Some Investigations on Delay Compensation mechanism in HILS of Aerospace Systems

Submitted in partial fulfilment of the requirements
for the award of the degree of

Doctor of Philosophy

by

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2023

Dedicated

To

My Wife,

Son & Daughter

Declaration

This is to certify that the work presented in this thesis entitled **Some Investigations on Delay Compensation mechanism in HILS of Aerospace Systems** is a bonafied work done by me under the supervision of **Prof. Patri Sreehari Rao**, and **Dr. I M Chhabra** and was not submitted elsewhere for the award of any degree.

I declare that this written submission represents my own ideas and even considered others ideas which are adequately cited and further referenced the original sources. I understand that any violation of the above will cause disciplinary action by the institute and can also evoke panel action from the sources or from whom proper permission has not been taken when needed. I also declare that I have adhered to all principles of academic honesty and integrity and have not misrepresented or fabricated or falsified any idea or data or fact or source in my submission.

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CERTIFICATE

This is to certify that the thesis work entitled **Some Investigations on Delay Compensation mechanism in HILS Of Aerospace Systems** is a bonafide record of work carried out by **Mr. L.A.V Sanhith Rao (Roll No.714137)** submitted to the faculty of **Electronics & Communication Engineering** department, in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy** in **Electronics and Communication Engineering, National Institute of Technology Warangal, India-506004**. The contributions embodied in this thesis have not been submitted to any other university or institute for the award of any degree.

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Acknowledgements

I am grateful to many people who made this work possible and helped me during my Ph.D studies. I am greatly indebted to my research supervisor Prof. Patri Sreehari Rao, HOD, Department of Electronics and Communication Engineering for giving me excellent support during my research activity at NIT Warangal. He encouraged me in choosing my research topic, his vision in my research area leads to successful investigations. I am very much thankful for giving research freedom and guidance, support in non-academic matters and for the humanity shown to me. With his inimitable qualities as a good teacher, he chiseled my path towards perfection. Ever since I met him, he has been an eternal source of motivation, inspiration, encouragement and enlightenment. He is responsible for making the period of my research work as an educative and enjoyable learning experience. The thesis would not have seen the light of the day without his insistent support and cooperation.

I take this privilege to thank all my Doctoral Scrutiny Committee members, Prof. T.V.K. Hanumnatha Rao - ECE, Prof. J.V. Ramana murthy - Department of Mathematics, Prof. N. Bheema Rao - ECE, and Dr. P. Muralidhar - ECE for their detailed review, constructive suggestions and excellent advice during the progress of this research work.

I am grateful to the former Heads of the ECE department Prof. N.V.S.N. Sharma, Prof. N. Bheema Rao, Prof. T. Kishore Kumar, and Prof. L. Anjaneyulu for their continuous support and encouragement. I would also appreciate the encouragement from teaching, non-teaching members and fraternity of Department of E.C.E. of N.I.T. Warangal. They have always been encouraging and supportive.

I take this opportunity to convey my regards to my closest friends for being always next to me. Thanks to Dr. A. Suresh, Dr. Mudassir Mir Basir, Dr. Mushahhid Majid, Dr. Pavan kumar Sharma, Dr. K. Krishna reddy, Raveendra, Nandini, and Jayaram Department of Electronics and Communication Engineering for their motivation and support throughout my work.

I acknowledge my gratitude to all my teachers and colleagues at various places for supporting and cooperating me to complete this work. I would like to thank my family members for giving me mental support and inspiration. They have motivated and helped me to complete my thesis work successfully. Finally, I thank God, for filling me every day with new hopes, strength, purpose and faith.

L.A.V. Sanhith Rao

Abstract

Hardware In Loop Simulation (HILS) testing is crucial in designing and developing aerospace subsystems. The developed sub-systems like a seeker, sensor, and actuator systems are independently validated during the design stage itself to correct any dodges in the system. Further, its performance would be evaluated in the HILS testbed in an integrated real-time scenario that is identical to the near-testing field. If any problem is observed in the HILS run, the design will be modified to get clearance from the HILS testbed to meet the mission requirements. The major problem observed here is diverging oscillations caused by the delay in test set-up during the HILS runs, which severely limits the performance evaluation and yet sometimes leads to mission failures due to false corrections. The first step in HIL Testing is to develop a mathematical model of the plant called as Six Degrees of Freedom (6DOF) model. The next step is the development of a testing scheme that describes the connectivity between various subsystems within the loop along with the 6DOF model and data acquisition of various signals required for validating the performance of the aerospace vehicle.

The HILS testing is essential before declaring readiness of the OBC mission software and other electronic subsystems like a seeker, sensor, actuator, etc. The characteristics and performance of the control autopilot design and guidance algorithm design are evaluated in the simulated dynamic environment of the total vehicle trajectory. The sensor characteristics in connection with autopilot performance are evaluated in a closed-loop dynamic environment. Similarly, the performance of Guidance and Control autopilot is evaluated with real hardware actuators for total trajectory dynamics. Apart from this, guidance and control performance is evaluated in real-time for various perturbation cases and worst-case scenarios. HILS makes it possible to debug and optimize the Control and Guidance offline before incurring the large costs of testing it in a real flight.

The critical sub-systems of the aerospace vehicle are introduced in the HILS testbed one by one to evaluate their performance. The results of HILS runs are presented and analyzed thoroughly to identify the cause of undesired oscillations. The present work focused on analyzing the HILS results continuously. Modeling and simulation of the delay effect are also carried out in Non-Real Time (NRT) and Real-Time (RT) simulated environments to understand the root cause of diverging oscillations. Further, efficient delay compensation mechanisms were implemented systematically in Real Time HILS scenario with all vehicle subsystems to nullify the delay effects and to perform the HILS effectively to meet the mission requirements.

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Abbreviations

`ADC` - Analog to Digital Converter

`ABM` - Anti Ballistic Missile

`APN` - Augmented Proportional navigation

`ATM` - Anti Tank Missile

`CCD` - Charge Couple Device

`CDRS` - Compensation of Dynamic Response of Simulator

`CFMS` - Compensation of Force Measurement System

`CGC` - Control & Guidance Computer

`DAC` - Digital to Analog Converter

`FLIP` - Flight Input Profile

`FMS` - Flight Motion Simulator

`FOV` - Field Of View

`GPS` - Global Positioning System

`HILS` - Hardware In Loop Simulation

`IIR` - Imaging Infrared

`INS` - Inertial Navigation System

`LC` - Launch Computer

`LOAL` - Lock On After Launch

`LOBL` - Lock On Before Launch

`LOS` - Line Of Sight

`NRT` - Non Real Time

OBC - On Board Computer

PGM - Precision Guided Munition

PN - Proportional Navigation

RT - Real Time

SART - Single Axis Rate Table

SLRA - Sight Line Rate Azimuth

SLRE - Sight Line Rate Elivation

TMS - Target Motion Simulator

6DOF - Six Degrees of Freedom

Chapter 1

Introduction

1.1 Hardware-In-Loop Testing

Hardware-In-Loop (HIL) Testing [1] is a methodology to validate the design of Aerospace vehicle subsystems namely autopilot, actuators, sensors, seekers, and On Board computers (OBCs) before actual flight testing. HIL is a real-time testing platform that adds "real" hardware in the loop to evaluate the performance of the system. All the on-board systems like Guidance, Navigation, Control sensors, and Actuators are integrated into a closed loop to perform HIL Testing. It is an important tool for system design and development. A fault in any one of the subsystems could leads to mission failure. Hence rigorous closed-loop real-time testing is required to validate the performance of each sub-system with trajectory dynamics. The first step in HIL Testing is to develop a plant mathematical model called the Six Degrees Of Freedom (6DOF). Subsequently, the testing scheme that describes the connectivity between various subsystems within the loop along with the plant model is to be developed. Moreover, the data acquisition of various signals through interfacing unit is required for validating the performance of the aerospace vehicle. The typical HIL testing of an aerospace vehicle is shown in Figure 1.1.

The HIL testing procedure consists of a 6DOF (i.e. plant) mathematical model connected to all other hardware sub-systems. A Flight Motion Simulator (FMS) is used to simulate flight rotational motion in (x, y, z) directions. The required rotational rates are generated by 6DOF model that excites FMS through real-time interface cards. The attained angular rates of the FMS are sensed by the navigation system which is mounted

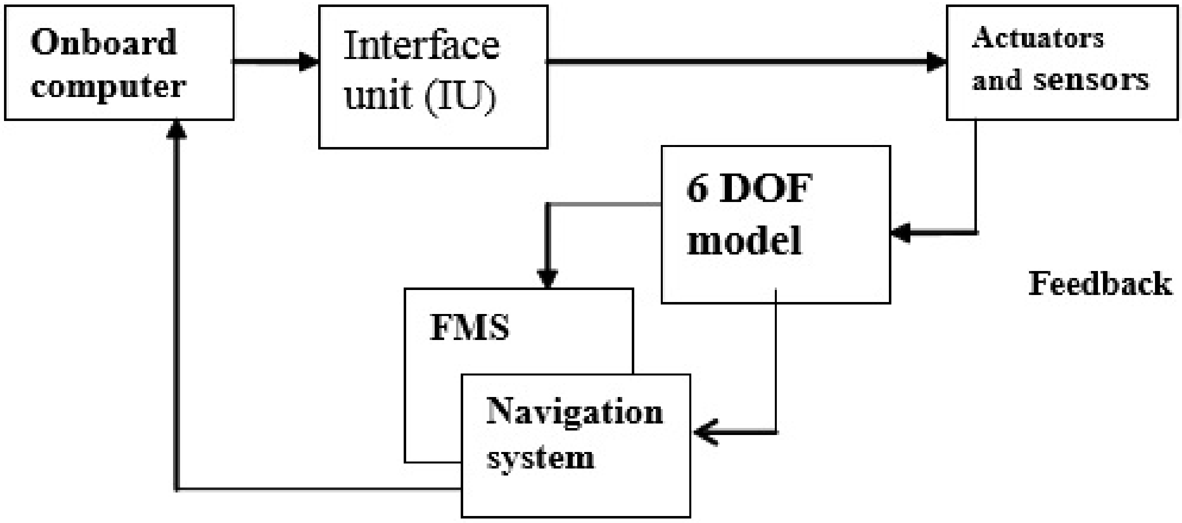


Figure 1.1 HIL Testing

on it, and the sensed rates are input to the OBC to generate deflection commands that excite the actuation system. The response from the actuation system is fed back to the 6DOF model for further computation of angular rates. Thus the closed-loop real-time process continues throughout the trajectory run time.

The HILS test bed is shown in Figure 1.2. It consists of mixed environment that includes hardware sub-systems like IIR seeker and Control Guidance Computer (CGC) and the software simulation models pertaining to actuators and sensors along with a 6DOF model. The performance of hardware actuator and sensor is evaluated in a real-time closed-loop environment, by replacing their models with required hardware step-by-step. Generally, the Imaging Infrared (IIR) seeker system is mounted on a Single Axis Rate Table (SART) to simulate the flight body rates in one plane, and the target dynamics are simulated by the Target Motion Simulator (TMS). An IR bulb is fixed on the TMS to create the pointed image of the target as in the field scenario. This image is tracked by IIR seeker system and decodes it as target dynamics. Based on the target data, the seeker system generates its output and send to CGC to produce deflection commands. These commands enter into simulation PC through real time interface cards to execute the actuator model and to generate deflection feedbacks. In addition to the actuator model, the simulation PC contains mathematical models like 6DOF, sensor, atmospheric, navigation, aerodynamic, euler rates generation, kinematic sight line rate generation etc.

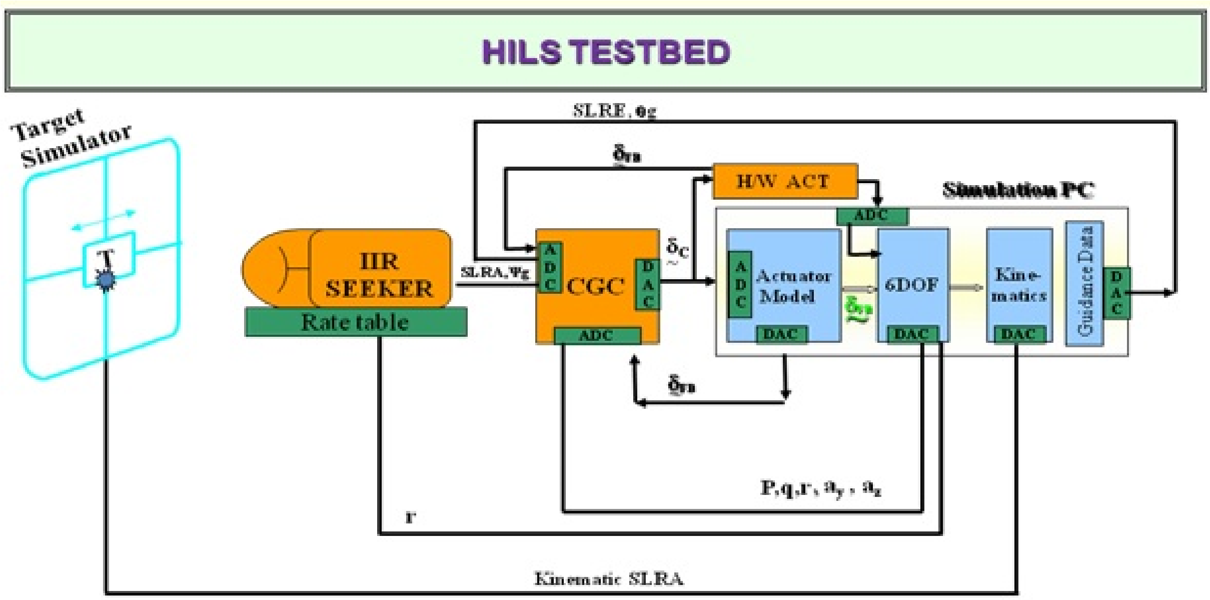


Figure 1.2 HILS Test-bed

The basic mathematical 6DOF model computes six parameters i.e. three rotational and three translational accelerations. The deflection feedbacks from the actuator model as well as the other models' outputs are used in real time to compute 6DOF parameters. The sensor model generates sensed outputs by using 6DOF parameters. The sensed rates and accelerations are forwarded to CGC through real time interface cards and given as input to navigation model as well. This inturn generates positional information and velocities of the aerospace vehicle. These parameters are further utilised to compute aero coefficients that are required to adapt 6DOF parameters. The angular rates and kinematic sight line rates are generated in 6DOF PC to excite SART and TMS respectively. These signals arrive at FMS and TMS through real-time interface cards. The whole process is continued from lift off to target hit i.e full flight trajectory of the aerospace vehicle.

1.2 Motivation

The HILS testing is very crucial in the design and development of aerospace subsystems. The developed sub-systems like seeker, sensor, and actuator systems are independently validated during the design stage itself to correct any pitfalls in the system. The developed hardware will be introduced in the HILS test bed to evaluate its performance in an integrated real-time scenario. If any problem is observed in the HILS run, the design will be modified so that it should pass through to meet the mission requirements. Hence the HILS validation is to be done in a simulated environment, which is identical to near field scenario. But in reality, the following issues were observed while performing the HILS activity.

- Diverging oscillations in the typical parameters of the HILS results
- Large value of body rates and accelerations
- Unexpected behaviour of the sub-system during HILS runs

The major problem in HILS runs is the diverging oscillations, which severely limits the performance evaluation and leads to failures of missions due to false corrections. With these undesired issues in the HILS testbed, the designing of aerospace sub-systems cannot be developed and validated. Hence attempts are to be made to develop a better HILS testbed adjusting the above-mentioned bottlenecks while simulating near-field test scenarios of the aerospace vehicles.

1.3 Research Objective(s)

The objectives of the proposed work carried out are:

- Establishing the HILS testbed in Non-Real Time (NRT) and Real Time (RT) platform.
- Evaluating the design and performance of each aerospace sub-system through sequential introduction into the HILS testbed.
- Analysing the HILS results to understand and address the issues observed when each sub-system is introduced.
- Implementing efficient techniques to minimize bottlenecks like delay or oscillations are experienced in HILS runs.
- For evaluating aerospace systems much prior to the actual field tests.

1.4 Thesis Contributions

The key contributions of this work are summarized as follows:

- Conducted HILS thoroughly with different sub-systems to understand the delay problem
- The delay was modelled using Matlab/Simulink. The corresponding results are nearly matching with the actual HILS results with undesired oscillations in a closed loop real-time run.
- The NRT model is developed and the diverging oscillations are simulated.
- The inverse compensation method was implemented in NRT and the run results are summarized. The compensated results are closely matching with OBC in loop simulation results where the delay effect is not there.
- The inverse and dynamic compensation methods are implemented in real-time HILS. The compensated results are fairly matching with all digital expected simulation results. With this compensation, the HILS testbed emerged as a suitable real-time platform to evaluate aerospace vehicle subsystems effectively.

1.5 Thesis Organization

The rest of the thesis is structured as follows:

Chapter 1 Gives introduction and explains the motivation for the chosen research.

Chapter 2 Presents literature survey and testing work carried out for HILS with different sub-systems of the aerospace vehicle. The issues observed during the HILS activity are also highlighted here.

Chapter 3 Presents characterization of HILS delay through accurate modeling & Simulation.

Chapter 4 Presents efficient delay compensation methods and implementation of inverse compensation and dynamic compensation in HILS.

Conclusions and Future scope are furnished in **Chapter 5**.

Chapter 2

Literature review & Prior work in HILS

2.1 Introduction

This chapter presents detailed review about the evaluation of embedded systems in aerospace vehicle and limited HILS conducted in real-time simulated environment. However, the diverging oscillations are observed due to delay during HILS activity. The delay considerations regarding the performance evaluation of aerospace vehicle are also analysed in this chapter.

2.2 HILS for different avionic systems

HILS is the basic approach to validate the system performance much prior to the actual field testing. The basic methodology to conduct the HILS for different subsystems of aerospace vehicles was considered in [1]. The development of the 6DOF model and its integration with different hardware like OBC, actuator, seeker, and sensor are presented in [1-2] to compute three rotational and three translational acceleration parameters. The input data like thrust, mass, and inertia were supplied to these parameters to compute the required six accelerations. The other models like sensors, actuators, atmosphere, and navigation are used to generate the required data for the 6DOF model presented in [3]. Whereas the semi-automatic guided vehicles are highly dependent on manual intervention to steer the vehicle toward the target and its HILS is presented in [4]. An open framework for highly concurrent HILS is implemented for Flexible AC Transmission System (FACTS) devices is presented in [5]. However, it provides a real-time HILS of a power transmission network.

The HILS methodology for aerospace systems was presented in [6] and conducted simulations using FPGA platform to achieve better simulation time. The Simulink-based HIL simulation [7] is proposed for the rapid prototyping of UAV (Unmanned Air Vehicle) algorithms. The FPGA based HILS [8] is a better approach whereas it is restricted due to its limitation against HILS when interfacing with other subsystems. The HILS for vehicles using infrared imaging [9] is very hard due to its complexity in the simulation of the infrared target background and tracking of that simulated image by the seeker system. The establishment of a HILS setup for vehicle launching from a helicopter is presented in [10] to simulate proper launch dynamics and aerodynamic effects. Moreover, the HIL simulations for the spacecraft attitude control system were presented in [11] to simulate the space scenario. The limitations of HILS of space robotics dynamics using industrial robots is presented in [12] to speed up the HIL testing. However, the HILS results are oscillatory when the actuator system (which is responsible for executing the desired task) introduces an unwanted delay [13-14] in the HILS setup.

The compensations for the actuator delay [15] present a dual compensation scheme which modifies the predicted displacement from the inverse compensation procedure using the actuator tracking error. A novel method for compensating actuator delay in real–time hybrid experiments is given in [16]. In this method, the compensated control signal is generated from the simulation results by using not only displacement but also velocity and acceleration. The actuator delay compensation method for real-time testing [17] is an attempt to analyze actuator delay using an equivalent discrete transfer function. For real-time hybrid structural simulation, an extrapolation procedure for delay compensation [18] is adapted in numerical integration procedures. To achieve better validation of HILS, a delay compensation procedure for multi-actuator real-time dynamic sub structuring using an adaptive polynomial based forward prediction algorithm is presented in [19].

The compensation of time delay techniques are not limited to vehicles but also implemented to validate the design for control of civil engineering structures [20] and testing of a jet engine fuel control unit in flight conditions [21]. Moreover, time delay compensation for a hybrid simulator [22] realizes the desired energy consumption at a collision, which is represented by the coefficient of restitution in the hybrid simulation. An analytical experimental stability investigation performed for HIL satellite docking simulator [23], and in [24] a time delay compensation technique based on coefficient of restitution for collision hybrid motion simulator is used for proper coupled translational and rotational motion. A prediction-based feed forward filter [25] has been developed to make a ground-based hydraulic simulator to generate contact forces and rebound velocities. And it matches with expected values during shuttle on-orbit berthing operations to estimate real-time dynamics.

Delay time problems in HILS for on-orbit docking and compensation is presented in [26] and a second order compensator is used to compensate the delay for proper on-orbit docking. In [27], the inverse and polynomial compensation techniques were proposed to compensate the actuator delay for HILS of a jet engine fuel control unit. A novel application of the smith predictor strategy in HIL testing of an electro-hydraulic fuel control unit for a turbojet engine is presented in [28] to reduce the delay time problems. Another delay compensation approach for HILS of space collision [29] consists of phase lead and error based force compensation techniques used for static delay of the force measurement and dynamic delay of the motion simulator respectively. The HILS divergence of a 6-DOF [30] compensation method is proposed to compensate individual delays like track delay and measurement delay. The development of a HILS system for UAV autopilot design using LabVIEW [31] and HIL testing of wireless systems in realistic environments [32] were proposed to establish suitable simulated testbeds.

Design and development of HILS for spacecraft attitude control system based on wireless Ad-Hoc Networking [33] and HIL testing of wireless sensor networks were discussed in [34-35] to establish testbed without cable interfacing. The active radar seeker modeling and simulation is discussed in [36] to perform seeker HILS efficiently. The current trends in Tactical Missile Guidance (TMG) [37] and chip HILS Framework [38] were introduced to guide the vehicle without any abnormal deviations. A Baseline 6-DOF Mathematical model of a generic missile [39] and a high performance real-time simulator for controller HIL testing [40] is implemented to perform HILS effectively. As a part of modelling, error and uncertainty[41] corresponding to gyro of IIR seeker is characterized and modeled[42]. However, the real-time spacecraft simulation and HIL testing is presented in [43] to have better insight into space vehicle simulation. In addition to this, modelling and closed loop testing for three-level photovoltaic grid-connected inverter based on RT-LAB [44] is implemented to perform HIL testing.

