Mathematical Modeling and Performance Evaluation of Electro-Hydraulic Servo Actuators

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Edifice

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3. Challenges & Solutions With MATLAB/Simulink
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5. Modelling Nonlinearities
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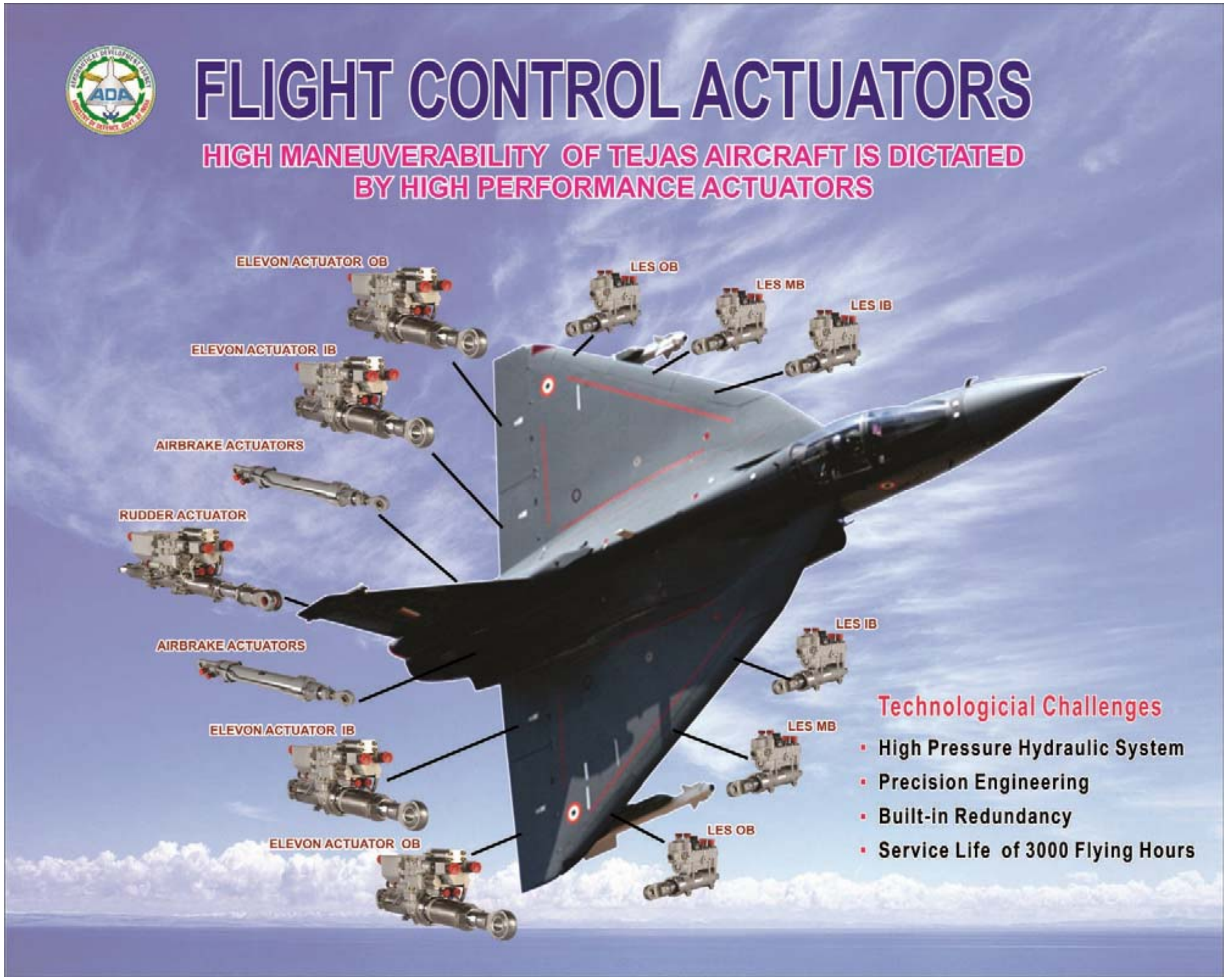
7. Performance Parameters – Experimental vs Simulation Results
8. Model Linearization & Order Reduction for HILS Implementation
9. Loading Rig and Robust Force control Design
10. Design Optimization for Software Thresholds
11. Conclusions

