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Aeroload Simulation of Interceptor Missile using Fin Load Simulator

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ABSTRACT

Interceptor missiles are designed to destroy enemy targets in air. Targets can be destroyed either in atmosphere or out of atmosphere. So for Air Defence scenario, a two layer protection system is required with one taking care of exo atmosphere and another endo atmosphere. In this Air Defence scenario, irrespective of target trajectory interceptor should neutralise it. So the control, guidance are to be designed and validated thoroughly with various scenarios of interceptor and target. These interceptors sense the rates from rate gyroscopes and accelerations from accelerometers which are fitted on board the interceptor. The navigation algorithm calculates the interceptor's position and velocity from these rates and accelerations from time to time. Using these interceptor data and target information received from ground RADAR or on board seeker, guidance calculates accelerations demand and subsequently rate demand. The control algorithm runs in on board mission computer along with guidance. The control algorithm calculates the commanded rate and eventually commanded deflections to the control fins to move towards the target. The fins have to move as per commanded deflections to meet the mission objective of hitting the target. But the load known as aeroload which comes on the control fins during mission, causes control fins not to move as per command. Due to the difference between control command and physical movement of fin, the expected path towards target deviates. This increases the miss distance and also misses the target hit. This aeroload scenario is to be simulated on ground and some feature is to be designed to take care of it during mission. By studying the control system behaviour due to load, the control autopilot is to be automatically tuned to compensate for the loss in commanded deflections. This scenario can be carried out in Hardware-in-Loop simulation (HILS) setup. Mission load conditions can be applied on hardware actuation system in HILS setup and mission performance can be seen and also with different loads and different autopilot tunings.

Keywords: Interceptor; Neutralisation; Rate gyroscopes; Accelerometers; Actuation; Hinge moment

NOMENCLATURE

*alp*13	Angle of attack in the direction of Fin1 & Fin3
*alp*24	Angle of attack in the direction of Fin2 & Fin4
Alpha_t	Total angle of attack
a_x	Forward acceleration
a_y	Lateral acceleration in Y
a_z	Lateral acceleration in Z
C_L	Roll moment coefficient
findefop[0][0]	Deflection of Fin1
findefop[1][0]	Deflection of Fin2
findefop[2][0]	Deflection of Fin3
findefop[3][0]	Deflection of Fin4
f_n	Natural frequency of operation of Actuator
Hm	Hinge moment
Hm[0]	Hinge moment of Fin1
Hm[1]	Hinge moment of Fin2
Hm[2]	Hinge moment of Fin3
Hm[3]	Hinge moment of Fin4
I_{xx}	Moment of inertia about x-axis
I_{yy}	Moment of inertia about Y-axis
I_{zz}	Moment of inertia about Z-axis
L_p	Angular moment about missile X-axis per unit roll rate (damping term)
M	Mass
M_α	Angular force about missile Z-axis due to alpha
M_δ	Angular Force about missile Z-axis due to delta
N_β	Angular force about missile Y-axis due to beta
N_δ	Angular force about missile Y-axis due to delta
P	Roll Rate
Phir	Aerodynamic roll
Q	Pitch Rate
R	Yaw Rate
Rho	Atmospheric Density
r2d	Radian to degree conversion
Talpha_h	Alpha component of hinge moment due to mach number
Tdelta_h	Delta component of hinge moment due to mach number
Th	Thrust
V	Missile velocity
X	Interceptor position in X
X_{CG}	Centre of gravity along X-axis
X_{NS}	Sensor location from nose cone
Y	Interceptor position in Y
y_β	Lateral force along missile body Y- axis due to unit side slip angle
y_δ	Lateral force along missile body Y- axis due to unit deflection
Z	Interceptor position in Z
z_α	Lateral force along missile body Z-axis due to unit angle of attack
Z_δ	Lateral force along missile body Z-axis due to unit deflection
α	Angle of attack in fin frame
α_{Body}	Angle of attack in body frame

