# Systems Engineering Approach for Aerospace Control Design

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***Abstract*—Flight control systems (FCS) are essential to the stability, safety, and performance of modern flight vehicles. Systems engineering for flight control systems involves applying a holistic, multidisciplinary approach to design, develop, and integrate all components of a flight control system, ensuring it meets performance, reliability, and safety requirements throughout the weapon design and operation cycle. This includes considering the interactions between the autopilot, airframe, environment, and various subsystems like mechanical linkages, actuators, sensors, and software. With the advancement of digital technology and increasing complexity, a systems engineering approach has become crucial in the design, integration, and certification of FCS. This paper surveys the literature on methodologies, modelling tools, control law design and standard compliance in FCS. It also presents the case studies and provides guide line for FCS performance and robustness parameters.**

***Index Terms*—Systems Engineering (SE), Systems Analysis (SA), Interconnectivity, Control Centric Approach (CCA)**

## I. Introduction

Control systems are an integral part of modern engineering products, ranging from industrial automation to automotive and aerospace systems. It regulates the behaviour of dynamic systems to achieve desired performance. Flight control systems govern a flight vehicle's behaviour by controlling its aerodynamic surfaces in general. These systems have evolved into highly complex, computer-controlled subsystems. As the scope and scale of integration increase, only Systems Engineering (SE) approach ensures structured methodology to design, develop and maintain these complex control systems effectively. SE also helps in managing complexity, optimizing resources and ensuring quality and compliance throughout the system's design cycle. The SE approach supports requirement traceability, risk mitigation, and system verification & validation with compromising robustness.

As a multidisciplinary approach, systems engineering overlaps with other disciplines and this can make it difficult to differentiate between what systems engineering **is and is not**. According to the INCOSE handbook [1], systems engineering provides a framework for requirement analysis, system decomposition, modelling, integration, and verification. In the context of flight control, this means bridging avionics, actuation, software and human interaction (if applicable) to develop robust and fault-tolerant control systems. In simple words *"The Art and Science of creating effective systems..."*

This paper presents a comprehensive overview of system engineering approach applied to control system design, focusing on the complete design cycle from requirements analysis to maintenance. This approach ensures robust, efficient, & reliable control systems aligned with stakeholder needs.

Researchers have made significant contributions to the design, development and validation of flight control systems using systems engineering methodologies. This section highlights notable works from open literature.

Systems engineering is an iterative process of top-down synthesis, analysis, development, and operation of a realworld system that satisfies the requirements of the system in a near optimal manner [2]. It is a tightly coupled interdisciplinary approach and meant to enable the realization of successful systems. Waterfall Process Model (WPM) is the first SE model was introduced by Royce in 1970 for software development activity [3]. In 1986, Barry Boehm proposed a new systems engineering model called Spiral Process Model (SPM). It is a combination of a waterfall model and iterative model. Each phase in spiral model begins with a design goal and ends with the client reviewing the progress [4].

Researchers from the Aeronautical Development Establishment(ADE), in collaboration with IIT Bombay, developed control laws for the Indian LCA program [7]. The digital Fly-By-Wire(FBW) system includes features like perplexity recovery, envelope protection, and pilot-induced oscillation suppression. The system was certified under DO-178C Level A for software criticality and tested extensively on the *Tejas* platform.

Raol and Girija [8] from National Aerospace Laboratories(NAL), Bangalore, introduced a closed-loop parameter estimation approach using the Controller-Information Based Identification Method (CIBIM). Their work addressed the challenge of system identification in operational FBW environments and supported real-time model updating.

Systems engineering perspective on control design and its linkages to Uncertainty and Disturbance Estimation (UDE) based approach was worked out by SE Talole and et al [10], [11] from DRDO. UDE compensates for uncertainties which ensures systems reliability under disturbance. UDE needs only measurable states which avoids complex modelling and simplifies the system integration within SE frame work. Stability proofs, simulations, Monte-Carlo analysis and partial experiments match SE's emphasis on rigorous validation. DRDO is specifically tasked with weapon systems design, development, integration, and validation. Control systems design here isn't just about writing an algorithms; it's embedded in a systems engineering framework to meet stringent requirements like accuracy, robustness, reliability, survivability and so on.

Ashok Joshi [6] from IIT Bombay studied the influence of variable hydraulic pressure on flight dynamics. The research offers detailed modelling of actuator behaviour under non-ideal conditions and presents adaptive solutions to maintain system performance, a critical aspect of systems integration. Rumit Kumar et al. [12] designed a morphing quadcopter capable of dynamically shifting its centre of gravity and inertia properties mid-flight. The adaptive control algorithms were tested in simulation, pushing the envelope of aerial manoeuvrability through real-time systems modelling. Kothari and Shastry [13] from IIT Kanpur have contributed extensively to robust and adaptive control strategies for variable-pitch VTOL aircraft and quadrotors. Their work integrates MBSE, flight dynamics, and experimental testing, providing a template for future UAV-based control system design.

The largest professional organization for control engineers is the International Federation of Automatic Control (IFAC, founded in 1957) aligns with ISO/IEC 15288. IFAC promotes co-simulation methods in SE that help in modelling, analysing and designing complex systems.

