Analysis on Guidance Laws Implementation based on Parallel Navigation Time Domain Scheme

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Abstract**—** How to develop a novel missile guidance law that can act effectively against very high speed incoming targets, such as ballistic missiles, has been a major concern in the defense technique. On the basis of this requirement, a new integrated proportional navigation guidance is developed in this research against very high-speed maneuverable targets on three-dimensional space. Proportional navigation (PN) has attracted a considerable amount of interest in the literature related to missile guidance and continues to be a benchmark for new missile guidance laws. The detailed analytical study of this empirical guidance law for nonmaneuvering and maneuvering targets was undertaken. Analysis of PN guidance for the homing stage was usually undertaken for nonmaneuvering targets assuming a constant closing velocity. The so-called augmented PN law and other modifications of the proportional navigation law were obtained based mostly on the relationships established for nonmaneuvering targets. However, any optimal guidance law assumes that the trajectory of a maneuvering target, as well as time-to-go and the intercept point, is known. In practice, such information is unknown and can only be evaluated approximately. The accuracy of prediction significantly influences the accuracy of the intercept. Taking into account that the PN law is a widely accepted guidance law and has been tested in practice, it is of interest to consider the possibility of its improvement.

Keywords**—**Guidance Law, Missile, MATLAB, Control System, Stability.

INTRODUCTION

THE engagement of hypersonic ballistic targets has been the new challenges in the world. When a ballistic target reenters the atmosphere after having traveled a long distance, its speed is high and remaining time to ground impact is relatively short. It has been a known design philosophy that the best trajectory for a defense missile to intercept a hypersonic target is called the nearly head-on [1, 2]. Under this setting, the interceptor can ultimately hit the target without resorting to huge lateral acceleration.

In the past, the guidance laws based on the above fundamental requirement were found to be efficient for the targets that are non-maneuverable, and an acceptable miss distance can be obtained. However, more and more new generation attacking targets possess higher speed and maneuverability. Under these situations, it is hard to track these targets by using classical guidance designs [3], since system performance sensitivity was rarely considered in the design procedure that usually caused an unacceptable miss distance. In addition, the missile-target dynamics are theoretically highly nonlinear partly because the equations of motion are best described in an inertial system, while aerodynamic forces and moments are represented in missile and target body axis system. Besides, un-modeled dynamics or parametric perturbations are usually remained in the plant modeling procedure, because of complexity of the nonlinear guidance design problem, prior approximations or simplifications were usually required before deriving the analytical guidance gains. Therefore, one does not know exactly what the true missile model is, and the missile behavior may change in unpredictable ways. Consequently, optimality of the resulting design cannot be ensured any more.

Several guidance design techniques such as linear quadratic regulator (LQR) [4], explicit guidance [5], modified proportional guidance [6] and geometric controls [7] have been previously proposed for the implementation of optimal midcourse or terminal guidance. In particular, linear quadratic regulator [2], modified explicit guidance [8] and neural networks [8, 9] have recently been applied to treat the ATBM

guidance design problem. However, solving the LQR problem or training the neural network in real time is often infeasible. Traditionally, midcourse guidance was often formulated as an optimal control problem to shape the trajectory to maximize the terminal energy or to minimize the flight time. However, the implementation of the optimal control midcourse guidance is very difficult since a nonlinear two-point boundary value problem has to be solved to obtain the optimal trajectory [4]. The neural network guidance might also be unreliable in practice; if the network was not well trained, it usually sensibly interpolates input data that are new to the network [8, 9].

It is well known that fuzzy systems have the ability to make use of knowledge expressed in the form of linguistic rules without completely resorting to the precise plant models. In control applications, fuzzy logic approaches using if-then rules can solve complex and practical problems. In recent years, researchers have also attempted to apply it on missile guidance designs [10-12]. However, only a few results were presented to support feasibility and performance of their proposed approaches. Although many applications of fuzzy logic theory on missile guidance and control have appeared with growing interest, no application to the three-dimensional (3D) midcourse and terminal guidance problem has been attempted.

The parallel navigation guidance approach is extended in this work to deal with the problem. An integrated midcourse and terminal guidance law of an aerodynamically controlled missile system to intercept a maneuvering target is developed. The principle aim to the guidance law is to cope with the complex interactions between a missile system and its changing environment to achieve excellent tracking performance. The design procedure is systematically and orderly. The parallel navigation strategy is robust to the changes of environments and is closer to the ideal thought of guidance law designers. Simulation studies are well performed to verify engagement performance, performance sensitivity and to estimate the defensible volumes under various operating environments.