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β	Side slip angle in Fin frame
β_{Body}	Side slip angle in Body frame
δ_y	Effective deflection in Yaw
δ_p	Effective deflection in pitch
$\dot{p}$	Rotational acceleration in Roll
$\dot{q}$	Rotational Acceleration in Pitch
$\dot{r}$	Rotational Acceleration in Yaw
ω_n	Natural frequency of operation of Actuator (2*PI*fn)
ξ	Damping factor

1. INTRODUCTION

An Interceptor missile is designed to neutralise a live enemy target in air as early as possible after detection (before it attacks us). For this Air Defence scenario, a two layer protection system is to be designed with one catering for exo atmosphere and another catering for endo atmosphere. In this Air Defence scenario the interceptor design should be such that the target is completely neutralised irrespective of its behaviour. So the control, guidance[1] design is to be validated meticulously with various interceptor and target scenarios. These interceptors are fitted with Rate Gyroscopes and Accelerometers[2]. The Rate Gyroscopes sense the rates (Pitch, Yaw and Roll) and the accelerometers sense the accelerations (in *X, Y* and *Z* directions). Double integration of these accelerations give the interceptor positions in *X, Y* and *Z* directions from time to time. With this information and target information (positions, velocities and accelerations), guidance calculates the required accelerations there by required rates to intercept the target. These required rates will be converted to actuation deflection commands by the Autopilot. The fins should move exactly as per given commands otherwise it leads to higher miss distance resulting in non neutralisation of target. But in air scenario the above is not possible due to load coming onto the fins known as aerodynamic load. So due to the aerodynamic load the fins would not be deflecting to the commanded value. They may deflect less or sometimes more due to the load which comes in the form of hinge moment. Positive hinge moment causes fin feedbacks to be higher than commands and negative hinge moment causes fin feedbacks to be lesser than commands . So this scenario of applying aeroload is to be simulated on ground to know the effect on mission performance (variation of miss distance). The steps involved in this test are clearly explained. This test with load is done for the first time in Hardware-In-Loop-Simulation (HILS) for any missile.

2. INTERCEPTOR SCENARIO

In any generalised interceptor scenario, first the incoming target is to be detected. Once the target is detected by the radio detection and ranging (RADAR), the target information is sent by the RADAR to control centre (CC). The CC will run its algorithm and checks for feasibility of intercepting the target. Once the interception is found feasible, the CC sends this target information and other target identifications to Ground. Then the ground based guidance computation calculates at what instant the target can be intercepted and back calculates to find the time of interceptor launch. The ground computer (GC) calculates when to start the Auto Launch based on this information so that the time of interception is met. The GC starts switching on interceptor subsystems and checking health of all the subsystems and prepares them for launch condition. GC finally gives Liftoff command to the interceptor and interceptor liftsoff. The interceptor gets information about its own position, velocity and acceleration through its Navigation System (NS). The target information as tracked by the RADARs are sent to the interceptor's target data receiver (TDR) from target transmitter (TT) positioned on ground through RF link. This Scenario is presented in Fig. 1.

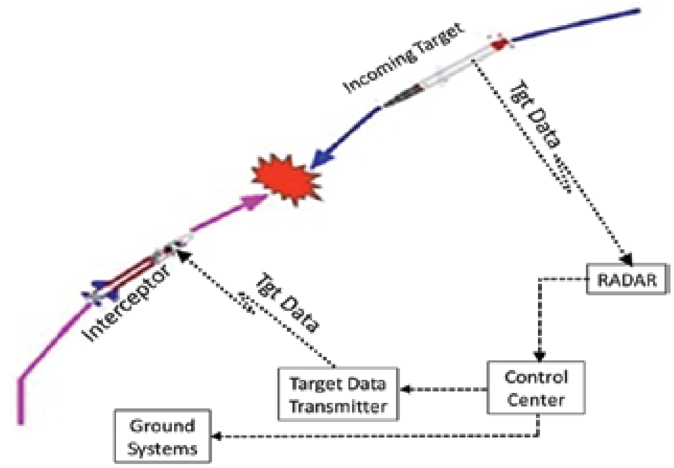

Figure 1. Interceptor target scenario for generalised area defence.