## II. **Need of Systems Engineering Approach**

SE required for large-scale interdisciplinary problems which involves multiple, heterogeneous, distributed systems with following perplexity,

1) System elements operate independently
2) System elements have different life cycles
3) The initial requirements are likely to be ambiguous
4) Complexity is a major issue
5) Management can overshadow engineering
6) Fuzzy boundaries cause confusion
7) Engineering of Save Our Mission (SoM) never ends

Need of such approach can be visualized for complex systems especially aerospace systems which generally have unique design requirements as follows:

1) High-risk, high-cost, low-volume of missions with significant societal and scientific impacts
2) Rigid design constraints from different stake holders
3) Extremely tight feasible design space
4) Highly risk-driven systems where risk and uncertainty cannot always be captured at the early stage
5) Highly complex systems where subsystem interactions and system-level impact cannot always be modelled
6) Highly software intensive systems

In order to solve such complex systems different formal methods applied by the researchers and industries at different stages of design and development activity are as follows:

1) **Early Stages**: Mathematical modelling techniques which deals with uncertainty modelling, decision theory, risk modelling, optimization, control theory, robust design methods, etc. Design based on system engineering methods aims for mitigation, maintainability, failure prevention, etc.
2) **Middle Stages**: Risk and reliability based design methods such as FTA, FMEA/FMECA, reliability block diagrams, event sequence diagrams, safety factors, knowledge-based methods, expert elicitation
3) **Advanced Stages** : Design for testability and production

Systems engineering is an interdisciplinary engineering process to evolve and verify an integrated design-cycle which provides a set of system solutions that satisfy customer needs. A good systems engineering requires competency in at least following three domains:

1) A controlled design process which provides **baseline** and coordinates the design efforts
2) A systems engineering **process** which provides a structure for solving design problems and tracking requirements through the design effort
3) Life cycle **integration** that involves the customers in the design process and ensure that the system developed is viable throughout its life

### *A. Requirements Definition and Sensitivity*

The function of systems engineering is to guide the *engineering of complex systems*. To do this it is essential to capture the critical requirements & understand its implication on other requirements and subsystems performance as given below.

1) The significance of requirements impact on the design
2) The sensitivity of metrics to requirements
3) How design requirements and constraints change as the stakeholders learn about the design problem

Above will emphasize the need of moving from deterministic, serial, single-point designs to **dynamic parametric** trade environments.

### *B. Integrating Multiple Disciplines*

1) Integrating different disciplines has many consequences
2) Increased number of constraints and inputs involved
3) Increased complexity of modelling environments
4) Disciplines may have conflicting goals (ex: aerodynamic performance vs. structural efficiency)

To support informed decision making, analysis need to be conducted, hence requiring the use of mathematical modelling with increasing system complexity, which causes growing number of interactions between the subsystems. All these need to be accounted for discipline interactions & dynamics at early stage design and trade-off studies. The codes & models used may have different levels of fidelity, resolution, and complexity (sometimes within the same discipline). Under such situation it is difficult to conduct sensitivity studies and identify driving parameters.

## III. **SE Approach in Weapon Design**

Design, development and flight testing of a vehicle system is highly interdisciplinary activity involving various subsystems like aerodynamics, propulsion, structures, control, guidance, navigation, warhead, on-board electronics etc., Each of the said areas have the complexities/intricacies of their own. Hence, it is not possible for a small team like Project Team to have an overall picture of design and development process. It will be highly beneficial, if entire mission scenario is divided into various design activities and connectivity can be provided between various parameters that could influence the particular design. Especially, if the criticality of the influencing parameters in the design process is established, it will alert the project team as well as the designer during the initial stage itself to take necessary steps for controlling the same. Systems Engineering Team (SET) generates list of such critical parameters for each subsystem. Doing so, the foremost task of SE is capturing requirements of all stakeholders & documenting them by paying attention to the best practices. Then comes the top-down systems architecture by involving stakeholders (in case of weapon development, armed forces & production agency are also the stakeholders) in to the design team.

In order to achieve users multi-purpose requirements for "guided vehicles" of high kill probability, a hierarchical top-down system design methodology has been evolved. This approach will take care of user defined threat profiles, system kill zone, fire power, mobility, low observability in the presence of constraints and safety of launch platforms such as aircraft & underwater vehicles, availability sensors and actuator and realization time frame and the unit cost. The following steps are carried out as part of systems engineering for flight-vehicle design & development at Directorate of Systems (DOS) of DRDL in consultation with other designers [14]:

1) Stakeholders Requirement Analysis
2) Threat Scenario Definition and Synthesis
3) Generation of System Requirements (also called as "base line specifications")
4) Design Constraints
5) System Architecture Evaluation
    a) Evolving Mission Definition in terms of range, CEP and damage potential
    b) Sizing Propulsion System based on max. range
    c) Designing aerodynamic configuration for lateral acceleration to shape the trajectory
    d) Ensuring launch platform safety
    e) Guidance, Control and Actuator requirements
    f) Assess the sensor need and generate specifications
    g) Trajectory design and analysis
6) System Characterization and Sensitivity Analysis
7) Failure Mode Effects and Criticality Analysis (FMECA)
8) Methodological Review Mechanism (Mission Review, PDR, CDR , FRR, TARB and so on)
9) Flight Instrumentation, Testing and Evaluation
10) Documentation of design process, production and new learnings during development exercise.