The 6-DOF digital simulations for missile guidance, navigation, and control [45] were studied for accurate modelling, whereas the design and integration of HIL system for a typical missile [46] is explained. For munitions HILS testing, the guidance, navigation, and control [47] is described and FPGA based HILS of induction machine model [48] is presented. The HILS of production systems dynamics [49] are presented to evaluate the flight control systems [50]. Additionally, the HILS methodology is explored for development of Instrumentation, Control and Navigation (ICON) for Anti Tank Guided Missile (ATGM) [51].

2.3 Evaluation of seekers

The seeker is a sub-system of aerospace vehicle that is highly responsible to track the target and to steer the vehicle towards the target. Seekers are used to locate and track the target to provide in-flight guidance for the flight vehicle and also increase the kill probability, based on the energy receiving from the target. The ability of a weapon system in field to attain good precision for striking multiple aim points at conflict region from short, medium and long range which demands the terminal guidance support from the seeker. In multi target neutralization, the decision for the deployment of unitary guided weapon or a force multiplier is dictated by the battle field scenario, state-of-the-art terminal guidance technology as well as the available simulation test-bed. The RF seeker and IIR seeker are shown in Figure 2.1 and Figure 2.2 respectively.

To meet the appropriate homing guidance design, proper vehicle dynamics and accuracy are to be maintained to guide the vehicle terminal. Latest advances in seeker/sensor technology need to be integrated with the guidance system by steering and stabilizing the guided vehicle for locating the target. Establishing the real-time simulation test-bed with seeker is a major challenge to guide and control the vehicles. A real-time 6DOF model is already available in HILS testbed and an attempt has been made to integrate

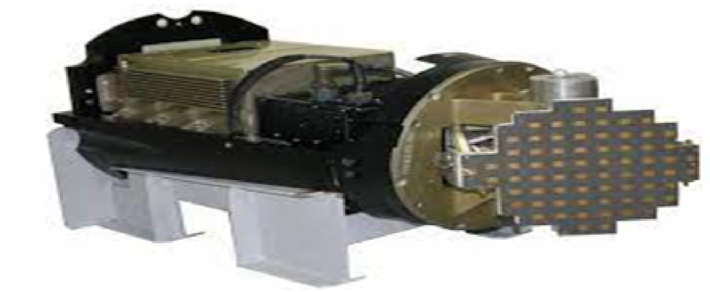


Figure 2.1 The RF seeker

Figure 2.2 The IIR seeker

the seeker system in HILS environment. An enhanced simulation facility available in the CCD/IIR seeker-based guidance system for testing the Anti Tank Missile (ATM) in HILS has resulted in successful test flight with a direct hit against the fixed target. Moreover, the enhancement for locating the target is achieved with the high-fidelity motion simulators to perform HILS effectively. However, the future guidance schemes for different scene generation concept is integrated with RF, Millimetric Wave (MMW) and IIR seekers to guide aerospace vehicles.

The current seekers working is based on the terminal engagement requirement that can be RF/IIR/MMW/Laser or even electro-optical, IR etc. The sensed data collected from these seeker-based sensors (multimode, multi spectrum etc.) is interfaced to guidance system to achieve precise target strike under all weather conditions. Suitably, a variable range flight vehicle using homing guidance system based on CCD/IIR stabilized seeker with Lock on before Launch (LOBL) configuration has been integrated for guiding the vehicle from lift-off to terminal engagement. Hopefully, the seeker with its stiff stabilization loop (Bandwidth $>$ 15 Hz) and accurate (= 1 milli radian) tracking loop (with agility $>$ 2 Hz bandwidth) needs to be tested with the 5-axis motion simulator to represent real flight combat environment. So, the real-time simulation guidance for flight vehicles is achieved with an integrated 6DOF vehicle model that is validated in real-time during control of the flight dynamics. Moreover, it is extended to a full-scale HILS that has been evolved for seeker characterization to fine-tune the performance of seeker before HILS along with target dynamics for guided flights.

A seeker model before dynamic tests is helpful in specifying the requirements of dynamic tables. A target motion system dynamic has to be much higher than that of guidance loop and preferably more than seeker track loop. Further, aerospace vehicle autopilot bandwidth requirement demands much higher as compared to the dynamics of Flight motion simulator (FMS). The isolation ratio of the seeker can be tested with higher dynamic FMS, moreover a typical HILS testbed has been established within the current limitation for validating the guidance and control system. The uncertainties arising due to simplifications in mathematical models for validating the image processing algorithms under dynamic conditions are avoided when HILS attempts are being made to introduce IR target growth, atmospheric attenuation and background scene generation. The guidance system needs advanced real-time signal processing technique with state-of-the-art distributed embedded systems and multi-protocol connectivity requires the support from the data fusion. However, the sophisticated hardware for input-output interfaces is used to bring connectivity in real time simulation environment.

2.3.1 Homing Guidance Requirements and Techniques

Vehicle dynamics and accuracy are the prime factors for guided vehicle terminal management, which can be met by appropriate homing guidance design. Basically, the homing guidance requirements and techniques need seeker modelling, dynamic tests and HILS with seeker system. The functional block diagram of a flight vehicle is shown in Figure 2.3. When considering a typical anti-tank weapon using homing guidance system based on IIR stabilized seeker, it uses LOBL for guiding the weapon. The seeker system as well as entire guidance and control system need to be evaluated independently before integration. A typical dynamic test plan, which is helped to evaluate the performance of the seeker is developed to meet the need of guidance system design. The flight vehicle homing guidance requirements with stabilized seekers, changes with miniaturization as well as the state-of-the art algorithm design. Similarly, for the Precision Guided Munition (PGM) weapon needs stabilized seeker to lock-on after ejection from the flight (mother) vehicle with appropriate automatic target recognition techniques. In this case, the PGM integration with mother vehicle avionics including transfer of navigation data which comes from appropriate sensor data fusion using GPS/INS techniques. Moreover, the mother vehicle strap down GPS/INS guidance scheme can be enhanced with the aid of IIR stabilized seeker with reasonable range (<10Km).

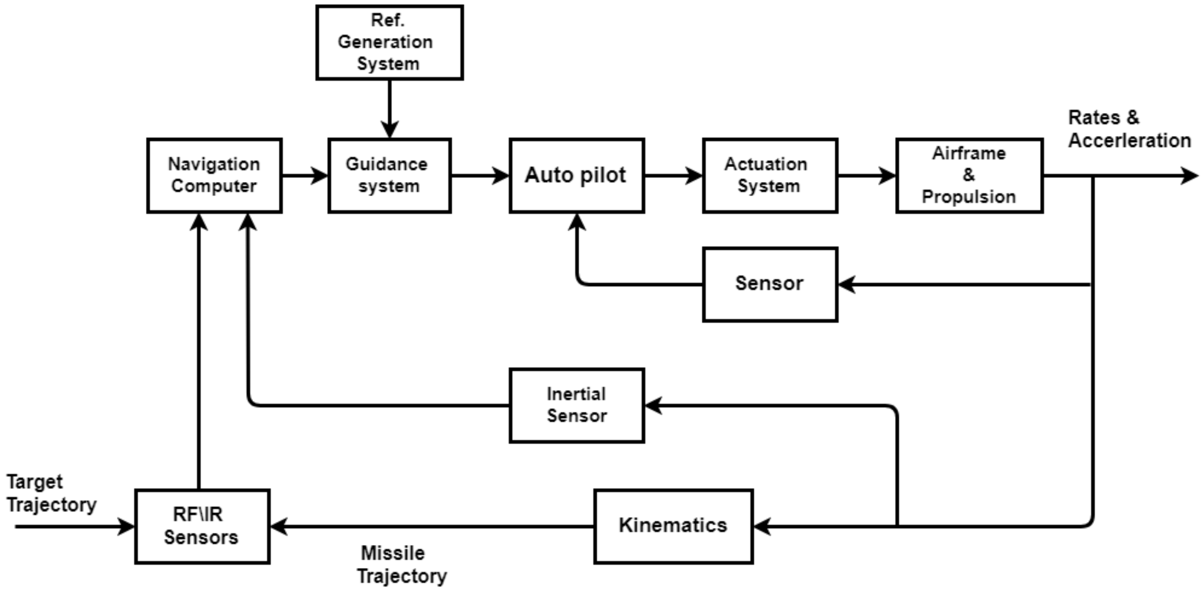


Figure 2.3 Functional block diagram of aerospace vehicle

The Anti Ballistic Missile (ABM) also need IIR based stabilized seekers with range around 30Km for endo and exo atmospheric engagement against high velocity air targets (with relative velocity 3-6Km/s). The former classical guidance schemes for homing uses pursuit path, constant bearing path and Proportional Navigation (PN). The accuracy is improved with Augmented Proportional Navigation (APN) law by the addition of acceleration command to account for target manoeuvring. The present modern guidance schemes for meeting the homing guidance requirements for flight vehicle are summarized below:

- Variants of PN (e.g. APN) with estimation techniques for vehicle positioning and other image processing techniques for target tracking.
- Enhanced guidance law (e.g. Zero sliding guidance law etc.) with more number of state estimations and prediction of target recursively.
- Use of optimal control based on linear quadratic techniques.
- Use of neutral nets in a hybrid fashion.
- Parallel structures with distributed storage and processing for faster numerical computations.
- Learning ability for adjusting weight and biases for nonlinear dynamics.

- Adaptability in the changing environment.

A typical seeker based terminal guidance scheme can be described by the Figure 2.4. The stiff stabilization loop (represented in blue) for precise tracking by the seeker is mandatory for various kinds of stabilized seeker systems. However, IIR/Electro-optical stabilized seeker based terminal guidance has been realized and proven for anti-tank aerospace vehicle.

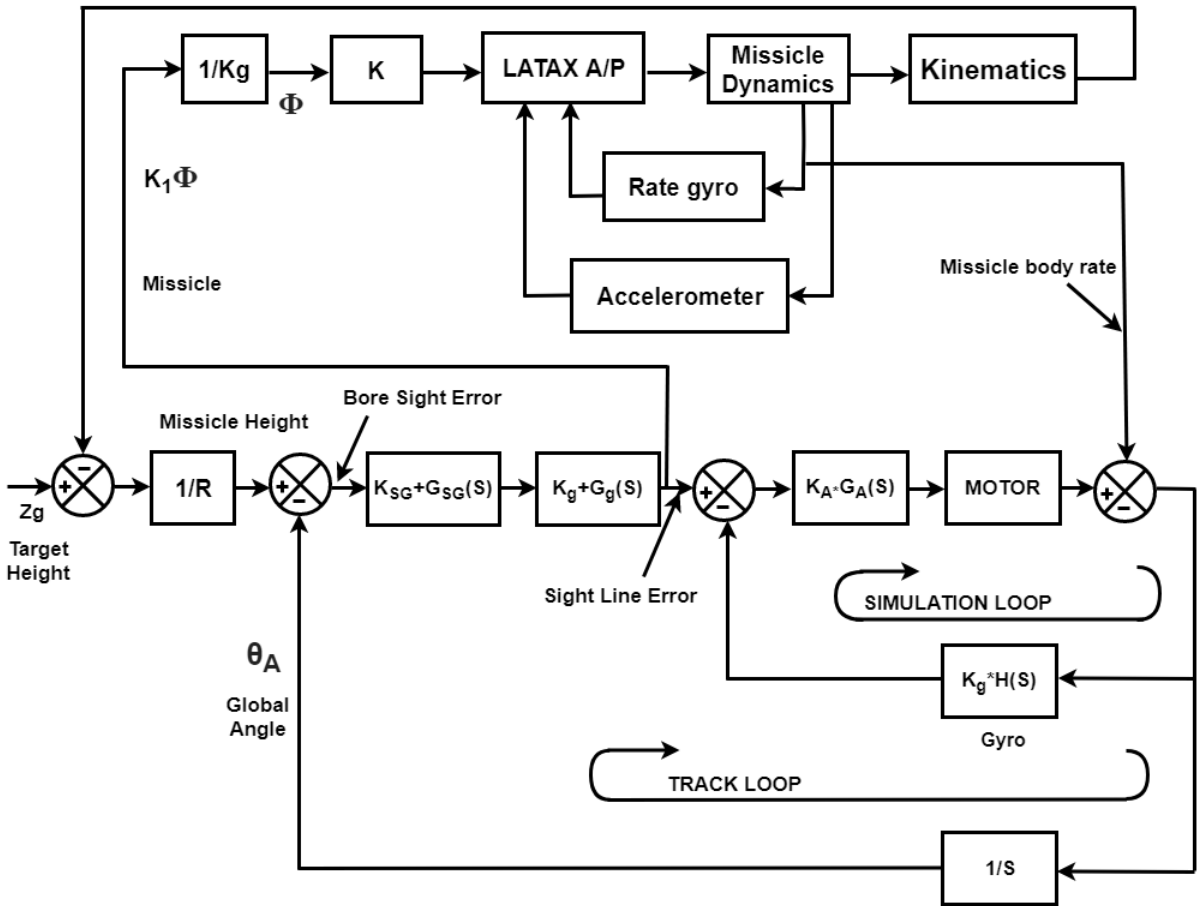


Figure 2.4 HIL Testing

The homing guidance requirements for seekers are summarized as:

- Lesser gathering basket based on mid-course, energy management inertial instrumentation and processing aided with GPS.
- Appropriate lock on to target (before or after launch depending on need)
- Reliable tracking data

  - Relative aerospace vehicle-target range
  - LOS angle
  - LOS angle rate
  - Bore sight error angle

- Appropriate guidance law leading to minimum miss distance in the presence of
  - Target manoeuvres
  - External and internal disturbances

- Effective flight control system
  - Steering capability for the guidance law
  - Required Latex generation
  - Stabilization of bare airframe
  - Reduction of sensitivity to disturbance inputs
  - Use of three loop autopilot with synthetic stability loop.

2.3.2 Seeker modeling & Dynamic tests

The use of seeker modelling and simulation in the development of military weapon system began to expand several years ago as the cost of flight testing began to rise. Since, the role of modelling and simulation has expanded to include HILS, which helps for system design and development. It also plays an important role in development of seeker based terminal guidance for guided aerospace vehicles. The seeker based terminal guidance system is shown in Figure 2.5. The mathematical modelling and its match with H/W characterization with appropriate test bed leading to total HILS is summarized below:

- Mathematical Model
  - Seeker dynamic system model
  - Seeker system front end model
  - Seeker model integration with aerospace vehicle model

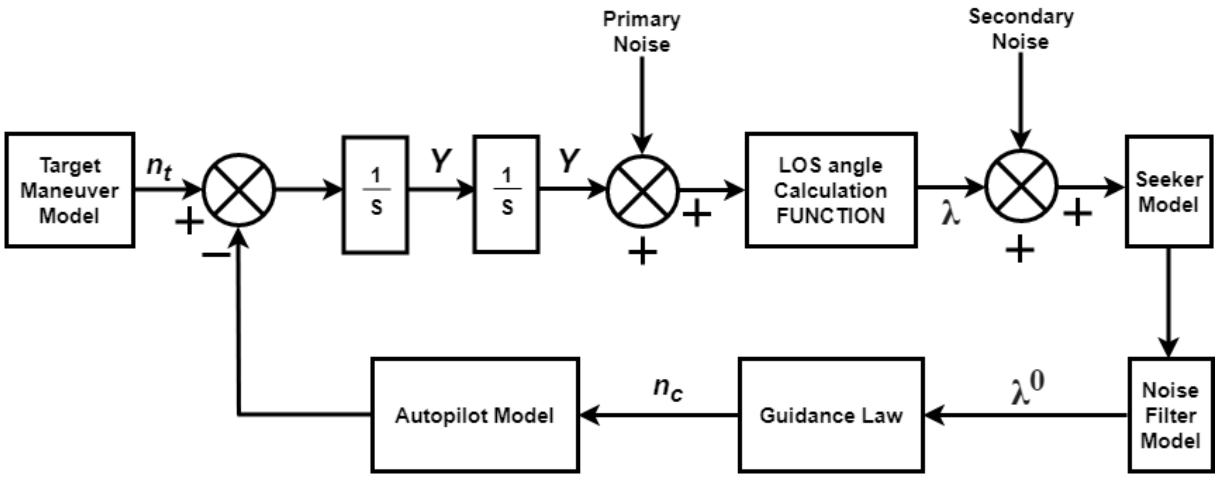


Figure 2.5 Seeker based terminal guidance System

  - Aerospace vehicle +seeker integrated model in mission scenario.

- Test-bed Preparation
  - Simulink / Matrix X Software and generated / developed S/W in Non-Real Time (NRT)/ Real time (RT) environment for seeker model.
  - Use distributed processing environment with Guidance laws, Navigation & Control modules for RT Rapid Prototype environment using PCs & state of the art RT simulation computers

- Seeker H/W Characterization
  - Dynamic characterization of H/W seeker
  - IIR system characterization including dome

- Test-bed Preparation
  - Use the RT test-bed with high-speed data link for control & visualization.
  - Independent test-bed for seeker system characterization.

Seeker modelling needs to be followed by dynamic tests as well as state of the art HILS techniques are presented for freezing terminal guidance system design. During development of CCD based seeker of ATM a full scale dynamic test bed is required for characterizing the seeker. The homing guidance loop with its inner tracking and stabilization is

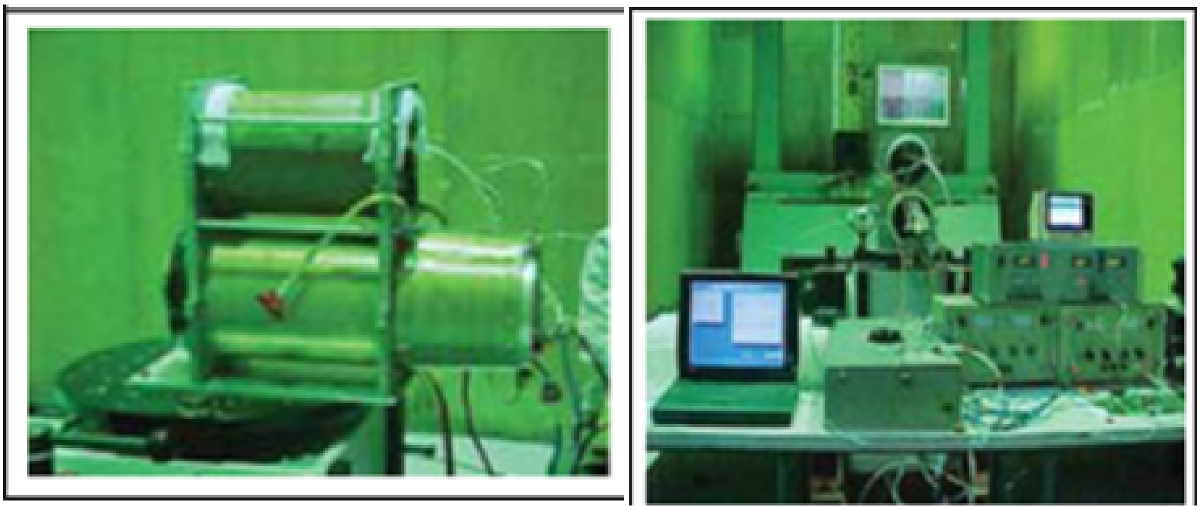


Figure 2.6 IIR Seeker mounted on SART & Testbed for conditioning HILS and dynamic tests

represented in Figure 2.4. During the course of seeker based guidance system design, an independent characterization of the stabilization loop and track loop is necessary to meet the performance requirements of PN guidance law. At present to perform the dynamic tests and HILS, the test bed with a high fidelity ($\pm 30°$/s body rate @ 40 Hz) SART and TMS with dynamic response much higher than the track loop (>1.5 Hz @ 10°/s SLR) are available. The test setup for dynamic testing is shown in Figure 2.6.

The following tests have been performed for characterizing the seeker dynamically.

- Isolation Ratio
- Decoupling Ratio
- Bore sight shifting test (Step body rate)
- Track loop bandwidth
- Bore sight step response
- Step target motion (Bore sight impulse response)
- Sight Line rate calibration

The ratio of aerospace vehicle body rate to gimbal angle rate, the ratio of body rate to sight line rate are defined as Isolation and decoupling ratios respectively. Isolation

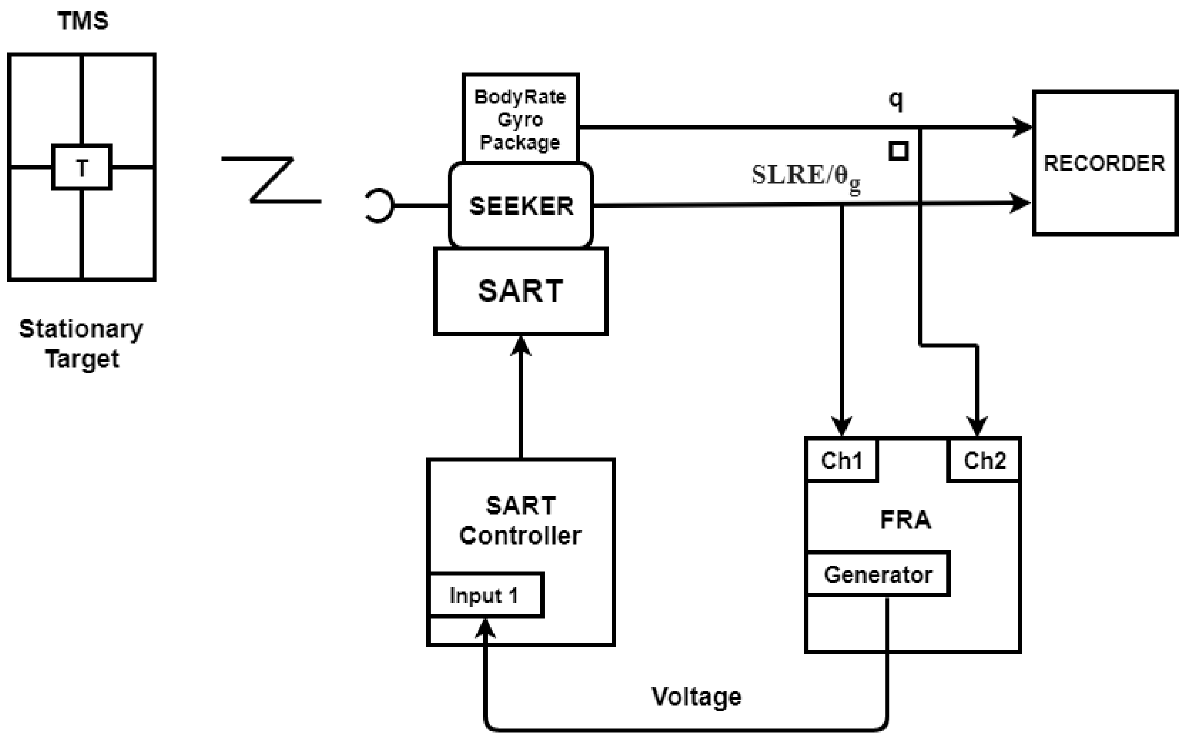


Figure 2.7 Isolation and Decoupling test

ratio defines the degree of isolation between aerospace vehicle body and seeker gimbal i.e irrespective of aerospace vehicle body disturbances seeker gimbal will continue to stare at the target. Whereas the decoupling ratio dictates the tracking of target irrespective of disturbances in body rate. The test set up for isolation and decoupling is shown in Figure 2.7.