After the interceptor lifts off, the Interceptor positions, velocities and accelerations calculated by the NS are given to the On Board Computer (OBC). The target positions, velocities and accelerations as received by TDR are also given to OBC where guidance and control algorithms are embedded and running in real time[3]. The guidance in OBC then calculates the guidance demands in lateral directions of Y (Y acceleration) and Z (Z acceleration). Based on the difference between demanded and sensed lateral accelerations, rates are commanded to meet the required accelerations. The commanded rates are realised by deflecting the control surfaces of actuation system. The Interceptor moves to the exact position provided, the control surfaces move to the exact deflections as commanded. But due to the Aeroload which comes onto the control surfaces in air, the control surfaces won't deflect to the commanded positions exactly. This difference is to be considered apriori in control design. But before considering any such design in control, this behaviour of actuation system with load is to be considered on ground. This is possible by carrying out aeroload simulation[4] test on ground. So simulation is to be carried out with Actuator model first to ascertain the behaviour of the vehicle with actuation i.e. response, delay and nonlinearities etc. . Then HILS is to be carried out with Hardware Actuator to know the hardware actuator response w. r. t. missile behaviour. This is to be done with no load. Later aeroload is to be applied to the actuation system and HILS is to be carried out to check missile behaviour on ground with that of during mission.

3. MISSILE MODEL

Six parameters are required to define any object in space completely. They are three translational accelerations (a_x, a_y, a_z) and three rotational accelerations (*pdot, qdot, rdot*).

These are developed as shown in equations 1 to 6 below.

$$a_x = \frac{Th - drag}{m} \tag{1}$$

$$a_y = \frac{y_\beta \beta}{m} + \frac{y_\delta \delta}{m} + (X_{CG} - X_{NS}) rdot \tag{2}$$

$$a_z = \frac{z_\alpha \alpha}{m} + \frac{z_\delta \delta_p}{m} - (X_{CG} - X_{NS}) qdot \tag{3}$$

$$Pdot = \frac{LpP}{I_{XX}} + \frac{L_{\delta r} \delta_r}{I_{XX}} + \frac{C_L QSd}{I_{XX}} \tag{4}$$

$$Qdot = \frac{M_\alpha \alpha}{I_{YY}} + \frac{M_\delta \delta_P}{I_{YY}} \tag{5}$$

$$Rdot = \frac{N_\beta \beta}{I_{ZZ}} + \frac{N_\delta \delta_Y}{I_{ZZ}} \tag{6}$$

The forward acceleration a_x is calculated by subtracting drag from thrust (Th) and the value is divided by mass (m). Acceleration in y axis i. e. a_y (lateral acceleration in Y) is calculated as missile body force y_β due to side slip angle β multiplied by β added with vehicle control force y_δ due to control deflection multiplied by effective control deflection δ_y in y axis. The sum of above two forces is divided by mass to get acceleration. This acceleration term is then added to contribution of rotational acceleration in yaw i. e. $\dot{r}$ (multiplied by difference between center of gravity and sensor location (X_{CG} - X_{NS})) to linear acceleration in y axis. Acceleration in z axis i. e. a_z (lateral acceleration in Z) is calculated as missile body force z_α multiplied with α (angle of attack) and added with force due to control deflection (Z_δ) multiplied by effective control deflection δ_p in Z axis. The sum of these two forces are divided by mass to get acceleration. The contribution of rotational acceleration in pitch i. e. $\dot{q}$ (multiplied by difference between center of gravity and sensor location (X_{CG} - X_{NS})) to linear acceleration in z axis is subtracted from previously calculated acceleration.

