# Wing Size vs Radome Compensation in Aerodynamically Controlled Radar Homing Missiles

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**The aerodynamic configuration of a homing missile is usually based on aerodynamic studies against the spectrum of threats to be engaged. The most "aerodynamically efficient" missile is often selected from single fly-out studies not specifically related to guidance. This paper delineates a tradeoff related to guidance system performance that can affect the aerodynamic configuration. This tradeoff is between radome compensation and wing size. It is shown that radome compensation can be used to reduce wing size, and thereby a missile's drag and weight. A quantitative example is presented for a representative design.**

## Introduction

IN radar-guided, aerodynamically controlled homing missiles, there is a fundamental coupling between the aerodynamic properties of the missile and the electromagnetic properties related to the radome and homing seeker.[1,2] One measure of this coupling is the product of radome refraction slope $R$ and the missile turning rate time constant $T_\alpha$. Radome refraction slope is determined from the angular error introduced into the line of sight to the target as measured by the seeker's radar antenna. The missile's turning rate time constant is determined frofm the amount of angle of attack $\alpha$ required to generate a velocity vector turning rate $\dot{\gamma}$. These two parameters may be the prime determinant of the homing missile's guidance time constant, which is a measure of the overall performance of the missile,[3] especially its miss distance. A fast guidance time constant is required to intercept modern accelerating targets. The product $RT_\alpha$ limits the speed of response of the missile and, therefore, determines the minimum attainable miss against an accelerating target. Since the essential parameter is the product $RT_\alpha$, a missile with a large radome slope and a small $T_\alpha$ will have essentially the same miss-distance performance as one with a small radome slope and large $T_\alpha$. A radome can be compensated electrically or computationally to reduce its slope.[4-6] A missile's $T_\alpha$ can be reduced by adding lifting-surface area such as wings. Therefore, the missile design requires a tradeoff of the benefits and costs of radome compensation vs the size of wings needed to achieve a turning rate time constant $T_\alpha$.

This paper examines the fundamental parameters that contribute to radome refraction slope in addition to those that contribute to the aerodynamic turning rate time constant. Two missile designs are presented: one without wings and another with wings to illustrate the effect of the basic factors. Miss-distance calculations and results are presented for each of these designs to show the relationships between miss distance, radome refraction slope, and wing area.

## Homing Missile Design Factors

Homing missiles are designed to intercept attacking air targets. Missile design begins with the pertinent characteristics and capabilities of these targets. Target speed is used to determine the minimum required missile speed. Target altitude and acceleration capability are used to size the missile lifting surfaces and required maximum angle of attack. The physical dimensions of the target determine glint noise effects and expected radar cross section. The radar cross section, in conjunction with the radar range equation, determines the amount of range-dependent noise seen by the missile's seeker. The target maneuver capability and radar noise properties are basic contributors to missile miss distance. As the missile guidance time constant increases, the miss due to glint decreases and the miss due to target maneuver increases. Therefore, there is a guidance time constant that yields minimum miss distance. The radome-aerodynamic turning rate product ($R \times T_\alpha$) may not allow this time constant to be achieved in practice. This constraint will be discussed subsequently.

## Design Target

For any missile system, a wide variety of targets are used to design the missile. For illustrative purposes in this paper, a single hypothetical design target is chosen to be an airplane with a span of 50 ft, a radar cross section of 100 ft$^2$, a maximum velocity of 2000 ft/s, and an acceleration capability of 2 $g$ at altitude of 60,000 ft.

## Velocity and Acceleration Requirements of the Missile

The velocity requirement of the missile is chosen as 1.5 times that of the target or $1.5 \times 2000 = 3000$ ft/s to ensure intercepting a receding target. The acceleration requirement of the missile is chosen as four times that of the target or $4 \times 2 = 8g$ at 60,000 ft because a proportional navigation missile needs that much acceleration to accomplish intercept.[1]

## Missile Dimensions

Missile dimensions are chosen based on the warhead weight, seeker weight, guidance electronics and instrument weight, actuator weight, structural weight, and fuel weight required to achieve the velocity increment needed to defend a desired area. These topics are beyond the scope of this paper. For the examples to follow, the missile diameter has been arbitrarily chosen as 1 ft and the length as 20 ft. The effect of these assumptions will be discussed subsequently. Using average surface-to-air missile density of 0.05 lb/in.$^3$, the nominal total weight is 1357 lb. For an average mass ratio of 0.6, typical of surface-to-air missiles, the weight after the fuel is burned is 543 lb. This is the weight at intercept, and was used to calculate the missile's acceleration capability and its turning rate time constant $T_\alpha$.

