Active Radar Seeker Modeling and Simulation

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Abstract

This paper describes the Mathematical Model of Active Radar Seeker. Seeker is an essential part of any Homing Missile which provides the accurate measurements of the target information in terms of Range, Relative velocity and Angle in the terminal phase. This paper highlights the basic subsystems of Seeker v.i.z RF Front end, Signal Processing and Servo System Models and their modeling and simulation methodologies.

Keywords: RF Seeker, Modeling, Simulation, Servo System

IINTRODUCTION

Mathematical Modeling and Simulation is an important tool in the process of design and development of any complex system such as a Homing Missile System. Mathematical Modeling is carried out based on the physical laws and principles governing the system and computer simulation is used to view the performance of the modeled system. The paper describes the Seeker mathematical model with its essential features. Figure 1 below gives the block diagram of the Seeker Mathematical Model[1].

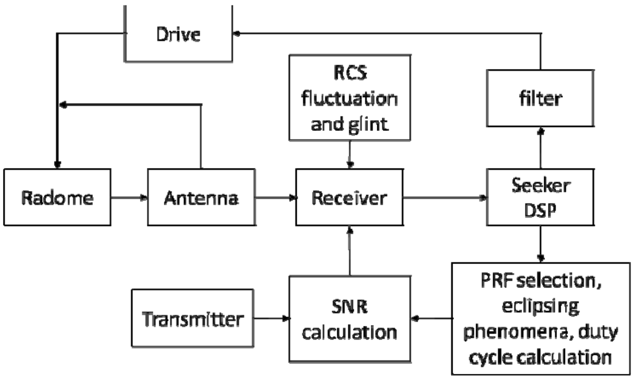

Figure-1 Seeker Mathematical Model Block diagram

This model helps to tune the design of the seeker subsystems iteratively. It also validates the missile On Board Computer (OBC) softwarewithout using the real seeker and RF simulators.It reduces the development cycleandaccelerates the testing and integration process.The design information is collected from the respective designers including the principle of design and is implemented in the model accordingly. The key components of model namelyRadome, Antenna, Transmitter, Receiver, Signal Processing, and Servo system are described in the following sections.

IIRF FRONT END MODEL

RF Front end model consists of Radome, Antenna, Transmitter and Receiver Modules.

1Radome

Radome introduces power loss and distortion in measurement of bore sight error. Loss factor (L) is a function of antenna full deflection angle and in a simplistic model it can be represented as in the following equation

$L(\emptyset) = 1 - a * e^{-b\emptyset}$(1)

Where $\emptyset$ is the full deflection angle given by

$$\emptyset = \cos^{-1}(cos\varphi_y \, cos\varphi_z) \qquad (2)$$

in whichφ_y and φ_z are the antenna angle deflections. The maximum loss occurs when $\emptyset = 0$ and with increase of antenna turn angle, losses decrease. $a$and$b$ are constants which are determined experimentally. At large angle, say 45^0 it reamains in 0.98 to 0.99 ranges. The preliminary analysis shows that radome errors i.e. offset value in a plane of bearing (δ_m) and in plane perpendicular to it(δ_c), depend only on value of full deflection angle $\emptyset$. In present model radome error is introduced as a look up table. Radome antenna pair is calibrated in plane of bearing and cross plane in range from 0^0 to 60^0 with a step of 1^0. For a given true LOS we can compute apparent LOS (in view of radome error) in following manner.

Let R_{True} = Direction vector to true target

R_0 = direction vector of the longitudinal axis in body coordinate system
R_B = direction vector of the apparent target in a plane of bearing
R_C = direction vector of the apparent target in cross plane
R_A = direction vector of the apparent target with radome
R_{True}components are $\{cos\varphi_z cos\varphi_y, -sin\varphi_y cos\varphi_z, sin\varphi_z\}$
And R_C components are $\{0, \frac{-sin\varphi_y cos\varphi_z}{sin\emptyset}, \frac{-sin\varphi_z}{sin\emptyset}\}$.
Finally we can write $R_A = cos\delta_c R_B + sin\delta_c R_C$

From R_A one can compute LOS angles in view of radome error (φ_{RZ} andφ_{RY})
$\varphi_{RZ} = \sin^{-1} R_{Ay}$ and $\varphi_{RY} = \sin^{-1}(R_{Az}/cos\varphi_{RZ})$ where $R_{Ay}$and R_{Az} are the components of R_A.