## IV. Control Centric Approach (CCA)

Control algorithms are usually developed at the end of that sequential process, once the mechanical, electrical, and other subsystems are completely defined which is referred as **Plant Centric**. Instead of sequential process, a concurrent engineering strategy with Control Centric Approach (CCA) is required for complex systems. This strategy considers multidisciplinary subsystem interactions from the beginning of the design process concurrently, further it applies control concepts to design the entire system and reach optimal solutions by giving a special emphasis to the system dynamics and control paradigms as shown in figure 1.

Normally measure of merit and effectiveness are derived from the mission need statement and used to evaluate the system architecture. CCA relies heavily on mathematical models to predict system dynamics. It focuses on how feedback and feed-forward loops maintain desired behaviour. Hence, it now becomes essential to bring out the inter-connectivity chart between the various models as indicated in figure 2 on trajectory level. Further in detail similar inter-connectivity chart drawn on autopilot in figure 3. The result of all these exercises is a System Architecture leading to efficient and faster development [15].

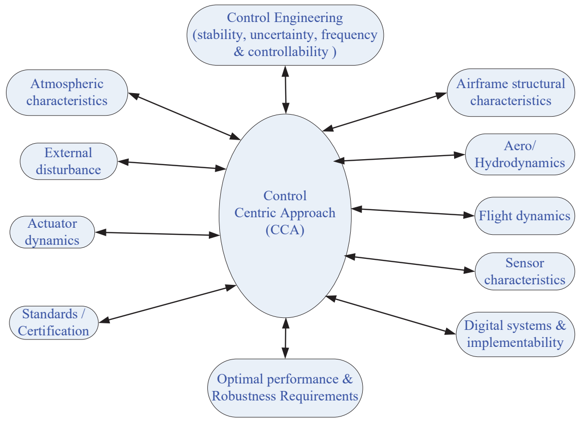


Fig. 1: Control Centric Approach (CCA)

CCA typically depends on system objectives, sub-system design, physics-based models, experimental data, and case studies to conduct the analysis. Systems engineering also helps in creating the work breakdown between different subsystems designers. The individuals who can play a central role in this concurrent design approach are the *control/ systems engineers*. They apply dynamics and control concepts to understand the interactions among subsystems and can naturally lead all the engineering disciplines to achieve a better system's dynamics, controllability and optimal design.

While all the above are the parts essential for systems engineering, creative part comes in investigating technology alternatives and supporting decision making through risk analysis.

## V. Case Study : Handling CSI in FCS Design

Control Structure Interaction (CSI) is defined as *detrimental* closed-loop coupling between structural modes and Flight Control System (FCS). Detrimental can imply poor performance or leading instability. Interaction between structural, aero and control dynamics is shown in figure 4. Frequency response methods are the most widely used tools to identify the degree of stability (nature) for design and analysis of linear feedback systems.

### A. Structural Modelling

Schematic representation of airframe flexibility shown in figure 5. In general **model complexity** is driven by complexity of the vehicle structure and design stage. Lumped mass approach may be appropriate for early assessments, or for full assessment for low bandwidth applications. Finite element models (FEM) typically required for more complex vehicles or when higher performance expected from the systems.

Lumped mass models are relatively straight forward to build and validate if *stiffness are well understood* to get the