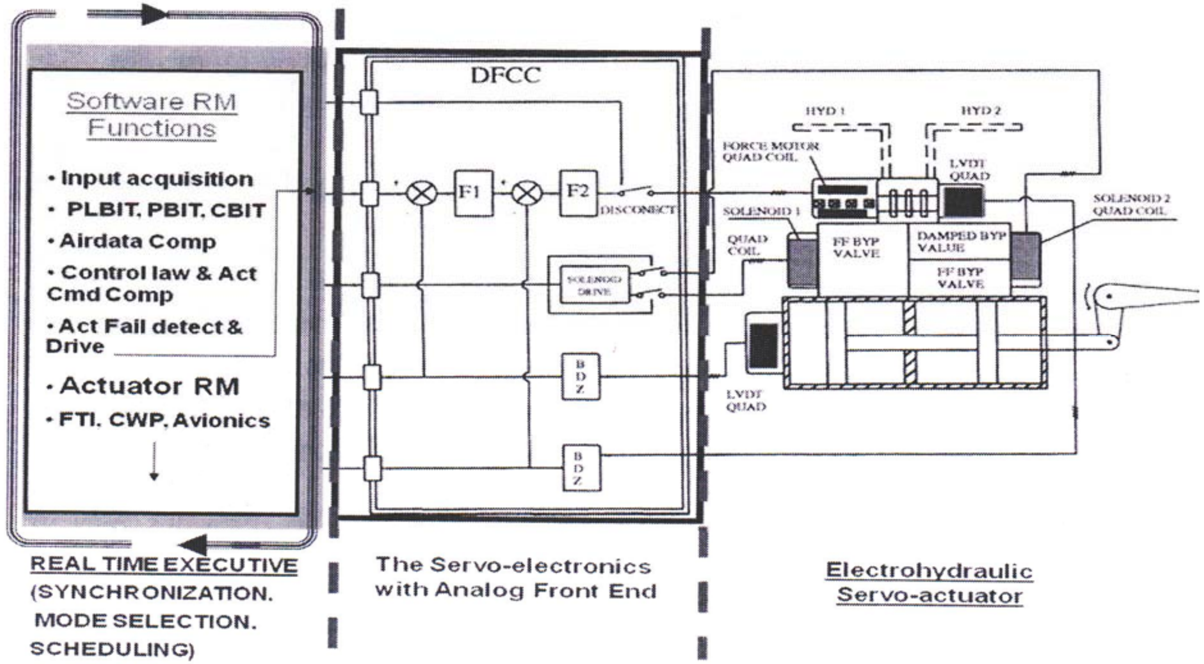
Flight Control Actuators & Key Design Challenges

- Unstable Aircraft
- State of art high performance Actuators
- Optimized Envelope and Weight
- Build in Redundancy
- Reliable development tools
- Design of Test Systems
- Independent validation and verification
- Stringent Certification Process – RCMA
- Airworthy /MIL Qualification Requirements



Fly By Wire Control Systems

- Actuators Connected to Flight Control Computer which houses the Servo Electronics or the Drive Circuitry for various units namely LVDTs, motor, solenoid valves etc.
- The flight control computer contain Software Algorithms for Health Monitoring (Built in Tests, Inhibition etc.) and implementation of Autopilot and Control Law functionalities.
- Power to overcome Aerodynamic Load provided by Hydraulic Power Source



Modelling Requirements in Servo Actuators

Key Requirements

- ❖Need for reliable modelling and simulation tools for state of art Direct Drive Valve (DDV) and Electro Hydro Servo Valve (EHSV) based Hydraulic Actuators
- ❖Robust Controller Design and Stability Analysis
- ❖Modelling Non Linearities like Friction, Hysteresis, Backlash and Dead Band which are very important in characterizing low amplitude behavior
- ❖Real time and Hardware/Software Implementation (HIL and SIL simulations)

Why MATLAB/SIMULINK is every Flight Control System Designer's Choice

- ➢ Ease of modelling with functional blocks and detailed components
- ➢ Vast set of libraries make it very easy to model and simulate inter disciplinary system like Fly By Wire Flight Control systems
- ➢ Physical system models and equation/signal based model can be easily coupled
- ➢ Easy interface with Aircraft model, other software and large data handling
- ➢ Quick Simulation of different test conditions and actual enviroment

Objective & Key Learnings

Objective

1. Non Linear Mathematical Model of a Electro-Hydraulic Servo Actuator
2. Controller Design to meet Dynamic Requirement
3. Actuator Test Rig for Loaded Performance of the Actuator
4. Robust Force Control Design for the Rig