2Antenna

A resonant slotted wave guide array antenna (distance between adjacent slots equals to the half waveguide wavelength) has been used in the seeker. Modeling of such type of antenna has been described well in [2].Since it is a mono-pulse system, antenna aperture is divided into four quadrants. For direction finding the SUM (∑), two DELTA (Δ) channels aregenerated by summing these four quadrants. Partial directional diagram $F_i$for one slot can be given as

$F_i(\delta_y , \delta_z) = a[i] * e^{\varphi[i]} * \cos \delta_y * \cos \delta_z$ (3)

Where
$a[i]$is the amplitude distribution,

$\varphi[i] = \frac{2\pi}{\lambda} * \sin\left(\frac{\pi}{4}\right) * ((\sin \delta_y - \sin \delta_z * \cos \delta_y) * z[i] * d_H + (\cos \delta_y * \sin \delta_z + \sin \delta_y) * y[i] * d_E)$ (4)

$y[i]$and $z[i]$ are the coordinates of individual slots.
d_E and d_H are the array periods in E and H plane respectively and equal to the half of the wavelength in a resonant slotted waveguide array. Also amplitude and phase errors have been modeled as random variables with a given standard deviation and zero mean. Similarly antenna pattern for each quadrant can be written as

$F_1 = \sum_i a_1 (i) * F_{1i}$;

After getting antenna pattern for each quadrant, Σ and $\Delta_y$and $\Delta_z$channels are calculated as below and kept in a 2D array.

$F_{Sum}= (F_1 + F_2 + F_3 + F_4) * cos\theta/|\sum|$ (5.1)

$F_{DeltaY} = (F_1 + F_2 - F_3 - F_4) * cos\theta/|\sum|$(5.2)

$F_{DeltaZ} = (F_1 + F_3 - F_2 - F_4) * cos\theta/|\sum|$(5.3)

Where $cos\theta = \cos \delta_y * \cos \delta_z$ and $\sum$ is the maximum complex gain in sum channel.Based on servo system feedback (gimbal angles) gain in each channels are interpolated and passed to the receiver modulefor further processing.

3Transmitter

A Klystron based transmitter is usually employed as the high frequency transmitter in the Seeker Applications.While modeling Transmitter, one should consider parameters which may affect the tracking performance of the seeker such as fluctuation in transmitted power. Peak power is proportional to the on-board missile power source i.e. battery which may decrease during the flight. Experimentally we can establish the empirical relationship between two and can be represented in the form

$P_{instant} = P_0 * f(\frac{d(BatteryVoltage)}{dt})^{\alpha}$ (6)

where $P_0$is the initial power and α is a constant determined experimentally.

4Receiver

The receiver module is to process the received RF energy and to produce the error signals proportional to the LOS errors. It is very essential to model the various factors which affects the Bore Sight Error (BSE) measurement and hence guidance accuracy. Some of the factorsare described in this section. The amplitude and phase mismatch between sum and difference channels determinesthe stability of d/s curve. Receiver noise appears as a fluctuating component in angular error measurement as well as glint. While modeling the receiver both should be included. Figure-2 shows the receiver basic model.

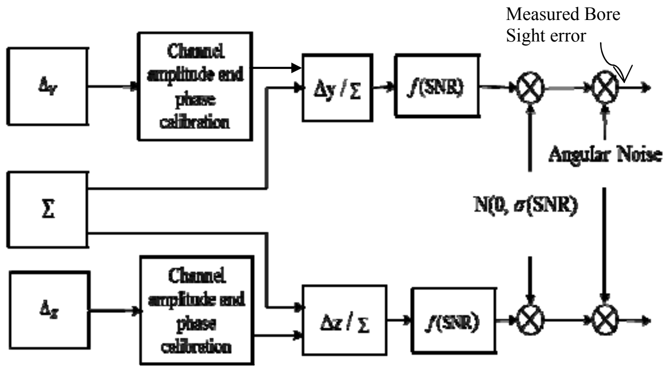

Figure-2 Receier Model

Channel amplitude and phase calibration modeling is done with the help of two random variables named as $\boldsymbol{C_{Ry}}$and $\boldsymbol{cos\ \varphi_R}$where $\boldsymbol{C_{Ry}}$is distributed under the normal law with zero mean and standard deviation $\boldsymbol{A_R}$and$\boldsymbol{cos\ \varphi_R}$is distributed under the normal law with zero mean and standard deviation equal to $\boldsymbol{\varphi_R}$. The theoretical research display that mean of angular error measurement depends on the S/N ratio and this can be expressed with the equation $\frac{S}{S+3N}$[3].Also standard deviation of measurement is a function of S/N and for modeling purpose it has been tabulated at various Signal-to-Noise Ratio (SNR) in a controlled environment for a number of samples. Target Radar Cross Section(RCS) fluctuation can be represented as Swerling case 1. The auto correlation function for RCS fluctuation($\boldsymbol{\rho}$) can be written as