The bore sight shifting against a sudden body jerk is tested in the dynamic test bench as shown in Figure 2.8. It is observed that Line-of-Sight (LoS) error was less than 0.36° (<1/3 FOV) even for 100°/s step body rate experienced. Bore sight step response test (test bed similar to bore sight shifting test) has been designed to test shift in bore sight at the start of track loop. This requirement is very typical for LOAL situation especially for PGMs. A typical bore sight step requirement of 1° gives an overshoot of 0.3° only (< FOV). A step target motion test is performed the impulse response of bore sight as shown in Figure 2.9. In case of IIR seeker of an ATM, even for a step input of 0.5° to the target (1/3 FOV) the seeker does not loose the track and bore sight error settles within 800ms with a peak SLR of 5-6°/s. The track loop bandwidth is tested with physical sinusoidal target motion (± 2°/s over a sweep of 0.5-3.0 Hz) and the seeker is

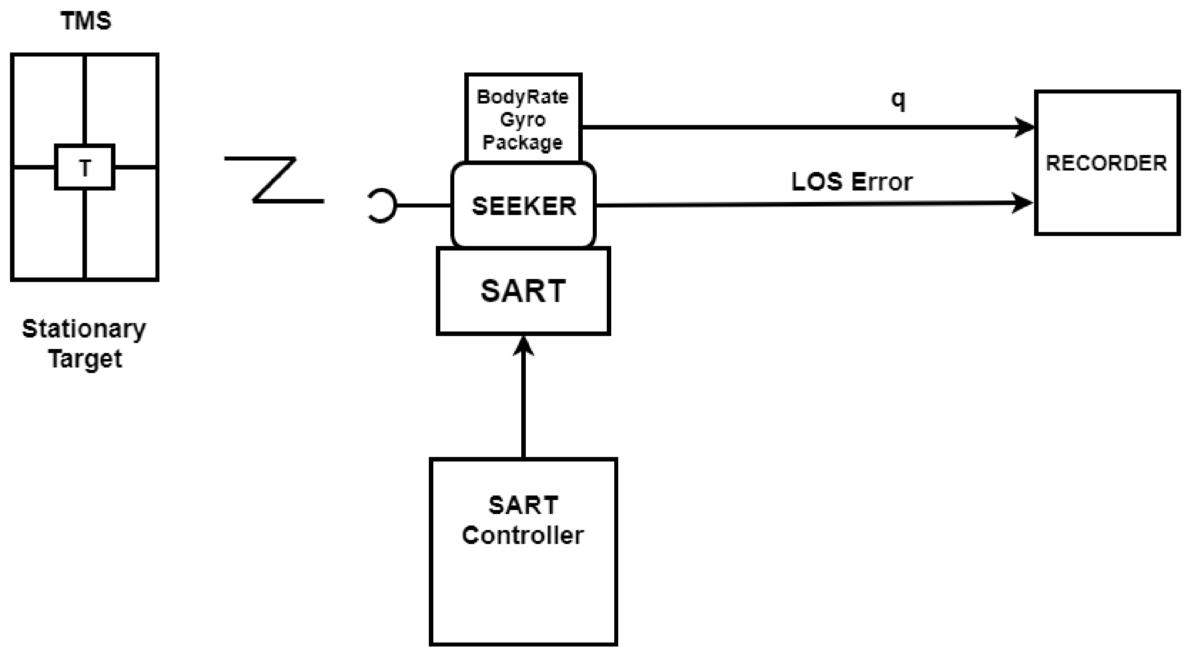


Figure 2.8 Bore sight shifting test

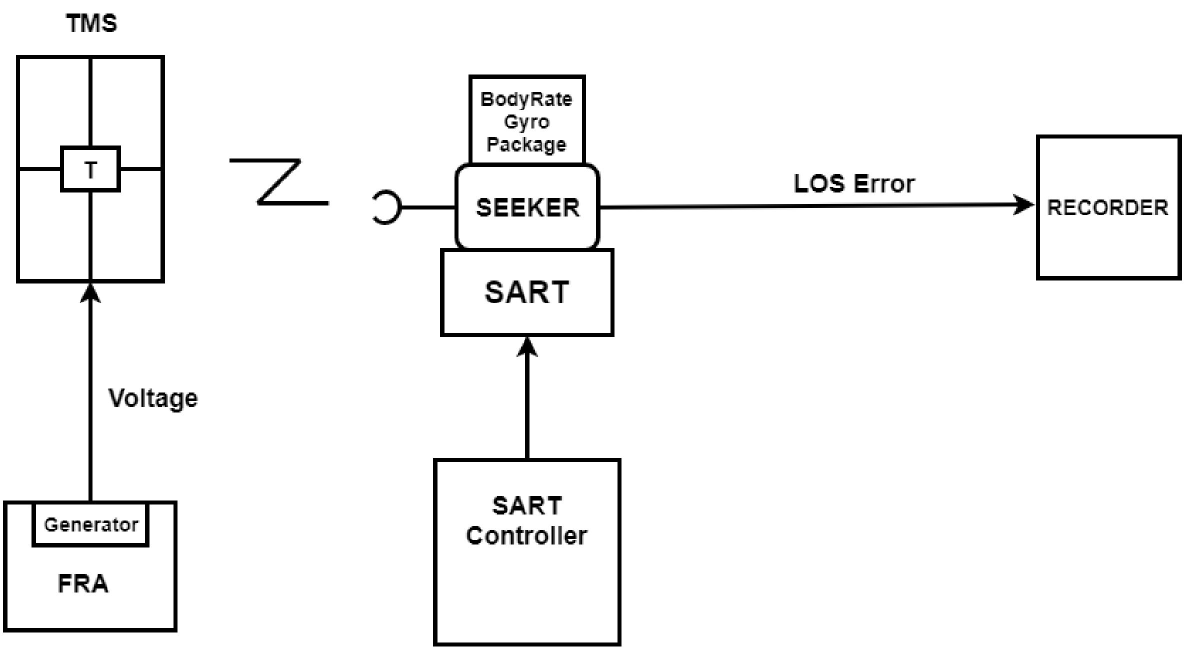


Figure 2.9 Step Target Motion test

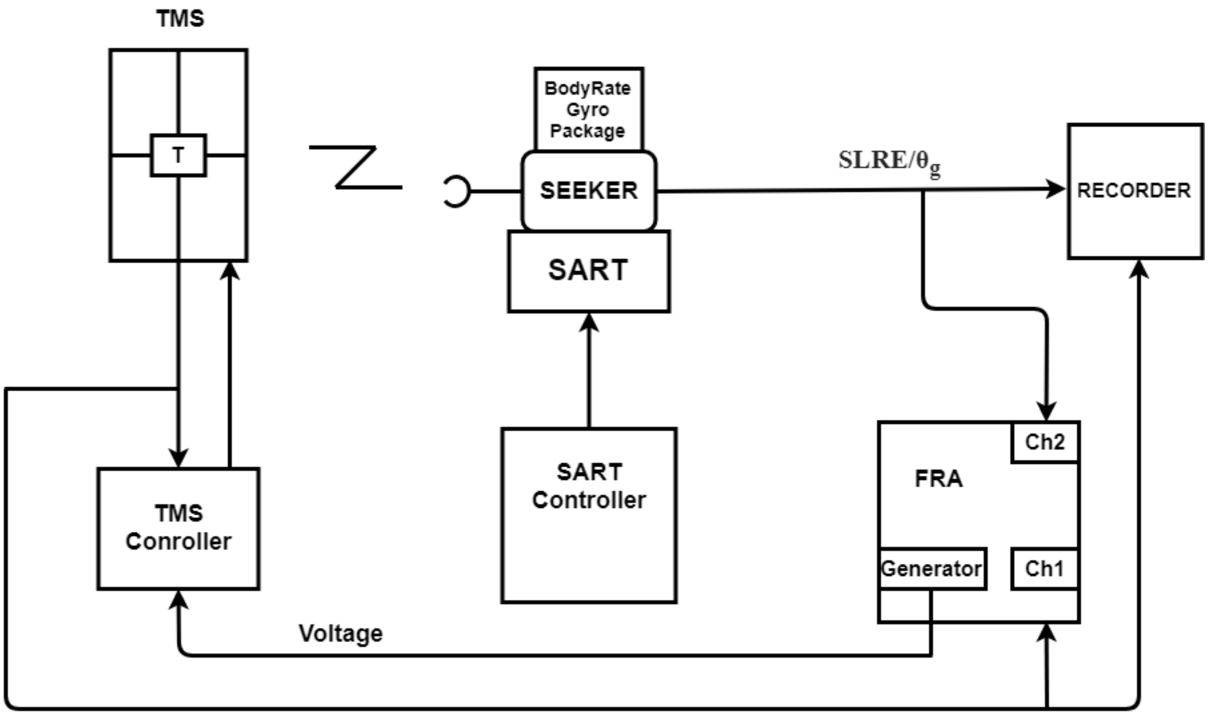


Figure 2.10 Track loop bandwidth

able to track upto 2.5 Hz (Guidance bandwidth of >0.5-0.6 Hz) with 90° phase shift. The test setup is given in Figure 2.10. Sight Line Rate (<10°/s) need to be calibrated against target accelerations of 10°/s^2. The calibrations are done in both Azimuth and Elevation planes over entire dynamic range of seeker gimbal angle. A typical trapezoidal SLR target motion is designed (4°/sec rate for 15 sec duration) for performing calibration test as shown in Figure 2.11 and test setup is shown in Figure 2.12. A typical isolation ratio, Decoupling ratio and track loop bandwidth test plots for IIR seeker with various

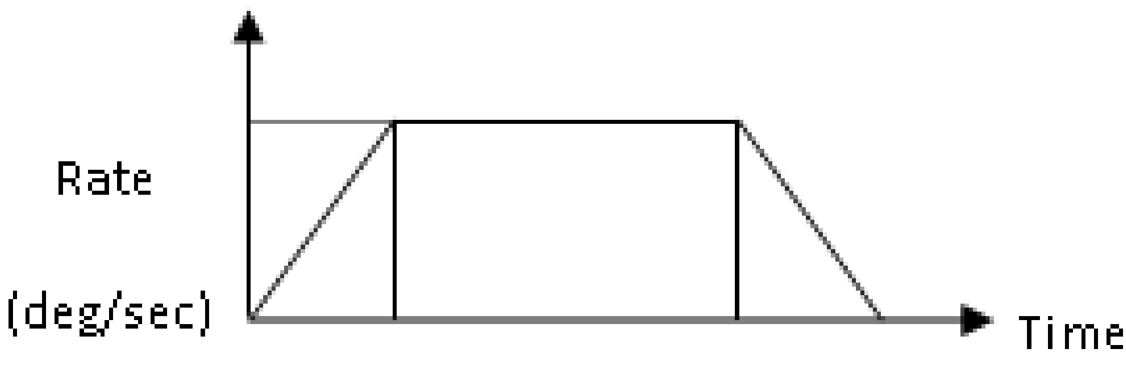


Figure 2.11 Trapezoidal waveform input to TMS

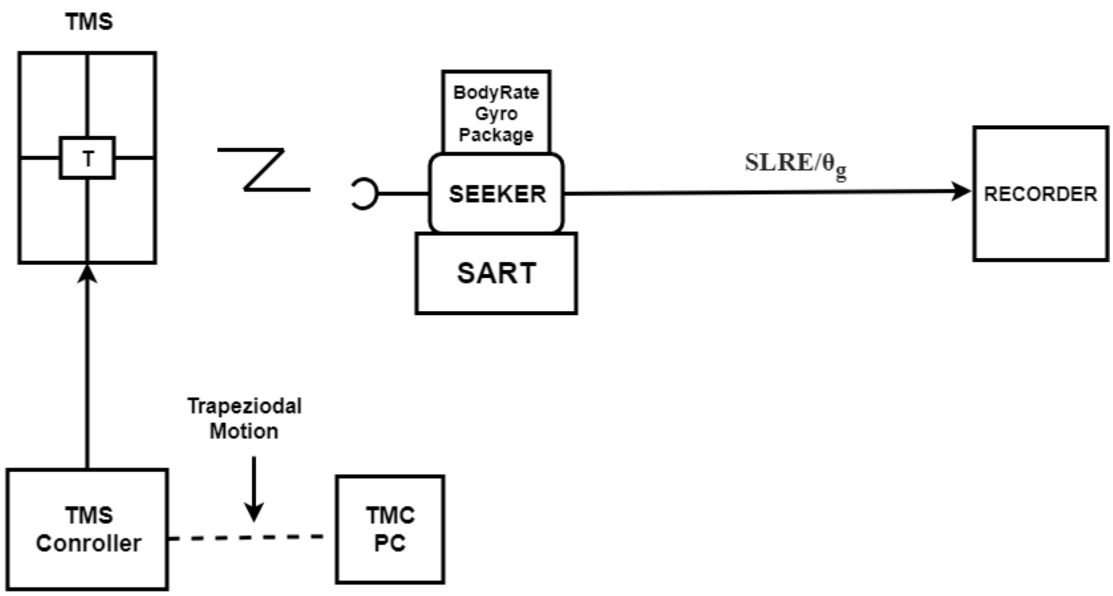


Figure 2.12 SLR Calibration

rates at different frequencies are shown in Figure 2.13. The testbed setup for performing dynamic tests and calibration is established and performance of the CCD & IIR seekers are thoroughly validated.

2.3.3 Hardware In Loop Simulation (HILS)

The dynamic tests are help to make the seeker ready for integrated HILS. Helicopter based captive flight trials are performed for validating the image processing algorithms independently. During HILS tests, a 6DOF rigid body model is integrated with the hardware seeker and CGC. A test plan was developed for performing HILS with CCD/IIR seeker. The main objectives of seeker in loop HILS are

- Validation of Control & Guidance system.
- To study seeker dynamic performance with Aerospace vehicle and trajectory dynamics.
- To check functionality & performance of various flight hardware

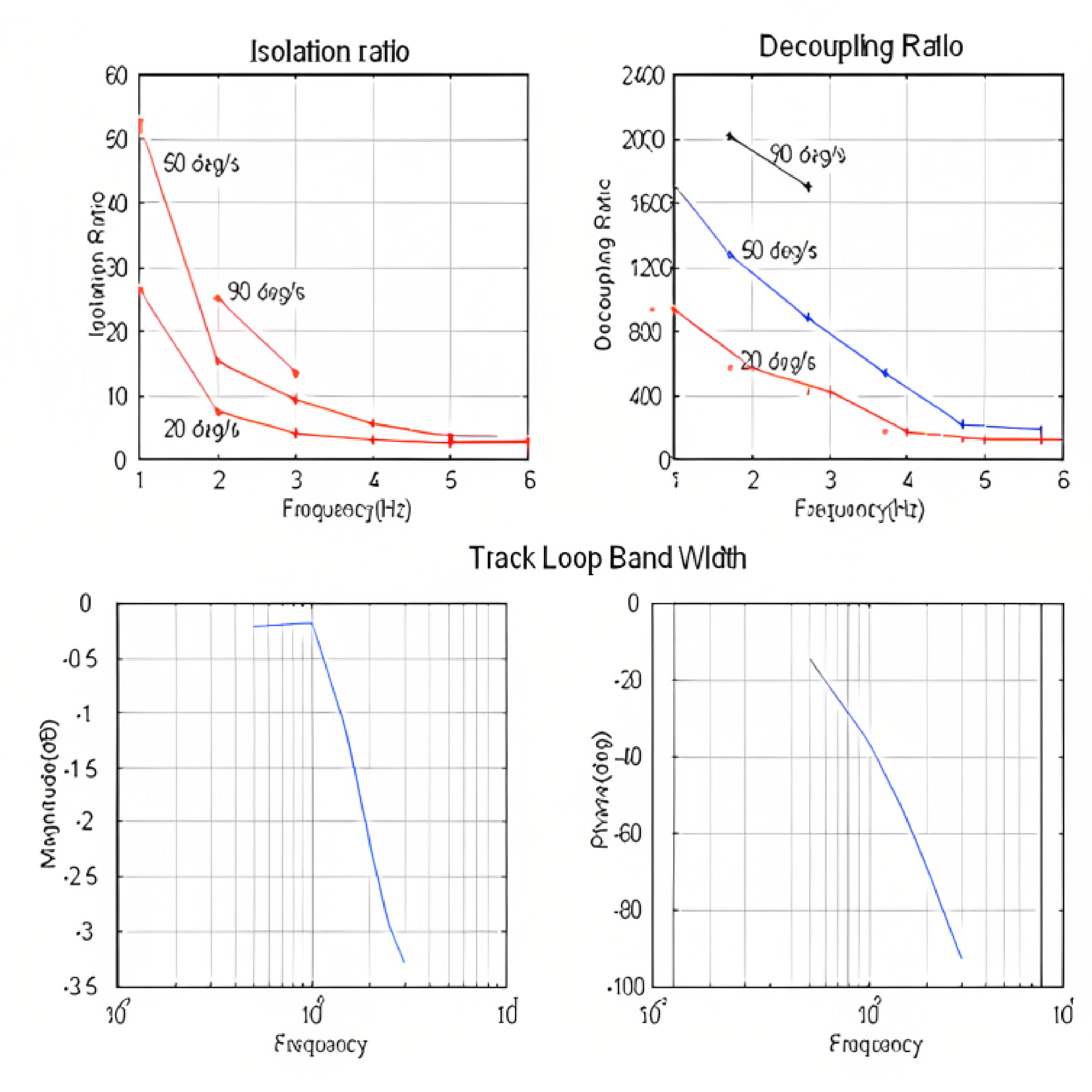


Figure 2.13 Typical dynamic test results

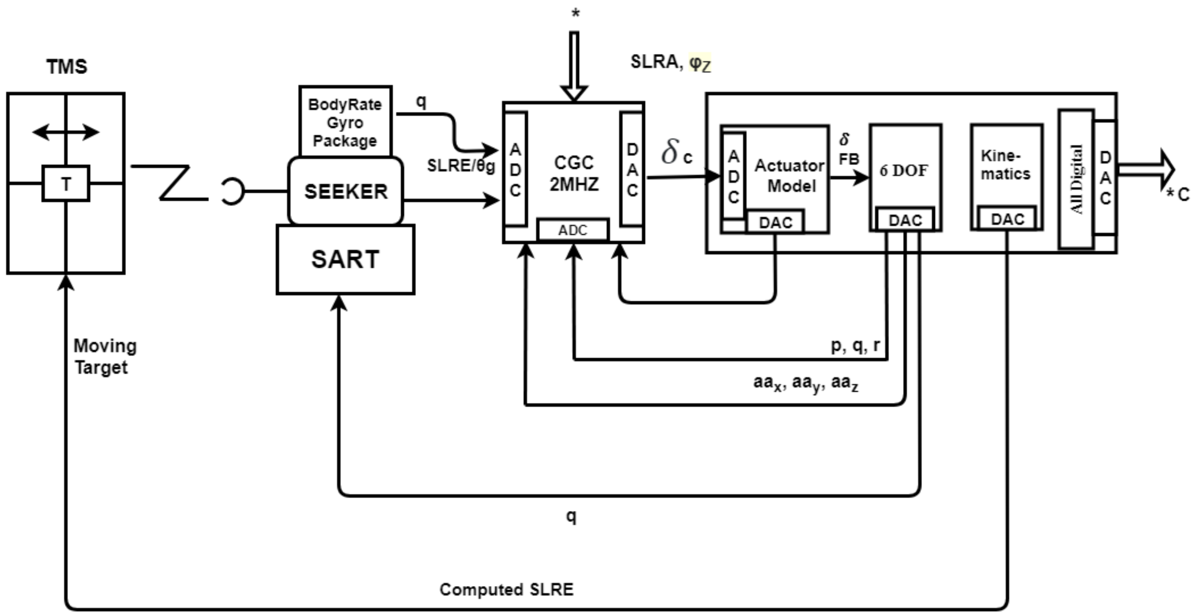


Figure 2.14 Single Plane HILS

- To check the Flight H/W & S/W in the integrated manner

The first step in the development cycle is to use SART and TMS for validating basic design related issues as well as clearance of subsystems for initial flight trials. In addition a point target (bulb) is used on the TMS for closing the track loop during HILS. An Open loop guidance, guidance FLIP run, semi closed loop HILS, and single plane HILS are performed in stepwise manner. Initially, tested the performance of the stabilization and track loop in guided flight trajectory, followed by testing of control and guidance algorithm in the CGC during guidance FLIP (Flight Input Profile) run.

For static and moving targets, a semi natural closed loop HILS is performed. It is observed that single plane HILS in azimuth and elevation planes with synthetic SLR to TMS and corresponding plane body rates to SART are created in real-time dynamic combat environment. Finally, it is validated with number of flight trial results to get the confidence. The semi natural single plane HILS, with complete 6DOF equations are enabled as shown in Figure 2.14. The SLRs and Gimbal angles from seeker and aerospace vehicle body rate from rate gyro in single plane are fed physically to CGC and the same in the orthogonal plane are fed from the data generated apriori from all digital 6DOF simulation runs.

2.4 Single plane HILS results and analysis

The single plane results of HILS runs are divided into two types, the first one is Azimuth plane and the second one is Elevation plane. The Figure 2.15 shows Azimuth plane HILS results represent the roll rate (p), yaw rate (r), yaw acceleration (ay) and effective yaw angle due to deflections (del yaw). All the parameters are having considerable oscillations compared to ideal digital simulation results. These oscillations are having magnitude of ± 20 deg/sec @ 3Hz in roll rate and yaw rate parameters. Around ± 5 deg/sec @ 3Hz oscillations are observed in yaw acceleration and del yaw parameters. These oscillations are highly undesirable and lead to failure of the mission.