Proportional Navigation for Missile Systems in the Time Domain

It is well known that investigation of processes and phenomena is linked, first of all, with the construction of mathematical models describing these processes and phenomena using mathematical language. The model is characterized by some parameters, including input variables or control actions, as they are called, or simply controls, output variables or output coordinates, or controlled variables, and also intermediate variables, the so-called state variables. In most cases processes are not considered in isolation but in direct connection with other processes and phenomena. The influence of external conditions—environment—is characterized by the so-called disturbing influences or, simply, disturbances.

As a matter of fact, the mathematical model is nothing but the analytical expression of an interconnection of the specified parameters. The parameters chosen are determined by the problem under consideration. The control theory approach was used to obtain the proportional navigation (PN) guidance law. The line-of-sight (LOS) rate was considered as the system output; the PN law, the commanded missile acceleration, was considered as control, or input; and the target acceleration was considered as disturbance.

The miss distance, the parameter that characterizes the missile guidance system performance, is the system output. The missile and target accelerations are control and disturbance, respectively. In control theory analytical tools were developed for describing the characteristics of control systems based on the concept of the system error. The goal of control is to reduce the error to the smallest feasible amount. The ability to adjust the transient and steady-state response of a control system to meet certain performance requirements is the main goal of its design. To analyze systems their performance criterion should be defined. Then, based on the desired performance, the parameters of the system and its structure should be adjusted to provide the desired response. Because the actual input signals are usually unknown, a standard test input signal is normally chosen. The time-domain analysis is usually based on the so-called step input.

The miss distance in guidance system analysis and design is, to a certain degree, analogous to the error in conventional control systems. The goal of guidance is to reduce the miss distance to the smallest feasible amount. Target maneuvering plays a major role in determining missile system performance. The miss distance due to a step target maneuver is the miss step response, similar to the well-known time-domain characteristic in control theory. Below we obtain analytical expressions of miss distance for simple models of PN guidance systems. Unfortunately, in the time domain the closed-form solutions cannot be obtained for high-order models realistically reflecting autopilot and airframe dynamics. Nevertheless, the models under consideration enable us to establish some properties of linear models of PN missile systems.

Proportional Navigation as a Control Problem

The basic philosophy behind PN guidance, which implements parallel navigation, is that missile acceleration should nullify the LOS rate. However, the realization of this philosophy was based on physical intuition: when the LOS rate differs from zero, an acceleration command proportional to the deviation from zero is created to eliminate this deviation. Below we will consider the PN as a control problem that realizes the parallel navigation rule. First, the linearized planar model of engagement is considered [see Fig.1]. By differentiating equation can be rewritten in the form

$$\dot{\lambda}(t)=\frac{\dot{y}(t)r(t)-y(t)\dot{r}(t)}{r^2(t)}=\frac{\dot{y}(t)}{r(t)}-\frac{\lambda(t)\dot{r}(t)}{r(t)}$$

$$\ddot{\lambda}(t)=\frac{\ddot{y}(t)r(t)-y(t)\dot{r}(t)}{r^2(t)}-\frac{\left(\dot{\lambda}(t)\dot{r}(t)+\lambda(t)\ddot{r}(t)\right)r(t)-\lambda(t)r^2(t)}{r^2(t)}$$

$$\ddot{\lambda}(t)=\frac{\ddot{y}(t)-\dot{\lambda}(t)\dot{r}(t)-\lambda(t)\ddot{r}(t)}{r(t)}-\frac{\dot{r}(t)}{r(t)}\frac{(\dot{y}(t)-\lambda(t)\dot{r}(t))}{r(t)}$$

$$\ddot{\lambda}(t)=\frac{\ddot{y}(t)-\dot{\lambda}(t)\dot{r}(t)-\lambda(t)\ddot{r}(t)-\dot{\lambda}(t)\dot{r}(t)}{r(t)}$$

$$\ddot{\lambda}(t)=\frac{\ddot{y}(t)-2\dot{\lambda}(t)\dot{r}(t)-\lambda(t)\ddot{r}(t)}{r(t)}$$

and introducing the time-varying coefficients

$$a_1(t)=\frac{\ddot{r}(t)}{r(t)}$$

$$a_2(t)=\frac{2\dot{r}(t)}{r(t)}$$

$b(t)=1/r(t)$

it can be presented in the form

$\ddot{\lambda}(t)=-a_1(t)\lambda(t)-a_2(t)\dot{\lambda}(t)+b(t)\ddot{y}(t)$

Taking into account that

$\ddot{y}(t)=-a_M(t)+a_T(t)$

it can be transformed in

$\ddot{\lambda}(t)=-a_1(t)\lambda(t)-a_2(t)\dot{\lambda}(t)-b(t)a_M(t)+ b(t)a_T(t)$

