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CONTROLLABILITY OF DISTURBED RETICLE TANK FIRE CONTROL SYSTEMS

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INTRODUCTION

The history of U.S. Tank Gun Stabilization and Fire Control has been replete with evolutionary changes in response to updated requirements. For example, the M60A1 was originally equipped with non-stabilized gun drives, to which gyro stabilization was added to allow aiming and firing on the move. Also, the M60A1 had a sight with fixed reticles (elevation manually adjusted for range), so the gunner was required to estimate lead angle. The later M60 vehicles, M60A2 and M60A3, were equipped with sights with servo-driven reticles so that computed super-elevation and deflection could be inserted automatically.

Presently, the Bradley Fighting Vehicle is equipped with a high-quality gun stabilization system which allows precision tracking for the TOW missile guidance with the vehicle stationary, and good gun aiming and firing accuracy with the vehicle on the move. No "fire control" in the form of automatic lead angle and super-elevation generation is included, but some such capability may be required as the missions for the BFV are extended. Any such upgrading of capability would logically build upon the existing system, and would thus most likely take the form of a disturbed reticle system. This study investigates the requirements and performance of such a disturbed reticle system, but it is not directed toward any particular system. Rather, it derives the necessary transfer function characteristics of the elements of such a system.

DISTURBED RETICLE SYSTEM ANALYSIS AND REQUIREMENTS

SYSTEM CONFIGURATION

Figure 1 shows a functional block diagram for one axis of the disturbed reticle system. (Figures 2 and 3 are modifications of Figure 1 that are useful for analysis purposes.) This representation follows quite closely that found in Reference 1. The primary tracking loop is closed by the gunner, who sees the error between target angular position and reticle angular position in his sight and corrects the observed error by commanding the gun turning rate by operating his hand station. For purposes of transfer function analysis, the gunner can be considered a quasi-linear transfer function of the form(2).