The seeker tracking is the major cause for these oscillations, when the seeker is in track mode it continuously tracks the target (bulb) placed on the TMS. The TMS is excited with kinematic sightline rates generated by 6DOF PC. The simulated target (bulb) placed on the TMS will experience these rates with delay in time due to response time of the TMS. The seeker which is in track mode generates the outputs based on delayed tracking. The delayed outputs of seeker will enter into guidance module and resulted into oscillations of the mission critical parameters. Similarly, the response time of SART also adds further delay which causes oscillations in mission critical parameters. The HILS results like body rate (p,r), acceleration (ay), del yaw in the Azimuth plane (represented in red) are compared with expected all digital simulation results (represented in blue) are shown in Figure 2.15.

Similarly, the HILS results like body rate (p,q), acceleration (a), del pitch in the elevation plane (represented in red) are compared with expected all digital simulation results (represented in blue) are shown in Figure 2.16. The pitch rate (q) of HILS is delayed by nearly 15ms comparing with digital simulation results as shown in Figure 2.16. The occurred delay can be attributed to TMS response delay due to elevation plane dynamics of aerospace vehicle. Furthermore, the respective delay at critical event of pitch down demands delayed turning latex on the aerospace vehicle which leads to more guidance requirements to track the target and resulted in to undue oscillations with a magnitude of ± 50 deg/sec @ 2.5Hz as shown in Figure 2.16. The effect of these oscillations in other parameters like roll rate (p), effective del pitch and pitch latex (az)

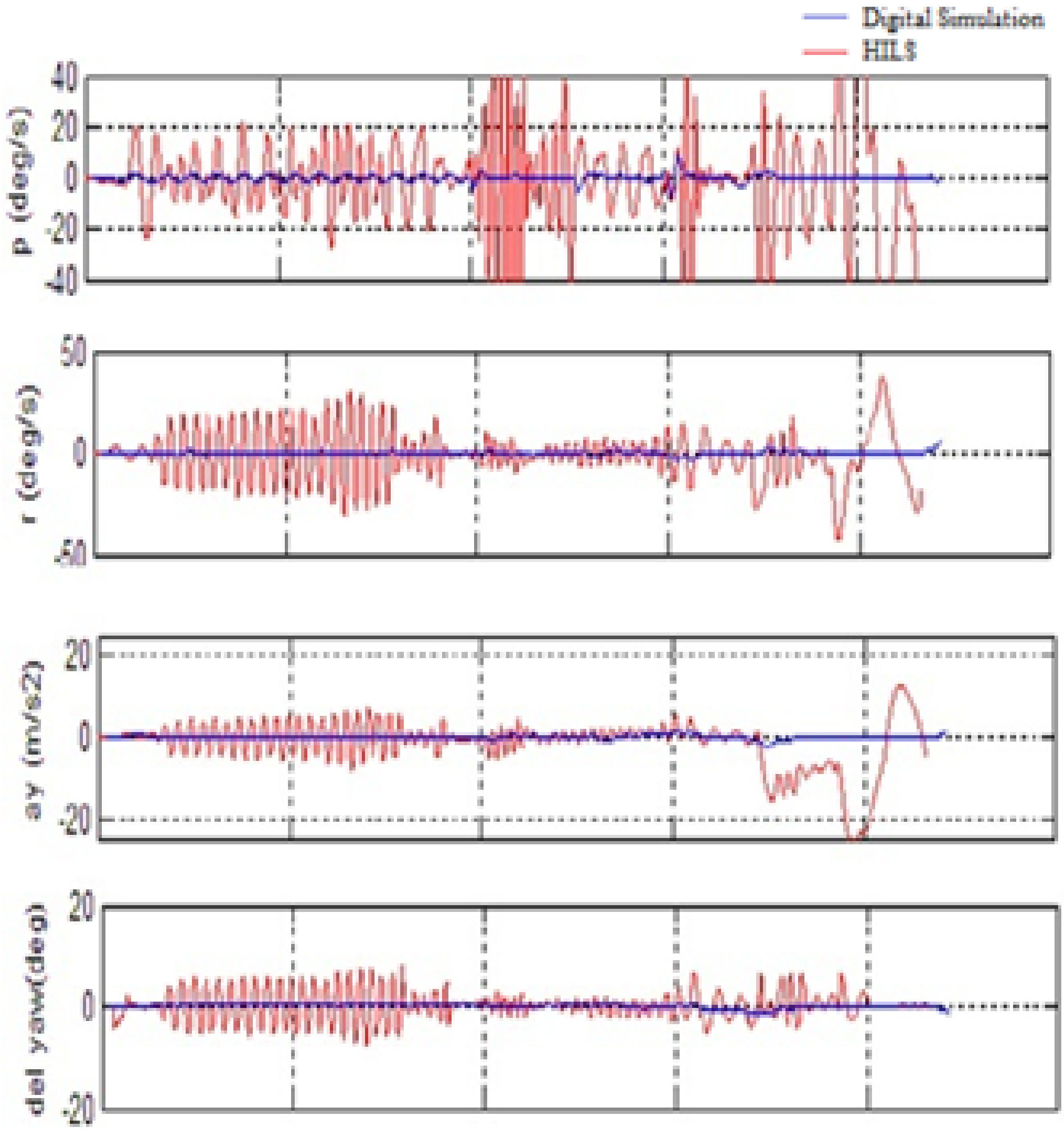


Figure 2.15 Azimuth plane results

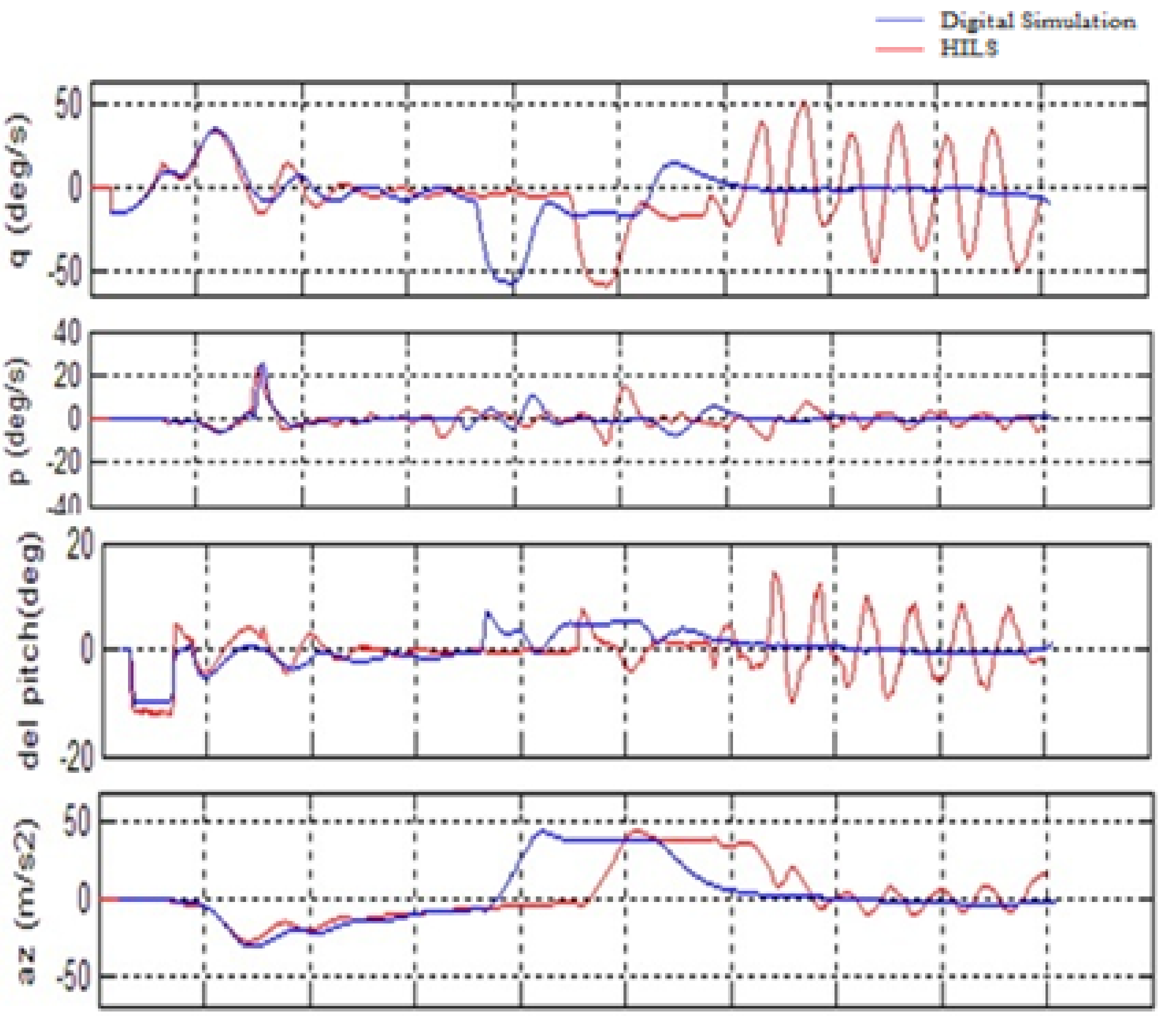


Figure 2.16 Elevation plane results

are also shown in the Figure 2.16.

2.5 Causes for the delay

The complete HILS test bed contains different sub-systems of aerospace vehicle, which are electrically connected with each other. During real-time simulation runs, all these sub-systems get excited and gives the outputs with respect to the inputs. Through the whole process of HILS test bed the delay is generated within the subsystems. The major consideration of the delay is offered in HILS test bed due to huge structure of the TMS. Once the TMS is in moving condition, the seeker which is in track mode tracks the simulated target (bulb) placed on the TMS. The seeker outputs are delayed due TMS response.

The single plane body rates from simulation PC excite the SART to simulate the vehicle rotational body rates. The seeker and sensor mounted on the SART will move in accordance with these body rates and generates their outputs. Due to the delay introduced by the SART, a considerable amount of delay is added to the seeker and sensor outputs. Similarly, the data acquisition cards like A/D and D/A converter in simulation PC will have deliberate sampling boundaries. Hence the overall delay is due to the time lag caused by the hardware subsystems, processing delay, SART, TMS bandwidth, span boundaries, and A/D and D/A cards conversion time in the HILS test bed during interfacing.

2.6 Effects of the delay

The different subsystems of aerospace vehicle are connected in HILS test bed to simulate the realistic field test environment. The HILS runs are basically to reduce the number of field flight trials during the development phase of the aerospace vehicle. Once the performance of subsystems are verified and validated in HILS test bed, they will be integrated electrically and mechanically to go for the actual field test. In this way the inherent problems in the subsystems will be surfaced in the HILS test bed during the HILS runs much before the actual field test. Once the issues identified, they will be corrected immediately. This process will reduce the possibility of mission failure and increase the percentage of success of the aerospace vehicle.

The delay associated with different subsystems and motion simulators in HILS test bed is very critical in conducting the HILS runs. As mentioned earlier the delay offered by SART and TMS will cause the tracking delay of seeker. However, the tracking delay gives delayed LOS errors along with SLR values. Subsequently, the delayed SLR enters into the guidance loop of aerospace vehicle and gives delayed latex. It will excite control algorithm where there is no sufficient boundaries to take care of this delay. Due to the interdependency of different subsystems delays, the HILS results will have diverging oscillations. The divergence in the HILS results is an unwanted phenomenon and it is a challenge to the HILS engineers to overcome these oscillations. The diverging oscillations observed during HILS runs is a cumulative process and those are generated by the plant model in simulation PC.

2.7 Issues observed during HILS

The HILS body rate is compared with expected digital simulation results as shown in Figure 2.16, it is observed that the HILS pitch rate is delayed by 15 to 20 ms with respect to expected body rate. The associated delay with different subsystems and motion simulators in HILS test bed is very crucial for conducting the HILS runs. A mechanism should be developed to overcome these delay issues to evaluate seeker system and control guidance algorithm effectively. Subsequently, to overcome the limitations of single axis HILS testbed, a 3-Axis HILS testbed to be established to conduct the evaluation of aerospace vehicle sub systems effectively without any unwanted issues.

2.8 Conclusion

Homing guidance requirements and techniques along with seeker modelling and various dynamic tests have been presented in this chapter. Integrated seeker dynamic tests have been evolved for IIR and CCD seeker characterization. It has helped in guidance system design and validation before flight trials. Moreover, typical modelling features and various HILS configurations have been highlighted starting from semi natural configuration within the limitation of available motion simulators. The single plane HILS results has been validated with flight trial results. However, state-of-the-art HILS facility with 3-Axis FMS to be established for simulating the near field aerospace vehicle flight environment. The delay issue existing in HILS runs is discussed and to be compensated to carry out HILS runs effectively.

Chapter 3

Characterization of HILS delay through accurate modelling & Simulation

3.1 Introduction

The HILS for different aerospace sub-systems are carried out in different stages and the 3-Axis testbed is established in this chapter to evaluate their performance. The hardware sub-systems of aerospace vehicle is augmented in HILS testbed one by one. The different configurations of HILS testbed is described in following sections along with the results and issues observed. The characterisation of HILS delay is carried out through accurate modelling and simulation. The delay effect is simulated in RT and NRT matlab/simulink environment.

3.2 OBC-In-Loop Simulation

The On-Board Computer (OBC) is a hardware unit that contains control and guidance algorithm required to steer the aerospace vehicle. The OBC and Launch Computer (LC) are connected as per the flight configuration and integrated with RT-6DOF model as shown in Figure 3.1. The RT-6DOF model includes the atmosphere model, actuator model, seeker model, navigation model along with sensor models. The launch computer loads required input data commands like range, height, temperature to OBC before lift off the vehicle. After lift-off, OBC takes navigation data (ps,qs,rs,ax,ay,az) from RT-6DOF

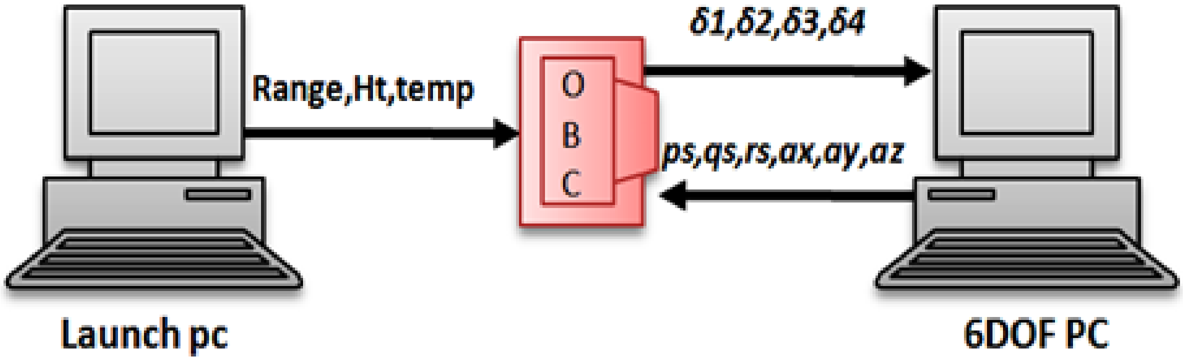


Figure 3.1 OBC-In-Loop Simulation

model, runs guidance and control algorithm to generate the deflection commands. The deflection commands ($\delta 1$, $\delta 2$, $\delta 3$, $\delta 4$) which are read by RT-6DOF model to excite the 6DOF equations. The angular rates and linear accelerations generated from 6DOF are used for navigation and control.

3.3 OBC-Actuator-In-Loop Simulation

The OBC and LC are connected as per the flight configuration and integrated with RT-6DOF model. The Real hardware actuators are required to move the vehicle to updated positions during the course of flight is shown in figure 3.2. The LC loads required input data commands before lift-off to OBC then the navigation data initiated from RT-6DOF model. Moreover, OBC runs navigation and control algorithm and issues the deflection commands to the real actuator. The deflection Feedbacks (δfb) of actuators are read by RT-6DOF model to excite the 6-DOF equations and the respective angular rates and linear accelerations generated for navigation and control.

3.4 OBC-Sensor-In-Loop Simulation

The inertial sensor system's hardware and software are evaluated with trajectory dynamics and the effect of sensor lag and noise on mission performance to be observed. The real hardware sensor rate gyros get excited in the HILS test bed by strapping it on

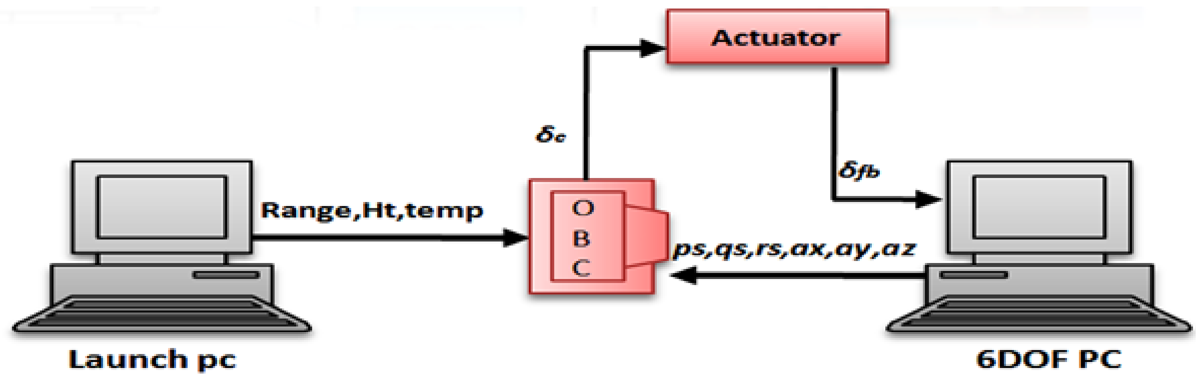


Figure 3.2 OBC-Actuator -In-Loop Simulation

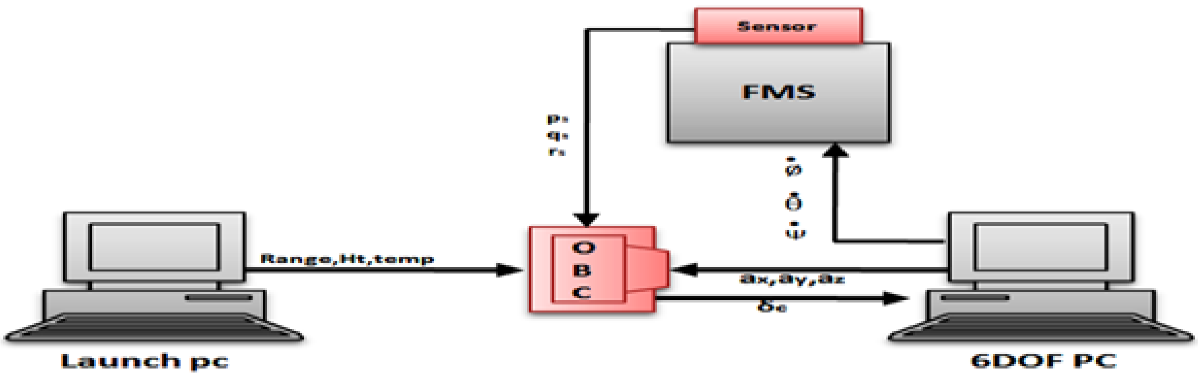


Figure 3.3 OBC-Sensor-In-Loop Simulation

the 3-Axis FMS as shown in Figure 3.3. During this process the orientation of flight sensor mounting is also gets validated. The FMS is excited by Euler rates (ϕdot, θdot, Φdot) generated by 6DOF PC. The sensor package senses these rates and forwarded to OBC along with the accelerations generated by 6DOF PC. Based on these inputs, respective deflections commands ($\delta 1$, $\delta 2$, $\delta 3$, $\delta 4$) are generated by OBC to excite the actuator model in 6DOF PC.

3.5 Seeker-Sensor-Actuator-In-Loop Simulation

The complete HILS test bed with IIR seeker and sensor package is mounted on the 3-Axis FMS is shown in figure 3.4. The simulated target (bulb) is mounted on the TMS. The FMS will be excited by the Euler rates and the TMS will be excited by the kinematic sight line rates generated by the Plant (6DOF) simulation PC. The outputs of

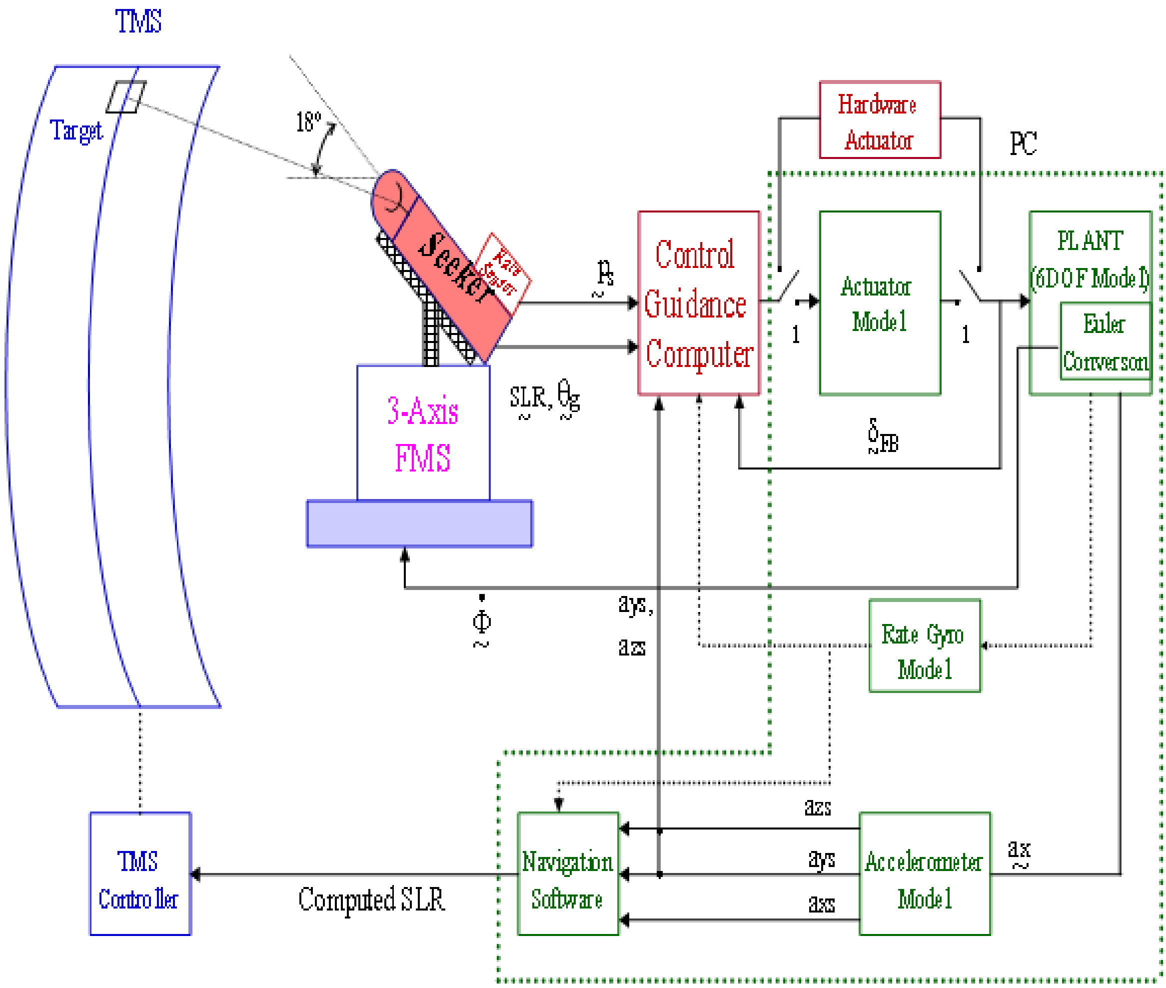


Figure 3.4 Seeker - Sensor-Actuator-In-Loop Simulation

seeker and the sensor package are fed into the OBC for processing of control and guidance algorithm to generate control actuation commands. These commands will excite the plant simulation PC to generate required commands for both FMS and TMS along with rates and accelerations for navigation and control. The whole process is continued in real time during the aerospace vehicle run time.