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## Missile Aerodynamic Model

A simple supersonic aerodynamic model of the missile was used to quickly generate the acceleration capability for the tail-controlled missile studied.[7,8] The normal acceleration in $g$'s is

$$N = QSC_N/W \tag{1}$$

where

$C_N$ = normal-force aerodynamic coefficient of the missile
$D$ = missile diameter, ft
$N$ = normal acceleration, $g$
$Q$ = $(1/2)\rho V^2$ = dynamic pressure, psf
$S$ = $(\pi/4)D^2$ = reference area, ft$^2$
$V$ = missile velocity, ft/s
$W$ = missile weight, lb
$\rho$ = air density at altitude, slugs/ft$^3$

Figure 1 shows the simple missile geometry used herein. The aerodynamic model[9] used for the normal-force coefficient is divided into four components—the nose, body, tail, and wing. These are given respectively by

$$C_N = 2\alpha + C_{DC}\frac{S_p}{S}\alpha^2 + \frac{8S_{\text{tail}}(\alpha+\delta)}{S\sqrt{M^2-1S}} + \frac{8S_{\text{wing}}}{S}\frac{\alpha}{\sqrt{M^2-1}} \tag{2}$$

where

$C_{DC}$ = cross-flow coefficient, $\triangleq$ 1.5
$L$ = length of missile
$M$ = Mach number
$S_p$ = missile planform area, $= (L - L_1)D + (2/3)L_1D$
$S_{\text{tail}}$ = tail area $= (1/2)h_T(C_{RT} + C_{TT})$
$S_{\text{wing}}$ = wing area $= (1/2)h_w(C_{RW} + C_{TW})$
$\alpha$ = missile angle of attack
$\delta$ = tail fin deflection angle

Note that this missile planform area and, hence, the lift and moment due to this missile body are roughly proportional to the product of the length and diameter of the missile. This is important when choosing missile size.

The moment equations use simple center-of-pressure distances for each of the component forces. These are defined in Eq. (3). The moment equations are used to ensure that the missile will trim, and to calculate the turning rate time constant.

$$C_m = 2\alpha\frac{X_{\text{CG}} - X_{\text{CPN}}}{D} + \frac{1.5S_p\alpha^2}{S}\frac{X_{\text{CG}} - X_{\text{CPB}}}{D} + \frac{8\alpha S_{\text{wing}}}{\sqrt{M^2-1S}}\frac{X_{\text{CG}}X_{\text{CPW}}}{D} + \frac{8(\alpha+\delta)S_{\text{tail}}}{\sqrt{M^2-1S}}\frac{X_{CG} - X_{\text{HL}}}{D} \tag{3}$$

where

$X_{\text{CG}}$ = center-of-gravity distance from the nosetip $= L/2$
$X_{\text{CPB}}$ = center of pressure of the body section measured from the nosetip $= (L_1 + L)/2$
$X_{\text{CPN}}$ = center-of-pressure location of the nose section measured from the nosetip $= (2/3)L_1$
$X_{\text{CPW}}$ = center of pressure of the wing section measured from the nosetip $= L_1 + L_2 + 0.7C_{RW} + 0.2C_{TW}$
$X_{\text{HL}}$ = location of the tail hinge line and tail center of pressure from the nosetip $= L - 0.3\ C_{RT} - 0.2\ C_{TT}$

Note that the center of pressure of the tail is assumed to be at the hinge line of the tail and that the center of pressure of the wing is assumed to be at the center of gravity of the missile. There are also assumptions made as to the center-of-pressure and center-of-gravity locations, which are based on empirical data.[9] These are all simplifying assumptions that clarify the result but do not affect is generality.