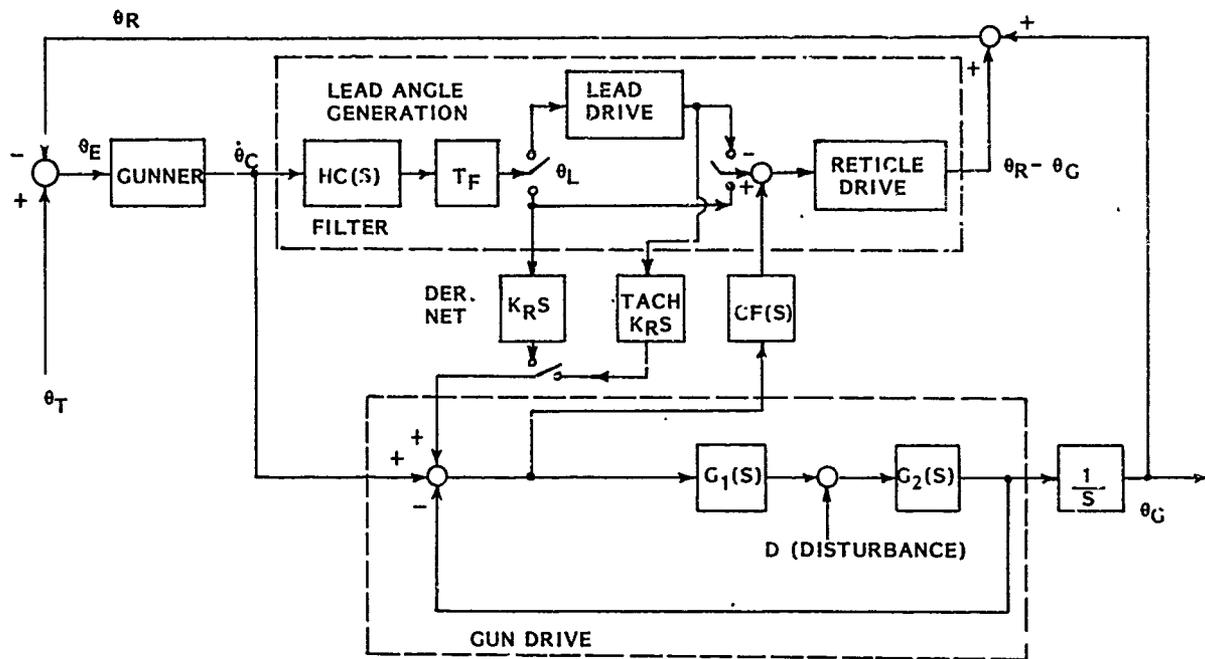


Figure 1. FUNCTIONAL BLOCK DIAGRAM—DISTURBED RETICLE SYSTEM

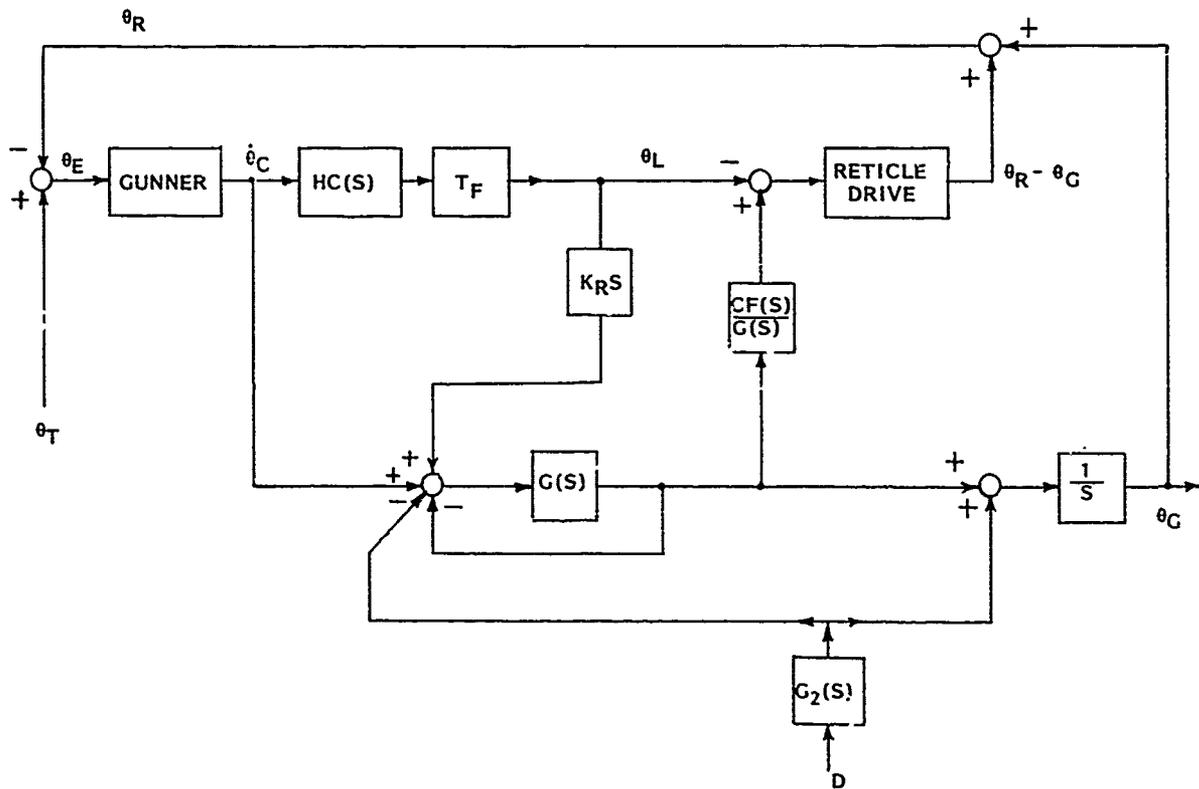


Figure 2. LINEAR TRANSFORMATION OF FIGURE 1 FOR USE IN GUN MOTION ANALYSIS

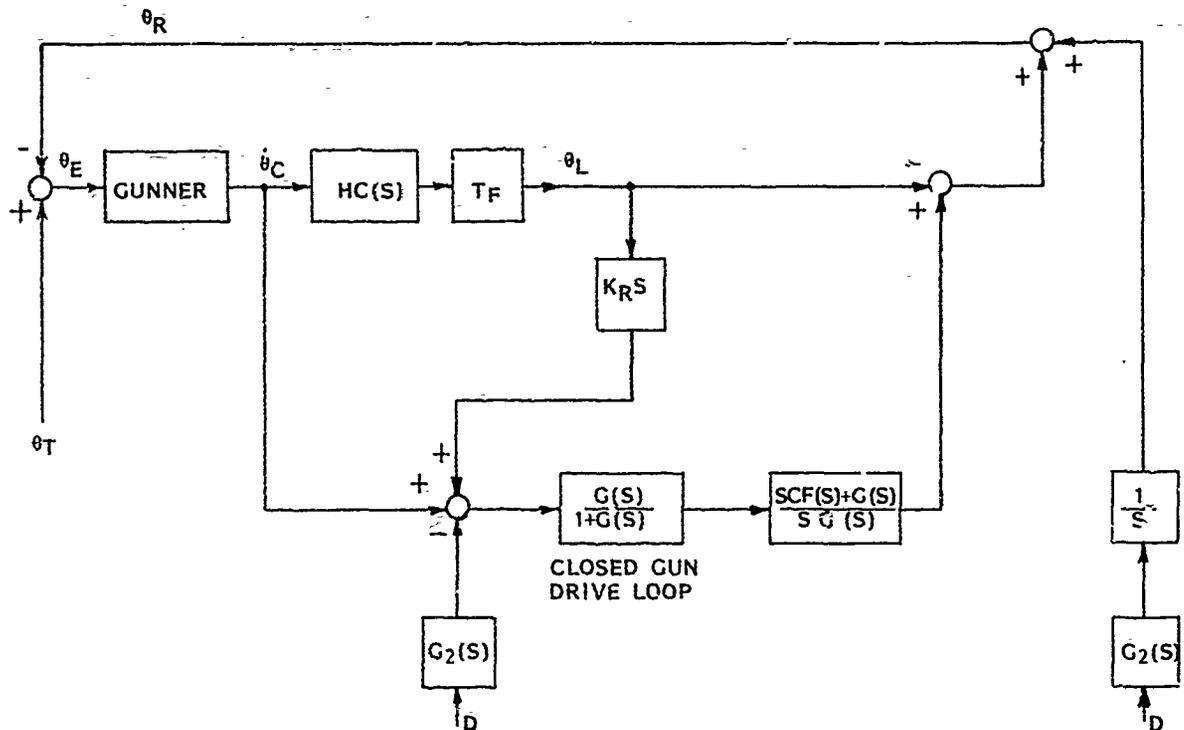


Figure 3. LINEAR TRANSFORMATION OF FIGURE 2 FOP, USE IN RETICLE MOTION ANALYSIS
(RETICLE DRIVE = 1)

$$\frac{\dot{\theta}_C}{\theta_E} = \frac{K e^{-\tau s} (1 + T_L s)}{(1 + T_1 s)(1 + T_N s)}$$

where K is the gain

T_1 is a lag time constant

T_2 is a lead time constant

τ is the visual delay

T_N is the neurological time constant,

somewhat adjustable

} Adjusted
adaptively
for the plant

The gunner adaptively adjusts his parameters to achieve a stable operation of his tracking loop at a crossover frequency, W_c . During tracking tests on the move on the M60A1E2⁽³⁾ and the MICV-65⁽⁴⁾ with electric gun stabilization drives, W_c was in the range 2 to 3 rad/sec. During stationary vehicle tracking tests,

W_c is 4 or more, and there is some tracking rate "feed forward." Functionally in Fig. 1, the gunner can be replaced with an automatic tracker, having a higher W_c and providing smoother tracking.

GUN STABILIZATION

When the system is using gun stabilization only, the lower half of Figure 1 applies. The gunner is working with a "load" or "plant" consisting of the gun drive, with rate gyro feedback, and the inherent integration to angle. That is, the plant is nearly a pure integrator, which is ideal for the gunner (1), with a high-frequency (relative to gunner responses) resonance and roll-off. The plant frequency characteristic, along with the overall open-loop characteristic achieved by the gunner, is shown in Figure 4. Note that for a well designed gun drive system, the bandwidth of the gun drive will be very much higher (an order of magnitude or more) than W_c . It should be mentioned in passing that functionally a stabilized sight system responds like a stabilized gun system, the only difference being the higher bandwidth achievable with the stabilized sight. From the considerations shown in Figure 4, this should make little difference as both bandwidths are well above W_c . The major advantage of a stabilized sight system lies in the reduced response to disturbances to the line of sight (LOS) caused by vehicle motions.