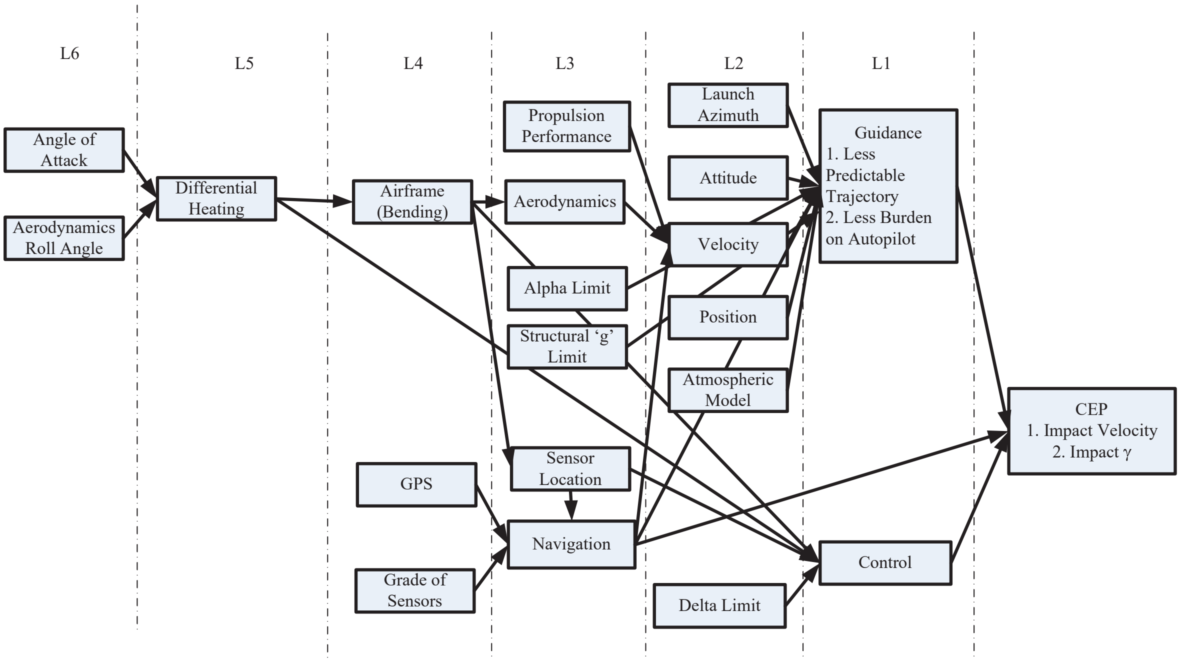


Fig. 2: Connectivity chart for trajectory design

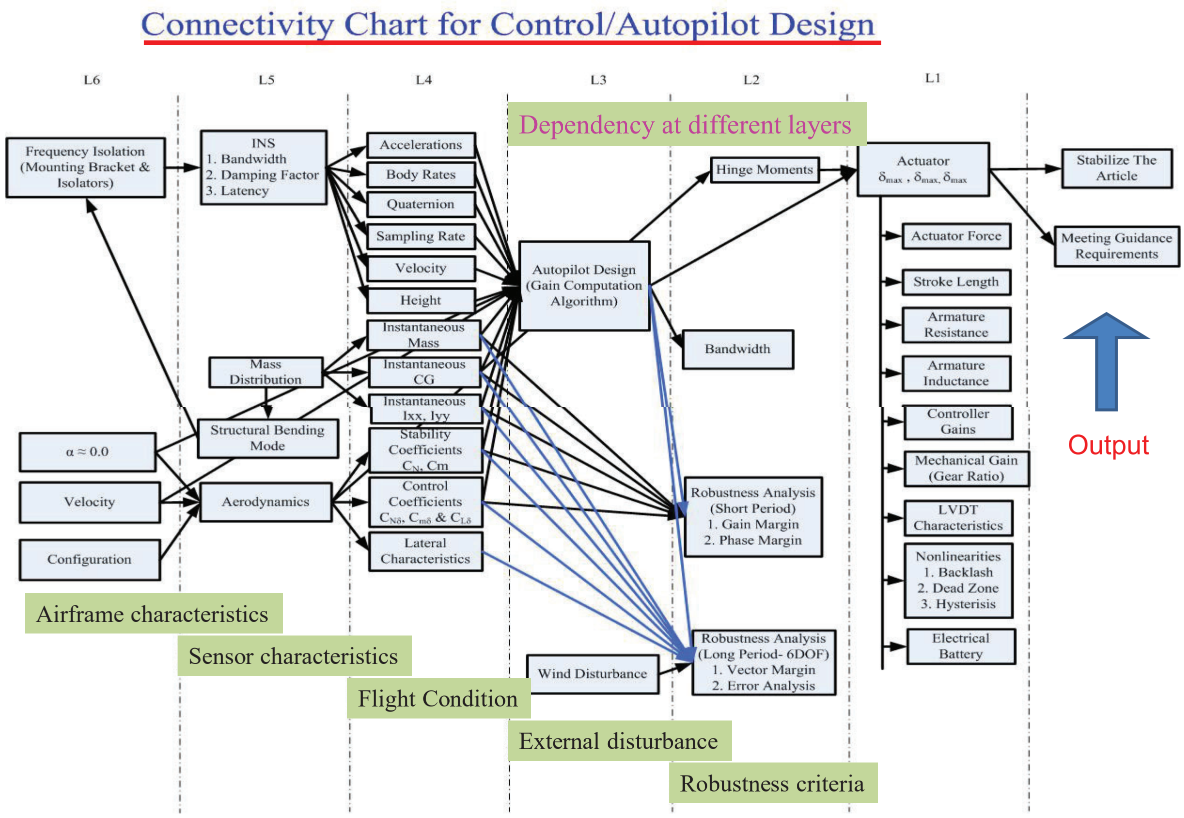


Fig. 3: Connectivity chart for control system design

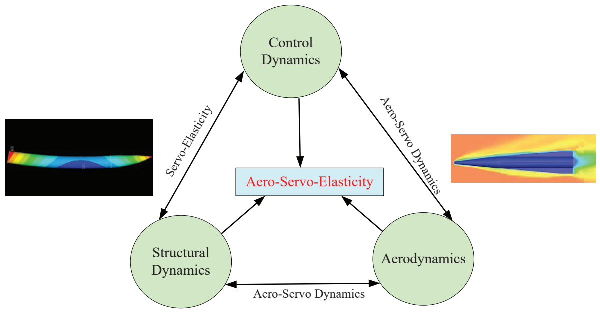


Fig. 4: Interaction between Structural, Aero and Control Dynamics

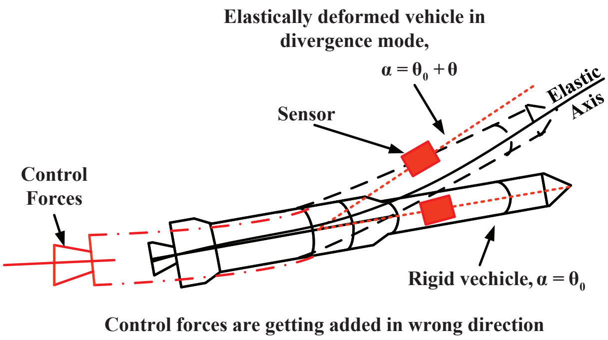


Fig. 5: Schematic representation of airframe flexibility

required **accuracy**. Further, models from different designers/manufactures need to be combined by the integrator for system analysis. When combining these models, interface modelling is critical which calls for FEMs based complex models with non-linearities. Structural damping ($\zeta$-factor) has significant impact on *modal* peaks and low damping can complicate control design. Most rules of thumb put damping ratio between 0.4 and 0.8 percent.