Key Learnings

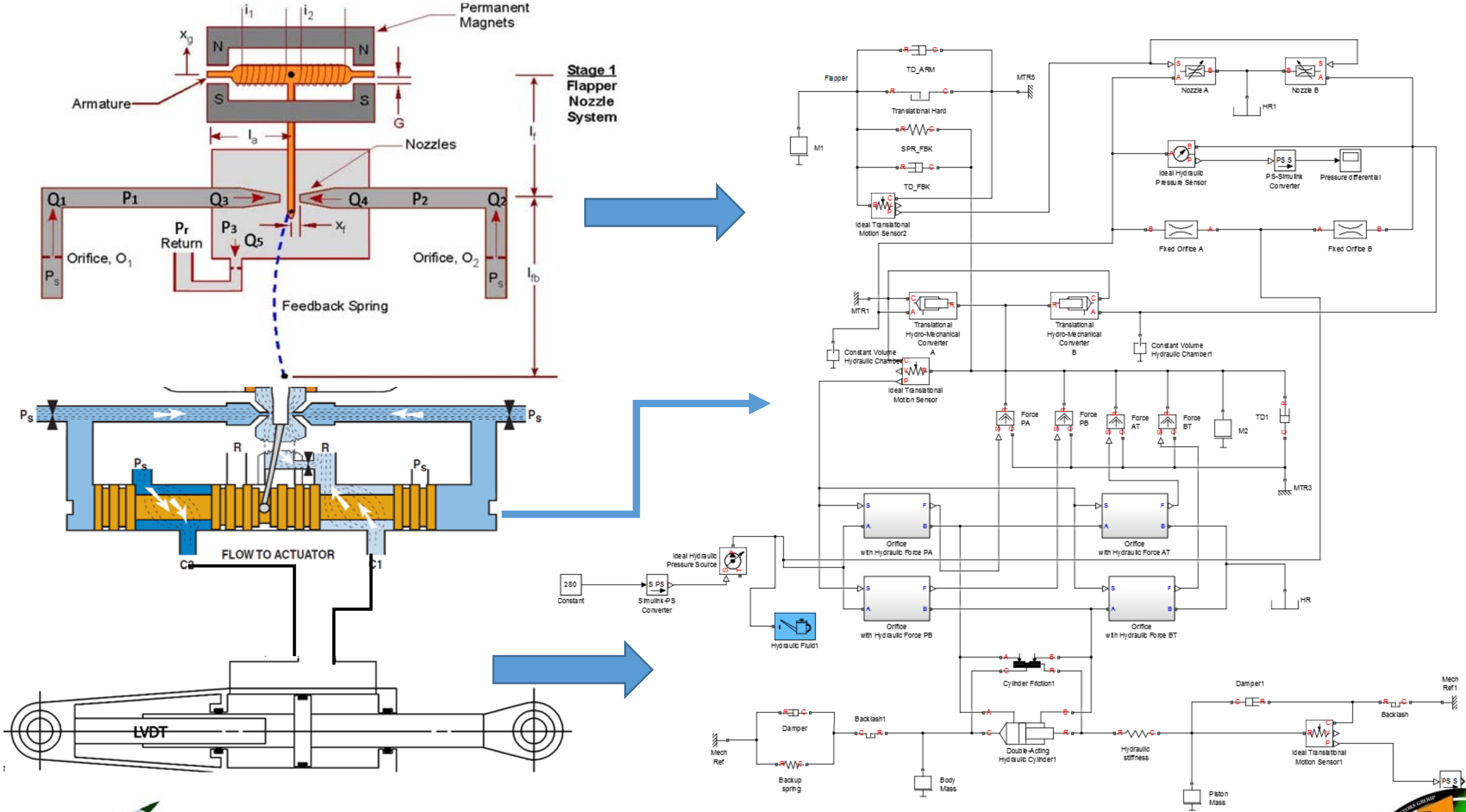
- ❖ Fly by wire Flight Control Systems and Actuators
- ❖ Equation and Physical Component Based Model
- ❖ Modelling Hydraulic Components
- ❖ Servo Valve Dynamics –EHSV
- ❖ Model Reduction Techniques & Linearization
- ❖ Modelling Non –Linearities
- ❖ Controller Design Optimization & DOE
- ❖ Loading Rig Simulation & Force Controller Design
- ❖ Software logic verification using model

Modelling Challenges & Solutions With MATLAB/SIMULINK

Challenge	Solution
Modelling Hysteresis & other Non Linearities	Functional Blocks/Non Linear Blocks in Simulink
Pressure Fluctuations due to Fluid Inertia and Capacitance	Resistive Pipe Elements in Sim Hydraulics
Non Linear Model Frequency Response	Customized MATLAB Code for FRA
Analysis at Different Test Points	MATLAB Code generation for Automation
Optimal Force Control	Robust Control Toolbox in Simulink

Physical Component Based Model of an EHSV Based Actuator

- Control Electronics is modelled with Transfer Functions
- Torque motor is model with equations



Equation based Model for Flapper–Nozzle Dynamics

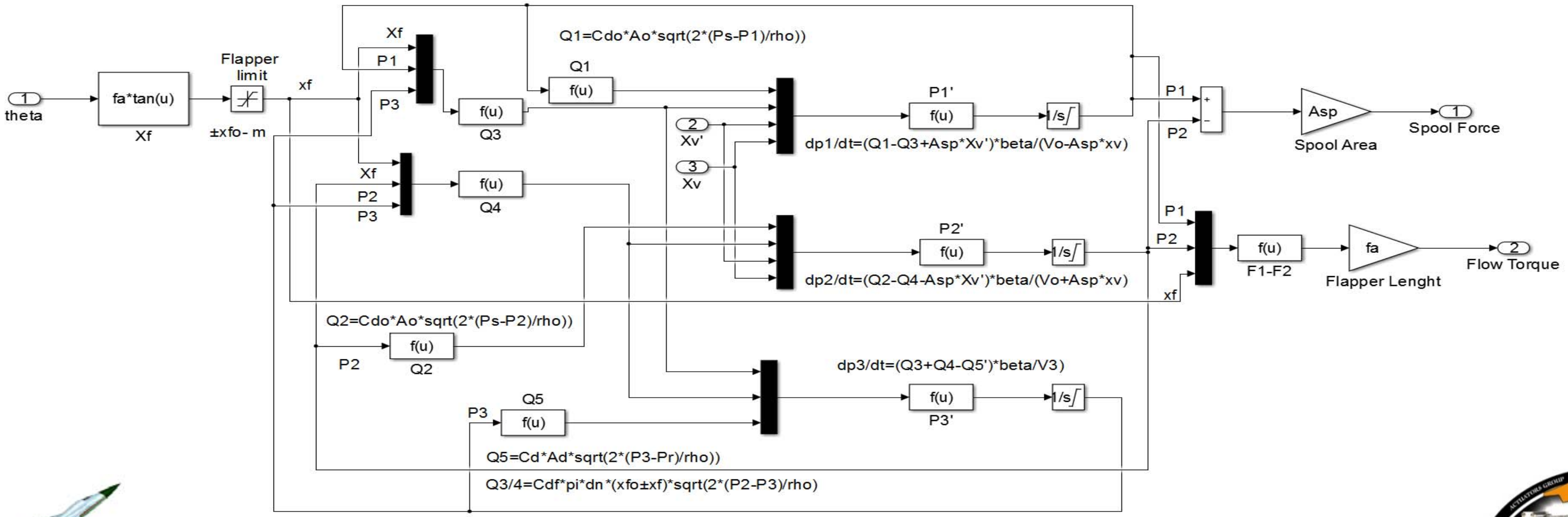
- Easy to Implement Certain Features
- Can be easily Coupled with Physical Component Based Model