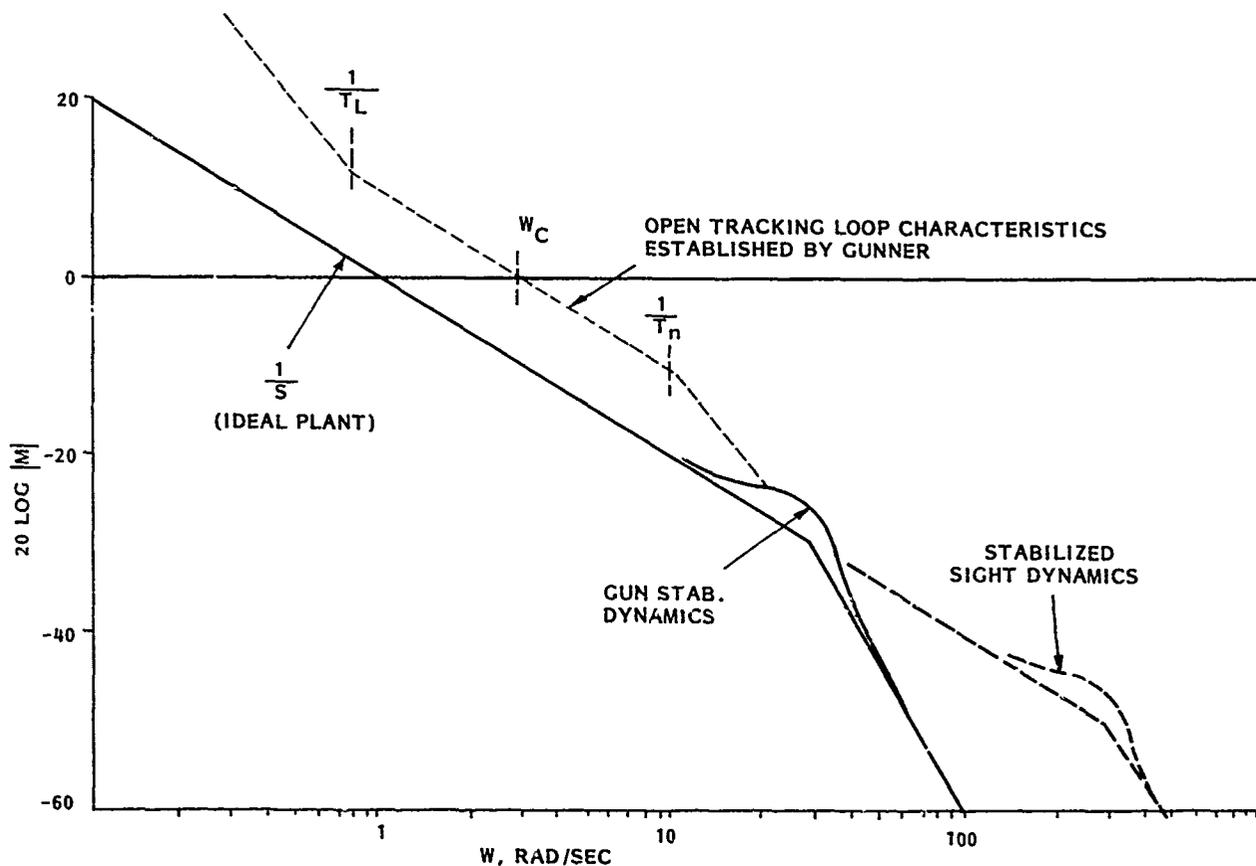


Figure 4. ELEMENTS OF TRACKING LOOP

LEAD ANGLE GENERATION

The lead angle generation is shown in the top half of Figure 1. The hand station rate signal is used as the measure of target angular velocity. This angular rate multiplied by the computed time of flight of the round, T_f , yields the lead angle. (This is a linear predictor, assuming straight-line, constant-speed target motion). At this stage the lead angle is in electrical signal form (either analog or digital) and must be converted to reticle and ultimately gun angular motion. Two alternate conversions are indicated in Figure 1. In one, the electrical signal drives a lead screw servo which is followed by the reticle (or mirror) servo. This system was described in detail in Reference 1 and is the system used in the traverse channel of the M-1 tank. It has the advantage that the target and reticle remain centered in the field of view of the sight as the lead angle is entered. In the second approach, which is representative of the M60A2 and A3 systems, the electrical signal feeds the reticle servo directly. In this approach, the reticle and target do not remain centered in the field of view as the lead is entered. From field tests on the M60A2, this characteristic does not seem to cause gunner performance degradation. Aside from this "human factors" difference, no functional difference exists between the two methods of entering lead angle, and this study will consider them to be the same.

It is seen in Figure 1 that the hand station command rate signal is filtered before lead angle is generated. This is necessary because the rate signal may be noisy (even when tracking angle error is being maintained at a low value), and this noise will result in erroneous lead angle values. Note that this filtering is required for either a stabilized sight or disturbed reticle system. Sometimes the filtering is greatly increased for a disturbed reticle system to compensate for an inadequate system configuration, as will be seen presently. However, such filtering presents an unnecessary penalty on the disturbed reticle system, if only the configuration of existing system elements is changed as indicated below.

CROSS CONNECTIONS BETWEEN GUN DRIVE AND LEAD GENERATION

Two cross connections are shown in Figure 1. The first is a derivative of lead signal that is fed into the input of the gun stabilization. This is necessary to move the gun by the amount of the lead angle, as the lead angle is being generated. If this is done properly, the motion is equal and opposite to the reticle presentation in the sight, and the gunner is unaware of lead angle insertion. To investigate this, refer to Figure 3; assume for the moment that there is no cross-feed, $CF(s)$, and no hand station signal, $\dot{\theta}_c$. Apply θ_L and observe θ_R .

$$\frac{\theta_R}{\theta_L} = K_R \left[\begin{array}{l} \text{Closed Gun} \\ \text{Drive Loop} \end{array} \right] - \left[\begin{array}{l} \text{Reticle} \\ \text{Drive} \end{array} \right]$$

$$\left. \begin{array}{l} \theta_c = 0 \\ CF(s) = 0 \\ D = 0 \end{array} \right\}$$

Under steady-state conditions, presumably both the gun drive and reticle drive have unity gain. Thus, the steady-state error angle appearing in the sight is zero, if $K_R = 1$. Furthermore, if the dynamics of the reticle drive and gun drive are matched, no transient error would appear in the sight. However, this matching of dynamics would be difficult to achieve. Normally, the bandwidth of the reticle drive can easily be made higher than that of the gun drive, and in the presentation to come this is a desirable characteristic. Now to repeat the previous equation, assuming infinite reticle bandwidth (unity transfer function):

$$\frac{\theta_R}{\theta_L} = \left[\begin{array}{l} \text{Closed Gun} \\ \text{Drive Loop} \end{array} \right] - 1 = \frac{G(s)}{1 + G(s)} - 1 = - \frac{1}{1 + G(s)}$$

$$\left. \begin{array}{l} \theta_c = 0 \\ CF(s) = 0 \\ D = 0 \\ K_R = 1 \\ \text{Reticle Drive} = 1 \end{array} \right\}$$

