A System Engineering Approach to Compensator Design for Fault Tolerant Actuators in PSLV

Koppula Pramodh Reddy
PSLV/VSSC/ISRO
Trivandrum, India
pramodh_koppula@vssc.gov.in

Deepa Jose
AVN/VSSC/ISRO
Trivandrum, India
deepa_jose@vssc.gov.in

Jeyajanaki B M
STR/VSSC/ISRO
Trivandrum, India
m_jeyajanaki@vssc.gov.in

Priya C Kurian
AVN/VSSC/ISRO
Trivandrum, India
priya@vssc.gov.in

Baby Sebastian
AVN/VSSC/ISRO
Trivandrum, India
baby_sebastian@vssc.gov.in

Damodaran P
PSLV/VSSC/ISRO
Trivandrum, India
p_damodaran@vssc.gov.in

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***Abstract*— The fourth stage (PS4) of the Polar Satellite Launch Vehicle (PSLV) employs simplex Electro Mechanical Actuators (EMA) for Thrust Vector Control of stage through engine gimballing. To enhance reliability, a new class of fault-tolerant actuators equipped with redundant motor coils, feedback sensors, and fault-tolerant electronics have been introduced. This implementation calls for a compensator redesign in the control electronics. As part of compensator tuning open-loop frequency response on a simulated PS4 stage, multiple dip frequencies were observed in the gain plot, indicating system-level structural interaction. Modal analysis using finite element methods revealed differences in behavior between pitch and yaw axes. This paper demonstrates the necessity of a system engineering approach in compensator design, integrating structural dynamics, actuator behavior and control logic to ensure the compensator performs robustly under all mission conditions.**

***Index Terms* — Fault-tolerant actuators, PSLV, compensator design, frequency response, finite element analysis, control system, systems engineering**

I. Introduction

The PSLV (Polar Satellite Launch Vehicle) is a versatile expendable launch vehicle system developed by Indian Space Research Organization (ISRO). PSLV is capable of injecting payloads into a wide range of orbits, Sun-Synchronous Polar Orbit (SSPO), Geostationary Transfer Orbit (GTO), Low Earth Orbit (LEO) and Highly Elliptical Orbits (HEO). The vehicle's adaptability has also enabled it to serve as launch platform for Lunar and Inter-planetary missions [1].

The fourth stage (PS4) of the PSLV is equipped with two liquid fueled engines, both of which have gimbal mounted nozzles to provide accurate attitude control during orbital insertion and subsequent maneuvering phases. Traditionally, these nozzles have been actuated using simplex electromechanical actuators (EMAs). However, as mission complexity and reliability requirements have increased, the limitations of simplex EMA configurations, particularly their vulnerability to single-point failures have become more pronounced.

To address these concerns, there has been a strategic shift towards the implementation of fault-tolerant actuators with built-in redundancy [2]. These advanced actuators are designed to ensure continued operation even in the event of a component failure, thereby significantly enhancing the overall reliability and safety of the launch mission.

The introduction of these fault tolerant systems introduces new challenges, particularly in the design and tuning of the compensator embedded within the actuator control electronics [3]. Compensators are filters that alter the overall plant dynamics to ensure that mission requirements are met. The compensator must now account for the added complexity arising from redundant pathways and the dynamic interactions between structural, mechanical, and control subsystems [4]. As a result, compensator tuning has evolved into a multifaceted problem, requiring careful consideration of stability, responsiveness, and fault accommodation.

The objective of this paper is to demonstrate that a system engineering framework is indispensable for the successful development and integration of advanced actuation systems in the PSLV.

Key aspects of this system engineering [5] - [8] approach include:

- Lifecycle Integration: Ensuring that design, testing, and operation considerations are addressed from the earliest stages of development.
- Cross-Functional Collaboration: Facilitating effective communication and coordination among multidisciplinary teams spanning mechanical, electrical, and control engineering domains.
- Requirements Verification: Implementing rigorous processes to validate that all system requirements, especially those pertaining to reliability and fault tolerance are met throughout the system lifecycle.

The structure of this paper is as follows: Section II describes the redundancy architecture of the PS4 actuation system. Section III covers servo design, compensator tuning, and key test observations. Section IV presents structural modeling and FEM simulations correlated with experimental results. Section V concludes the paper, highlighting key findings and implications. The importance of a systems engineering approach to solving multidisciplinary challenges is emphasized throughout.