3.6 HILS Results & Analysis

The different configurations of HILS testbed are established and successfully simulated the flight conditions of aerospace vehicle by conducting multiple HILS runs. The

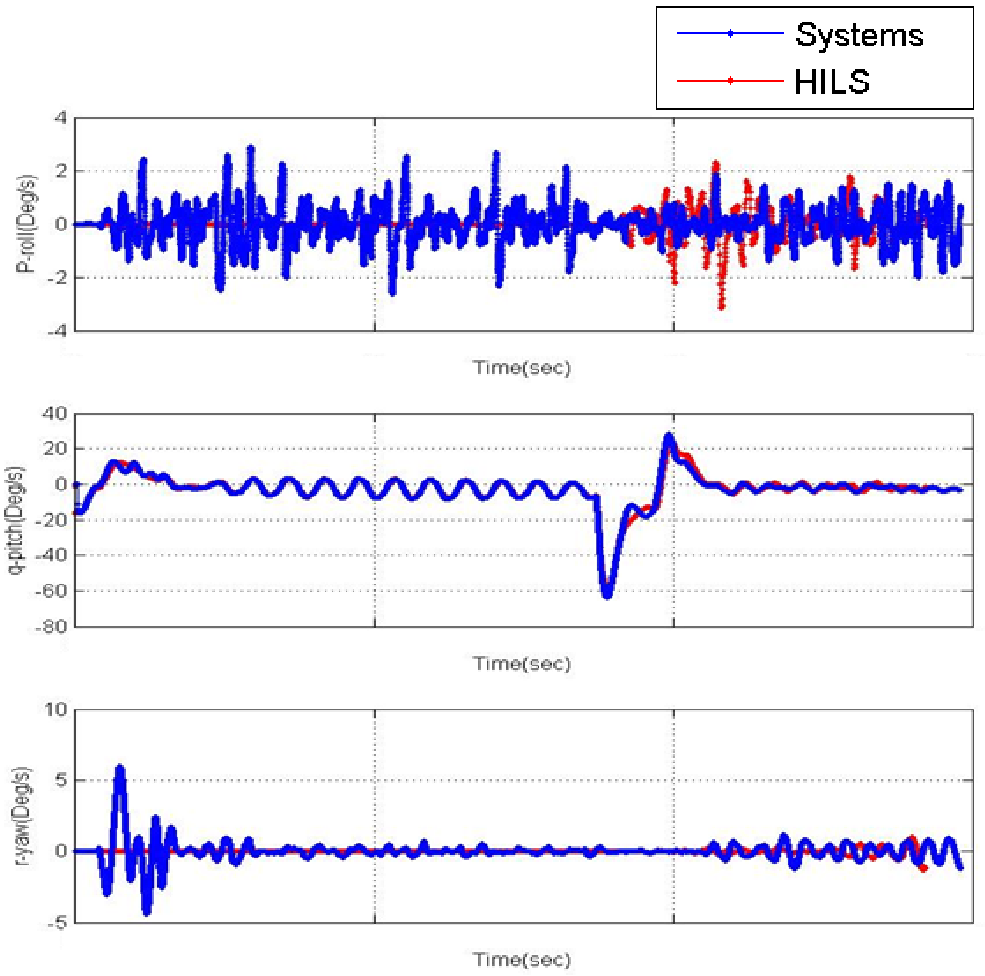


Figure 3.5 OBC-In-Loop results

HILS results were summarised and analysed thoroughly to highlight the issues observed.

3.6.1 OBC-In-Loop Simulation Results

The initial step in Real-Time HILS is the OBC_IN_LOOP which is crucial for establishing RT aspect in flight trails. The all sensed input data from 6DOF PC sent to OBC within prescribed time intervals whereas the OBC communicates with external subsystems at fixed time interval for evaluation. There is a strong constraint on 6DOF PC computation to compute all the rates and accelerations, and should send them to OBC within this time interval. Similarly, the 6DOF PC should read the deflection commands that are generated by OBC at specific time intervals. If there is a time overflow occurs between OBC and 6DOF while sending and receiving the data it leads to erroneous results.

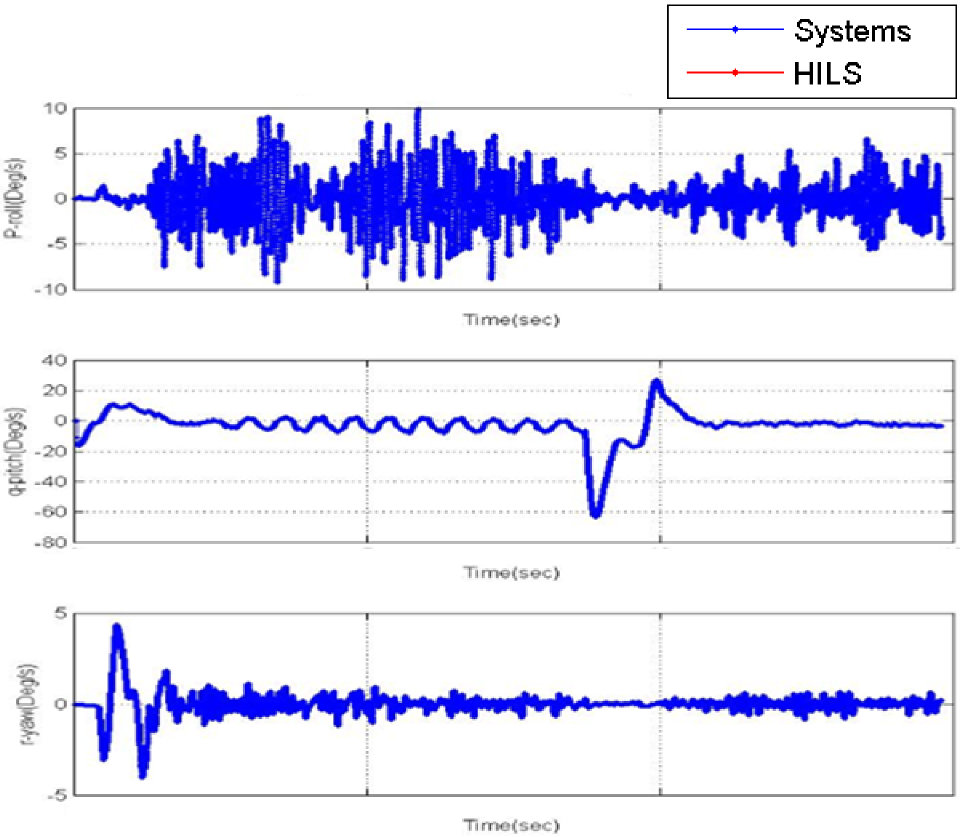


Figure 3.6 OBC-Actuator-In-Loop results

This is a challenge in establishing RT OBC_IN_LOOP testbed. To meet these challenges the models are developed using c++ language in RT Linux platform for 6DOF PC. The typical results of OBC-IN-LOOP are shown in Figure 3.5.

The RT OBC in loop HILS results achieved the roll rate of $\pm 2°$/sec @7Hz oscillations throughout the run time. These small roll rate oscillations are arises due to the effect of Real-Time and data acquisition aspects between hardware OBC and 6DOF PC interfacing. Whereas in the simulations performed for digital systems (by designers) the oscillations and interfacing issues are not observed because of no hardware used for simulation. When comparing HILS results with system group digital simulation results (Ref. Figure 2.14), fair matching is observed and indicates that real time testbed is established. The OBC in loop results are considered as reference results for HILS with other subsystems. In this HILS configuration, the control and guidance algorithms residing in OBC and its hardware is getting validated thoroughly.

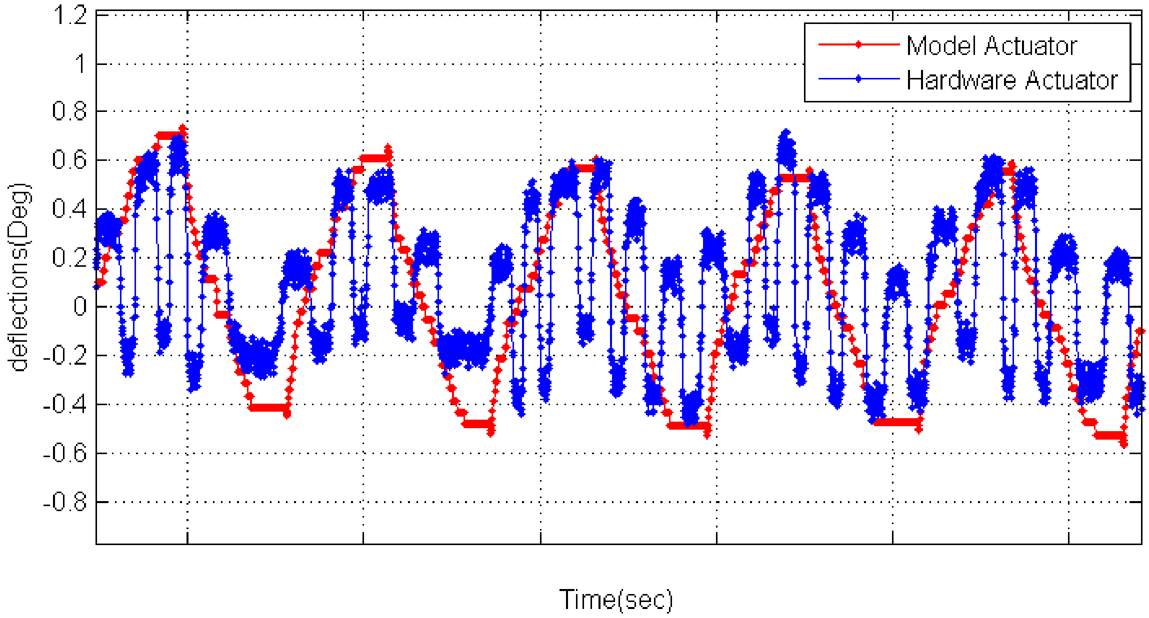


Figure 3.7 Deflections of Model Actuator Vs Hardware Actuator

3.6.2 OBC-Actuator-In-Loop Simulation

The model actuator in 6DOF PC is replaced with real hardware actuation system consisting of four actuators. It is derived from the former testbed of hardware actuators along with OBC as discussed in section 3.3. The HILS results with OBC actuator are shown in Figure 3.6. The oscillations ($\pm 10°$/sec @9Hz in roll rate) obtained for the actuator in loop results are more as compared with OBC in loop. A basic second order model actuator is used in OBC in loop simulation with natural frequency of 180 rad/sec and damping ratio of 0.6. But in real actuators, the band width may not be equal to the threshold which is specified in the model actuator. The four actuation systems will have various band widths due to their frequency response characteristics, and dead band values. Due to difference in bandwidths, the four deflection feedbacks are generated by the hardware actuator system having considerable oscillations as shown in Figure 3.7.

3.6.3 OBC-Sensor-In-Loop Simulation

The OBC-Sensor-In-Loop Simulation is performed through the sensor package that is mounted on FMS along with HILS test setup as shown in Figure 3.8. The validation of

Figure 3.8 OBC-sensor-In-Loop Simulation testbed

inertial sensor system's hardware & software with trajectory dynamics, the effect of it's lag, and noise on mission performance is very crucial in HILS. During this run, orientation of sensor mounting also gets validated. The results obtained during this process are compared with OBC In Loop results. The model sensor in 6DOF PC will be replaced by real hardware sensor and interfaced with hardware OBC even though the model actuator is used. The 6DOF PC generates the flight profiles of roll rate, pitch rate and yaw rate. These profiles excite the three gimbals of FMS. The sensor system mounted on FMS experiences these rates and generates sensed rates, which are fed back to hardware OBC. The comparison between input rates to FMS and sensed rates of sensor system is shown in Figure 3.9 and observed that there is nearly 15ms time delay between the inputs and outputs which is contributed by the FMS. During the HILS run, the delayed sensed rates are given as input to the OBC and forwarded to the control and guidance algorithm. Based on these sensed rates and demanded rates in the algorithm, OBC generates four deflection commands which are again given as inputs to the model actuator in 6DOF PC. The HILS run results are shown in Figure 3.10. From the results, it is observed that the roll rate oscillations having the magnitude of $\pm 5°/sec$ @ 7Hz. These oscillations are closely matched to OBC–in-Loop results even though there is delay of 15ms in sensed rates. The overall loop delay in OBC-Sensor-In-Loop configuration run is sufficient within

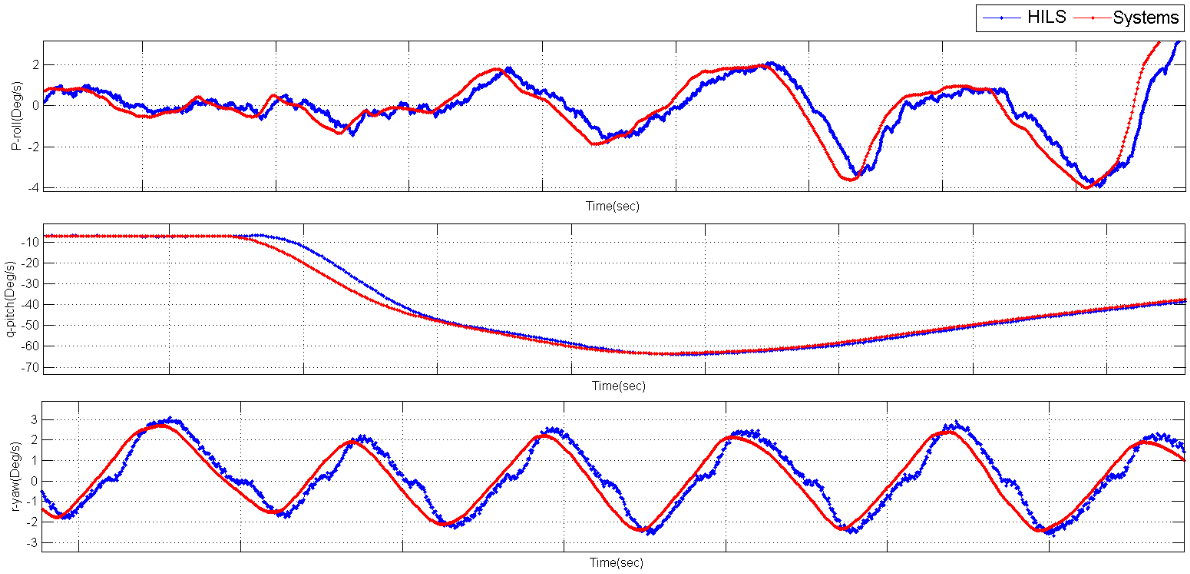


Figure 3.9 Comparison of input rates and sensor rates

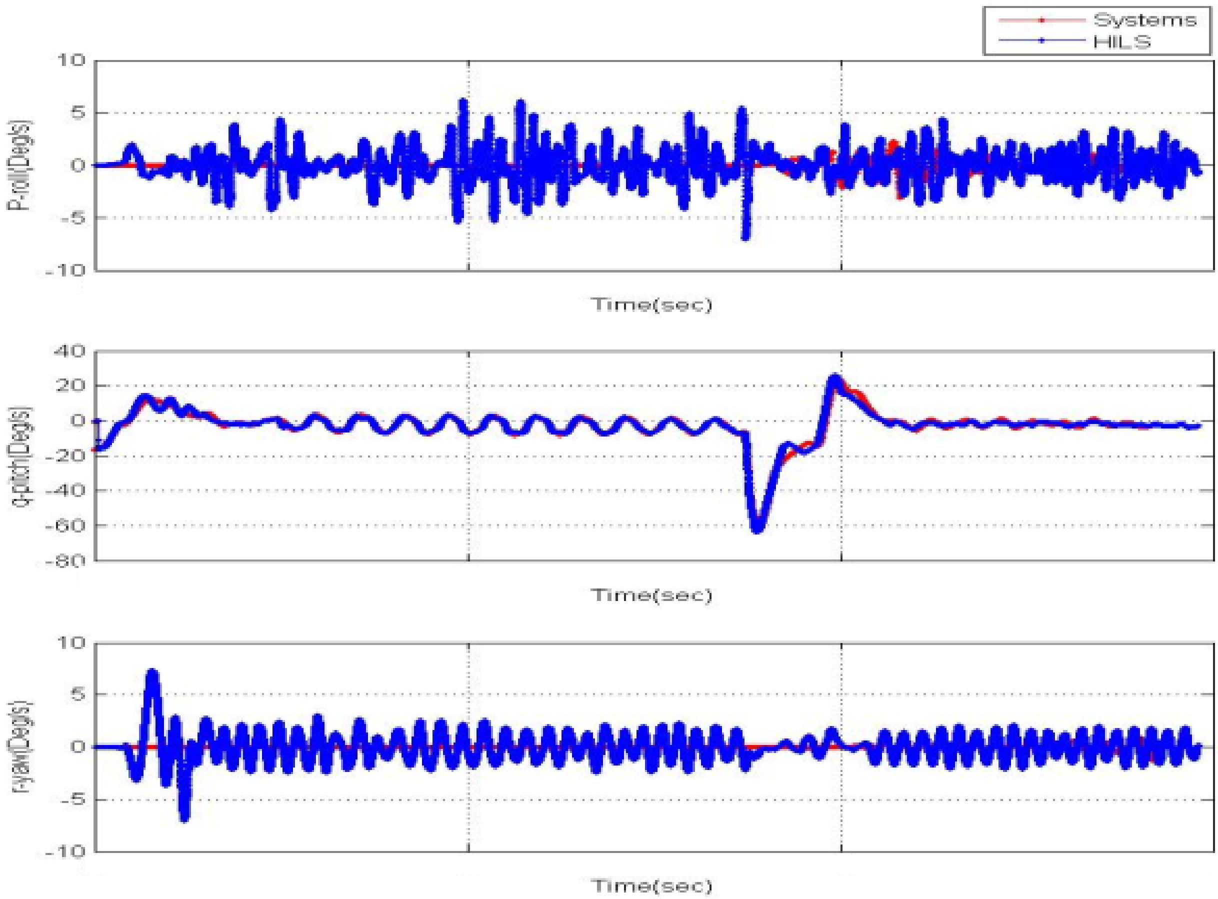


Figure 3.10 OBC-Sensor-In-Loop simulation results

the phase and gain margins of control and guidance algorithm. The real dynamics of sensor system along with its hardware interfacing and software aspects got validated in this configuration.

3.6.4 OBC-Sensor-Actuator-In-Loop Simulation (Complete HILS)

The replacement of model actuator and the model sensor in 6DOF PC by real hardware is considered as complete HILS. A real hardware OBC, hardware actuation system and hardware sensor system are inter connected as per the flight configuration. Real-time communication is established among OBC, actuator and sensor system to boost up the performance of the HILS. The sensor system is mounted on FMS and OBC whereas the actuator is placed on the test bench. The HILS runs are conducted with this configuration and results are shown in Figure 3.11.

The observations shown in Figure 3.11 are crucial to analysing the issues occurred in the HILS setup. The amplitude and frequency of the parameter roll rate is increased i.e. $\pm 15°$/sec @9Hz. When comparing with other configurations, these oscillations are higher than OBC-in-Loop results. Moreover, a 60Hz unwanted frequency component also entered into the HILS results and, the deflection feedbacks generated are noisy with inherent frequency of 10Hz. Complete HILS results as shown in Figure 3.11 are not at all acceptable, and the complex embedded systems like OBC and actuator cannot be developed and evaluated under this type of HILS testing environment. However, the oscillations in the flight parameters are observed high in HILS configuration whenever all the flight hardware are introduced into HILS testbed.