This is an anomalous response that may be confusing to the gunner, if it is large enough. It can be used to determine the overall plant that the gunner perceives:

$$\frac{\theta_R}{\theta_c} = \frac{1}{s} \left[\begin{array}{l} \text{Closed Gun} \\ \text{Drive Loop} \end{array} \right] - \frac{HC(s) T_F}{1 + G(s)}$$

$$= \frac{1}{s} \left[\frac{G(s)}{1 + G(s)} \right] - \frac{HC(s) T_F}{1 + G(s)}$$

These transfer function components are shown in Figure 5 for several values of T_F . It is seen that at the "confusing" part of the response predominates at frequencies just above the frequency at which the gunner is attempting to establish tracking loop crossover. This is particularly confusing because it is a positive feedback type of response. Such a system would be impossible to stabilize at gains anywhere near the normal value. It is seen that the problem gets worse with increasing target range (T_F) and with decreasing gun drive bandwidth. The problem can be alleviated by adding a lot of filtering ($HC(s)$) in the hand station signal. To reduce the "confusing" response to the magnitude level of the "expected" response would require a single lag break at about $W = 1$ or a double break at about $W = 3$. This amount of filtering can degrade overall system performance appreciably(1).

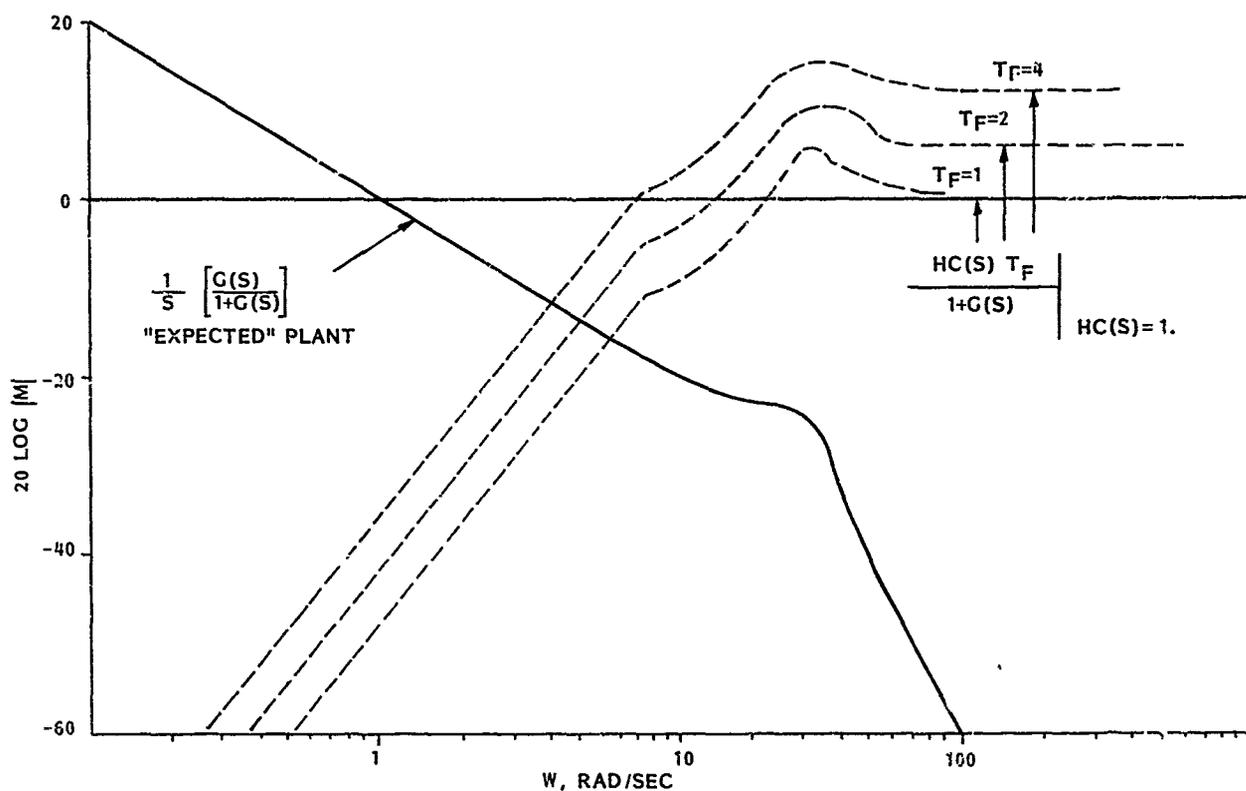


Figure 5. PLANT TRANSFER FUNCTIONS WITHOUT CROSS FEED OR HANDSTATION FILTER

The problem described above can be greatly relieved by the use of the cross-feed, CF (ϵ), shown in Figure 1. Physically, the error of the gun drive is measured and applied to the reticle servo, so that the gunner is not bothered by the delays in the gun drive response. For successful application, the reticle drive bandwidth must be high, relative to the gun drive. The response of the reticle to lead angle generation can be easily determined from Figure 3.

$$\frac{\theta_R}{\theta_L} = K_R s \left[\frac{G(s)}{1 + G(s)} \right] \left[\frac{sCF(s) + G(s)}{s G(s)} \right] - 1$$

From this, an ideal cross-feed, CF(s), can be selected. If $K_R = 1$, as found above, and $CF(s) = 1/s$, then

$$\frac{\theta_R}{\theta_L} = 1 - 1 = 0$$

regardless of the gun drive response. This means that the implementation of lead angle in gun pointing is completely removed from the gunner's view, just as it is in the stabilized sight case.

It is, of course, necessary to explore the effect of this cross-feed on the normal tracking response of the plant and the disturbance response of the plant. The tracking response is

$$\frac{\theta_R}{\theta_c} = \left[\frac{G(s)}{1 + G(s)} \right] \left[\frac{sCF(s) + G(s)}{sG(s)} \right] = \frac{1}{s} \quad \text{if}$$

$$CF(s) = \frac{1}{s}$$

Thus, the cross-feed has caused the plant response to approach the ideal of a simple integrator, just as the stabilized sight does.