Model uncertainty must be captured in control analysis process, typically by varying model parameters (Modal and discrete damping Mode amplitudes, Mode frequencies) over a range. Parameter ranges should be carefully selected to ensure robustness, but not excessively constrain the design. Typical 10-20% variation on modal frequencies and twice on modal amplitudes is practical.

### B. Control Analysis Techniques

Typical control design & analysis techniques used after incorporating flexible models are as follows:

1) Linear analysis : design compensator, verify rigid/flex stability margins
2) Nonlinear analysis : describing functions, nonlinear *time domain simulations*

The linear analysis / nonlinear time domain analysis are coupled and will likely require iteration. Dynamic model uncertainty also to be included during this analysis. Poor stability margins will impact time domain response, specific behaviours in nonlinear simulation need to be addressed by loop shaping in linear frequency domain. It is good practice to check *phase* and *gain* margins in time domain simulation through gain and time delay adjustments in 6 DOF model.

*Gain* stabilization is preferable to over *phase* stabilization. *Gain* stabilization is more robust but generally requires more separation between control bandwidth and flexible modes. Where *phase* stabilization is necessary (e.g., very low structural modes frequency), analysis of modal frequency variations and understanding of system time delays is critical. Extra precaution required while considering *notch filters* for *gain* stabilization, slight changes in modal frequency can wreak havoc.

There is no universally accepted standard for stability margin requirements. Many organizations have their own internal standards. Programs should clearly state margin requirements for rigid body and flex modes in specification documents. Good practice to hold additional margin early in program when models are immature. As a rule of thumb, *gain* stabilization of flex modes should be mandated. Phase stabilization should require a waiver or, at a minimum, extensive supporting analysis.

### C. Control Design Process

Block diagrammatic representation is shown in figure 6.

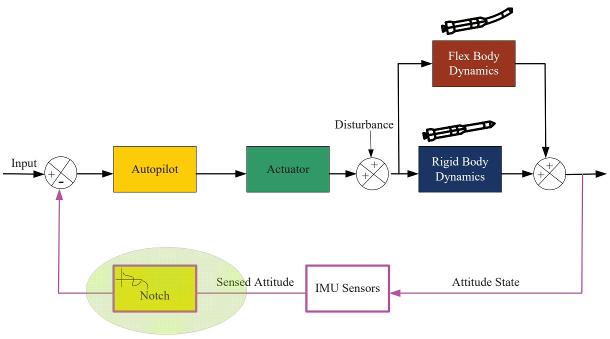


Fig. 6: Block diagrammatic representation

1) Elaborate system modelling by considering, vehicle structural flexibility, local flexibility effects, and inertial forces (due to engine gimballing, fuel sloshing, and control surface inertia)
2) Identify potential risks for CSI at early stage and ensure proper interaction between aero, structures and mechanisms groups. Complete ICDs should be put in place early in the program between the main stake holders. This requires good "*back of the envelope*" control assessment. If it is difficult to nail down the specifics at early, highlight and follow up on the areas of concern
3) Identify required bandwidths and discrete sample rates. It should be noted that the "goal is to prevent late hardware changes which are expensive and time consuming"
4) Complete hardware testing for determination of Mode shapes, frequencies and damping and select detrimental flex modes depending on modal gains
5) Try to maintain plenty of stability margin in early control designs to allow for model updates based on the test, account for stage separation dynamics, & wind effects

6) Make smart choices about placement of sensors and actuators, if possible ensure stiff structure between them
7) Pay close attention to modelling of joints and interfaces in structural models
8) Keep features in the control implementation in flight software (FSW) for additional filters if needed. Changing database is easier than changing FSW if control tweaks are needed. Like implementing *tustin* digital filter with unity coefficient, were coefficient data based can change at any stage.

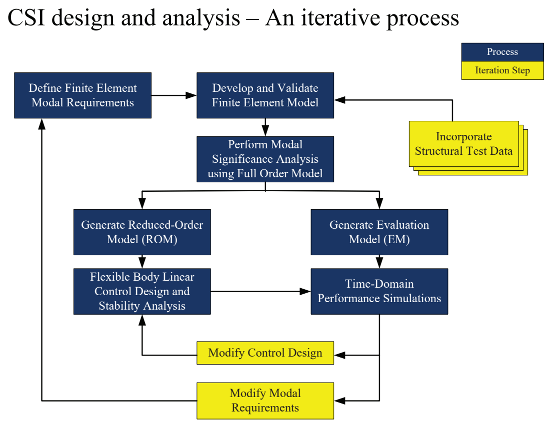


Fig. 7: Control design is a cross-discipline iterative approach

9) Computerized simulation incorporating flexible structure dynamics for evaluations of performance
10) Control Ground Resonance Test (Control-GRT) should be done before flight trial

Control design is an inherently highly cross-discipline iterative process which needs high cooperation and coordination between the stake holder which only can leads to mission success. Figure 7 indicates the cross-discipline iterative approach of control design.