When sensor system and OBC in loop run is conducted, the oscillations observed in HILS are not prominent even though there is a time delay of 15ms observed between input and output rates of sensor package. This time delay is due to the lag offered by FMS. When the OBC and actuation system are connected in HILS runs, the oscillations are observed but they are not prominent. These are occurred due to the band width and dead band values of real hardware actuation system presented in the HILS. The proper design of control and guidance algorithm in real hardware actuation system pertaining to good phase and gain margins are helpful to overcome the effects occurred due to sensor

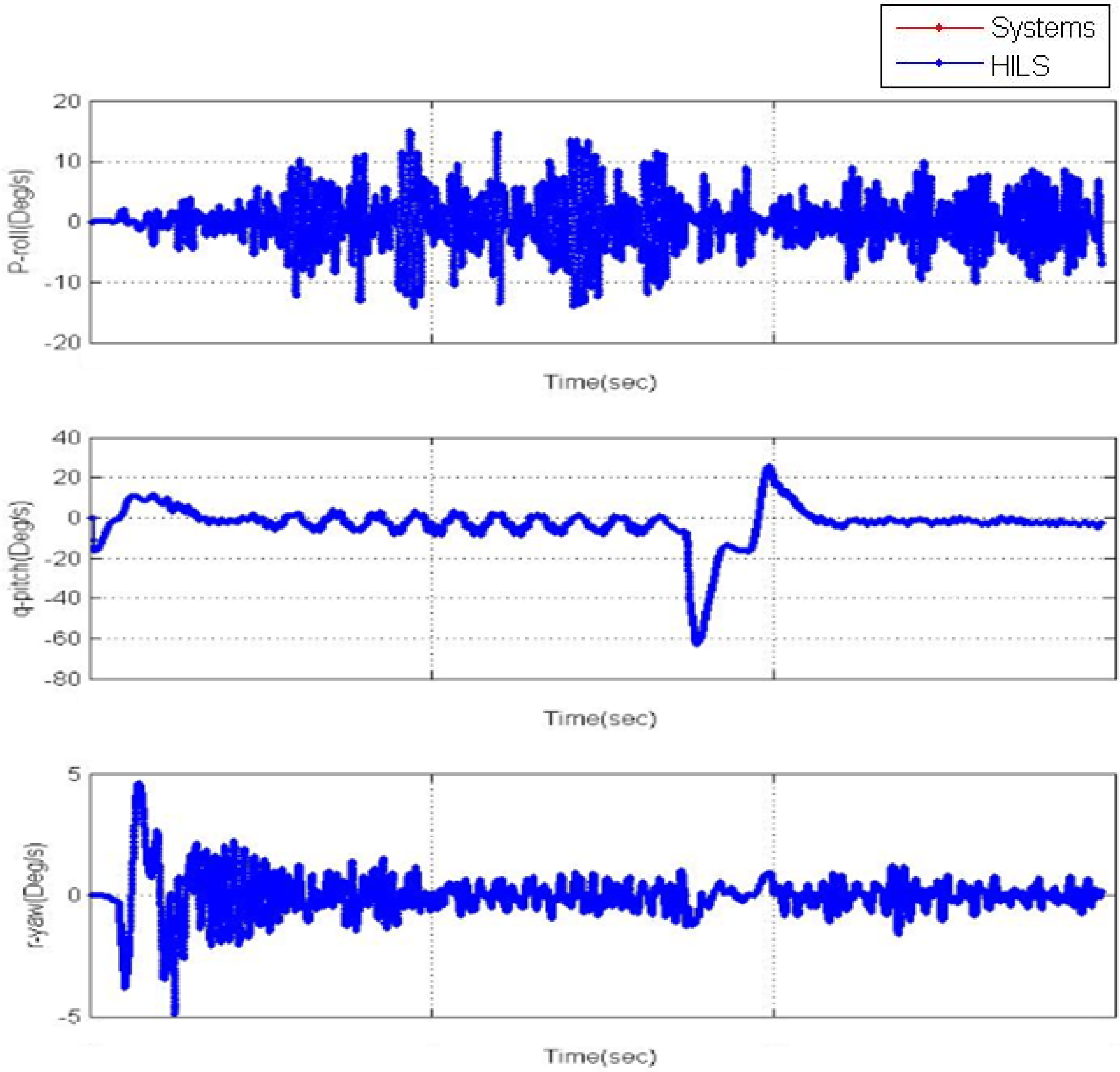


Figure 3.11 OBC-Sensor-Actuator-In-Loop simulation results

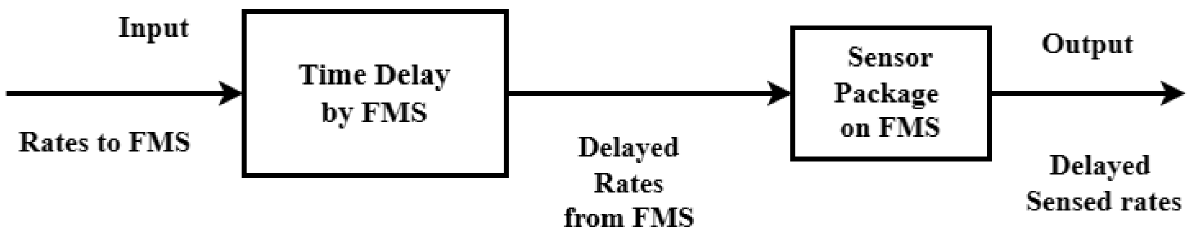


Figure 3.12 Delay block diagram

delay. Moreover, the oscillating roll rates are set as high priority that are obtained from real hardware actuation system need to be stabilized in control and guidance algorithm to perform HILS effectively.

3.7 Delay block diagram

The euler rates generated from 6DOF PC excites the FMS and the response of the FMS is delayed by its bandwidth limitation. The sensor package which is mounted on FMS will generate delayed outputs with respect to the input rates. The delay representation is shown in Figure 3.12.

3.8 Delay simulation using Simulink system

The oscillations observed in HILS are due to delay offered by different subsystems. The overall delay observations are modelled using Matlab/Simulink simulation. The delay modeling of actuator is shown in Figure 3.13. The embedded controller in simulink system generates deflection commands based on inputs from 6DOF model. The delay obtained from sensed rates and accelerations due to bandwidth limitation are forwarded to the embedded controller. Additionally, sufficient delay is introduced intentionally in reading the deflection commands to model actuator block in simulink system. The Matlab/Simulink implementation block is shown in Figure 3.14(a) & 3.14(b).

As shown in the figure 3.14(a), the four input delayed deflection commands from embedded controller will be given to second order model of actuator. And outputs will be

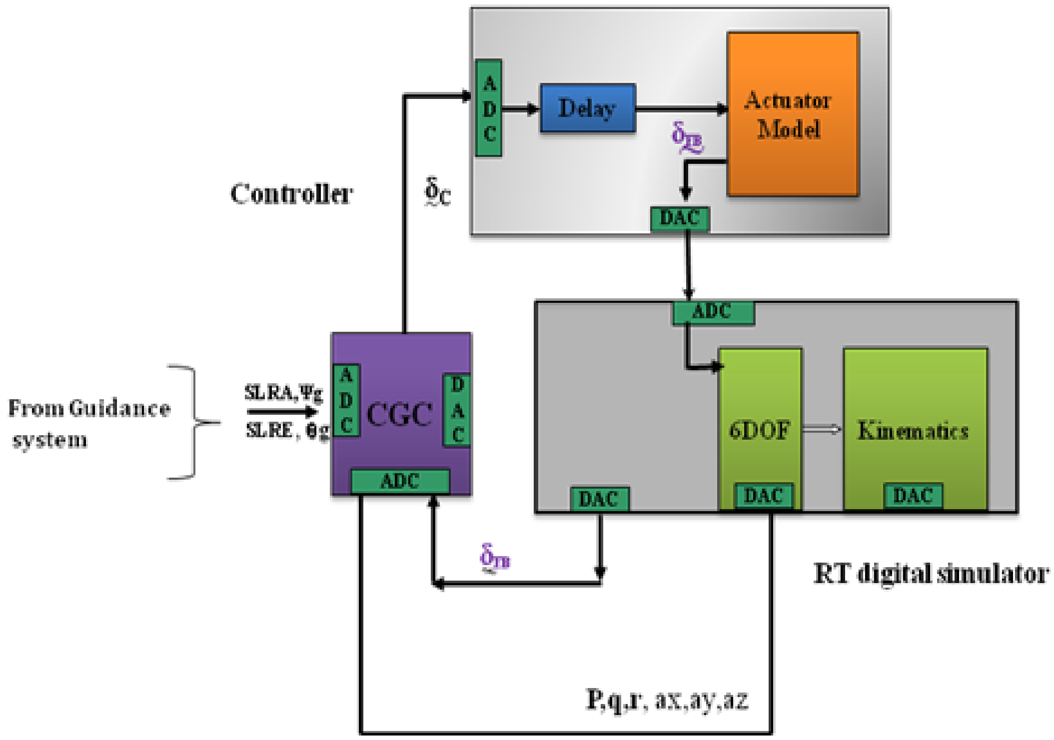
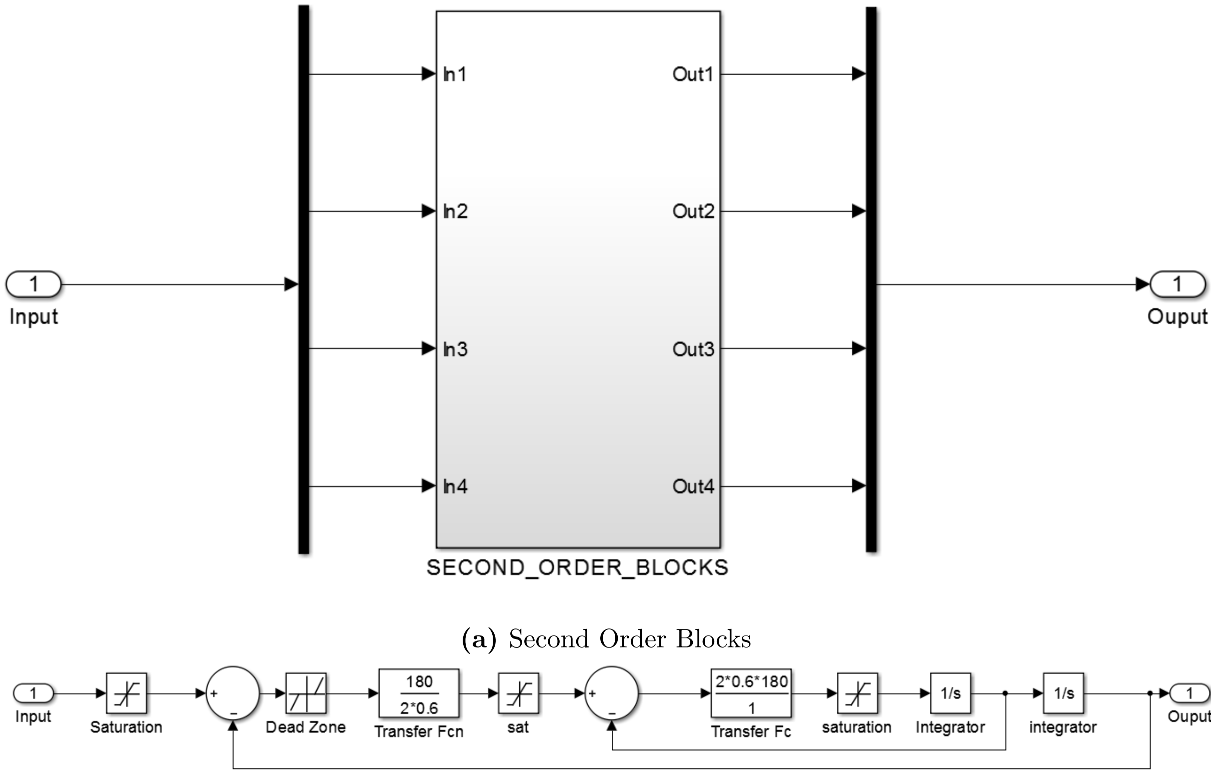


Figure 3.13 Block diagram of Delay modelling

given to 6DOF model of RT digital simulator for further processing to generate rates and accelerations. The simulink implementation of actuator block is shown in Figure 3.14(b). The natural frequency of actuator model is 180 rad/sec and the damping factor is 0.6. The dead band is ±0.3°. The outputs of four actuators are again fed back to the 6DOF model in RT simulation PC. Because of the delay added to the inputs during feedback, the results of the HILS are oscillatory. The Table 3.1 provides the performance comparison of HILS results. It states that the Matlab/Simulink model based delay simulation results are matching with the actual HILS results with delay issue.

The MATLAB/Simulink implementation block is shown in Figure 3.14(a) & 3.14(b)



(a) Second Order Blocks

(b) Actuator Block Diagram

Figure 3.14 Simulink implementation block

3.9 NRT Simulation & Modelling of Delay Effect

3.9.1 Non Real Time Simulation (NRT)

A Non-Real-Time simulation test bed is established for guidance, control, mission sequence along with 6DOF model including atmosphere model, actuator model and sensor model are implemented as a single program as shown in Figure 3.15. The equations from Equation 3.1 to Equation 3.6 are implemented as a model and the required data to generate the pdot,Qdot, rdot, Ax, Ay, and Az are provided after proper computation. Basically, the four deflection commands given by the control and guidance algorithm generates the main excitation parameters. These parameters will be given to 6DOF which is modelled during the NRT PC. The deflection commands will passed through the actuator model and generates four deflection feedbacks.

$$pdot = \frac{Rolldisturbance * RDF - L_{\delta} * delroll}{I_{xx}} \tag{3.1}$$

Table 3.1 Results with Actual delay Vs Simulated delay

Typical HILS Parameter of Aerospace system	**With Actual delay**	**With Simulated delay**
Roll rate	±40 deg/sec	±30 deg/sec
Yaw rate	±20 deg/sec	±25 deg/sec
Yaw acceleration	±5 deg/sec^2	±5 deg/sec^2
Effective yaw (yaw deflection)	±5 deg/sec	±5 deg/sec

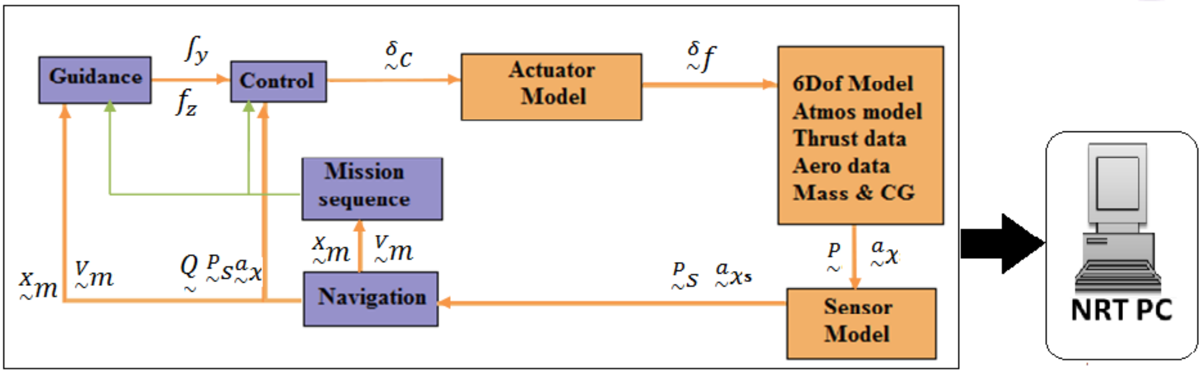


Figure 3.15 NRT simulation

$$Qdot = \frac{M_\alpha * \alpha + M_\delta * delpitch}{I_{yy}} \tag{3.2}$$

$$rdot = \frac{N_\beta * \beta + N_\delta * delyaw}{I_{zz}} \tag{3.3}$$

$$A_x = \frac{ForwardThrust}{Mass} \tag{3.4}$$

$$A_y = \frac{Y_\beta * \beta - Y_\delta * delyaw}{Mass} \tag{3.5}$$

$$A_z = \frac{Z_\alpha * \alpha + Z_\delta * delpitch}{Mass} \tag{3.6}$$

These deflection feedbacks will utilized to compute delpitch, delyaw and delroll parameters. The forces and moments terms to be computed as per their conventional equations. The Ixx,Iyy,Izz, and mass terms are interpolated from the existing tables of the experimental data. Once the p, q, r, Ax, Ay, and Az are computed, they will pass through sensor model to generate sensed rates and accelerations. These parameters will be given to the navigation model to generate positions and velocities. The outputs of navigation model are applied to guidance module to generate latex demands as well as sensed rates. Subsequently, the accelerations are given to control module, to generate four deflections commands based on the 3-loop auto pilot (roll, pitch and yaw). The second order model used for actuator and sensor model is given in equation 3.7.

$$\frac{c(s)}{R(s)} = \frac{w_{n^2}}{s^2 + 2\zeta w_n s + w_n^2} \tag{3.7}$$

Whereas, C(s) = Output, r(s) = Input,
wn is natural frequency in Rad/sec
wn = 180° Rad /sec for actuator model
wn = 377° Rad /sec for sensor model
ζ is damping factor and it is 0.6 for both actuator and sensor model.

3.9.2 Importance of Roll Autopilot

The Roll autopilot is an essential component in 3-loop autopilot design. It is highly responsible for controlling the unwanted roll rate during the course of avionic vehicle. Aerospace vehicles are basically roll stabilized and any small disturbance like thrust misalignment or aerodynamic effect may leads to unwanted roll rates. The resultant roll angle due to this roll rate may cause the vehicle to loose the track of the target. Hence the roll disturbance to be properly cancelled during the course of flight. The Roll autopilot is to be designed properly to take care of this stabilization. The typical results of NRT model and its comparison with digital simulation results of systems group are shown in Figure 3.16.

There is a slight mismatch between the results is occurred due to modelling differences between HILS platform and Systems group platform. The HILS team platform

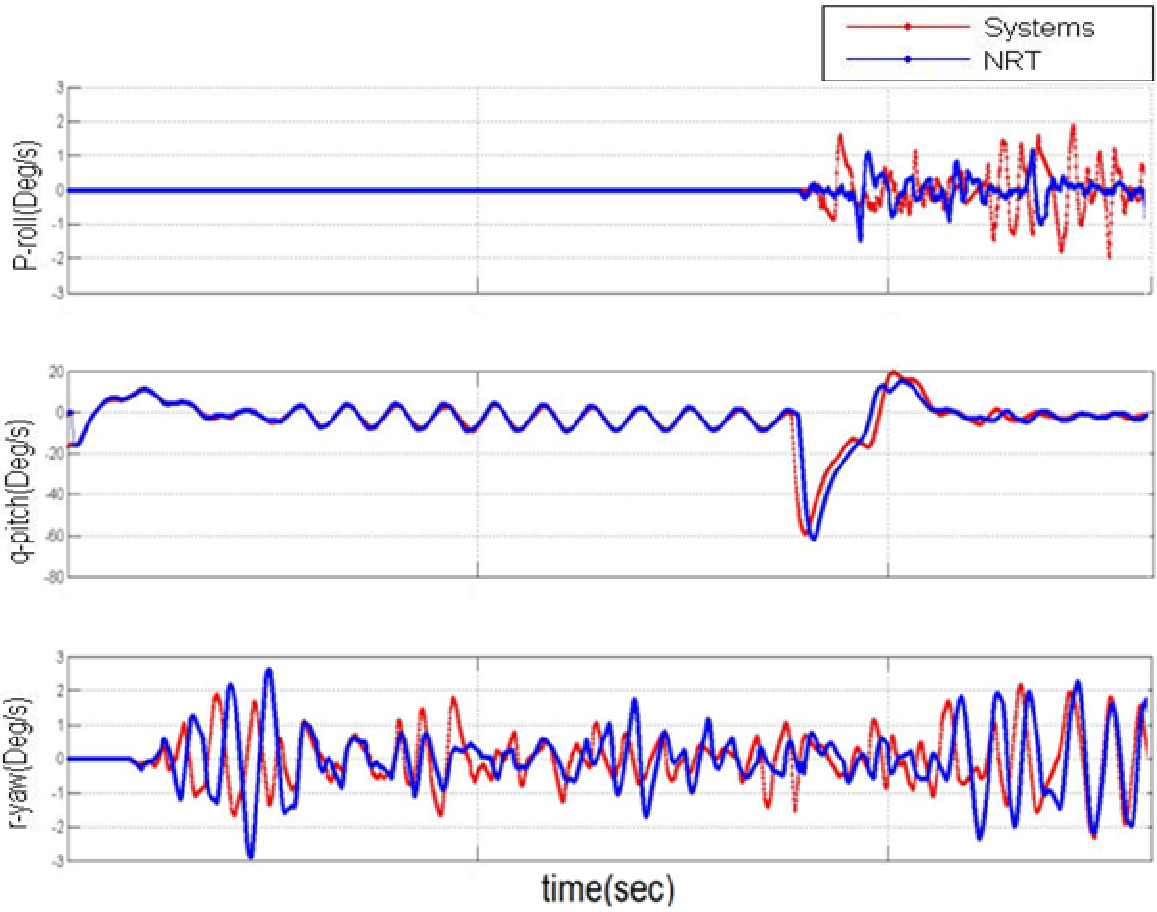


Figure 3.16 NRT results

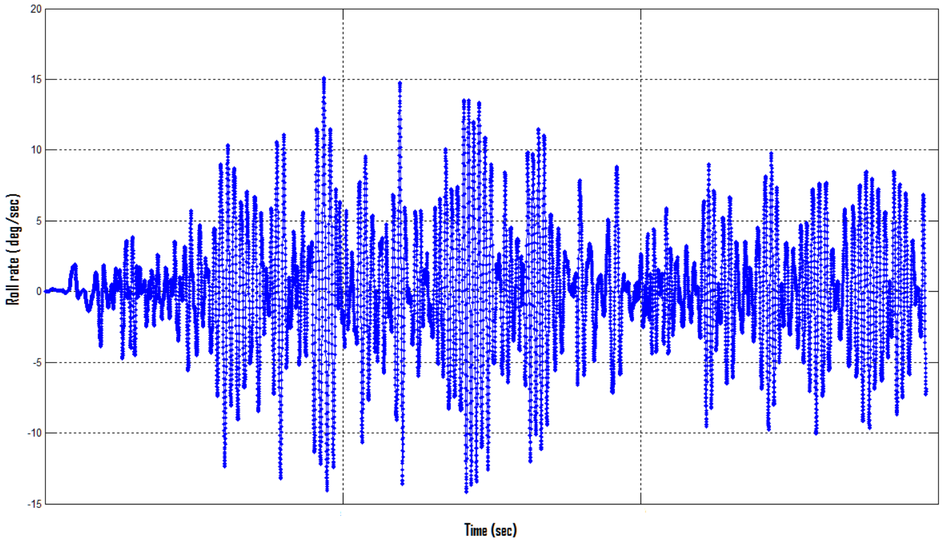


Figure 3.17 Simulated Roll rate in deg/sec

is developed using c++ language on windows and systems team platform is developed using FORTRAN language in Matlab in addition with Monte Carlo simulation method to generate various best possible results. This NRT platform establishment gives enough confidence to proceed further for Real-Time HILS.

3.9.3 Modelling of Delay Effect

The major issues observed in HILS runs are diverging oscillations, which limits the effectiveness of HILS testbed in evaluating the performance of aerospace vehicle subsystems. Following transfer function given in equation 3.8 is derived in MATLAB to simulate the delay effect. The diverging oscillations with a magnitude of $\pm 15°$/sec are generated using this transfer function as shown in Figure 3.17. The generated oscillatory rate is nearly same as the oscillatory roll rate in Sensor plus Actuator In Loop HILS results (ref Figure 3.11).

$$TF = \frac{Output}{input} = \frac{14050}{s^2 + 17.86s + 14050} \tag{3.8}$$

3.10 Conclusions

Different HILS configurations are performed to validate aerospace vehicle sub systems in real-time environment. The HILS results for these configurations are analysed in depth and the issue of diverging oscillations are addressed. The inherent delay in testbed is the main cause for diverging oscillations are discussed. The delay is simulated in real time simulation PC and the effect of delay is simulated in Real time Matlab/Simulink environment. The results of delay simulation is matching with the diverging HILS results. Moreover, the delay is modelled in the NRT platform and the delay effect i.e diverging oscillation in roll rate is simulated. Finally, the characterisation of HILS delay is carried out through accurate modelling and simulation.