II. PS4 ACTUATION SYSTEM AND REDUNDANCY ARCHITECTURE

The actuation system in PS4 is designed to manage multiaxis control using four EMAs two for each engine as shown in Fig. 1. Actuators are assembled to the engine at one end and other end to PS4 stage as shown in Fig. 2. Linear movement of the actuator is converted to rotary motion of engine about the gimbal joint. In the upgraded configuration, fault-tolerant actuators are introduced with features like dual-coil motors for continuity in the event of a coil failure, redundant position sensors to maintain feedback fidelity and redundant control electronics with Fault Detection and Isolation capabilities to ensure signal continuity.

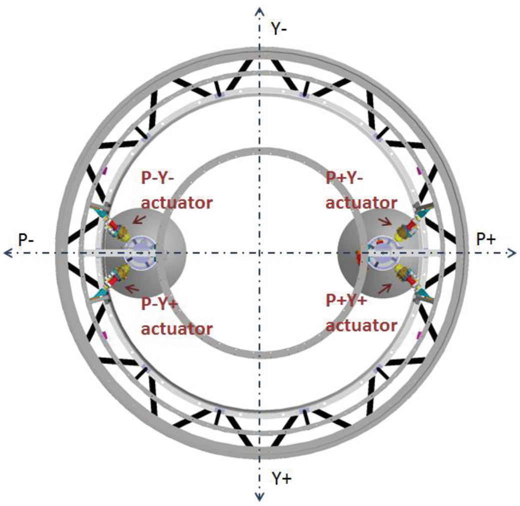

Fig. 1. Configuration of actuators in PS4 stage

This redundancy is part of the system's reliability improvement strategy. Applying system engineering principles, redundancy was not only implemented at the hardware level but also considered in software. This architecture ensures required performance in the presence of component failures, improving mission assurance. However, such design complexity requires end to end validation.

III. SERVO DESIGN AND COMPENSATOR TUNING

The compensator, an essential element of the control loop, was redesigned to accommodate the new actuator characteristics. From a system engineering perspective, the compensator design process included iterative requirement decomposition, interface analysis, and validation planning. As part of actuation system design, bandwidth and slew rate are core mission requirements to be achieved while ensuring the stability of the system. System engineering practices were employed to trace the redundancies back to mission-critical requirements.

Plant characterisation is the first step in compensator design and plant dynamics is accurately characterised in this process. Testing was conducted on a ground-integrated PS4 stage, where one actuator was actively commanded and the remaining three were held at null. An open-loop frequency response test revealed two unexpected dip frequencies in the gain plot as shown in Fig. 3 against the expected plant dynamics given in Fig. 4.

The dip frequency represents anti-resonance points (locations of minimal response) that occur before the resonance frequencies, where the response is at its maximum, in engine gimbal systems. It is essential to

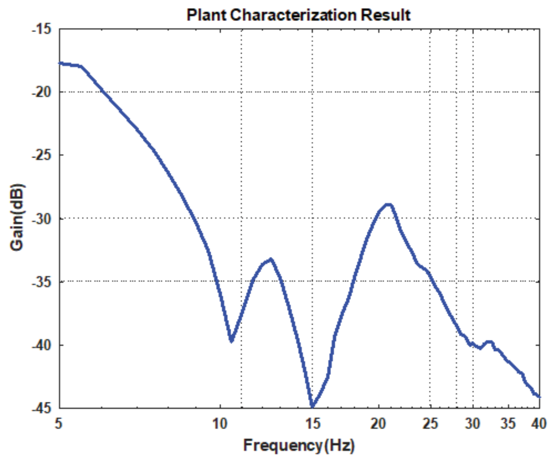

Fig. 3. Plant characterization result

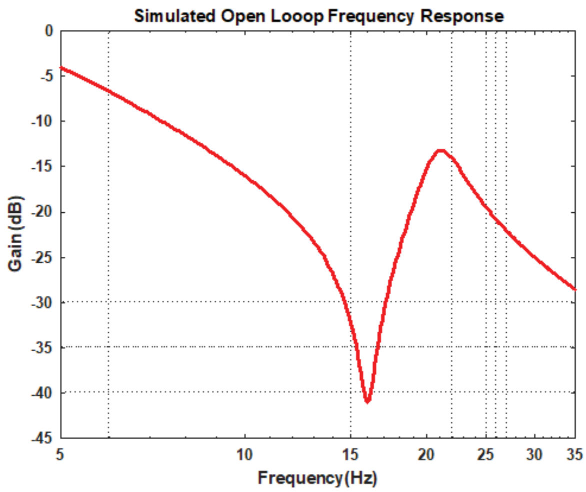

Fig. 4. Simulated (Expected) plant dynamics

account for both anti-resonance and resonance in control system design to maintain stability and achieve accurate control actuation system performance.