Nozzle Flapper Equations

$$Q_1 - Q_3 + A_s \frac{dx}{dt} = \left(\frac{V_0 - A_s x}{\beta}\right)\frac{dp_1}{dt} \qquad Q_2 - Q_4 - A_s \frac{dx}{dt} = \left(\frac{V_0 + A_s x}{\beta}\right)\frac{dp_2}{dt} \qquad Q_3 + Q_4 - Q_5 = \frac{V_3}{\beta}\frac{dp_3}{dt}$$

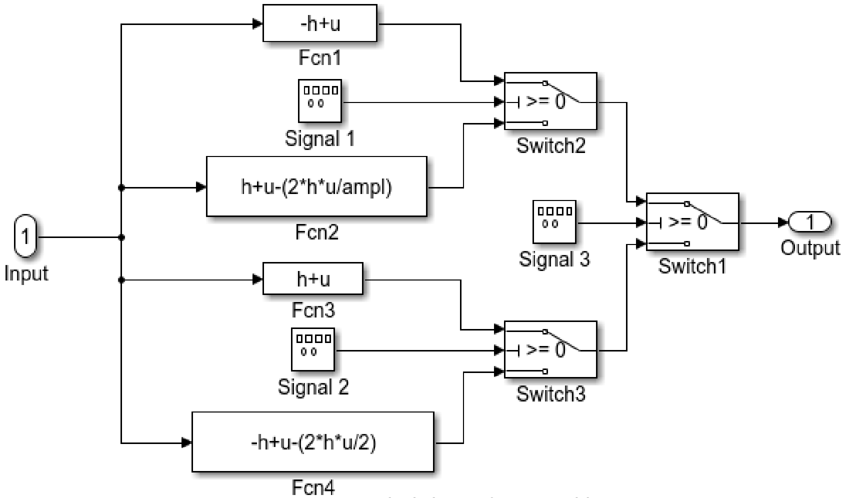
$$F_1 - F_2 = (P_1 - P_2) * An + \frac{\pi Cdf^2}{4}[P_1(Xfo - Xf)^2 - P_2(Xfo + Xf)^2]$$