The disturbance response of the plant, as it appears to the gunner, is

$$\frac{\theta_R}{D} = G_2(s) \left[\frac{1}{s} - \left[\frac{G(s)}{1 + G(s)} \right] \left[\frac{sCF(s) + G(s)}{sG(s)} \right] \right]$$

$$= G_2(s) \left[\frac{1}{s} - \frac{1}{s} \right] = 0 \quad \text{if } CF(s) = \frac{1}{s}$$

This is in contrast to the actual motion of the gun; see Figure 2.

$$\frac{\theta_G}{D} = G_2(s) \left[\frac{1}{s} - \frac{1}{s} \left[\frac{G(s)}{1 + G(s)} \right] \right] = G_2(s) \frac{1}{s} \left[\frac{1}{1 + G(s)} \right]$$

That is, the gun aim is being erroneously disturbed from the proper

position by the torque disturbances, but the gunner is completely unaware of these disturbances. This situation is desirable for the gun motions at suspension frequencies (and above) which are beyond the gunner's capability to correct. However, any low-frequency errors in gun pointing should not be shielded from the gunner's view, but should be presented to him so that he can correct for them. That is, instead of $CF(s) = 1/s$, the cross-feed should be of the form

$$CF(s) = \frac{1}{s + W_0} \quad \text{or possibly } CF(s) = \frac{s}{(s + W_0)^2}$$

so that $CF(s)$ performs an integration function above W_0 , thus effectively removing high-frequency transients, which are beyond the range of the ability of the gunner to correct, from the gunner's view. However, at the low frequencies, below W_0 , the gunner is aware of the gun pointing errors and can correct them. The value of W_0 can be found by substituting this $CF(s)$ function into the pertinent transfer functions. That is,

$$\begin{aligned} \left. \frac{\theta_R}{\theta_c} \right|_{\dot{\theta}_c = 0} &= K_R s \left[\frac{G(s)}{1 + G(s)} \right] \left[\frac{\frac{s}{s + W_0} + G(s)}{sG(s)} \right]^{-1} \\ &= \frac{-1}{(1 + s/W_0) [1 + G(s)]} \Bigg|_{K_R = 1} \end{aligned}$$

and the overall plant response is

$$\frac{\theta_R}{\theta_c} = \frac{1}{s} \left[\frac{\frac{s}{s + W_0} + G(s)}{1 + G(s)} \right] - \frac{HC(s) T_F}{(1 + \frac{s}{W_0}) [1 + G(s)]}$$

The first term is very nearly the ideal integral response. The second term is the undesirable "confusing response", but now it is already filtered by the $1/(1 + s/W_0)$ term. In terms of the previous discussion, W_0 should be of the order of 1. The hand station signal can still be filtered in $HC(s)$, but the filtering needs to be only that required to smooth gunner input noise, as it is in the stabilized sight case.

SIMULATION STUDY

HITPRO* MODEL

The derivations performed above have assumed linear and relatively simple transfer functions for the major system elements. Since the gun power drives and reticle servos may contain considerable non-linearity, it seemed worthwhile to check some of the derived conclusions using a realistic simulation of the system. This simulation work employed HITPRO, (3)(4) which was developed for the U.S. Army as a general purpose tool for studying the effect on gun firing accuracy of various elements of an armored vehicle - suspension, gun drives, fire control, etc. Various vehicles that have been modeled on HITPRO are MICV-65, M60A1/AOS, M60A3, M1, HIMAG and HSTVL. This study used a modified version of HITPRO that has been used for studying the Bradley Fighting Vehicle (BFV) gun stabilization drives. The modifications were associated with a larger gun (75 mm) than is used on BFV, and a somewhat lighter hull. This was done to include the possibility of a yaw suspension flexibility effect on tracking.

HITPRO uses a McRuer model for the gunner. (See Reference 2). Extensive tracking tests have been made with the BFV. These tests were made with three different individual gunners. The parameters of the McRuer model were selected so that the HITPRO tracking performance matches quite closely the poorest of the three gunners. This was done because the tracking tests were made without the gun gyro feedback, which helps the gunner performance slightly. These simulation runs were made with the gun gyros in place.

The scenario chosen for the study was the same as that used in Reference 1. Own vehicle was stationary. Target was initially approaching head-on at a speed of about 10 meters/sec. at a range of 750 meters. Thereafter it turns, performs a rather violent evasive maneuver, and ends up on a near crossing course. The target trajectory is shown in Figure 6, and the required tracking angle and rate are shown in Figure 7. The round time of flight of 2 seconds, as used in Reference 1, is unusually long for this relatively short range, but is useful in showing the difficulty of aiming correctly to hit a maneuvering target.

SIMULATION RESULTS

First, the system was run with hand station signal-filtering break set at $W = 1$. This amount of filtering was described previously as excessive. The results of this run are shown in Figure 8. Note that the tracking error (the error observed by the gunner) is small, generally well under 1 mr. However the ideal linear prediction