Previously, ground testing of individual simplex actuators on the simulated PS4 stage, while holding the other three actuators at null was not feasible due to limitations in the simplex control electronics and the checkout system. These constraints prevented stand alone testing of actuators within the fully integrated system. However, with the development of new control electronics and enhanced checkout systems, it has become possible to carry out individual actuator testing even when the actuators are integrated into the PS4 stage. This advancement necessitated an update to the testing methodology to leverage the new capabilities. As a consequence of this revised testing approach, specific phenomena such as the appearance of multiple dip frequencies in the actuator response were observed for the first time. These observations underscore the significant influence that testing methodology and system integration have on accurately characterizing actuation system behavior.

The functional block diagram of an Engine Gimbal Control (EGC) actuation system is shown in Fig. 5 which encompasses a BLDC (Brush Less Direct Current) motor (control by power amplifier) and a rocket engine represented by second order dynamics, with an associated bracket structure for their interconnection, ball screw for rotary to linear motion conversion and potentiometer for position sensing. Detailed mathematical modeling of an EMA based control actuation system for an EGC system is available in [9].

Theoretical values of dip and resonance for an EGC system are computed using (1) and (2).

$$f_{dip} = \frac{1}{2\pi} * \sqrt{\left(\frac{lm^2 * K_l}{J_e}\right)} \qquad (1)$$

$$f_{res} = \frac{1}{2\pi} * \sqrt{\left(\frac{lm^2 * K_l}{J_{eff}}\right)} \qquad (2)$$

Where K_l is the equivalent mounting bracket stiffness including all elements in series with the actuator, lm is the lever arm length, J_e is the engine moment of inertia and J_m is motor rotor moment of inertia. Motor rotor inertia reflected to engine side is derived using (4), where nb is the ball screw gear ratio. J_{eff} is the effective moment of inertia derived from J_e and J_{me} using (3).

$$J_{eff} = \frac{J_{me} J_e}{J_{me} + J_e} \qquad (3)$$

$$J_{me} = J_m \times \left(\frac{lm}{nb}\right)^2 \qquad (4)$$

Suitable filters are designed in the front end to achieve mission specific requirements. Notch filter which attenuates the resonant mode of the system is also appended. Notch filter transfer function is given in (5) and the frequency response is shown in Fig. 6.

$$G_n(s) = \frac{s^2 + 2\zeta_{nn}\omega_{res} s + \omega_{res}^2}{s^2 + 2\zeta_{dn}\omega_{res} s + \omega_{res}^2} \qquad (5)$$

where ω_{res} is the center frequency of the notch filter and ζ_{nn} and ζ_{dn} are numerator and denominator damping terms which determines the sharpness of the notch filter.

System level tests involving individual actuator commanding revealed unexpected anti-resonance behavior, prompting a cross-domain review. This iterative review cycle represents the feedback rich nature of system engineering validation. Consistency of the performance is validated by testing six different actuators, showing same dip and resonant