$\boldsymbol{\rho(\tau) = e^{-2\pi B_C \tau}}$ (7)

where $\boldsymbol{B_C}$ is the spectrum bandwidth of angular noise &
$\boldsymbol{\tau}$ is the simulation step size

The RCS amplitude fluctuation $\boldsymbol{\sigma}$ can be represented as the sum of the square of two identical independent normal stochastic processes with zero mean[3] and dispersion $\boldsymbol{2\sigma_{AVG}}$.

$\boldsymbol{\sigma = \varepsilon_1^2(n) + \varepsilon_2^2(n)}$(8)

Where

$\boldsymbol{\varepsilon(n) = \rho * \varepsilon(n-1) + N(0,1) * \sqrt{(1-\rho^2)2\sigma_{AVG}/2}}$ (9)

In the receiver model weak signals are amplified and down converted for further processing.The receiver provides One SUM (∑), two DELTA (Δ) outputs.

III SIGNAL PROCESSING MODEL

The target detection, acquisition and Tracking are achievedusing the Signal Processing Module. Receiver gives three channel output after primary processing and downconversion i.e.one SUM (∑), two DELTA (Δ)outputs.

In addition the designation inputs in terms of angle, Range and Doppler frequency are available from the Seeker OBC. The received signal is suitablyprocessed to obtain the target information in terms of velocity, Range and angle. A simplistic block diagram of the signal processing model is given below in figure-3.

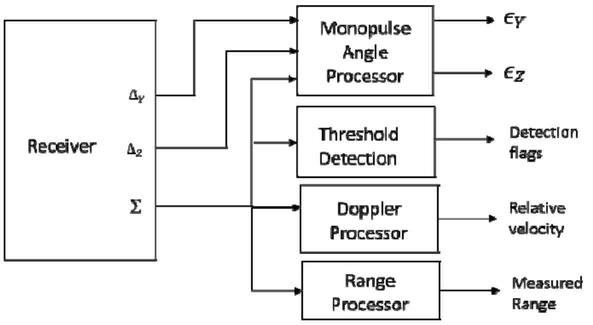

Figure-3 Block Diagram of the Signal Processingmodel

Detection decision is taken in the Threshold detection logic block based on SNR. If the SNR is sufficiently above the threshold consistently for a given observation interval the target acquisition takes place and lock on is declared.Tracking in Doppler and Angle will start immediately after lock-on. Range tracking will start after the built up of sufficient SNR.Sum channel output is used to extract Doppler and range information. In Doppler processing model, after collecting the required samples in a given accumulation period, FFT is computed and Doppler is corrected in Doppler tracking loop. The sum channel is processed by different time gates to search in range. After establishing the track in range, sum is processed by the range discriminator gate only.The range tracking algorithm is modeled in the Range Processor block. With the help of Sum and difference signal outputs given by the receiver model [4] the Monopulse processor block computes d/s values which are proportional to the bore sight errors (ϵ_Y , ϵ_Z).

All the extracted information goes to Data processor which coordinates data transfer among all the seeker subsystems. It can also include Search and Anti Jamming algorithms like Range Gate Pull Off (RGPO) Jamming and Velocity Gate Pull Off (VGPO) Jamming.Angle, Doppler and Range information is passed on to the Guidance system for terminal guidance.

IV SERVO SYSTEM MODEL

The Seeker Servo System meets the dynamic requirements of the Active Radar Seeker. It acts as an interface between the Missile dynamics and the Seeker dynamics.It consists of the mechanical assembly to house the Antenna and associated Control Electronicsand feedback sensors. Modeling of Servo system is done in two modes v.i.z. Position Mode and Track Mode[5]. In each mode the Antenna rotation in Azimuth and Elevation planes is modeled independently. The body disturbance rejection is achieved by the Stabilization Loop which is part of the Track Loop. The innermost loop is the Actuator loopwhich physically imparts the rotation to the Antenna, modeling of the same is similar to both the Position and the

Track loops. The block diagram of the Servo system describing all the control loops is shown in Figure-4.It has a switching logic to change from Position to Track Mode.