Let $x_1 = \lambda(t)$ and . The missile-target engagement is described by the following system of first-order differential equations:

$\dot{x}_1=x_2$

$\dot{x}_2=-a_1(t)x_1-a_2(t)x_2 -b(t)u+ b(t)f$

where control $u = a_M(t)$ and disturbance $f = a_T(t)$.

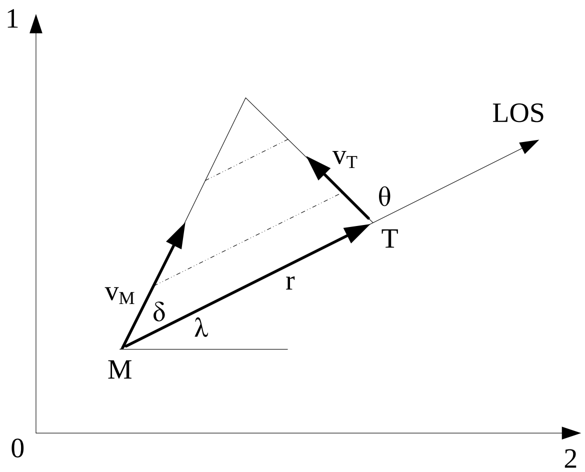

Fig.1. Geometry of Planar Engagement

First, let the case of a nonaccelerating target (i.e., $f = 0$, the assumption that accompanies the main relations used in PN guidance). The asymptotic stability with respect to x_2 (i.e., lim $x_2 \to 0$, corresponds to the parallel navigation rule, so that the control law that satisfies this condition is the guidance law that implements parallel navigation).

The guidance problem can be formulated as the problem of choosing control u to guarantee the asymptotic stability of system with respect to x_2. It is important to mention that the guidance law is determined based on the partial stability of the system dynamics under consideration, only with respect to the LOS derivative. The approach for examining asymptotic stability is based on the Lyapunov method. For above equation, it is natural to choose the Lyapunov function Q as a square of the LOS derivative, i.e.,

$$Q=\frac{1}{2}cx_2^2$$

where c is a positive coefficient.

Its derivative along any trajectory of equation equals

$\dot{Q}=cx_2(-a_1(t)x_1-a_2(t)x_2-b(t)u)$

The negative definiteness of above equation, that is, the asymptotic stability with respect to x_2, can be presented in the form

$(-a_2(t)+ c_1/c)x_2^2 -a_1(t)x_1x_2-b(t)x_2u\le 0$

It follows that for $a_1(t) = 0$ and $c_1 << c$ the control

$u=kx_2=k\dot{\lambda}(t)$

stabilizes system if k satisfies

$kb(t)+a_2(t)>0$

$$k>-\frac{a_2(t)}{b(t)}$$

Introducing the closing velocity $v_{cl}=-\dot{r}(t)$ and the effective navigation ratio N, expression can be written as $k > 2v_{cl}$ and the control law can be presented as

$u=Nv_{cl}\dot{\lambda}(t),\ N>2$

which is the well-known property established for the PN guidance law. For the three-dimensional case and the Earth-based coordinate system, the LOS and its derivative are presented, so that analogous to

$\ddot{\lambda}_s(t)=-a_1(t)\lambda_s(t)-a_2\dot{\lambda}_s(t)+b(t)(a_{Ts}(t)-u_s)(s=1,2,3)$

where (s = 1,2,3) are the LOS second derivative coordinates, $a_{Ts}(t)$ (s = 1,2,3) are the coordinates of the target acceleration vector, and $us(t)$ are the coordinates of the missile acceleration vector, which are considered as controls. The Lyapunov function is chosen as the sum of squares of the LOS derivative components that corresponds to the nature of proportional navigation.

$$Q=\frac{1}{2}\sum_{s=1}^{3} d_s\lambda_s^2$$

where d_s are positive coefficients.