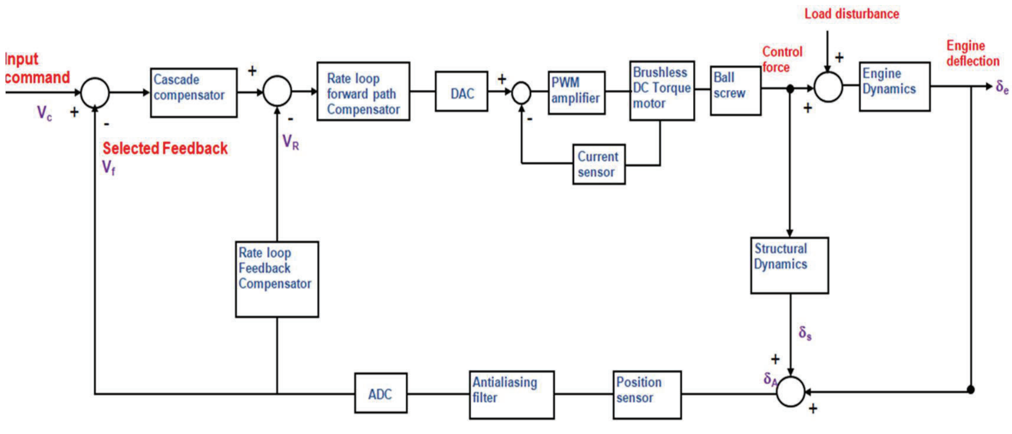

Fig. 5. Block diagram of EGC actuation system

Single dip frequency was observed when all four actuators were commanded simultaneously, but the frequency differed across pitch and yaw axes, indicating axis-specific structural behavior as given in Fig. 8. This shows the importance of comprehensive integration testing and system level verification early in the life cycle. This variation in dip frequencies between the pitch and yaw axes is applicable for simplex actuation systems also. However, it becomes particularly critical in the context of fault-tolerant system design, as the fault tolerant configuration exhibits higher gain beyond the bandwidth frequency compared to the simplex system. Higher gain in fault tolerant system is an added advantage for disturbance rejection along with assured performance under coil failure condition. This increased gain can significantly influence the design and performance of the Digital Auto Pilot. In contrast, the simplex system, being power-limited, displays a sharp gain roll-off after the bandwidth frequency, resulting in minimal impact on the Digital Auto Pilot design.

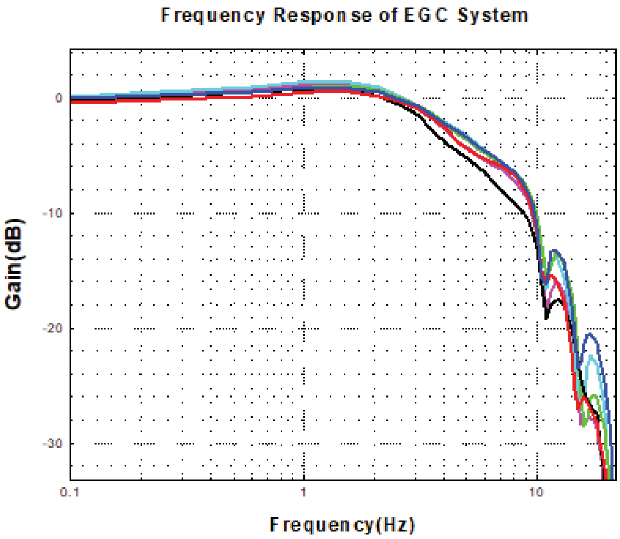

Fig. 7. Comparison of response of six actuators with one actuator commanded at a time.

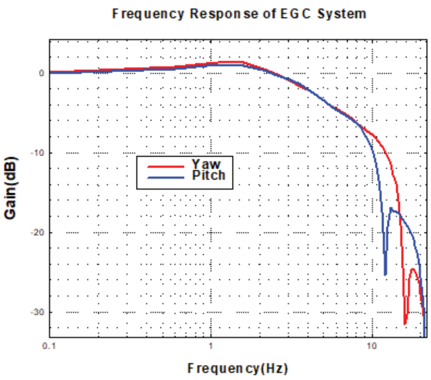

Fig. 8. Response w.r.t pitch and yaw axis when all four actuators were commanded together.

The finite element method is a powerful computational technique for solving differential equations that describe physical phenomena such as stress, vibration, and thermal responses. It works by discretizing a complex structure into a finite number of smaller, manageable sub-domains known as elements, which are connected at points called nodes. These elements can take various forms such as beams, shells or solid bricks depending on the geometry and nature of the problem. Each element obeys a simplified form of the governing equations and the global system of equations is assembled from the contributions of all individual elements. This process transforms the continuous structure into a system of algebraic equations, which can be solved using numerical methods to obtain displacement, stress and strain fields under dynamic or static loading conditions.

For this study, the PS4 stage was modeled using both shell and solid elements to accurately represent overall bending and local stiffness near attachment points. In the context of structural dynamics, FEM enables the computation of natural frequencies, mode shapes, and response under time-varying loads. Structural dynamic simulations of the PS4 stage, including the mounted engines with actuator loop stiffness, were carried out to evaluate its dynamic characteristics. This approach allowed for precise assessment of the PS4 stage's vibrational characteristics and helped identify local deformations, particularly around the engine interface, that contributed to the observed dynamic behavior.

Modal analysis was first conducted in the test configuration to identify the natural frequencies and mode shapes of the structure [11]. The analysis revealed distinct natural frequencies in the pitch and yaw directions. This frequency difference is attributed to localized deformation in the engine attachment ring, which results in varying stiffness contributions along the pitch and yaw axes.