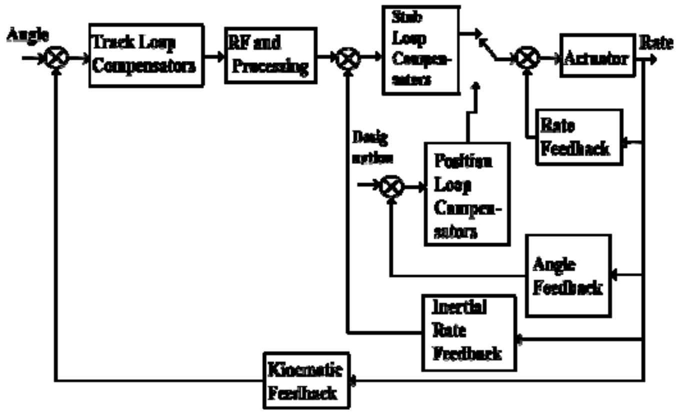

Figure-4Active Radar Seeker Servo System

1 Position Mode

Position Mode is used for the initial orientation of the Antenna in the direction of the Target. The designation command is generated based on the ground Radar information which first detects the target. The seeker servo system responds to the designation commands in the Position mode which operates at a high rate and orients the antenna in the target direction. Angle sensor is used as a feedback element. Compensators can be used to tune the Position Loop design requirements. There is a selection logic incorporated to choose between the Position and Track modes depending upon the mission scenario.

2 Track Mode

Track Loop is required to track the target in Angle. The bore sight error is computed by the Radar Sensor using the monopulse techniques such as amplitude comparisonmonopulse [1] and given to the Servo System. The servo system responds to the angular error sensed by the radar sensor and steers the antenna in a direction to nullify the error thus keeping the antenna bore sight on the target. As the corrections in the angular error are being made the Line Of Sight (LOS) rate varies in accordance with the angular error correction rate. The LOS rate is a crucial parameter required in the Proportional Navigation (PN) Guidance. Servo system makes accurate measurement of LOS rates in the track loop and provides the same for the purpose of Homing Guidance. Servo system also measures the gimbal angles and provides the same to the guidance system.

The stabilization loop is required to maintain the spatial rigidity of the Antenna. Stabilization loop consists of a rate gyro as the feedback sensor and the effective body disturbance which is carried onto the payload will be negated by the stabilization loop compensators in the presence of the track loop requirement.

Momentary search command may be issued in case of track loss. But in view of the shortest engagement times the search option will normally be avoided in the active radar seekers. In case of loss of tracking information, appropriate track filters such as Kalman filter can be employed to estimate the target track. The Search logics required are also included in the model.

3 Modeling Methodology

Modeling of a Servo System starts with the calculation of loads coming on to the servo system due to the maximum Missile Accelerations in Roll, Pitch and Yaw. The input to the Servo system is obtained from the Missile 6-Degrees of Freedom (DOF) model after appropriate Transformations such as Euler angle Transformations. The Seeker Antenna is mounted on a set of mechanical gimbals and has two degrees of freedom i.e. in Azimuth and Elevation. The system is modeled in two independent channels one for Azimuth plane and the other for elevation plane.

The prime actuator is typically a Motor which is modeled in accordance with the loads coming on to it under the maximum acceleration conditions. Drive Motor Loop includes a Power Amplifier and a first order Motor transfer function. Inherent feedback is present in the Drive Motor Loop in the form of back e.m.f.The Tachogenerator acts as the feedback sensor.Appropriate gear ratio is also included in the Model.

Typical Torque Equations for the Actuator include:

$$T = J\frac{d^2\theta}{dt^2} + B\frac{d\theta}{dt} + \theta \qquad (9)$$

whereT is the Torque, Newton-mete

J is the Moment of Inertiaof Load, N-m/ (rad/s^2)

B is the damping coefficient, N-m/ (rad/sec)

k is the torsional spring constant, N-m/rad

The system will have nonlinearities. The dominant nonlinearities such as saturation, dead zone, backlash and friction (both static as well as dynamic) are considered in the model.

Appropriate Flags are set for Detection, acquisition and Target Lock On and the total Radio Frequency (RF) chain gets activated and the bore sight error is computed. Based on the magnitude of the bore sight error computed the drive motor will rotate the antenna in the appropriate direction to nullify/minimize the bore sight error.