The rotational acceleration $\dot{q}$ (pitch acceleration) is calculated as sum of moment of vehicle due to α (M_α) multiplied by α and moment due to δ (M_δ) multiplied by effective deflection in Pitch δ_p divided by moment of inertia about y axis (I_{yy}). The rotational acceleration $\dot{r}$ (yaw acceleration) is calculated as sum of moment due to β (N_β) multiplied by β and moment due to δ (N_δ) multiplied by effective deflection in Yaw δ_y divided by moment of inertia about z axis (I_{zz}).

Similarly the roll acceleration $\dot{p}$ is calculated from rolling moment due to damping L_p, the effect due to control i. e. due to effective roll deflection, due to rolling moment with coefficient C_L. Then the sum is divided by I_{xx} (moment of inertia about x axis).

These rotational accelerations are converted into rates by integration. These rates along with translational accelerations are given to OBC where navigation, guidance and control are executed. The deflections generated by control in OBC to correct the errors are given to the actuator model in the missile plant. The output deflections from the actuator model excite the plant and generate translational and rotational accelerations for the next iteration. The navigation, guidance, and control are validated with actuator model to find the lag and nonlinearity for gain and phase margin[5] calculation. Then actuator model is replaced with H/W actuation system to simulate the actual mission.

4. ACTUATOR MODEL

The actuator is considered as a second order model. With experiments it is found that higher order terms higher than second order contribute negligibly to the response of the actuator. First HILS is carried out with Actuator model of an Electro Mechanical Actuation system[6]. In this case an actuator model is developed as a second order model. The two main parameters for a second order model are natural frequency of operation of actuator ω_n (ω_n=2. 0*pi*f_n) and damping factor ξ. The frequency of operation of the actuator is considered as f_n = 18Hz and the damping factor is taken as 0. 7(ξ = 0. 7)[7]. The HILS setup for actuator model in loop simulation is shown in Fig. 2.

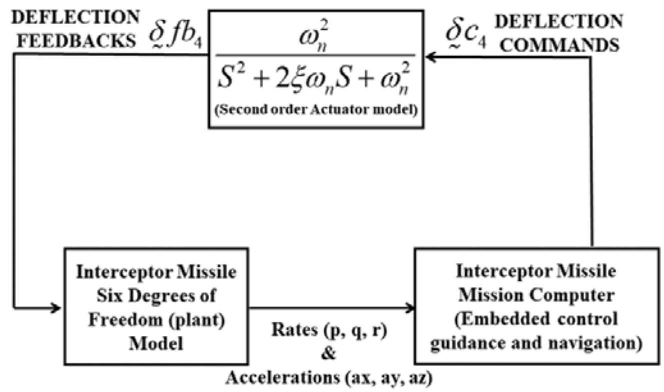

Figure 2. HILS setup for actuator model in loop simulation.

5. HARDWARE (H/W) ACTUATION SYSTEM SIMULATION WITH AEROLOAD

The setup for carrying out simulation with hardware actuation system[8] is shown in Fig. 3. In comparison to Fig. 1 here the Actuator model is replaced with H/W Actuation system. So the deflection commands from the mission computer are given to hardware actuation system instead of actuator model and deflection feedbacks are given to missile model. The simulation results i. e. rates, accelerations, deflection commands and feedbacks are compared with results with actuator model in order to validate the Hardware actuation system.

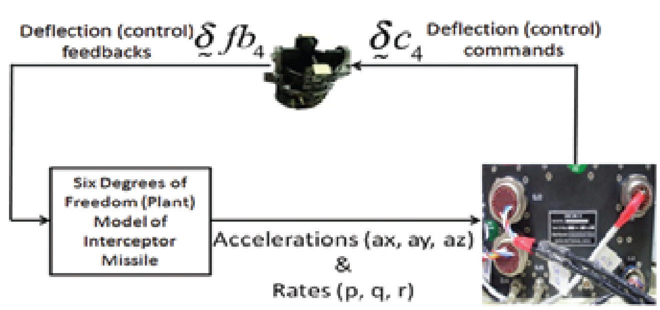

Figure 3. HILS setup for H/W actuator in loop simulation.

In this setup simulation is carried out with no load on the actuation system. But in actual mission load comes on the actuation system either opposing or aiding known as Aeroload.