### D. General Guidelines

1) Sensor locations : accelerometers at nodes & gyroscopes at anti-nodes
2) *Gain* stabilization of high frequency modes and *Phase* stabilization of low frequency modes
3) *Gain* margin $\geq 6$ dB, and *Phase* margin $\geq 30^o$
4) If sufficient gain or phase stabilization is not possible by conventional control law, use **Notch Filter** or **Multiple Sensors**
5) Control and guidance frequency should be less than $1/5^{th}$ of first bending mode frequency

## VI. Case Study : Optimal Compensator Design using GA

### A. Plant model and Structure of Compensator

Pneumatic actuation system used in flight vehicle control applications is considered as the plant. This actuator is driven by double acting piston and each side of the piston is controlled by an ON-OFF three-way two position solenoid valve, which is normally open. Pulse Width Modulation (PWM) control with a carrier frequency of 100 Hz is used for the control. An experimentally characterized linear model is :

$$G_p(s) = \frac{K_{pt}\omega_{np}^2}{(s-\omega_{p1})(s^2+2\zeta_p\omega_{np}s+\omega_{np}^2)} \tag{1}$$

The open loop Bode diagram of the uncompensated plant with stability margins is shown in Fig. 12. The objective of the compensator design is to stabilize the plant and to meet the frequency domain specifications given in Table I.

TABLE I: Design specifications

| Performance parameter | | Design goal |
|---|---|---|
| GC Frequency (rad/s) | GCF | 60.0 to 95.0 |
| Positive Gain margin (dB) | PGM | 8.0 to 10.0 |
| Negative Gain margin (dB) | NGM | -8.0 to -10.0 |
| Phase margin (deg) | PM | 40.0 to 55.0 |

A double lead-lag compensator is used in the forward path along with a complex lead compensator in the feedback path. The lag compensator helps in improving the disturbance rejection ability by enabling use of higher DC gain apart from achieving the desired GCF. The double lead compensator is used to improve the phase margin at GCF [16]. Instead of a single lead stage, the double lead compensator is used as the required phase addition is more due to the unstable nature of the plant. The lag compensator is given as

$$G_{Lag}(s) = \frac{(\frac{s}{\omega_{lgz}}+1)}{(\frac{s}{\omega_{lgp}}+1)} \tag{2}$$

whereas the double-lead compensator is given as

$$G_{Lead}(s) = G_{Lead_1}\cdot G_{Lead_2} = \frac{(\frac{s}{\omega_{ldz1}}+1)}{(\frac{s}{\omega_{ldp1}}+1)}\cdot\frac{(\frac{s}{\omega_{ldz2}}+1)}{(\frac{s}{\omega_{ldp2}}+1)} \tag{3}$$

Further, the complex lead compensator is given by

$$G_c(s) = \frac{\frac{s^2}{\omega_{n1}^2}+\frac{2\zeta_{z1}}{\omega_{n1}}s+1}{\frac{s^2}{\omega_{n2}^2}+\frac{2\zeta_{z2}}{\omega_{n2}}s+1} \tag{4}$$

and is used in the feedback path for compensating the additional magnitude gain contribution by the lead compensator. The complex lead compensator is selected because the smaller ratio between the high-frequency and low-frequency gain asymptotes of the complex lead compensator offers advantage compared to the double lead compensator with real poles and zeros [17]. The block diagram of the resulting feedback system is shown in Fig. 8.

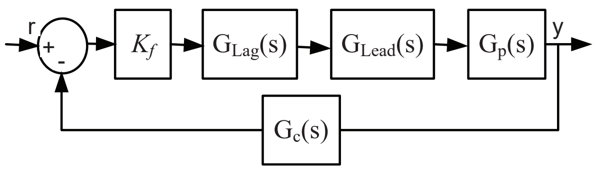


Fig. 8: Block diagram of plant and compensator

With this choice of the compensator, the design objective is to select the poles and zeros of the lag, lead, and complex lead compensator. Additionally, forward path gain, $K_f$, is also a design parameter. Arriving at appropriate values is an iterative and time consuming process and a large number of iterations may be needed to converge to the required specifications. To address the issue, compensator parameters selection process is automated & optimum values of the parameters are obtained using genetic algorithms in this work.

### B. Compensator design using GA

Genetic algorithms have potential for global optimization, compared to the gradient based methods. The number of design parameters consists of one forward gain ($K_f$), two lag compensator parameters ($\omega_{lgz}$ and $\omega_{lgp}$), four double lead compensator parameters ($\omega_{ldz1}$, $\omega_{ldp1}$, $\omega_{ldz2}$, and $\omega_{ldp2}$) and four complex compensator parameters ($\omega_{n1}$, $\omega_{n2}$, $\omega_{z1}$, and $\omega_{z2}$ ). Thus, total 11 design parameters involved in the design need to be found out. The cost function, being a measure of violation of design specifications, is taken as

$$J_{min} = J_{gcf}^2 + J_{pgm}^2 + J_{ngm}^2 + J_{pm}^2 \tag{5}$$

Component of the objective value tends to zero when respective values lies within the specified bound given as

$$\begin{aligned} J_{gcf} &= 0 \quad \text{for} \quad 60 < GCF \leq 95 \\ J_{pm} &= 0 \quad \text{for} \quad 40 < PM \leq 55 \\ J_{gm} &= 0 \quad \text{for} \quad 8 < |GM| \leq 10 \end{aligned} \tag{6}$$

From (5), it can be seen that the penalty is more when the performance deviates from the design specifications. Since the desired GCF is between 60 to 95 $rad/s$, any deviation from the desired value is penalized as

$$\begin{aligned} &\text{if}(GCF < 60) \quad \text{then} \quad J_{gcf} = (60 - GCF)^2 \\ &\text{if}(GCF > 95) \quad \text{then} \quad J_{gcf} = (95 - GCF)^2 \end{aligned} \tag{7}$$