*Hit Probability

FIG 6
 TARGET TRAJECTORY FOR STUDY
 X DISTANCE VS Z DISTANCE, METERS

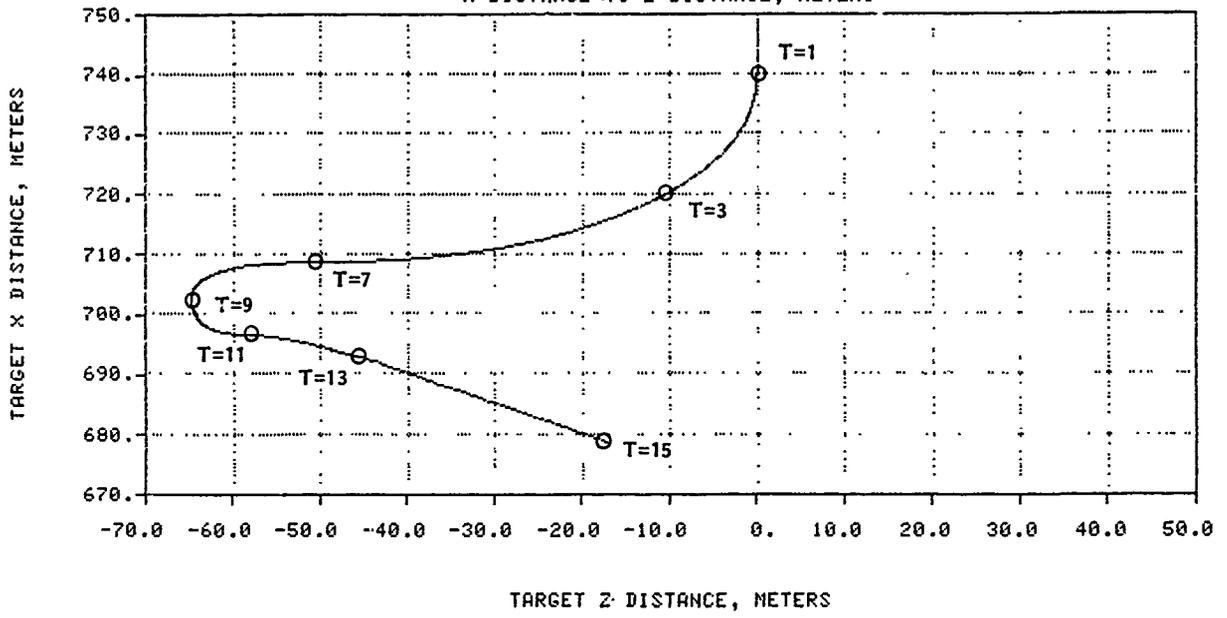
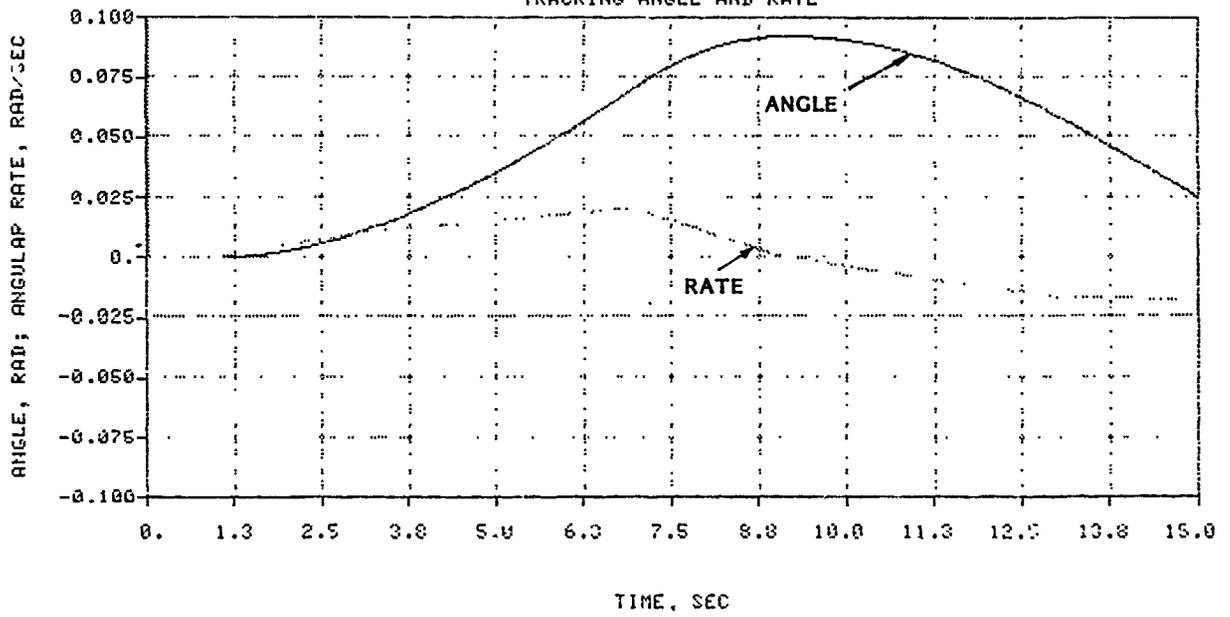
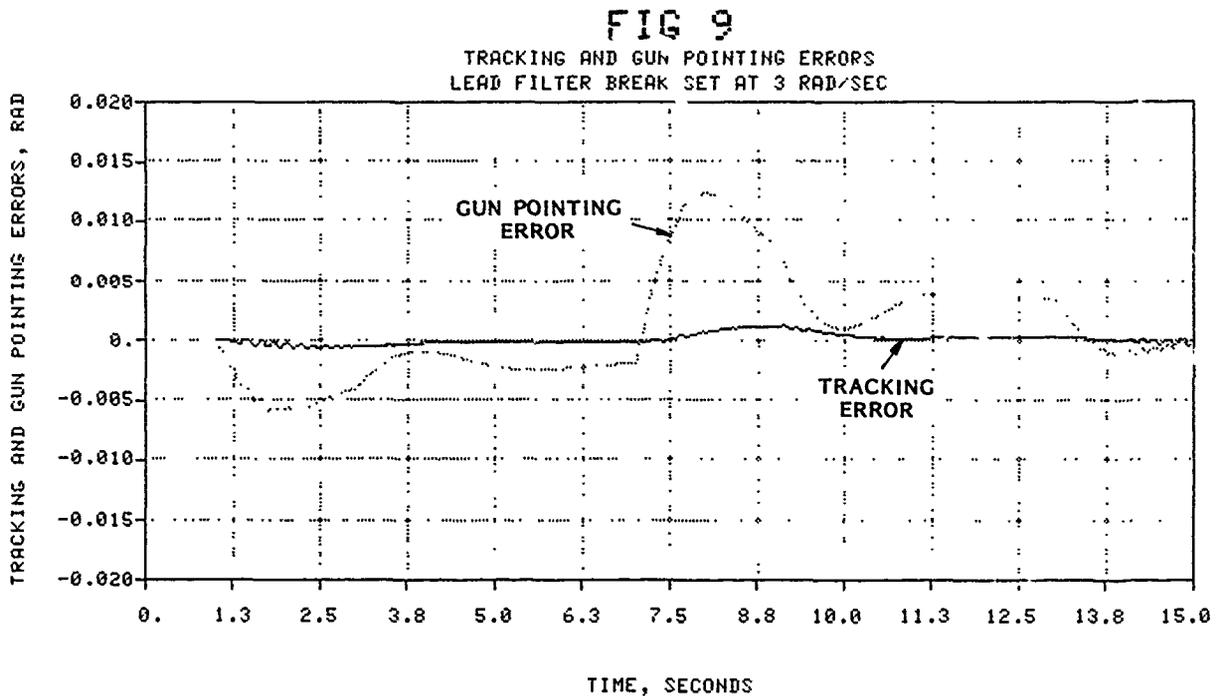
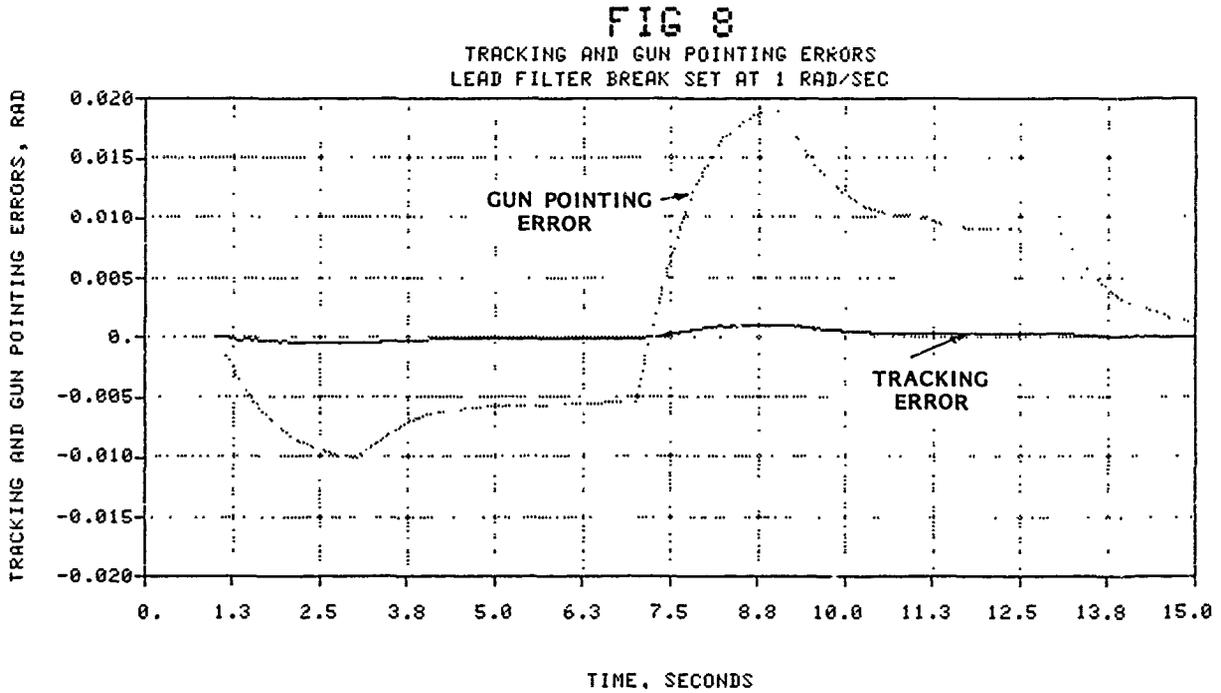