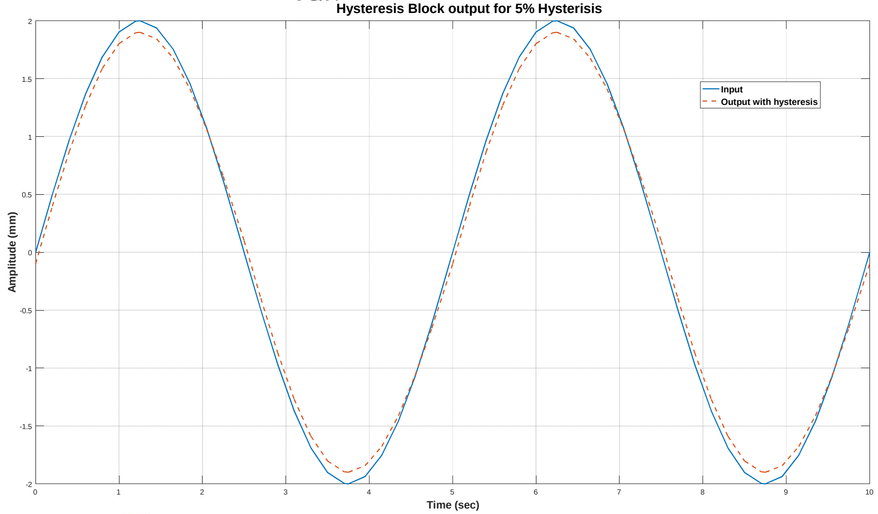
Simulink Implementation



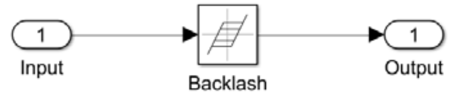
Modelling Non Linearities

❖ Hysteresis

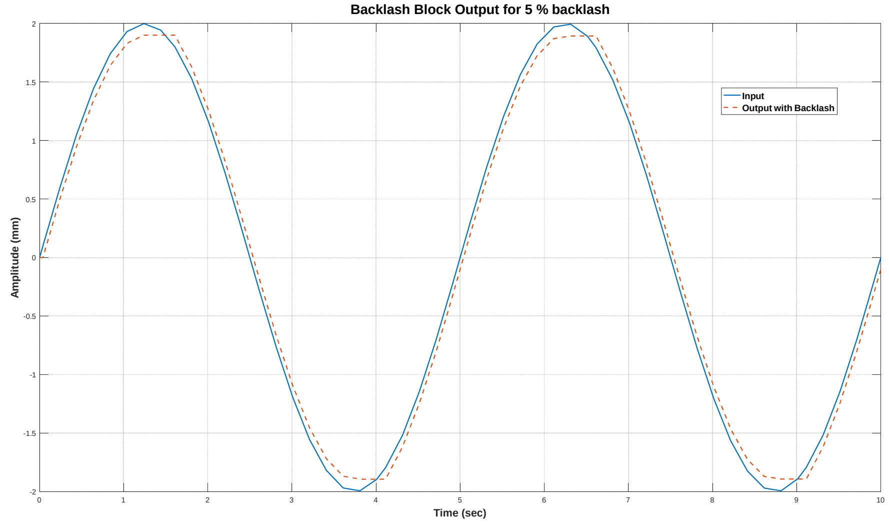




❖ Backlash

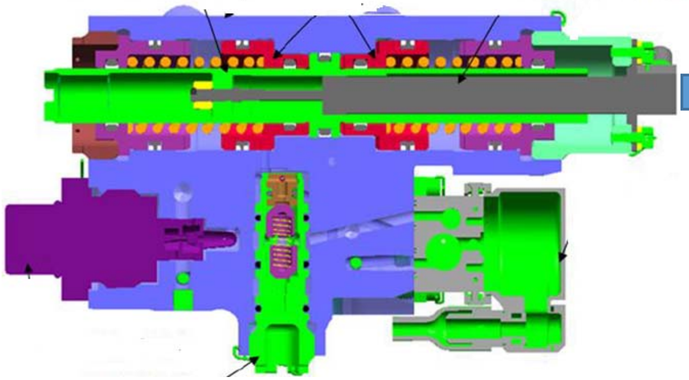


- ➢ Single & Multivalued Non Linearities
- ➢ They are not same



Translating Complex Systems into Models

- ❖ Self Centering Actuator with Complex Dynamics
- ❖ Failure Logic Simulation



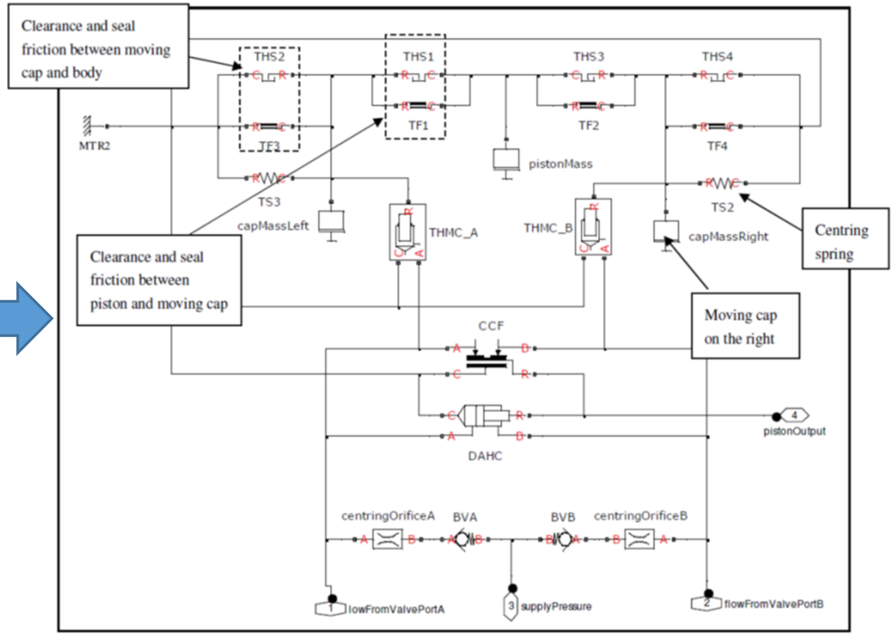
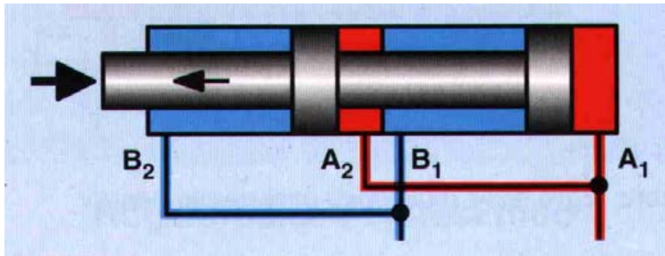
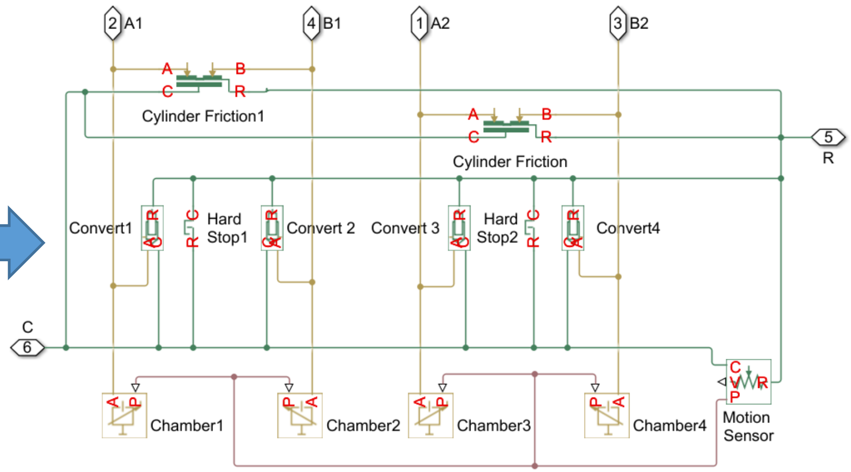


Figure 30. CSAS Simulink Model. (Including Bypass Valve)

- ❖ Dual Tandem Actuator with Force Addition
- ❖ Hydraulic Failure Simulation during external Force

