were no significant variations due to the experience of the pilot (see ref. 1). With regard to the aerodynamics, introducing nonlinearities such as pitch-up resulted in the airplane becoming uncontrollable in the tracking sense (see ref. 1). Introducing poor lateral-directional damping in the presence of moderately rough air resulted in aim wanders of the order of 15 mils (see ref. 2). With regard to the control system, introducing power-boosted or irreversible controls with good dynamic response had small effect, but irreversible controls with poor response increased the aim wanders to the order of 8 mils. And, finally, with regard to the fire-control system, the most significant critical effect noted was a twofold to threefold increase in the gun-line wanders of a disturbed-reticle system at high values of gain and time constant.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Apr. 12, 1955

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