A setup is established in HILS to carry out aero load[9] simulation of interceptor missile. The setup for carrying out load simulation is shown in Fig. 3. Here the control deflection commands generated by OBC based on missile rates and accelerations sent from 6DOF (Six Degrees of Freedom) model which is also known as missile model and plant model are given to the actuators mounted on Fin Load Simulator. The aerodynamic load which is also known as hinge moment (Hm[]) is calculated in 6DOF model as given in Eqns (7) to (10) below.

Hm[0]= Talpha_h*alp13+Tdelta_h*findefop[0][0]*r2d*Qsd; (7)

Hm[1]= Talpha_h*alp24+Tdelta_h*findefop[1][0]*r2d*Qsd; (8)

Hm[2]= Talpha_h*alp13+Tdelta_h*findefop[2][0]*r2d*Qsd; (9)

Hm[3]= Talpha_h*alp24+Tdelta_h*findefop[3][0]*r2d*Qsd; (10)

where alp13 and alp24 are given by,

alp13= Alpha_t*cos(phir); (11)

alp24= Alpha_t*sin(phir); (12)

And Alpha_t is calculated as, $\text{Alpha\_t} = \sqrt{\alpha_{body}^{2} + \beta_{body}^{2}}$ (13)

Talpha_h & Tdelta_hare calculated as one dimensional interpolation of alphat and delta with mach number. Findefop[0][0], Findefop[0][1], Findefop[0][2] and Findefop[0][3] are deflection commands of fins 1, 2, 3 and 4 respectively. Phir is aerodynamic rotation angle of missile. Q is dynamic pressure (0. 5*rho*v*v), s is surface area, d is diameter of missile and v is velocity of the missile. Radian to degree conversion is carried out with r2d term. Hm[0] , Hm[1], Hm[2] and Hm[3] represent the Aeroload for Fin1, Fin2, Fin3 and Fin4 respectively. This hinge moment as experienced in the mission for each actuator is individually sent through Digital to Analog converter of 6DOF computer to Fin Load Simulator controller as shown in Fig. 4.

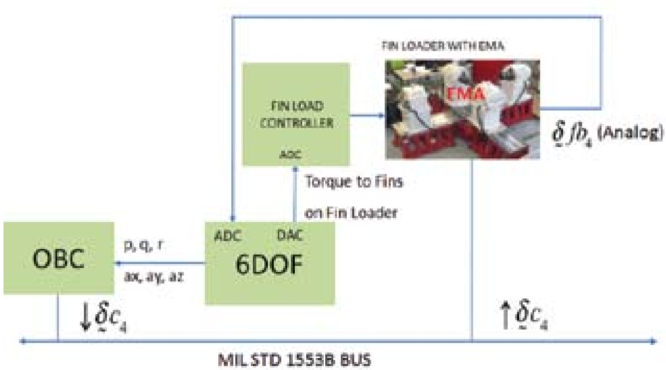

Figure 4. HILS setup for aeroload simulation.

The Fin Load Simulator controller will apply this load (torque) to individual flight actuators[10] through load cell of Fin Load Simulator. The load from 6DOF computer and deflection commands from OBC are synchronised with liftoff. The torque is thus applied throughout the mission and corresponding control deflection feedbacks are recorded. These deflection feedbacks are compared with deflection commands. Mission performance is checked through rates, accelerations and other parameters.

The Fin Load Simulator with four actuators mounted on it is shown in Fig. 5. Fin Load Simulation is carried out for interceptor missile with all four actuators loaded. Actuator closed loop HILS is carried out with actuators loaded with load profile of mission. Torque as sent from 6DOF computer, as received by FLS (Fin Load Simulator) controller, torque feedback received from FLS, Actuator commands and feedbacks are recorded. In the next section the results are presented with details.