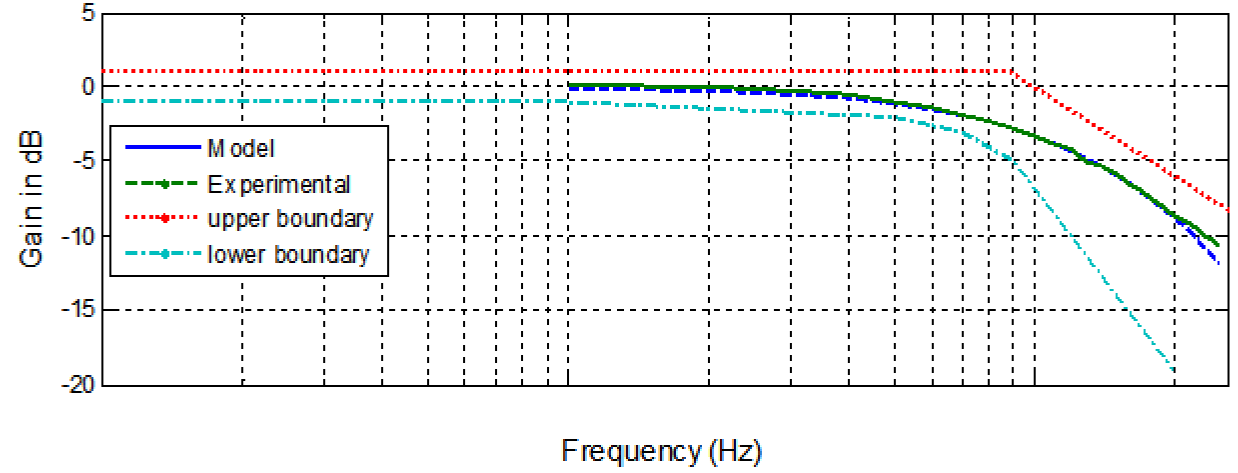


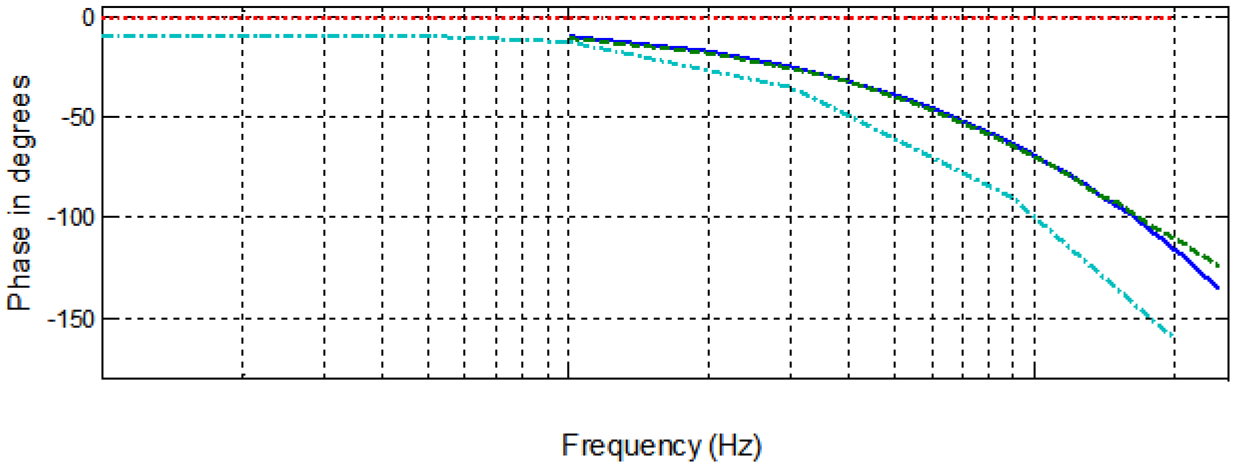


Frequency Response for Nonlinear Model vs Experimental Data

Important Performance Requirements for Servo Actuators

- ❖ Stall Load, No Load Rate, Frequency Response, Dynamic Stiffness
- ❖ Failure Transients