Its derivative can be presented in the following form:

$$2\ddot{Q}=\sum_{s=1}^{3} d_s\ddot{\lambda}_s\dot{\lambda}_s$$

or

$$2\ddot{Q}=\sum_{s=1}^{3} d_s(a_1(t)\lambda_s(t)\dot{\lambda}_s-a_2\dot{\lambda}_s^{\,2}+b(t)\dot{\lambda}_s((a_{Ts}(t)-u_s))$$

Analogous to the planar engagement, under the near-collision course assumption, the controls $u_s(t)$ that guarantee lim $\|\lambda\|\to 0$, $t \to \infty$, can be presented as

$u_s=Nv_{cl}\dot{\lambda}_s,\ N>2\ (s=1,2,3)$

SYSTEM FLOWCHART

The system flowchart for observer compensator design for high gain fast response control system for missile is illustrated in Fig.2.

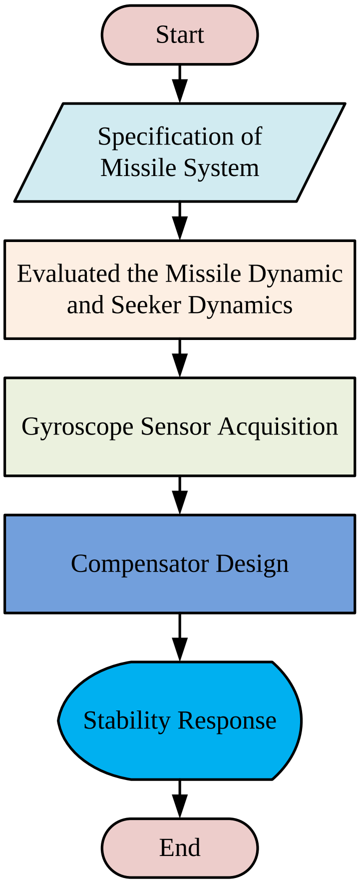

Fig.2. System Flowchart

The unguided missile model for stability analysis is developed by the typical missile system parameters. The missile dynamic and fin dynamic are evaluated from the specification of the typical missile system. The state observer design for missile system is also implemented according to the state space analysis. The lead compensators for missile system are evaluated consistent with the state observer design for missile stability analysis. There are at least two lead compensators design for state observer design techniques. Based on the advanced control system analysis, the missile is guided with stable condition by using missile analysis function and Bode analysis with the help of MATLAB and the observer design evaluation are based on the SIMULINK model of the unguided and guided missile system with stability response.

Flowchart of Miss Distance Analysis

The generalized missile guidance model gives more accurate estimates of the miss distance. Target missile dynamics are presented by the time constant Tt, natural frequency wt, damping dampt, and airframe zero frequency wzt, respectively. Its amplitude characteristic GT(i,1) is written but is not used in the program. To use the generalized model program to determine the peak miss distance the symbol should be deleted from the lines where GT(i,1) is determined, and placed on the line GT(i,1) = 1. The MATLAB program is more powerful for the fourth-order model. Since the two time constants T1 and T2, instead of the factor ac2(i,1) and the program also contains the expression for the phase characteristic f(i,1). As a result, the real RE(i,1) and imaginary IM(i,1) parts of the frequency response can be obtained. The expression of RE(i,1) is used to obtain the miss step response INT(j,1) based on the procedure described in Fig.3.

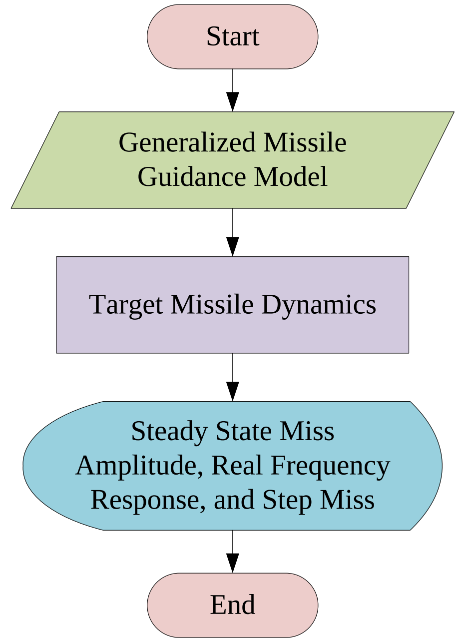

Fig.3. Flowchart of Miss Distance Analysis

Simulation Results of Typical Missile System

Based on the literature survey and background knowledge on the stability analysis of observer compensator for high gain fast response missile stability analysis is evaluated in this chapter. The simulation results of high gain fast response control system for missile system stability analysis are linked with the MATLAB GUI windows.