FIG 7
 TARGET TRAJECTORY FOR STUDY
 TRACKING ANGLE AND RATE

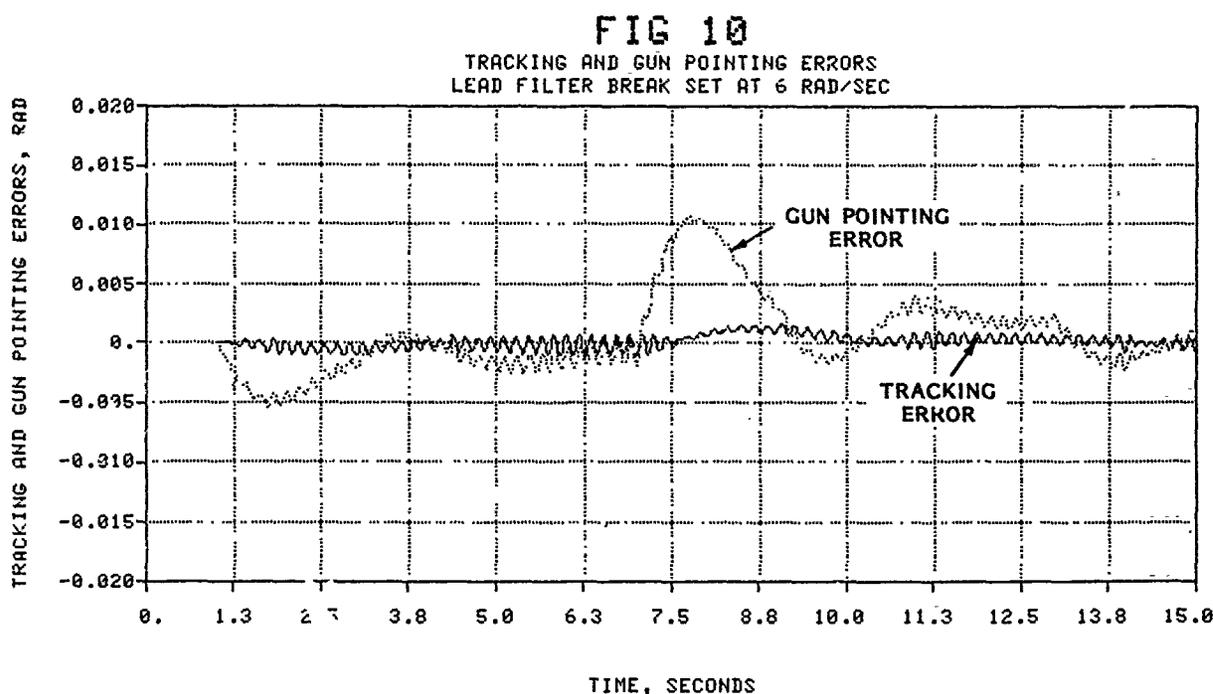


"gun pointing error" is quite large, reaching a peak of 19 mr. This error is large because the lead angle being generated from the filtered hand station signal is not "keeping up" with the lead that would be associated with the actual target angular rate.



Second, the system was run with the hand station filter break set at $W = 3$, with the results of this run shown in Figure 9. The tracking error is about the same as before, but the gun pointing error is substantially reduced, having a peak of about 12 mr.

Figure 10 shows the results with the hand station filter break set at $W = 6$. The gun pointing error is reduced slightly to a peak of about 10.5 mr. Great improvement should not be expected as this filter break is already well above the gunner bandwidth. Note in Figure 10 the high frequency oscillation in the error response which is associated with suspension resonant frequency. It is expected that a "real" gunner would not excite this noise at all.



The large gun pointing errors presented above do not represent the whole story. These errors are simply those associated with failure to follow a lead angle based on a straight-line target course. For a maneuvering target, such as used here, the simple lead is far from correct. After the target trajectory has been completed, the correct lead angle at every point can be determined. Figure 11 shows the "gun pointing error" of Figure 9, and also the additional error associated with an incorrect lead solution. It is clear that the latter error is greater than the former during most of the trajectory. The true error is of course the sum of these components, and is shown in Figure 12.