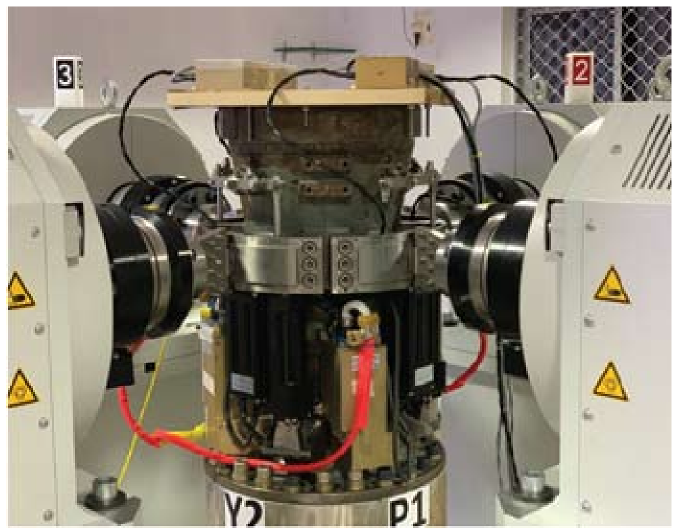

Figure 5. Fin load simulator with four actuators.

6. ACTUATOR IN LOOP RESULTS WITH FIN LOAD

The deflection command and feedback for fin1 called delta1 with load and without load is shown in Fig. 6 along with its 7 to 8 seconds expanded plot in Fig. 7. Similarly deflection command and feedback for fin2 called delta 2 with load and without load is shown in Fig. 8 along with its expanded plot from 24. 7 to 25. 3 seconds in Fig. 9. The aerodynamic load experienced by the interceptor missile fins i. e. fin1 and fin2 are presented in Fig. 10 and Fig. 11. The maximum aerodynamic load experienced by fin1 is 250 Nm. At 8secs, whereas the maximum aerodynamic load experienced by fin2 is 270 Nm. At around 8. 5 secs.

From Fig. 7 and Fig. 9 it is evident that due to the load coming onto the fin the commanded delta requirement is increasing to meet the guidance requirement. This observation is satisfied in case of both fin1 and fin2. The miss distance is found to be increasing as the aerodynamic load increases on the fins.

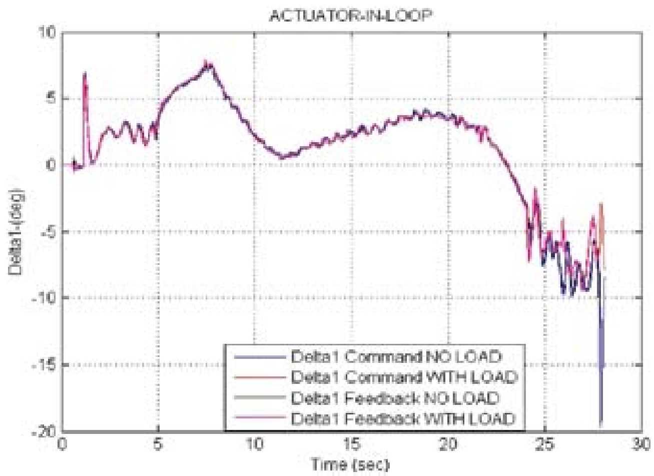

Figure 6. Deflection command Delta1 and feedback with no load and with load.

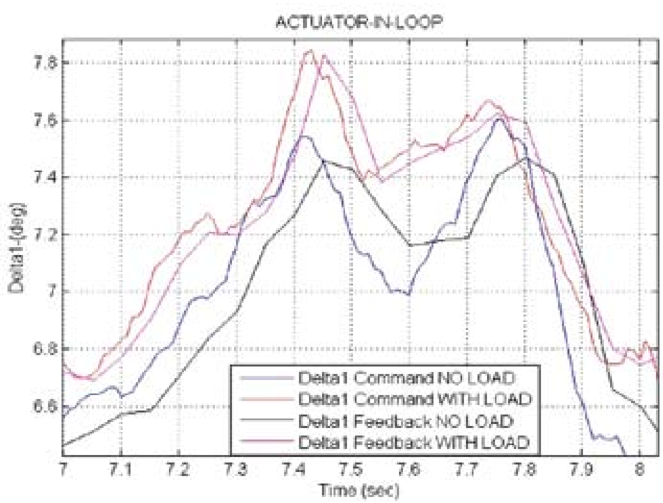

Figure 7. Expanded plot of Deflection command Delta1 and feedback with no load and with load.