To replicate and understand the multiple dip frequencies observation during the system level testing, a frequency response analysis was carried out for various forcing conditions. Actuator 1 & 2 are assembled in one engine and actuator 3 & 4 in another.

Case 1: Forcing function was applied to one actuator along the actuator axis direction which is at 45° with respect to both the pitch and yaw axes. As a result, the response along the actuator axis exhibited two peaks corresponding to the natural frequencies of the system which is along the pitch and yaw directions. Additionally, response was observed at all other actuator locations due to the coupled structural behavior. This response is consistent with test observations. The response of all actuators for this case are presented in Fig. 10.

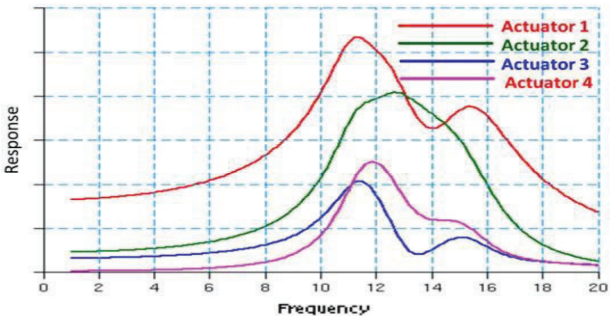

Fig. 10. Frequency response for one actuator forcing function (Case 1)

Case 2: Forcing function is applied to all four actuators such that yaw command is given to the engine. In this scenario, a single peak was observed, corresponding to the yaw mode. Fig. 11 illustrates the actuator responses for this case. When all actuators are simultaneously excited along their respective axes, the engine response aligns strictly along those axes, and a single dominant peak is seen in each corresponding response.

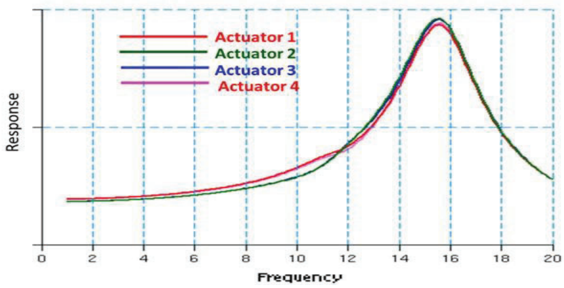

Fig. 11. Frequency response for yaw command to all actuators (Case 2)

Case 3: Forcing function is applied to all four actuators such that pitch command is given to the engine. In this scenario, a single peak was observed, corresponding to the pitch mode. Fig. 12 illustrates the actuator responses for this case.

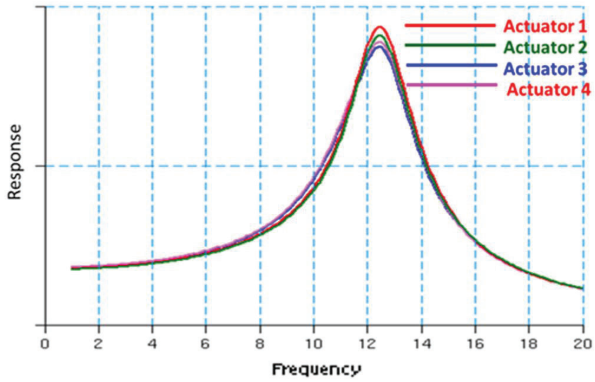

Fig. 12. Frequency response for yaw command to all actuators (Case 3)

These simulations corroborates the dynamic behavior ob served in the tests and confirm the influence of attachment ring stiffness asymmetry on the pitch and yaw responses as well as the structural coupling resulting in responses at all actuator locations even when only one actuator is forced.

These results reaffirm the value of co-engineering across control and mechanical domains. Using the systems engineering V-model, modal analysis serves as both a design input and a validation measure, closing the loop between structural predictions and servo behavior.

V. Conclusion

The redesign of compensators for fault-tolerant actuators in the PSLV PS4 stage has highlighted the limitations of addressing control challenges through isolated engineering disciplines. The identification of axis specific dip frequencies and the presence of high gain contours provided essential design inputs for the Digital Auto Pilot. Moreover, the complex interplay between structural dynamics, actuator redundancy, and control electronics was found to have a significant impact on overall system performance. These results underscore the necessity of integrated testing, comprehensive simulation, and close cross disciplinary collaboration throughout the compensator design process for fault-tolerant actuators. The adoption of a systems engineering approach ensured that design evolution was managed holistically, with traceable decisions, robust interface control, and integrated verification processes driving higher confidence in the fault-tolerant actuation system.

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