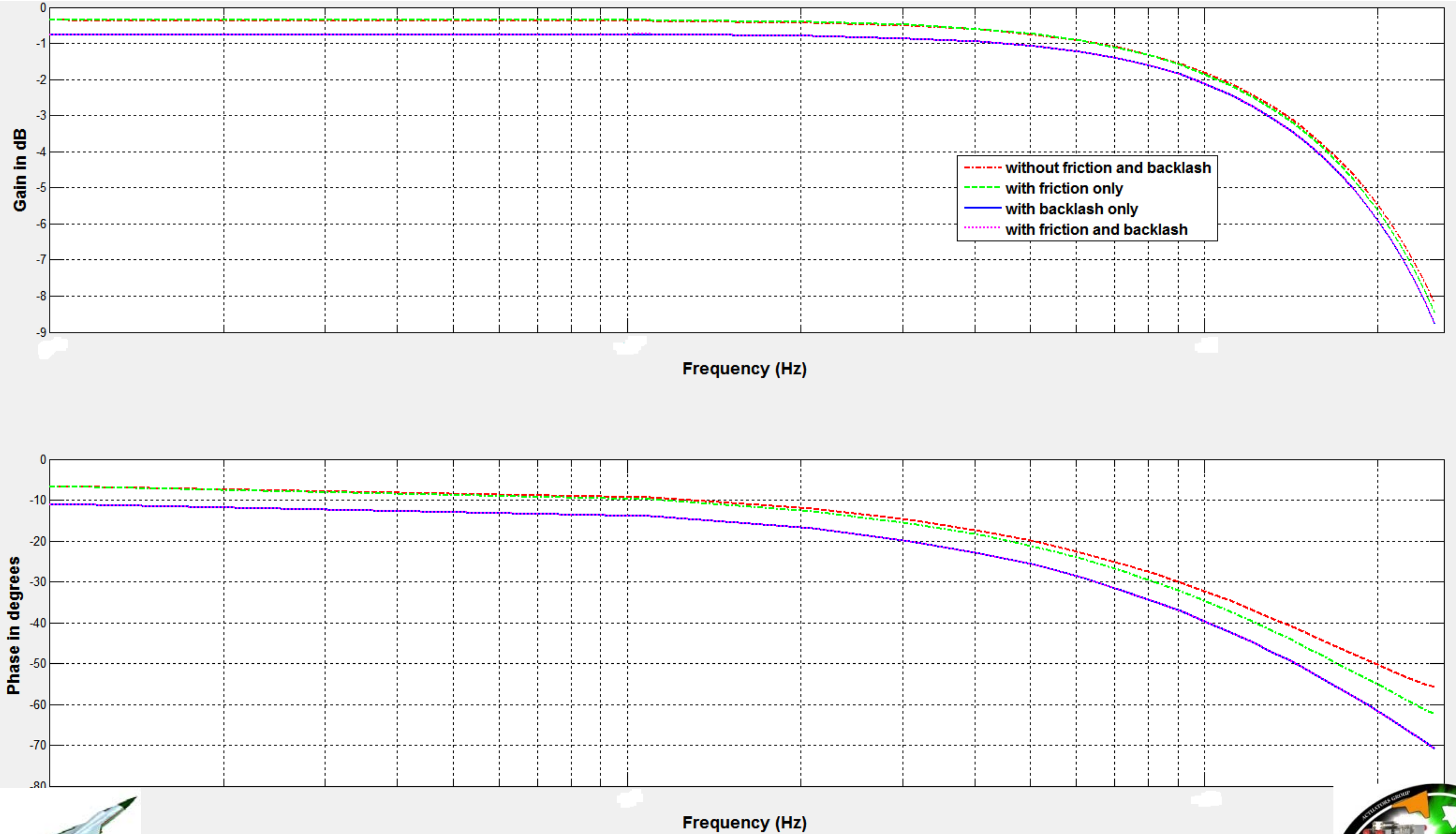




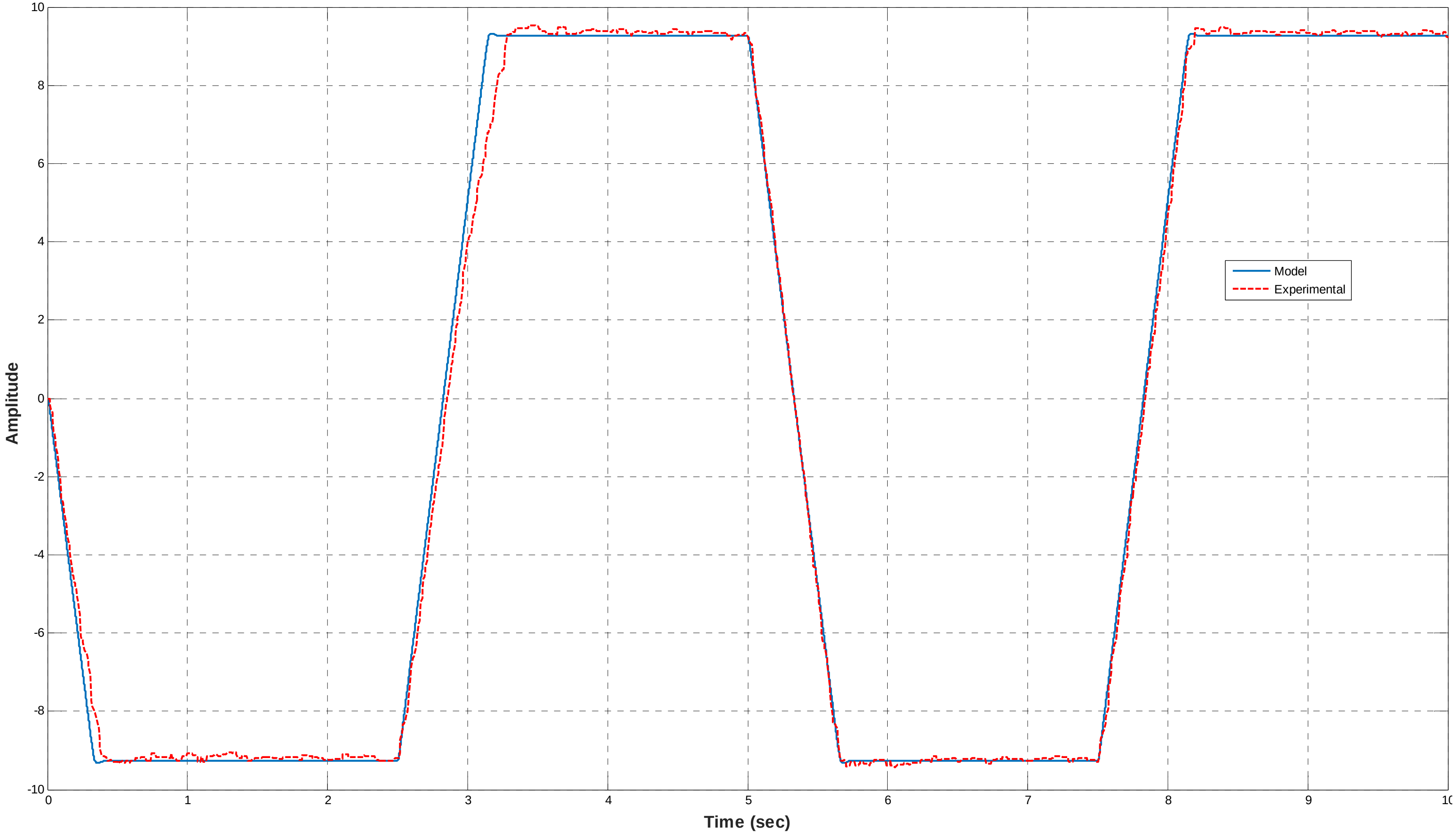
Effect of Non Linearities on Frequency Response

Why Modelling Nonlinearities is important ?