In view of the incorrect lead solution being a large part of the total error, a logical improvement would be to use a higher order lead predictor. That is, instead of

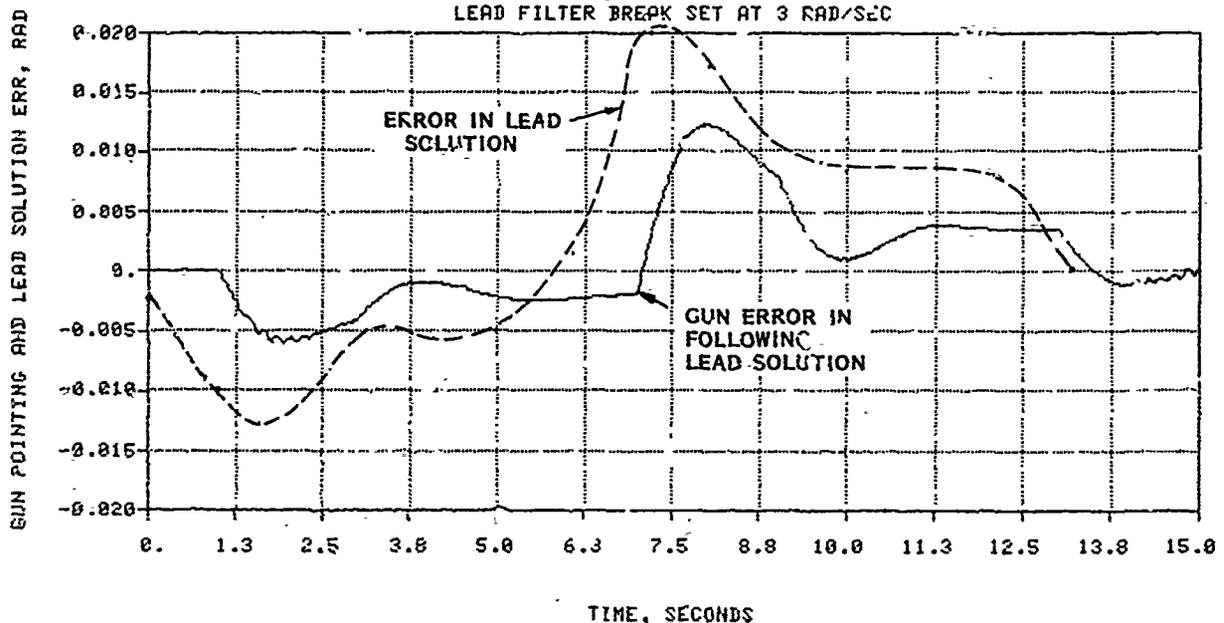
$$\text{Lead} = \dot{\theta} T_F$$

the following function was tried:

$$\text{Lead} = L = \dot{\theta} T_F + \ddot{\theta} \frac{T_F^2}{2}$$

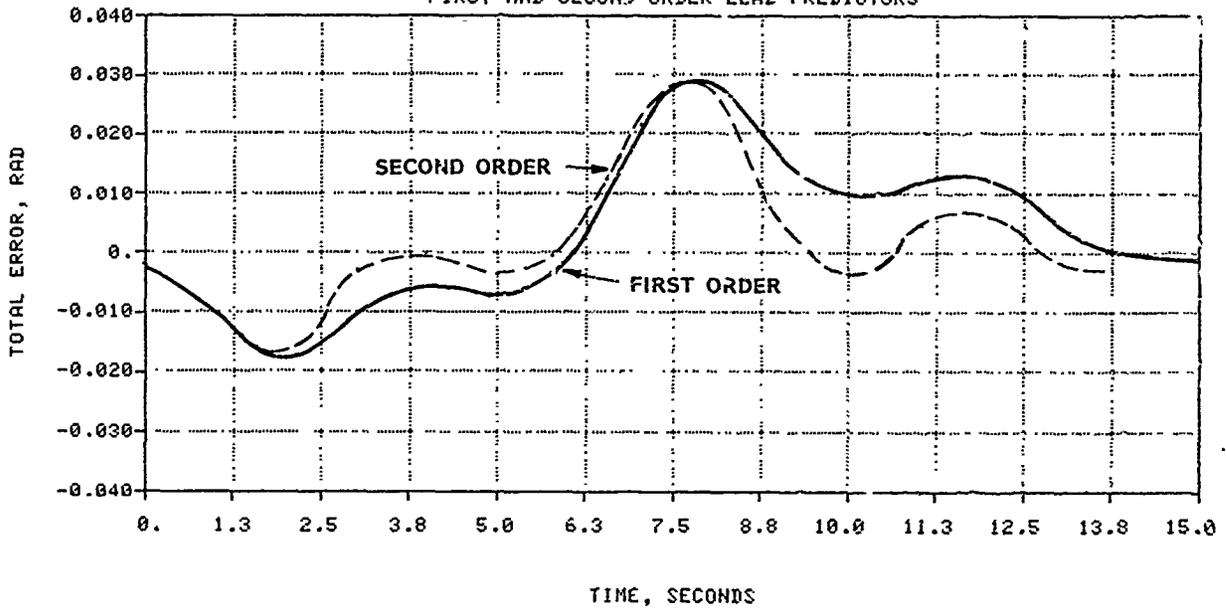
FIG 11

GUN POINTING AND LEAD SOLUTION ERRORS
LEAD FILTER BREAK SET AT 3 RAD/SEC



The results of this are also shown in Figure 12. The accuracy is improved considerably during the "well behaved" portions of the trajectory, but not at all during the unpredictable portions of the trajectory. Obviously, large target maneuvers occurring within the time of flight of the round are going to cause large miss distances regardless of the sophistication of the fire control system.

FIG 12
 TOTAL ERRORS
 FIRST AND SECOND ORDER LEAD PREDICTORS



CONCLUSIONS

Functional requirements for some of the elements of a disturbed reticle "add on" fire control system have been defined, particularly those that have an important effect on the plant that the gunner sees and feels. These requirements have been checked using a simulation of a real system. In particular, excessive filtering of the gunner's hand station rate signal for lead generation is not required, and the performance of a disturbed reticle system can be adequate relative to inherent overall errors in a fire control system.

This study has concentrated on target tracking from a stationary vehicle. The complete fire control system may include rate aided tracking, dynamic cant correction, and other features for aiding the gunner during own vehicle maneuvers.⁽⁵⁾ The simulation results have shown the value of own vehicle maneuvers as a defensive measure.

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SESSION II: MISSILE/AIR DEFENSE FIRE CONTROL

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