The normal-force coefficient $C_N$ and the moment coefficient $C_M$ both vary with angle of attack and fin deflection. The partial derivatives of these coefficients are defined as

$$C_{N_\alpha} \triangleq \frac{\partial C_N}{\partial \alpha} \tag{4}$$

$$C_{N_\delta} \triangleq \frac{\partial C_N}{\partial \delta} \tag{5}$$

$$C_{M_\alpha} \triangleq \frac{\partial C_M}{\partial \alpha} \tag{6}$$

$$C_{M_\delta} \triangleq \frac{\partial C_M}{\partial \delta} \tag{7}$$

The aeroderivatives $M_\alpha$ and $M_\delta$ are related to partial derivatives of the moment coefficient $C_M$ by

$$M_\alpha = QSDC_{M\alpha}/I \tag{8}$$

$$M_\delta = QSDC_{M\delta}/I \tag{9}$$

where $D$ is the missile body diameter and $I$ is the moment of inertia about a line through the center of gravity and normal to the missile length. These aeroderivatives must be kept within certain bounds in order to trim the missile without excessive fin deflections and obtain controllable moments due to angle of attack.[10,11] The normal-force derivatives are used to calculate $T_\alpha$ using the following definitions:

$$Z_\alpha = -32.2QSC_{N\alpha}/(WV) \tag{10}$$

$$Z_\delta = -32.2QSC_{N\delta}/(WV) \tag{11}$$

Then the turning rate time constant is given by

$$T_\alpha = M_\delta/(M_\alpha Z_\delta - M_\delta Z_\alpha) \tag{12}$$

## Wingless Design

In the wingless design, most of the lift comes from the body and nose at an angle of attack to the wind. The tail contributes the necessary moment to trim the missile and to achieve controllable moment derivatives.[10,11] Using Eq. (3), it can be shown that a tail area of 1 ft$^2$ can control the missile at angles of attack up to 30 deg. From Eq. (2), using this tail size, an angle of attack of 21 deg will give the required 8$g$'s at an altitude of 60,000 ft. The resultant turning rate time constant from Eq. (12) is 5.6 s.

## Winged Configuration

The winged configuration can develop the required acceleration at a smaller angle of attack than the wingless one because of the additional lift produced by the wing. The relationship between wing area to develop the required acceleration, angle of attack, and turning rate time constant is shown in Fig. 2. This figure was generated using Eqs. (2), (3), and (12). If a nominal 10-deg angle of attack is chosen, Fig. 2 shows that a wing area of 6.5 ft$^2$ allows the missile to meet its acceleration specification. The center of pressure of the wing was placed at the missile's center of gravity so that no additional moments were added to the missile. The wing changed only the normal force and aerodynamic partial derivatives. At these conditions, Fig. 2 also shows the turning rate time constant to be 2.6 s, less than one-half that of the wingless missile. Of course, the wings add drag at zero lift but also reduce drag at maximum lift. This tradeoff is not considered in this paper.