Chapter 4

Efficient implementation of Delay Compensation in Real Time HILS

4.1 Introduction

The diverging oscillations occurred in HILS results will impact the performance evaluation of aerospace systems. Several industries like aeronautical, mechanical, civil, space robotics etc, were proposed different types of delay compensation mechanisms to conduct HILS efficiently [13-32]. In this chapter, four popular compensation methods are proposed such as inverse compensation, polynomial extrapolation, smith predictor, and static & dynamic compensation methods. Among them, the inverse compensation method is implemented in NRT simulation platform to observe its effectiveness. Whereas inverse compensation and dynamic compensation methods are implemented in RT testbed to overcome the issue of diverging oscillations in HILS.

4.2 Delay compensation methods

The inherent delay observed in HILS testbed is compensated using different compensation methods to conduct HILS effectively. The following sections gives the overview of the delay compensation methods.

4.2.1 Inverse compensation method

Inverse compensation method [29] was introduced to minimize the delay effect of the system. In this method, for the commanded (input) signal the idealization of system response can be considered as linear. The sampling time is δt, and the time interval for the system to achieve the command signal from the numerical model is td, where td is equal to α*δt. α is the delay constant, which is greater than 1. Hence the system time delay is equal to (α - 1)δt. The compensated signal is associated with the command signal of current and previous time steps. Inverse compensation method in time domain can be described as an extrapolation using the previous command signals.

4.2.2 Polynomial Extrapolation method

The polynomial extrapolation [29] is a delay compensation method that follows the concept of forward prediction. In this method, the command signal is a periodic wave, and the signal affected by time delay 't' is the resultant signal. Where an error is occurred between the desired command, and the response. To compensate time-delay effect, the command signal will be shifted forward by 'K' time steps of 'Δt', such that 'KΔt', should be predicted. By feeding the predicted signal to the system, the resulting output is almost closer to the estimated one. The steps ahead of present time can be predicted by a polynomial with a proper order and it will be helpful in obtaining an accurate estimation of future steps approximately.

4.2.3 Smith predictor strategy

Smith predictor [30] strategy proposes time delay compensation by comparing transfer functions of the closed loop systems with and without time delay. When the smith predictor is introduced in a delayed system transfer function, then the resultant system is same as ideal system without any time delay. So, it assures that the system will be stable with smith predictor.

4.2.4 Static & dynamic compensation

The phase lead technique is used in static compensation [31] approach to compensate the static delay in the force measurement system. Whereas in dynamic compensation [31] the response error based force compensation technique is used to compensate the dynamic delay occurred in the motion simulators. These methods can effectively compensate the simulation divergence and guarantee the reproduction fidelity.

4.3 Feasibility of Implementing the Compensation methods in Simulation PC

The dynamic compensation method is chosen to observe the feasibility of implementing delay compensation in simulation PC as shown in Figure 4.1. Generally, the 6DOF model PC will generate desired euler rates to excite the FMS and the FMS will respond to these euler rates based on its response time. The sensor sub-system mounted on FMS that senses the responded rates to generate actual sensed rates. Moreover, the actual sensed rates will pass through static compensation (CFMS) model which is a lead compensator in simulation PC. Simultaneously, the desired angles generated in 6DOF model are given to FMS and the actual angles from the same are obtained. The comparison between these angles generates the error which passes through dynamic compensation (CDRS) model in simulation PC. Based on the outputs of CFMS and CDRS, the compensated rates are computed. These compensated rates along with 6DOF generated accelerations enters into embedded controller to generate proper deflections commands 'δc' to hardware actuator. The deflection feedbacks from hardware actuator excites the 6DOF model in simulation PC for the generation of euler rates to the following cycles. This process is repeated until the complete run time of flight vehicle.

The four basic compensation methods are explored and the comparison among them is presented in Table 4.1.

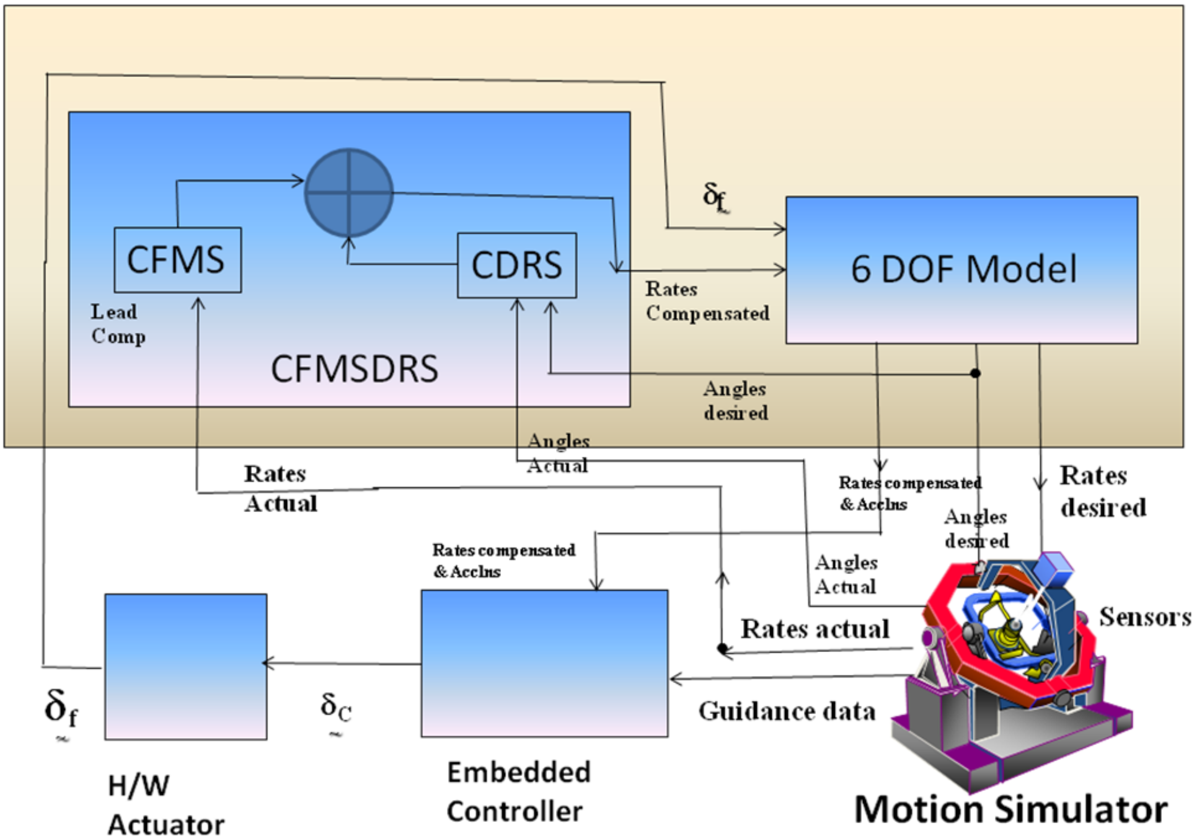


Figure 4.1 Feasibility of delay compensation

Table 4.1 Comparison of different compensation methods

Method Name	Advantages	Disadvantages
Static & Dynamic Compensation	Does not require the model of the dynamic response of the motion simulator	Needs accurate measurements of the motion simulator feedback and Force measuring system
Smith predictor	It will not disturb the original closed loop system	Needs accurate model of physical system transfer function
Inverse compensation	It is not model based method and less errors	Slight phase lag occurs during the test
Polynomial extrapolation	It is not model based method	Introduces a phase lead and needs over compensation

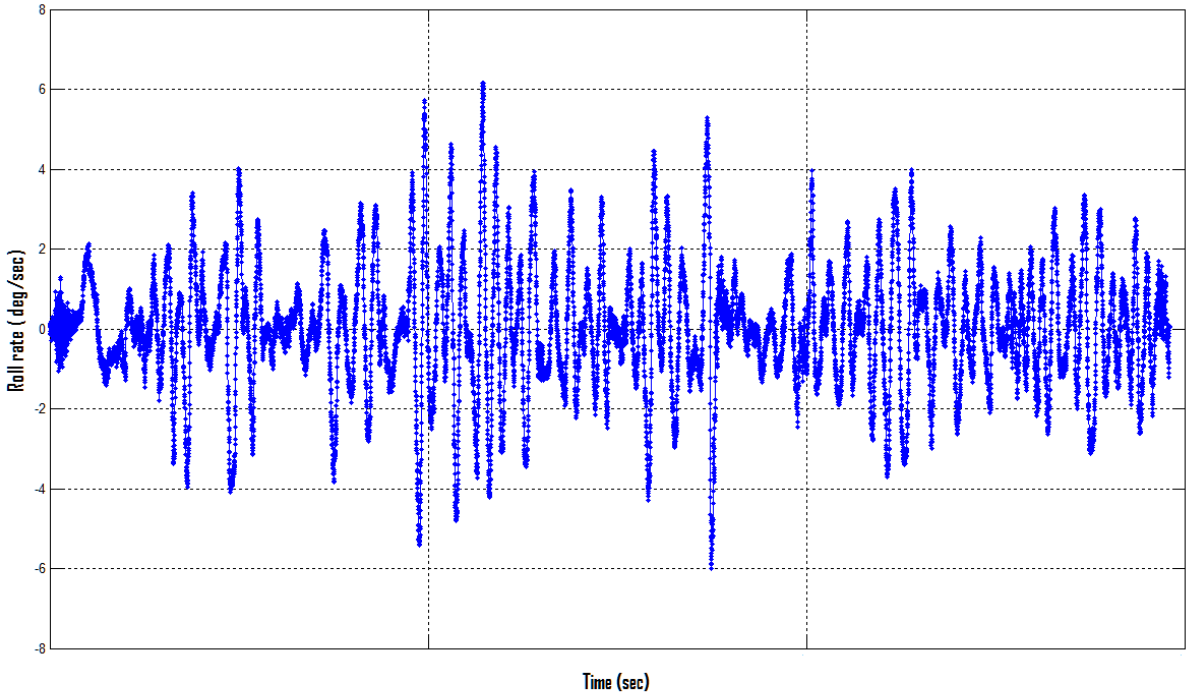


Figure 4.2 Compensated Roll rate in deg/sec

4.4 Inverse Compensation Method in NRT

The inverse compensation method is implemented to compensate the delay effect which is simulated during NRT. The basic principle of inverse compensation is given in equation 4.1.

$$Thecompensatedsignal = \alpha * present\,delayed\,signal - (\alpha - 1) * previous\,delayed\,signal \tag{4.1}$$

Where, α =delay constant > 1.0;

The value of α chosen is 16 based on following calculation

Delay = (α-1)δt; δt=sampling time; Since the delay is 15ms & sampling time is 1ms , α= 16 as per calculation; Hence, Compensated signal=16*present delayed signal-(16-1)*previous delayed signal i.e. Compensated signal=16*present delayed signal-15*previous delayed signal As explained in Chapter 3, Section 3.9.3, the high roll rate due to delay effect is simulated in NRT model. The implementation of inverse compensation in NRT model is given below. float yyy=0.0;

yyy=fdeltaout[1];

Ps = 16*yyy-15*fdeltaoutold;

fdeltaoutold=yyy;

Where, fdeltaout[1] =simulated roll rate at present instance

fdeltaoutold = simulated roll rate at previous instance

Ps = compensated roll rate

yyy = temporary variable to update simulated roll rate

The compensated roll rate is shown in Figure 4.2. With inverse compensation method the high roll rate of $\pm 14°$/sec is reduced to $\pm 5°$/sec which is very less when compared with state-of the art designs. However, the achieved low roll rate can be easily controlled by the onboard control and guidance algorithm to maintain the stability and to steer the flight vehicle within pre-defined trajectory.

4.5 Inverse Compensation Method in RT HILS

The effectiveness of inverse compensation method was validated in NRT simulation, and the same was implemented in real time HILS with hardware subsystems of the aerospace vehicle. The setup diagram of RT HILS is shown in the Figure 4.3. The hardware sensor unit is mounted on FMS and the same is excited with flight profile rates generated by RT simulation PC. The sensed rates with the expected delay of 15ms offered by FMS are fed as inputs to the inverse compensation model in simulation PC. In real time aspect, the major difficulty lies in the compensation execution existed in simulation PC within a time frame. The inverse compensation model in RT simulation PC is given in equation 4.2.

$$compensatedrate = \alpha * present\, delayed\, sensed\, rate - (\alpha - 1) * previous\, delayed\, sensed \tag{4.2}$$

Since $\alpha = 16$ (due to delay =15ms) Compensated rate = 16 * present delayed sensed rate – 15 * previous delayed sensed rate

The HILS results with compensation (represented in red) are shown in Figure 4.4 and it is observed that the diverging oscillations are fairly reduced. Hence, the delay effect of high roll rate oscillations are reduced to nominal values which are acceptable by

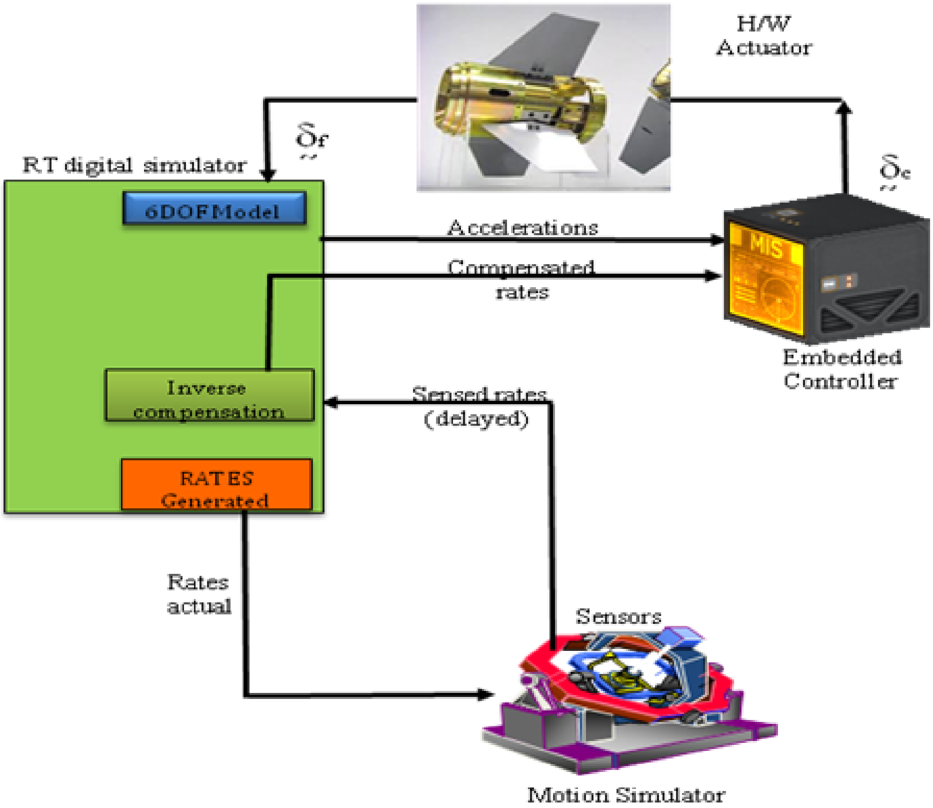


Figure 4.3 Inverse compensation in RT HILS

control and guidance algorithm.

4.6 Implementation of Dynamic Compensation

4.6.1 Jet vane effect in HILS

Aerospace vehicles of tactical type needs high controllability in design to steer the vehicle in the defined path. Initially, in the launch phase of the trajectory, thrust vector controlling is used instead of aerodynamic control since there is no sufficient dynamic pressure to use aerodynamic control. Subsequently, in other phases of trajectory an aerodynamic control is used. Additionally, jetvanes are added in the aerospace vehicle to have better controllability in the initial phase of trajectory where the dynamic pressure is low. Hence, any drooping of the vehicle and touching the ground is avoided with addition of jet vanes. Accordingly, the following modifications are made in 6DOF model (plant model) as given in Equation 4.3 to Equation 4.8 to simulate the jet vane effect.

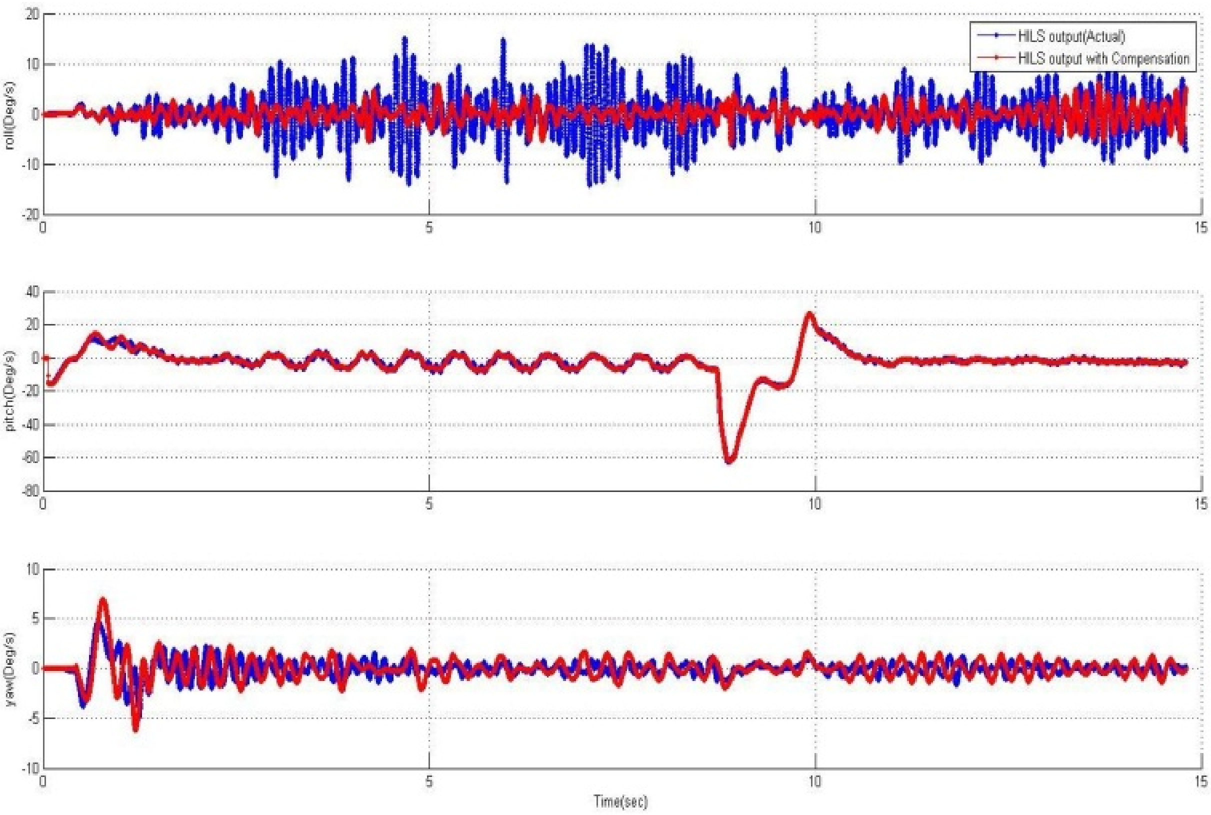


Figure 4.4 Compensated Vs Uncompensated HILS Results

The resultant force due to jet vane in body frame is represented as

$$thrstx = thrstx1; \tag{4.3}$$

$$thrsty = (thrsty1 - thrstz1) * 0.707; \tag{4.4}$$

$$thrstz = (thrsty1 + thrstz1) * 0.707; \tag{4.5}$$

The resultant moment due to and jet vane in body frame is represented as

$$thmistx = thmistx1; \tag{4.6}$$

$$thmisty = (thmisty1 - thmistz1) * 0.707; \tag{4.7}$$

$$thmistz = (thmisty1 + thmistz1) * 0.707; \tag{4.8}$$

The 6DOF equations are modified like below to simulate jet vane control, i.e the above moments terms are added into rotational accelerations and the force terms are added into linear acceleration terms as shown in below equations from Equation 4.9 to Equation 4.14.

$$pdot = \frac{Rolldisturbance * RDF - L_\delta * delroll + thmistx}{I_{xx}} \tag{4.9}$$

$$Qdot = \frac{M_\alpha * \alpha + M_\delta * delpitch + thmisty}{I_{yy}} \tag{4.10}$$

$$rdot = \frac{N_\beta * \beta + N_\delta * delyaw + thmistz}{I_{zz}} \tag{4.11}$$

$$A_x = \frac{ForwardThrust}{Mass} \tag{4.12}$$

$$A_y = \frac{Y_\beta * \beta - Y_\delta * delyaw + thrsty}{Mass} \tag{4.13}$$

$$A_z = \frac{Z_\alpha * \alpha + Z_\delta * delpitch + thrstz}{Mass} \tag{4.14}$$

Control and guidance algorithm is modified accordingly to take care of jetvane effect. Subsequently, OBC is loaded with the revised algorithm and HILS runs are conducted with OBC, actuator and sensor. With this test setup the HILS run failed immediately in the initial phase i.e, jetvane control phase of nearly 400ms after the lift-off by generating high body rates (represented in blue) as shown in Figure 4.5. When the sensor package and actuation system are introduced in HILS test bed (Refer Figure 3.4) the diverging oscillations are observed with certain roll rate. These oscillations are due to the limited band width (25Hz) and dead band values ($\pm 0.3°$) of real hardware actuation system and limited bandwidth (nearly 25Hz) of FMS. Moreover, when control and guidance algorithm is modified to take care of jetvane control, the HILS run is totally failed. This is due to overall loop delay which cannot be handled by control guidance algorithm (after modification for jetvane).

4.6.2 Dynamic Compensation in HILS

The dynamic compensation method [31] is the solution to overcome the initial phase failures in conducting HILS runs. The equations to implement dynamic compensation are given in equation 4.15.

$$Compensatedsignal = Kcon * (the\, desired\, rate\, input\, signal\, to\, FMS$$

$$\text{-}the\, actual\, rate\, output\, signal\, from\, FMS)(4.15)$$

Kcon = stiffness constant of FMS and Kcon chosen as 1.2 based on its structure The setup diagram for dynamic compensation is shown in Figure 4.7. While the same test set up followed from the inverse compensation, the sensed rates offered by FMS are fed as inputs to the dynamic compensation model in simulation PC. In real-time aspect, the major difficulty lies in the compensation execution in RT simulation PC within the time frame. The dynamic compensation model in RT simulation PC is given below.