A. SIMULINK Model of Proposed System Design

The SIMULINK Model of observer compensator for high gain fast response control system for missile system is illustrated in Fig.4. In this figure, the main portion is high gain fast response missile and the state observer design. According to the state observer design the stability analysis is accomplished to the implementation of lead compensator for proposed system.

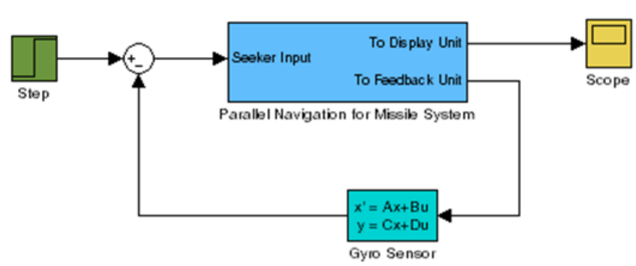

Fig.4. SIMULINK Model of the Proposed System

After debugging the SIMULINK model, the frequency response of typical control system for missile system is demonstrated in Fig.5. Based on the theoretical knowledge of the compensator design, the frequency response has a small amount of the overshoot and it is the stable state of the missile analysis. The specifications are met with the desired situation.

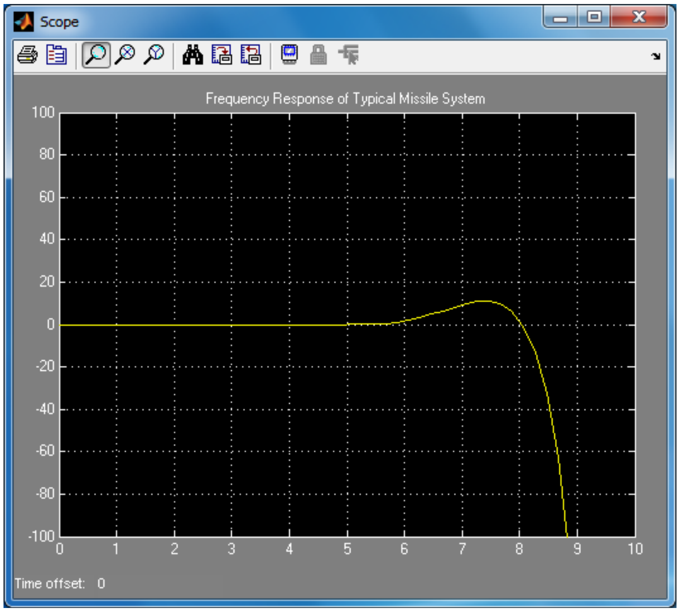

Fig.5. Frequency Response of Typical Control System for Missile System

B. *Miss Distance Analysis*

The steady-state miss amplitude between zero to five radian per second frequency range has the maximum values and the amplitude value approaches to zero after five radian per second. The imaginary values (IM) with respect to real values (RE) for missile trajectory are also mentioned in Fig.6.

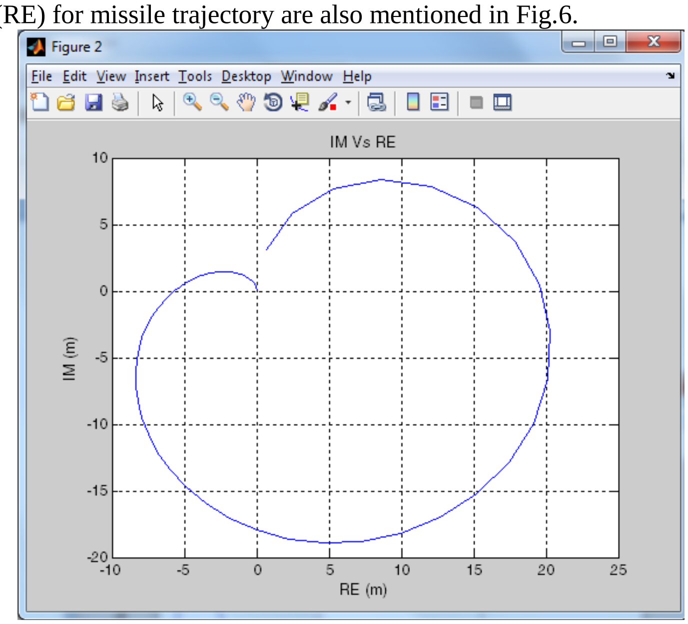

Fig.6. Plot of IM Vs RE

C. *Bode Plots and Frequency Response Plots*

The unguided condition and guided condition of high gain fast response missile system is given in Fig.7. The unguided condition is only stability analysis on the missile dynamic with fin dynamic. The guided condition means the missile dynamic with state observer design and lead compensator for stability analysis. The guided Bode plot meets with the specifications of the gain and phase margin for typical missile system.