In order to ensure the required damping for the servo system, a phase margin of 40 to 55 degree is desirable and any deviation from this is penalized as

$$\begin{aligned} &\text{if}(PM < 40) \quad \text{then} \quad J_{pm} = (40 - PM)^2 \\ &\text{if}(PM > 55) \quad \text{then} \quad J_{pm} = (55 - PM)^2 \end{aligned} \tag{8}$$

Typically for unstable systems, both positive and negative gain margins play vital role in the stability analysis [20]. The positive gain margin indicates margin available for increasing the overall loop gain whereas negative gain margin shows available margin for reducing it. The specified gain margin is between 8 to 10 dB as lower than 8 dB makes the system less robust whereas above 10 dB leads to a sluggish system. Hence, taking this aspect into account, any deviation of both positive and negative gain margins from these limits are penalized as

$$\begin{aligned} &\text{if}(PGM < 8) \quad \text{then} \quad J_{pgm} = (8 - PGM)^2 \\ &\text{if}(PGM > 10) \quad \text{then} \quad J_{pgm} = (10 - PGM)^2 \end{aligned} \tag{9}$$

$$\begin{aligned} &\text{if}(NGM > -8) \quad \text{then} \quad J_{ngm} = (-8 - NGM)^2 \\ &\text{if}(NGM < -10) \quad \text{then} \quad J_{ngm} = (-10 - NGM)^2 \end{aligned} \tag{10}$$

### C. Fitness function

Fitness function indicates the goodness of every individual population with respect to all others. Proper selection of the fitness function plays a key role in convergence to an optimum solution. The fitness function is selected for maximization as it is naturally compatible with the genetic based search algorithms [21]. The maximum value of the fitness function becomes one when all the performance parameters are within the design constraints as is obvious from

$$F = \frac{1.0}{1.0 + J_{min}} \tag{11}$$

Forward gain and lag compensator parameter bounds are chosen to achieve required gain crossover frequency and disturbance rejection. The parameter bounds for the double lead compensator with real poles and zeros are chosen to give maximum phase lead in the vicinity of the gain crossover frequency. The complex phase lead compensator bounds are chosen to improve positive gain margin and to extend the phase crossover frequency. Accordingly, the bounds on individual parameters are considered as given in Table II.

TABLE II: Bounds on design parameters

| S. No. | Parameter | Units | Lower | Upper |
|---|---|---|---|---|
| 1 | $K_f$ | - | 12.0 | 25.0 |
| 2 | $\omega_{lgz}$ | $rad/s$ | 10.0 | 20.0 |
| 3 | $\omega_{lgp}$ | $rad/s$ | 1.0 | 5.0 |
| 4 | $\omega_{ldz1}$ | $rad/s$ | 40.0 | 65.0 |
| 5 | $\omega_{ldp1}$ | $rad/s$ | 90.0 | 110.0 |
| 6 | $\omega_{ldz2}$ | $rad/s$ | 60.0 | 80.0 |
| 7 | $\omega_{ldp2}$ | $rad/s$ | 90.0 | 120.0 |
| 8 | $\omega_{n1}$ | $rad/s$ | 180.0 | 250.0 |
| 9 | $\zeta_{z1}$ | - | 0.1 | 0.2 |
| 10 | $\omega_{n2}$ | $rad/s$ | 500.0 | 600.0 |
| 11 | $\zeta_{z2}$ | - | 0.5 | 1.0 |

### D. Simulation results

As stated earlier, total 11 design variable are optimized with 50 population size. Initial population is generated randomly for each design variable based on the allowable range bracket as described in Table II. This process is continued for 500 generations for the optimum parameter convergence and in every generation, the best solution is retained. Figures 9 to 11 depict the initial and final ($500^{th}$) generation population statistics. The forward gain and lag compensator pole-zero statistics is given in Fig. 9, it can be seen that they have reached to narrow spread from very wide spread & the transfer function corresponding to the best solution is obtained as

$$G_{Lag}(s) = \frac{(\frac{s}{16.4} + 1)}{(\frac{s}{2.34} + 1)} \tag{12}$$

Figure 10 show the double lead compensator pole-zero statistics and the resulting lead compensator corresponding to the best solution out of 25000 solutions is obtained as

$$G_{Lead}(s) = \frac{(\frac{s}{44.9} + 1)}{(\frac{s}{102.2} + 1)} \cdot \frac{(\frac{s}{78.5} + 1)}{(\frac{s}{93.6} + 1)} \tag{13}$$

The statistics of complex compensator parameters is shown in Fig. 11, the resulting optimum compensator obtained from the proposed optimization formulation is

$$G_c(s) = \frac{\frac{s^2}{218.2^2} + \frac{2(0.19)}{218.2}s + 1}{\frac{s^2}{546.0^2} + \frac{2(0.57)}{546.0}s + 1} \qquad (14)$$