Different compensators such as lag, lead and lag-lead compensators [6], [7], [8] are used in the Control Loop modeling. The parameters of the compensators are suitably tuned to obtain the required time and frequency responses of the Control Loops. All the control loops are modeled to meet the Stability margins and Steady state error requirements.

The modeling of Mechanical Gimbal structure of the Servo system considers various parameters such as moment of inertias, centre of gravity, axes of rotation, weight and volume requirements.

Tachos, Gyros, Potentiometers, Resolvers etc. are a few of the feedback sensors used in the Servo System. The same are modeled using first order / second order transfer function models. Position and Stabilization loop compensators are modeled in accordance with the Servo system specifications and requirements.

As the track loop consists of invariable delays the signal at the input of the stabilization will be proportional to the true LOS rate. The relationship between the LOS Rate ($\dot{\lambda}$) and bore sight angular error (ε') is given by [9]

$$\frac{\varepsilon\prime}{\dot{\lambda}} = \frac{\tau}{\tau s+1} \qquad (10)$$

Where τ is the Track Loop Time Constant

$s$is the Complex Frequency (Laplace Variable)

At low frequencies the bore sight error is proportional to the LOS rate and this forms the required rate command to the stabilization loop. This Rate will be given to the missile Guidance loop as the measured LOS rate. The true rotational rate will be sensed by the Rate Gyro and compared with the computed LOS rate. Ideally the computed LOS rate must be equal to the rate sensed by Gyro. Thus the antenna rotates at the same rate as the rotation of Line Of Sight (LOS) thereby maintaining the track of the target.

With the help of the measured Los Rate $\dot{\lambda}$, the lateral acceleration (a_n) is computed using the following equation:

$$a_n = N \times V_c \times \dot{\lambda} \qquad (11)$$

Where N is the Navigation Constant and

$V_c$is the Closing Velocity

Thus a Seeker Servo System is a Mechanical Assembly housing the Antenna, Control electronics and Sensors. It steers the Antenna in Azimuth and Elevation channels to nullify the bore sight error given by the Radar Sensor and maintains the continuous track of the target in Angle. In the process it generates the LOS rates and Gimbal angles and provides this information for the purpose of Guidance.

The Model is simulated with different input conditions in terms of Missile Accelerations and Track loop requirements. Linearized time delay model is included in the Track loop to account for the processing delays. Sampling times are so chosen to meet the overallseeker system timing and bandwidth requirements. Frequency response analysis is carried out using Bode Plots. The model is used to tune the design requirements of the system stability and steady state response.The transfer functions are represented in zero-pole-gain (z-p-k) form, s-domain form and state space form.The Seeker Servo Model is simulated using

MATLAB®/SIMULINK®[10]platform. The Model is optimized for its execution time using the Debugging and Code optimization tools in MATLAB®.A typical Step response plot of the Track loop Linear Model with Gain variations is shown in Figure-5.

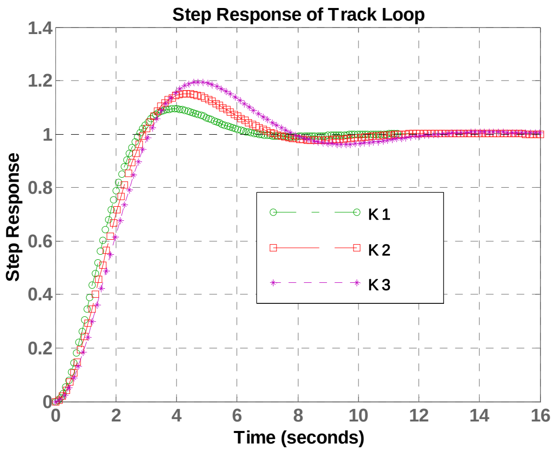

Figure-5 Track Loop Response

V SIMULATION RESULTS

The Active Radar Seeker Mathematical Model is simulated in Matlab®/ Simulink® and C++. The results show adequate performance close to the real hardware. All the simulation Results are available with Authors.

VI CONCLUSION

The model is used in iterative design of complete Seeker system. The parameter variation study of subsystems is carried out using the Model. The model is helpful in simulating critical mission scenarios and to fine tune guidance parameters.Various parameters like Gimbal angles, velocity, range and SNR have been compared with output of the hardware seeker and found to be sufficiently adequatetoresemble the Hardware Seeker for use in Hardware In Loop Simulation (HILS).

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