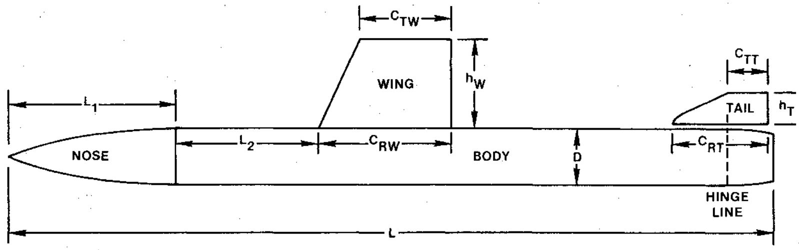


**Fig. 1 Components of the missile aerodynamic model—nose, body, wing, and tail.**

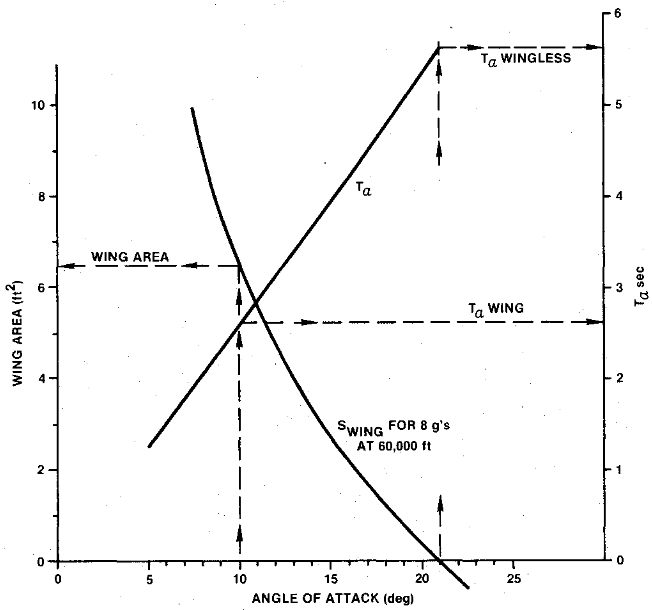


**Fig. 2 Wings reduce turning rate time constant.**

## Configuration Comparison

Both configurations provide adequate acceleration capability to intercept the design target. From a system design point of view, the major differences are in the zero-lift drag, the induced drag at maximum angle of attack, and the turning rate time constant. In this paper, we focus on the turning rate time constant difference. The wingless missile's $T_\alpha$ is 5.6 s and the winged missile's $T_\alpha$ is 2.6 s. This is a major difference from a guidance system dynamics point of view.

## Radome Slope

Radome slope generates a radar boresight error as the missile pitches that looks like a target maneuver to the guidance system. The radome slope is determined by the physical dimensions of the radome, its material, signal wavelength, and the diameter of the seeker antenna.[4,5] For preliminary design, it is useful to treat the radome slope as a constant and use the following empirical formula[2,4,5] for its 90th percentile value:

$$R_T = \frac{2.83[F-0.5][1+(2.35\,\epsilon B)^2]\lambda}{k_m d_s \sqrt{\epsilon - 1}} \tag{13}$$

where

$B$ = deviation from design frequency
$d_s$ = dish diameter (slightly less than radome diameter)
$F$ = radome fineness ratio = radome length/radome diameter
$k_m$ = figure of merit
$R_T$ = maximum expected swing for 90% of slopes
$\epsilon$ = radome material dielectric constant
$\lambda$ = signal wavelength

**Table 1 Room-temperature dielectric constants for typical radome materials**

| Material | Dielectric constant |
|---|---|
| Slip cast fused silica | 3.5 |
| Rayceram III® | 4.8 |
| Pyroceram 9606® | 5.5 |
| BeO | 6.7 |
| 97% $Al_2O_3$ | 9.0 |

The radome dielectric constant, used in Eq. (13), is material-dependent and can also be a function of temperature. Dielectric constants for various radome materials can be found in the literature and typical values are listed in Table 1 (Ref. 2).

The figure of merit, $k_m$, is related to manufacturing technology, where higher numbers are indicative of an advanced radome grinding process and better control of material impurities. The radome fineness ratio is chosen as a compromise between the ideal electromagnetic properties of a hemisphere ($FR = 0.5$) and lower drag higher fineness ratio shapes. Radome slope is related to the total radome swing by

$$R = \pm R_T/2 \tag{14}$$

For the configurations in this paper, the parameters used to estimate radome slope are

$B = 0.02$, percent bandwidth
$D = 12$ in., missile diameter
$d_s = 11$ in., seeker diameter
$F = 2$, tangent ogive
$k_m = 6$
$\epsilon = 3.5$, slip cast fused silica
$\lambda = 2$ in., $\approx 6$ GHz frequency

Therefore, the radome slope is

$$R = \pm 0.0418 \tag{15}$$

## Guidance Loop Stability

Radome effects create an unwanted parasitic feedback path in the missile homing loop. This loop effectively modifies the guidance time constant as shown in Eq. (16).[2]

$$T_{G_{\text{eff}}} \approx T_G + \frac{N' V_C R T_\alpha}{V_M} \tag{16}$$

where $T_G$ is the nominal guidance time constant without radome effects, $N'$ the effective navigation ratio, $V_C$ the closing velocity, $R$ the radome slope, and $V_M$ the missile velocity. Positive radome slopes tend to increase the guidance time constant, while negative slopes tend to decrease the time constant. Therefore, for stability,

$$T_{G_{\text{eff}}} \geq 0 \tag{17}$$

or

$$T_G \geq \frac{N' V_C |R| T_\alpha}{V_M} \tag{18}$$

The minimum guidance time constant permissible is obtained when the equality sign of Eq. (18) holds, or

$$T_{G_{\min}} = \frac{N' V_C |R| T_\alpha}{V_M} \tag{19}$$

For the head-on engagement and missile design of this paper, the minimum time constants are $T_{G_{\min}} = 1.17$ s for the wingless missile and 0.54 s for the winged missile (for $N' = 3$).