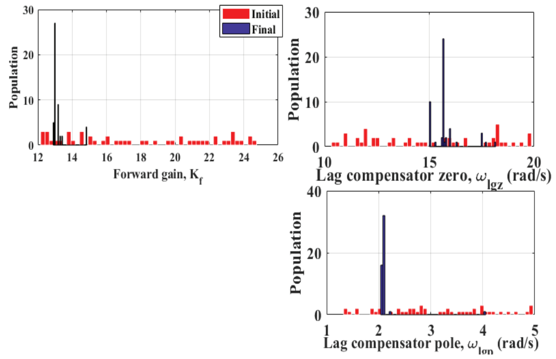


Fig. 9: Statistics of Forward gain ($K_f$) and Lag compensator

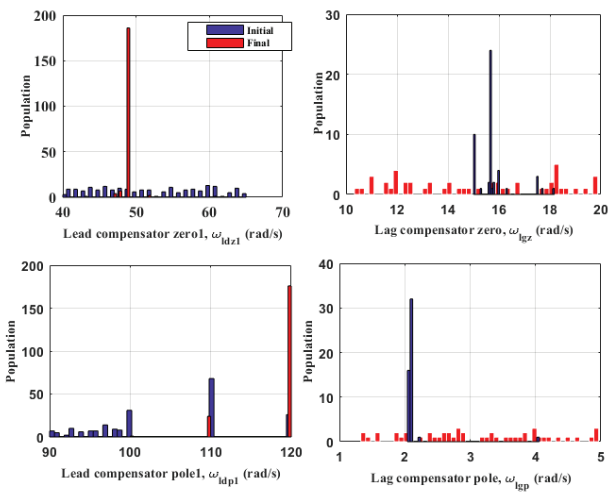


Fig. 10: Statistics of Lead Compensator-1 and 2

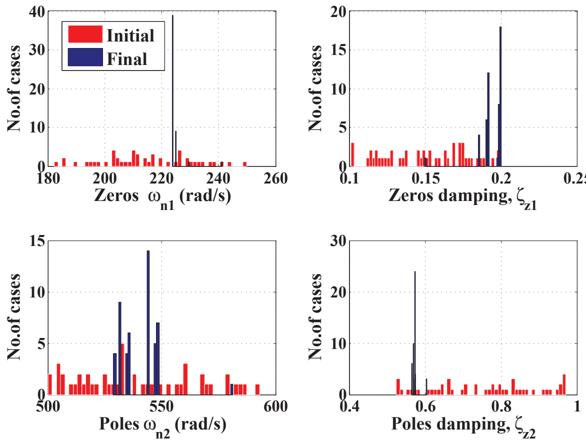


Fig. 11: Population statistics of complex compensator

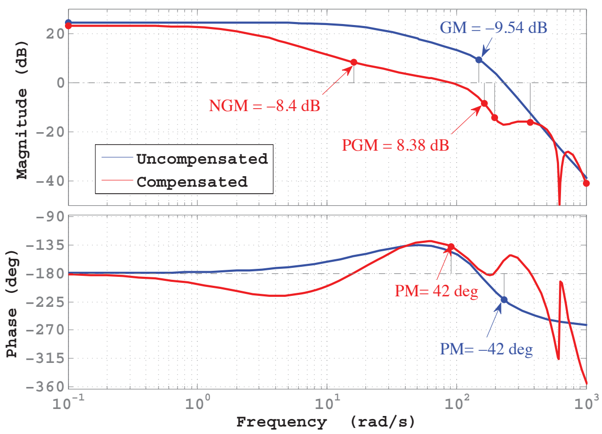


Fig. 12: Bode Diagram: Compensated & uncompensated Plant

Figure 12 depicts the Bode diagram of the uncompensated as well as compensated plant. From the plot, it can be seen that the optimum compensator design has resulted into overall system stability. Further, the design has met all the specifications such as gain crossover frequency, gain margin, and phase margin given in Table III.

Next, the performance of the GA based compensator is compared with the one obtained using classical approach. In classical approach, more than 10 iterations are needed for reaching to the final solution. The comparative performance results are tabulated in Table III from where it can be seen that while the GA results met all the specifications, the positive gain margin using classical tuning is more than design specification (14 dB against of 8 to 10 dB). Also reduction in 14 dB PGM could not be achieved even with several iterations in classical approach. The main disadvantage of this higher value is the degradation of agility of system. Lastly, noise attenuation at high frequency (200 rad/s) is better with GA compensator.

TABLE III: Stability margins: Compensated plant

| | Design goal | GA | Classical |
|---|---|---|---|
| GCF (rad/s) | 60.0 to 95.0 | 91.4 | 88.4 |
| PGM (dB) | 8.0 to 10.0 | 8.38 | 14.0 |
| NGM (dB) | -8.0 to -10.0 | -8.40 | -8.36 |
| PM (deg) | 40.0 to 55.0 | 42.0 | 48.0 |

## VII. **Summary**

1) Systems engineering is the art and science of creating a product, it needs dedicated efforts. As there is no unique methodical approach to apply SE on our day to day problems, one should evolve a SE approach and articulate it.
2) An organization must have a curriculum to support individual development in best SE practices.
3) A systems engineering approach provides the discipline and tools necessary to manage the complexity of modern flight control systems. Through SE, robust control laws, and adherence to standards, flight vehicle ensure performance and safety in increasingly automated and autonomous systems.
4) Ultimate goal of a Systems Engineering Efforts(SEE) is
    a) To address system integration issues as early as possible, and reduce late design changes
    b) To get good understanding of the system and their subsystem interactions
    c) To keep good coordination among users, designers, production agencies, working teams, and others organizations
5) Emerging trends include autonomous FCS, AI-driven control, digital twins, and cyber-security in avionics. MBSE will play a pivotal role in these next-generation systems.

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