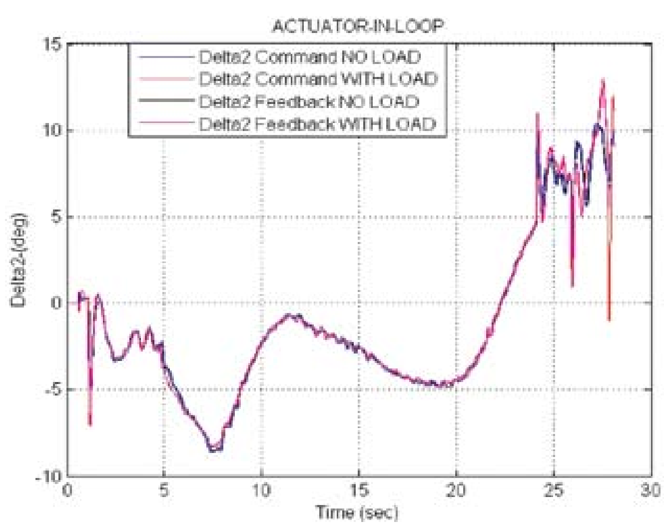

Figure 8. Deflection command Delta2 and feedback with no load and with load.

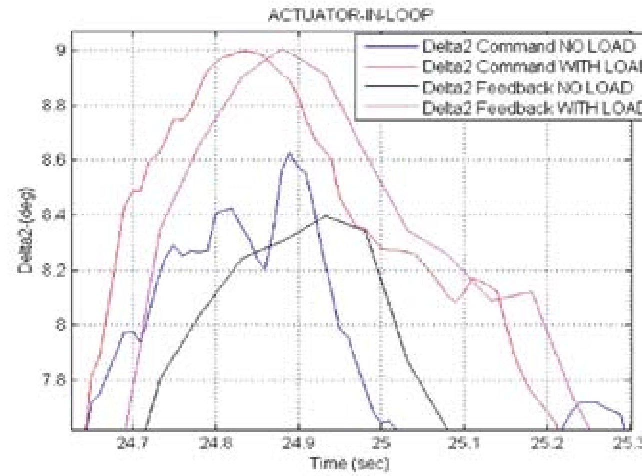

Figure 9. Expanded plot of Deflection command Delta2 and feedback with no load and with load.

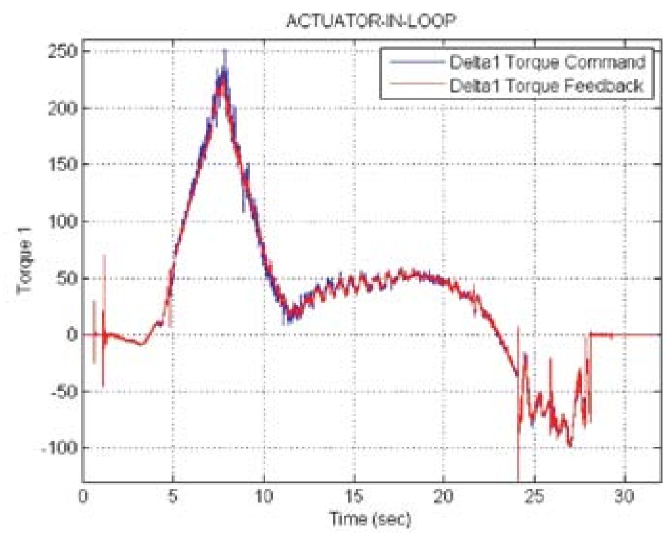

Figure 10. Delta1 Torque command and feedback.