The compensated roll rate is observed as $\pm 5°$/sec as shown in Figure 4.8 which is considerably low in amplitude and allowable by the control & guidance algorithm. The HILS results with dynamic compensation are fair and the initial phase failure is not experienced. The comparison of compensated roll rate with OBC in loop roll rate is shown in Figure 4.9. The fin deflections and body rates generated during HILS run after the dynamic compensation are shown in Figure 4.10 & Figure 4.11.

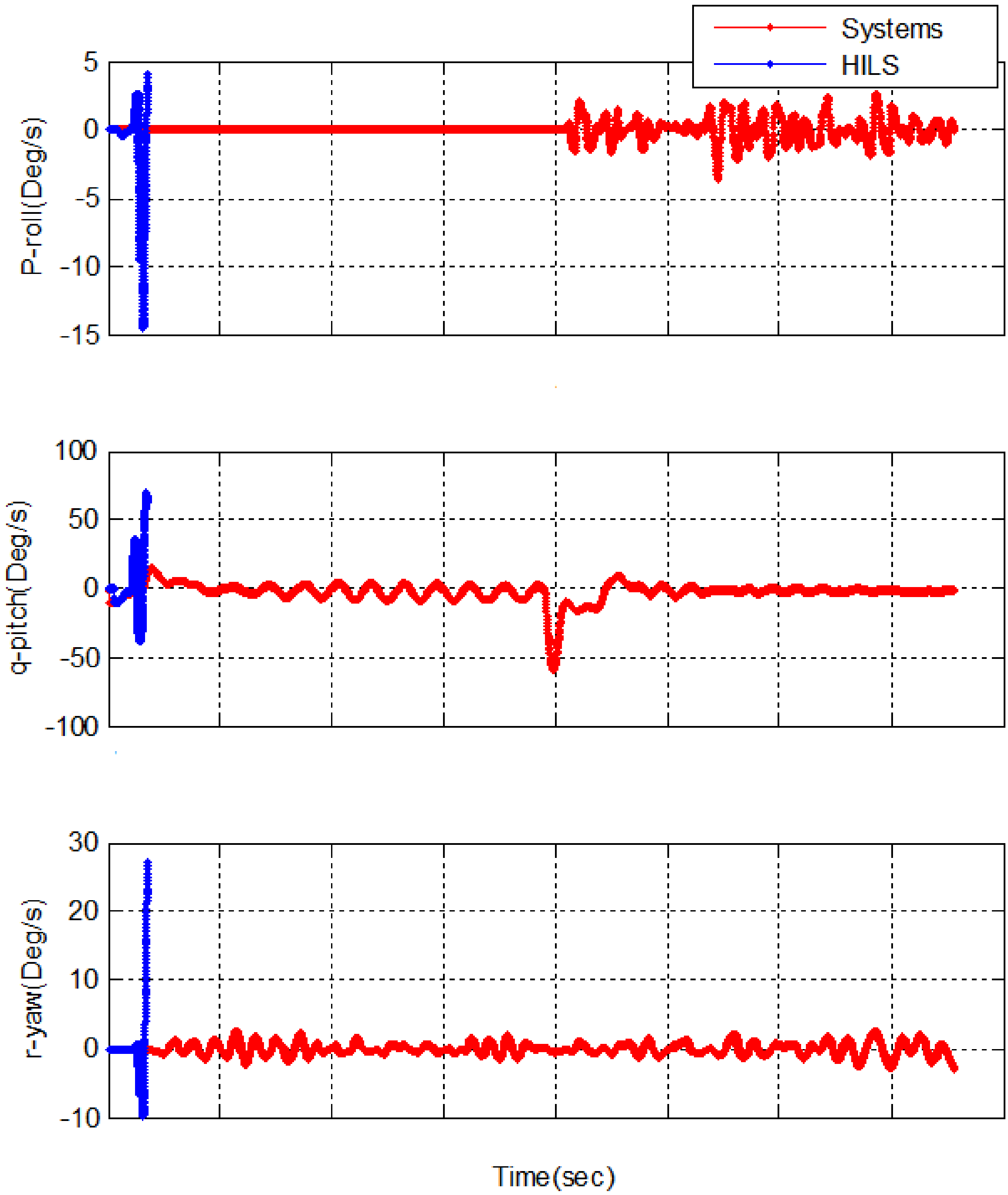


Figure 4.5 High Body rates(failed)

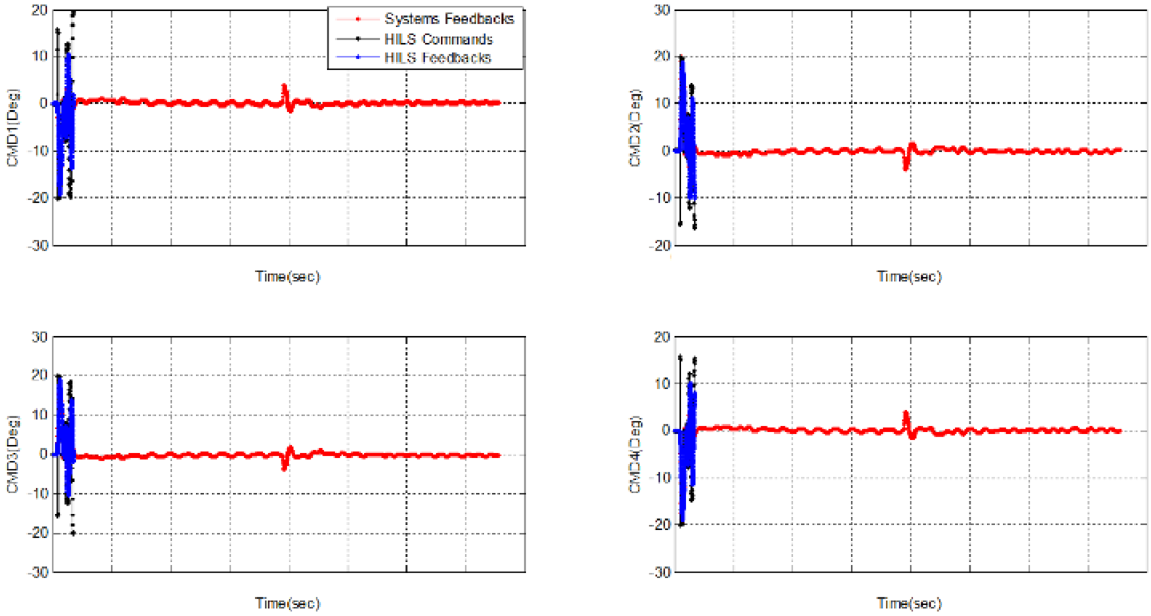


Figure 4.6 Fin Deflection commands

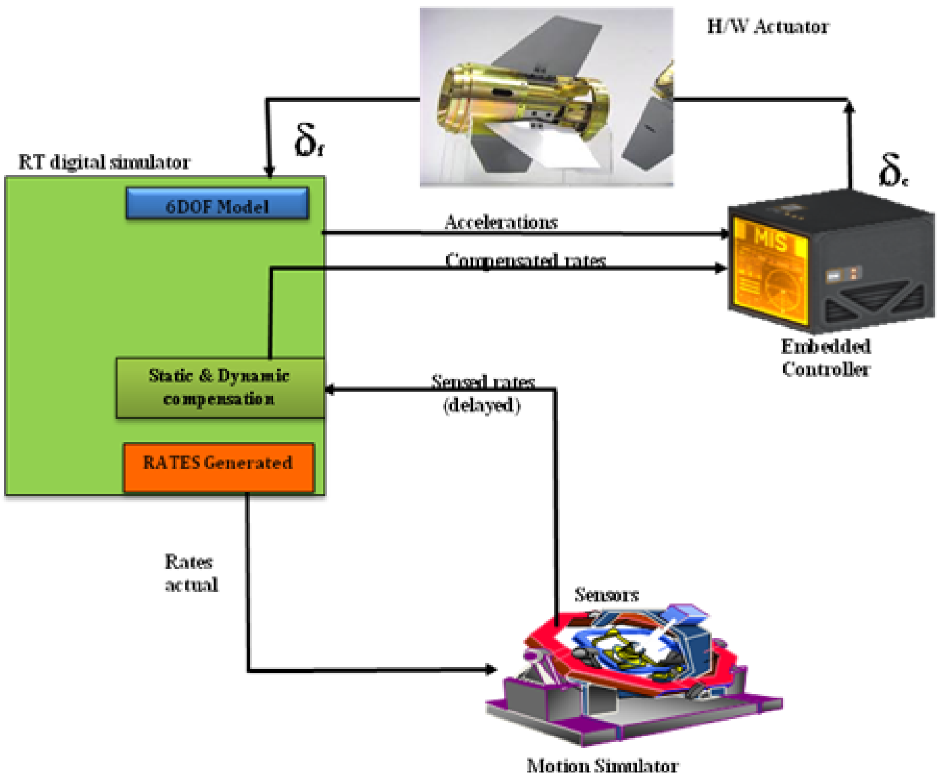


Figure 4.7 Dynamic compensation in HILS

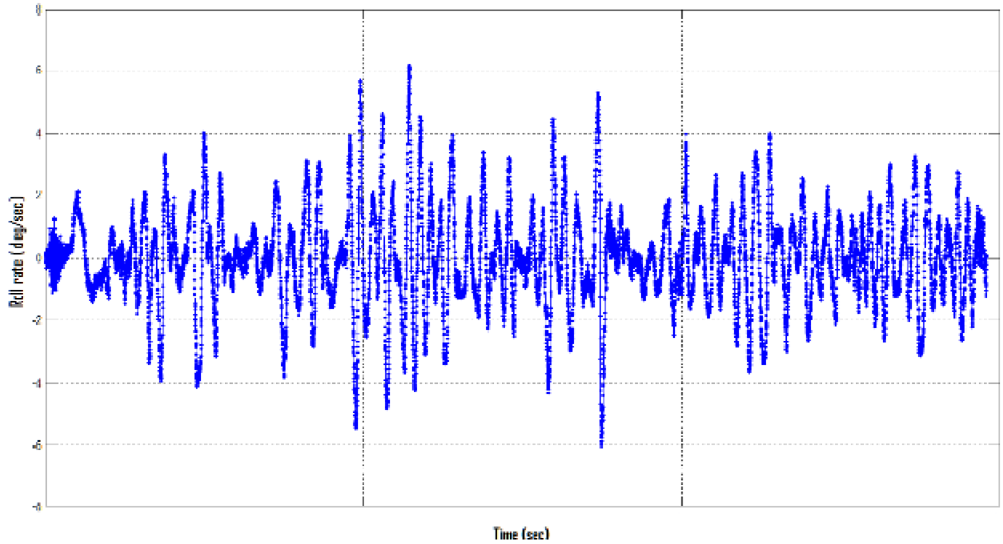


Figure 4.8 Compensated Roll rate in deg/sec

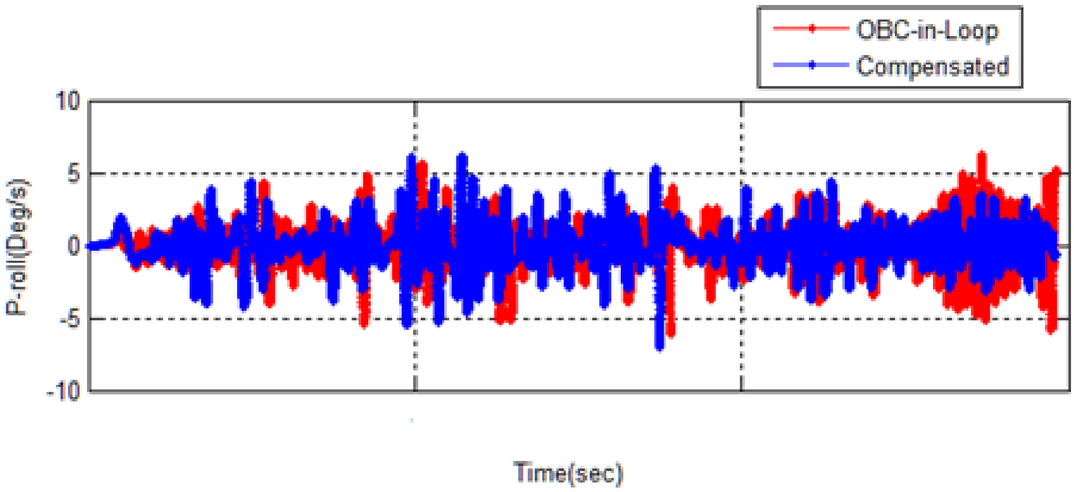


Figure 4.9 Compensated Roll rate Vs OBC in Loop Roll rate

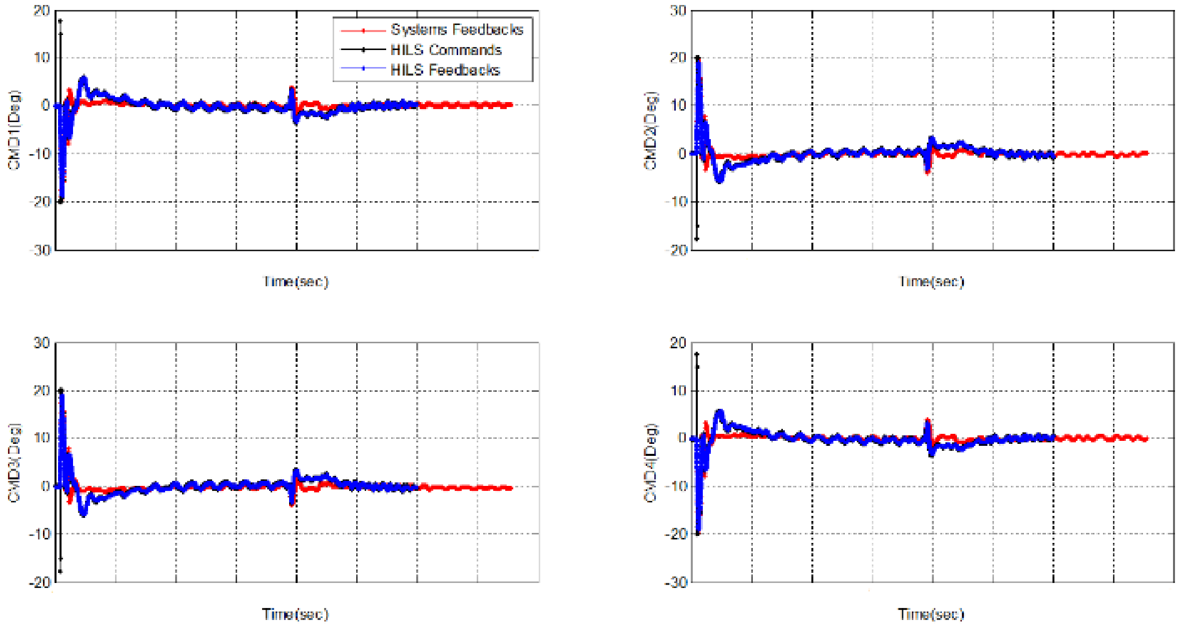


Figure 4.10 Fin Deflections of Compensated HILS run

4.7 Conclusions

Different delay compensation methods are implemented to eliminate the unwanted diverging oscillations occurred in HILS results. The inverse compensation method is implemented in NRT & RT simulation and the run results are summarized. The compensated results are matching with OBC in loop simulation results. While modifications in control and guidance algorithm to take care of jetvane control, the delay effects are more prominent and HILS runs are failed due to huge body rates developed in the initial phase. Dynamic compensation scheme is implemented in RT HILS to overcome the initial phase failures. With this compensation the HILS runs are going through and results are fairly matching with designer's predictions indicating that the evaluation of aerospace subsystems has been carried out efficiently.

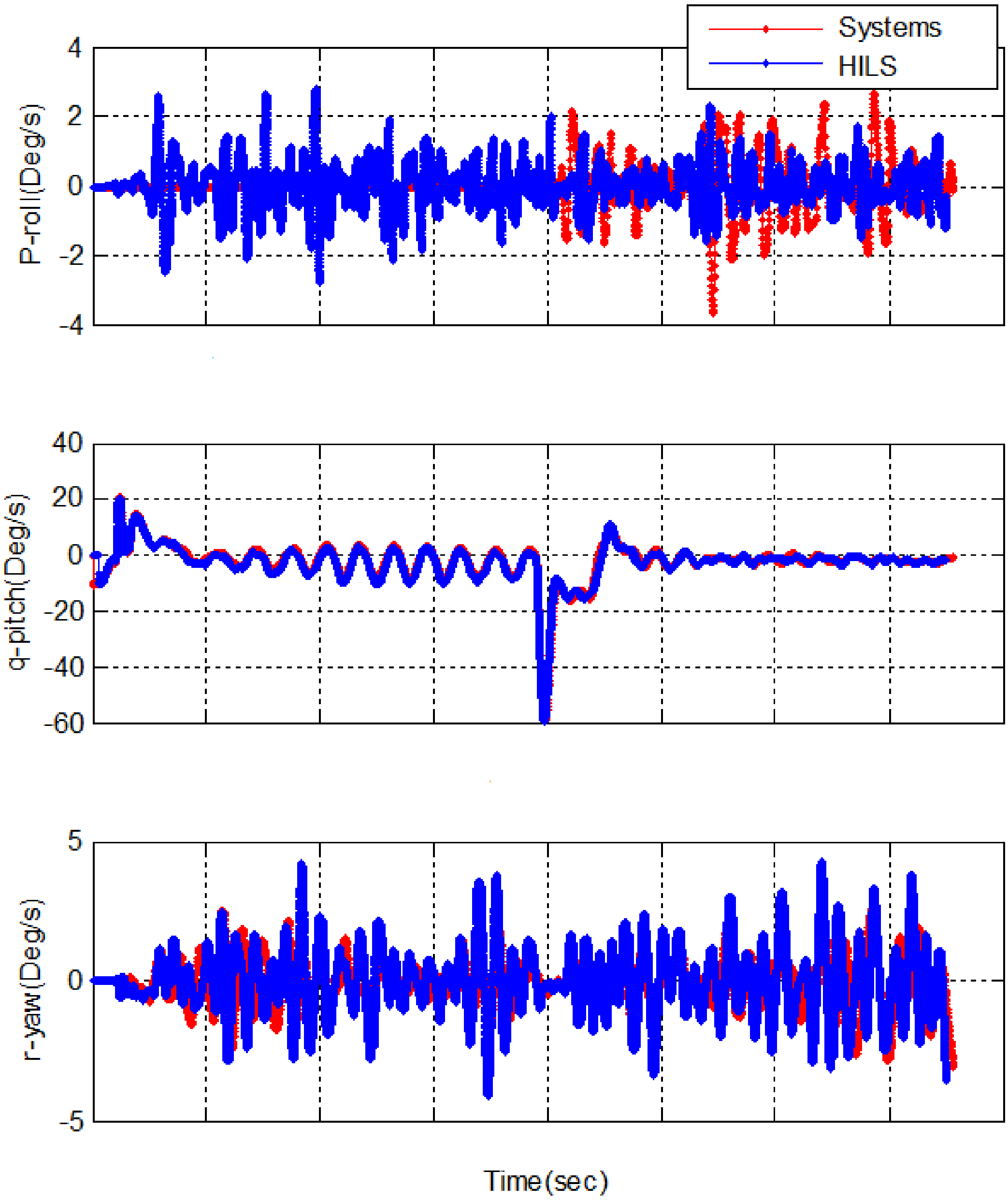


Figure 4.11 Body rates of Compensated HILS run

Chapter 5

Conclusions and Future Scope

5.1 Conclusions and Future scope

The design and development of the aerospace vehicle subsystems is very crucial and their evaluation should be efficient. A testing methodology is highly essential for verification and validation of subsystems much prior to the actual field tests to avoid any failures to reduce the development cost. HILS is a platform to carry out this task in real time simulated scenario which is almost mere to the actual field tests. The validation of seeker system for homing guidance requirement is carried out independently by conducting modelling, dynamic tests and single plane HILS. Subsequently, 3-Axis HILS testbed is established and tests are conducted for different sub-systems with different configurations like OBC in Loop, Actuator In Loop, Sensor In Loop and Seeker In Loop. Moreover, the results are analysed to observe the unwanted diverging oscillations in HILS runs of aerospace vehicle. The delay effect is modelled using Matlab/Simulink delay block by feeding the delayed deflection commands to the actuator model. The results obtained in the simulation are closely matched with the actual HILS results with delay.

The Characterisation of HILS delay through accurate modelling and simulation is conducted in NRT and RT simulated environments. Further different delay compensation methods were explored thoroughly and efficient delay compensation methods like Inverse and dynamic compensation methods were implemented in the NRT environment. Moreover, these methods are also implemented in an RT environment with real flight hardware in the loop. The compensated results are fairly matching with all digital expected simulation results. With this efficient compensation, the HILS testbed emerged as a suitable real-time platform to evaluate aerospace vehicle subsystems effectively before the actual field tests.

The overall implementations on the delay aspect in the HILS test bed helped in finding out a better solution to carry out HILS for aerospace systems effectively. In future, advanced compensation schemes to be identified to rectify the divergence effects caused by the time-varying delay, which is occurring rarely in the HILS testbed.

Publications

List of International Journals:

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1. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar, "Testing Setup and Delay Compensation in HILS of Aerospace Systems" *IETE Journal of Research*, 39(2), pp.1-13, 2021. **(SCI)**
2. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar, "Modeling and Compensation of Time-Delay Effects in HILS of Aerospace Systems" *IETE Technical Review*, 39(2), pp.375-388, 2022. **(SCI)**

List of International Conferences:

---

1. L.A.V. Sanhith Rao, P Sreehari Rao, and L. Sobhan Kumar "Delay Compensation in HILS of Aerospace Systems" *In 30th International Symposium on Ballistics, 2017.*
2. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar, "Causes & Effects of delay in HILS of Aerospace systems" *In 2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*,(pp. 158-162). IEEE.
3. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar "Delay Compensation in HILS of Aerospace Systems" *In 31st International Symposium on Ballistics, 2019.*
4. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar, "Evaluation of Real-Time Embedded Systems in HILS and Delay Issues" *In Advances in*

Communications, Signal Processing, and VLSI,(pp. 123-137). Springer, Singapore, 2021.

5. L.A.V. Sanhith Rao, P Sreehari Rao, I.M. Chhabra and L. Sobhan Kumar, "Compensation of Delay in Real-Time HILS for Aerospace Systems" *In Data Engineering and Communication Technology*, (pp. 141-152). Springer, Singapore, 2021.

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