The comparison plot of unguided and guided missile response with frequency domain analysis is also developed in Fig.8. After guiding the typical missile system, the overshoot of guided missile system is very less amount than the unguided missile system.

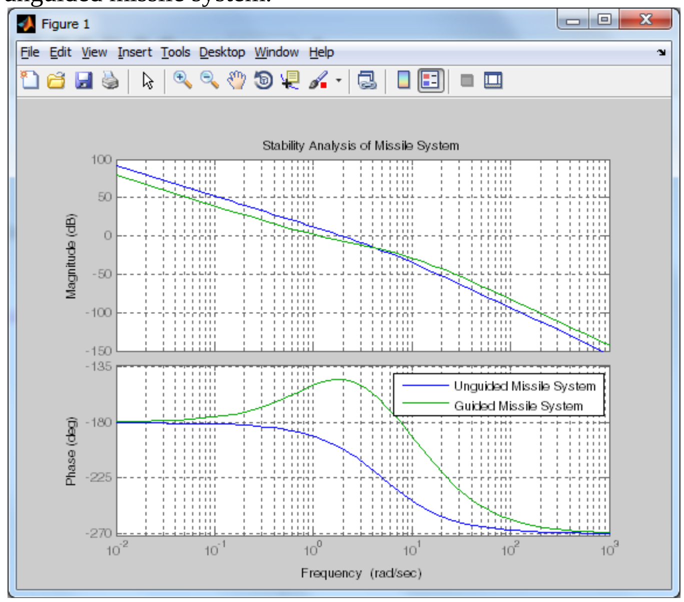

Fig.7. Plot of Stability Analysis of Missile System

CONCLUSION

Experimental results using guidance control system for missile system indicate that, the proposed guidance control is able to achieve higher tracking accuracy than the parallel navigation guidance without compensation, which verifies the effectiveness of the control algorithm. The guidance control method that can be used together with passivity-based controllers in order to enhance the guidance control system for missile system accuracy. The parallel navigation implementation, though similar to an integral action from the point of view of performance in free motion, has several advantages. First, it avoids saturation or overflow of the integrator in case of external disturbance torques (e.g. unexpected contacts). Second, only friction is compensated, instead of the sum of friction and external disturbance, so that it can be used also by impedance control in contact with the environment. Third, the design of the friction observer can be done independently of the MIMO controller design, whereas when adding an integrator all gains of the controllers have to be changed for good performance. Finally, this approach preserves the global asymptotic stability of the original MIMO controller even in the presence of friction. Experimental results validate the approach for the guidance control system for missile system.

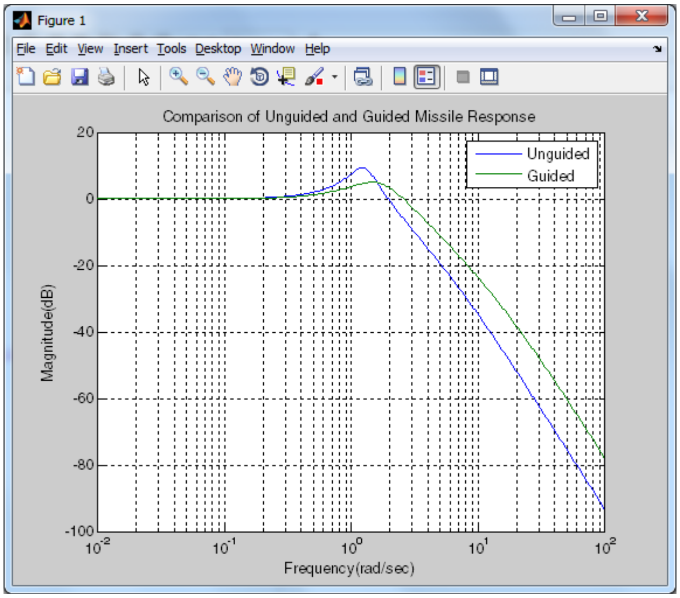

Fig.8. Comparison Plot of Unguided and Guided Missile Response

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