## Radome Compensation

The slower minimum guidance time constant for the wingless missile would lead to larger miss distance due to target maneuver and receiver noise. Fortunately, it is possible to compensate for radome slope either mechanically or electrically.[5] For compensation by a factor of 2 (reducing $|R|$ from 0.0418 to 0.0209), the wingless missile guidance time constant is essentially the same as that of the winged missile. A factor of 3 compensation gives a minimum guidance time constant of 0.4 s for the wingless missile. For the engagement used herein

$$T_{G_{\min}} = 5 |R| T_\alpha \tag{20}$$

As long as the product $R \times T_\alpha$ is the same for the two configurations, the minimum guidance time constants will be equivalent. In this case we have traded a radome compensation of a factor of 2 for four wings, each panel of which was 6.5 ft$^2$ in area. This tradeoff can be carried as far as the designer's knowledge of the radome slope will allow. There will always be a residual radome slope because the radome slope changes with aerodynamic heating during flight, mechanical manufacturing tolerances, impurities in the material, and a host of other effects. Nevertheless, the tradeoff of radome compensation vs wing area can be used to reduce missile mechanical complexity and, possibly, missile weight; the latter trade is beyond the scope of this paper.

## Miss Distance

To put these results in perspective from a system point of view, we calculate the miss distance to be expected from target maneuver, glint noise, range-independent noise, and semiactive range-dependent (receiver) noise. The formulas for rms miss are taken from Ref. 3 and are reproduced here for completeness. A fifth-order guidance system was chosen with $N' = 3$.

$$M_{TM} = 62.5\, n_T\, T_G^{2.5} / T_F^{0.5} \tag{21}$$

$$M_{GL} = 1.7\, (\phi_{GL} / T_G)^{0.5} \tag{22}$$

$$M_{\text{RIND}} = 3 V_c\, (\phi_{\text{RIND}} T_G)^{0.5} \tag{23}$$

$$M_{\text{RDSA}} = 9.5 V_c^2 (\phi_{RN} T_G^3)^{0.5} / R_0 \tag{24}$$

where

$M_{TM}$ = target maneuver miss
$M_{GL}$ = glint noise miss
$M_{\text{RIND}}$ = range independent noise miss
$M_{\text{RDSA}}$ = range dependent semi-active noise miss
$T_G$ = guidance time constant
$T_F$ = time of flight
$\phi_{GL}$ = glint noise power spectral density, psd
$\phi_{\text{RIND}}$ = range independent noise, psd
$\phi_{\text{RN}}$ = range dependent noise, psd
$R_0$ = reference range

For the engagement in this paper, we used

$n_T = 2g$

$V_c = 5000$ ft/s

$T_F = 10$ s = flight time

$\phi_{GL}^{0.5} = 4$ ft/$\sqrt{\text{Hz}}$ = root power spectral density of glint noise

$\phi_{\text{RIND}}^{0.5} = 1.4 \times 10^{-4}$ rad/$\sqrt{\text{Hz}}$ = root power spectral density of range-independent noise

( 1 mr in a correlation time of 0.01 s)

$\phi_{\text{RN}}^{0.5} = 1.06 \times 10^{-3}$ rad/$\sqrt{\text{Hz}}$ = root power spectral density of range-dependent noise

(7.5 mr in a correlation time of 0.1 s at a range of 50,000 ft)

$R_0 = 50{,}000$ ft = initial range to target

The sources of these numbers depend on the radar illumination power, intercept range, detection range, and other parameters in the semiactive radar equation.

Since the miss distance for each term is a power of $T_G$, the miss from each is a straight line whose slope is the power when miss is plotted on log-log paper. For the sources of mass used, these terms and the total rms miss are plotted in Fig. 3. From this figure it can be seen that the dominant miss sources are the target glint and target maneuver. Increasing the guidance time constant reduces the glint miss and increases the target maneuver miss. Therefore, there is a minimum miss of 11.6 ft at a guidance time constant of 0.42 s. We call this the optimum guidance time constant $T_{G_{\text{opt}}}$ to distinguish it from $T_{G_{\min}}$, which is the minimum time constant allowed by system stability. The miss in Fig. 3 does not include stability considerations. From Fig. 3, it can be seen that the winged missile minimum time constant is greater than $T_{G_{\text{opt}}}$; therefore, this missile allows a miss of 12.8 ft to be achieved. However, the uncompensated wingless missile, where $T_{G_{\min}} = 1.17$ s, would give a miss of five times the optimal, or 60 ft. Improving the radome compensation by a factor of 2 for the wingless missile reduces its minimum guidance time constant to 0.58 s, and,