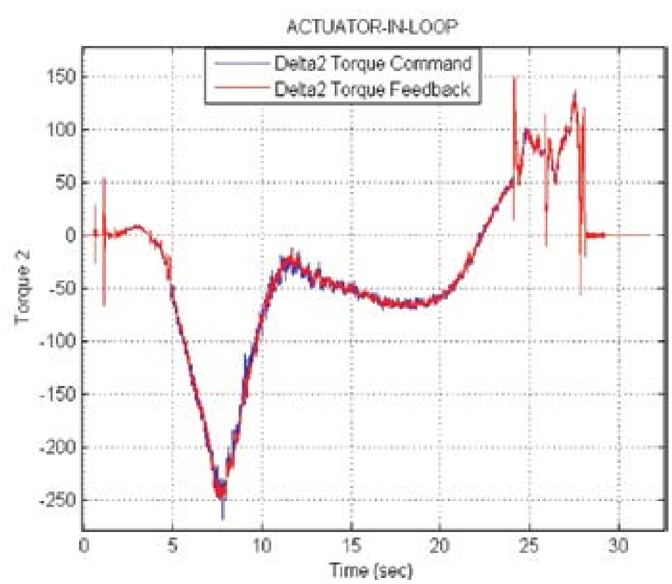

Figure 11. Delta2 Torque command and feedback.

7. CONCLUSION

Carrying out HILS with Actuator in loop without applying load on fins is not mission equivalent as aerodynamic load occurs during missile flight. The behaviour of missile dynamics change due to load. So by carrying out HILS for Actuator in loop with flight load gave confidence for the flight trial as this brings out exact requirement of fin commanded deflections and ability of the actuation system to meet the requirement. This will have direct bearing on miss distance. As the load increases the miss distance will increase unless care is taken in control and guidance design. Whenever load is higher the autopilot is to be speeded up sensing the load to achieve same miss distance irrespective of load as long as the hardware control system can take the load as per its structure. So in future attempt will be made to increase the load in steps and see upto what load the actuation system can work faithfully and we can meet miss distance requirement. These results will be provided to the control and guidance designer to make the design robust for various load conditions.

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CONTRIBUTORS

Mr M.V.K.S. Prasad received his BE in ECE from Osmania University, Hyderabad in 1988. He did his MTech in Software Systems from BITS Pilani in the year 2017. Currently, he is pursuing his PhD from NIT Warangal. He is working in the area of modelling and Hardware-in-Loop-Simulation of various missile systems.
In the present work, he developed integrated real-time simulation software and integrated it with Aero load model of missile. He has established the HILS set up for carrying out Aero load simulation and logged the test results and compared the results of load and no load.

Dr Patri Sreehari Rao received his BTech, ECE in the year 1991 from Nagarjuna University. He has obtained his master's from IIT Roorkee in communication systems and PhD in the IC design from NIT Warangal. He has been working as faculty at NIT Warangal since 1999. He published papers in various national and international journals.
In the present work, he guided in providing interface between 6 DOF model and FLS Controller. He has also guided in interfacing Actuation system to mission computer and 6 DOF computer.

Dr Jagannath Nayak received MSc (Engg.) and PhD in Electrical Communication Engineering from the Indian Institute of Science (IISc), Bangalore, India. He Joined RCI Hyderabad in 1992. He led the development of Fiber Optic Gyroscopes (FOG) as Project Director and served as Associate Dean in Electro-Optical Instrumentation Research Academy (ELOIRA), Hyderabad from 2009 till July 2016. He is currently Director of the Centre for High Energy Systems and Sciences (CHESS) Laboratory, DRDO. He has published over 75 research papers in national, international journals and conferences. He is a recipient of Agni Excellence Award for Self-Reliance, the Nina Saxena Excellence in Technology Award, and the Aeronautical Society of India Swarna Jayanti Award.
In the present work, He guided in developing Rate Gyroscope and Accelerometer model in the Six Degrees of Freedom (6 DOF) model. He verified the rates and accelerations calculated in the 6 DOF model.