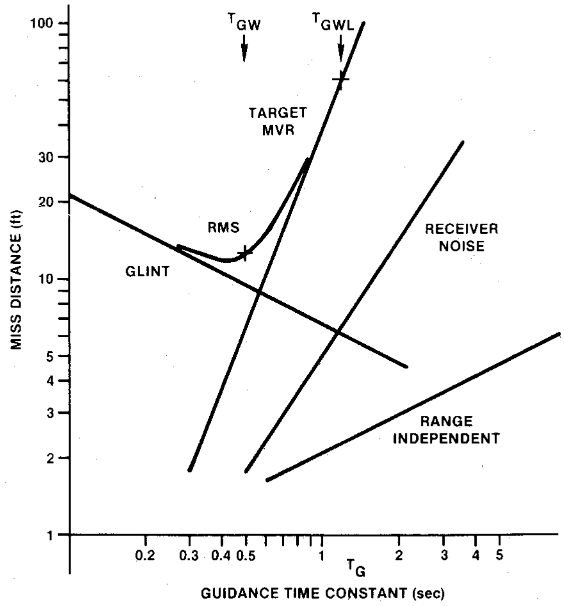


**Fig. 3 Choice of guidance time constant to minimize miss.**

consequently, its miss is reduced to 14 ft, almost identical to that of the winged missile.

## Conclusions

This paper shows that a fundamental tradeoff between radome compensation and wing area of the missile exists for radar-guided, aerodynamically controlled missiles. An example design is presented for a wingless missile and a winged missile defending against the same threat and using the same radar. The results for this example show that a radome compensation of a factor of 2 in the wingless missile yields the same miss distance as the winged missile having a single-panel wing area of 6.5 $ft^2$. Eliminating the wings has the advantages of reducing the missile's zero-lift drag, and possibly its weight. The methodology of the study is presented in sufficient detail to enable this tradeoff to be made for any missile design.

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## References

[1]Nesline, F. W. and Zarchan, P., "Missile Guidance Design Tradeoffs for High Altitude Air Defense," *Journal of Guidance, Control and Dynamics*, Vol. 6, May-June 1983, pp. 207-212.

[2]Nesline, F. W. and Zarchan, P., "Radome Induced Miss Distance in Aerodynamically Controlled Homing Missiles," *AIAA Guidance and Control Conference Proceedings*, Aug. 1984, pp. 99-115.

[3]Nesline, F. W. and Zarchan, P., "Miss Distance Dynamics in Homing Missiles," *AIAA Guidance and Control Conference Proceedings*, Aug. 1984, pp. 84-98.

[4]Youngren, R., "Guided Missile Radomes," *Electronic Progress*, Vol. 3, Sept.-Oct. 1958, pp. 6-8.

[5]Youngren, F. R., "Minimizing Boresight Errors in Aerodynamic Radomes," *Electronic Design*, Dec. 20, 1961, pp. 152-157.

[6]Garnell, P. and East, D. J., *Guided Weapon Control System*, Pergamon Press, 1977.

[7]Koelle, H. H., *Handbook of Astronautical Engineering*, McGraw-Hill Book Co., New York, 1961, pp. 5-1 to 5-26.

[8]Nielson, J. N., Pitts, W. C., and Kaattari, G. E., "Lift and Center of Pressure of Wing-Body-Tail Combinations at Subsonic, Transonic, and Supersonic Speeds," NACA TR 1307, 1957.

[9]Giragosian, P., "Aerodynamic Considerations in the Design of a Vertically Launched Advanced Interdiction MIssile," AIAA Paper 82-1340, Aug. 1982.

[10]Nesline, F. W. and Nesline, M. L., "How Autopilot Requirements Constrain the Aerodynamic Design of Homing Missiles," *American Control Conference Proceedings*, June 1984, pp. 716-730.

[11]Nesline, F. W. and Nesline, M. L., "Homing Missile Autopilot Response Sensitivity to Stability Derivative Variations," *IEEE Decision and Control Conference Proceedings*, Dec. 1984, pp. 1116-1121.