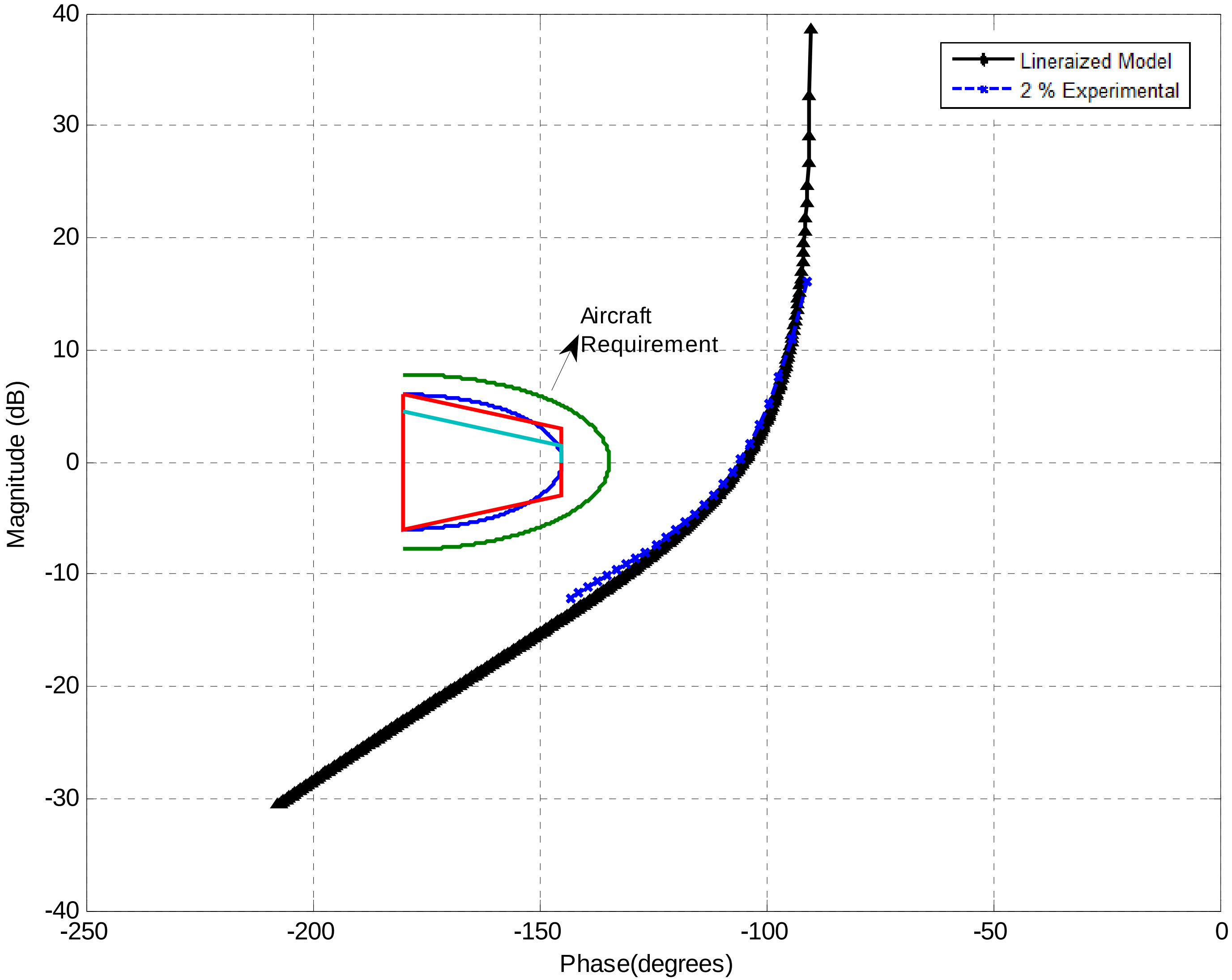
Frequency Response for Hydro Mechanical Servo



No load Rate-Experimental data Match

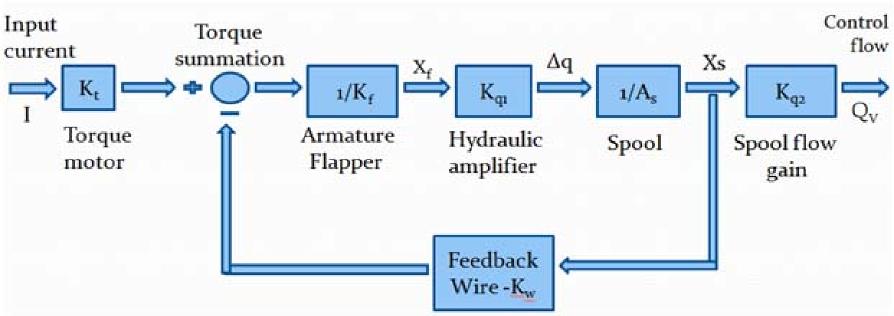


Nichols Plot Showing Linear Behavior of the Servo Actuator

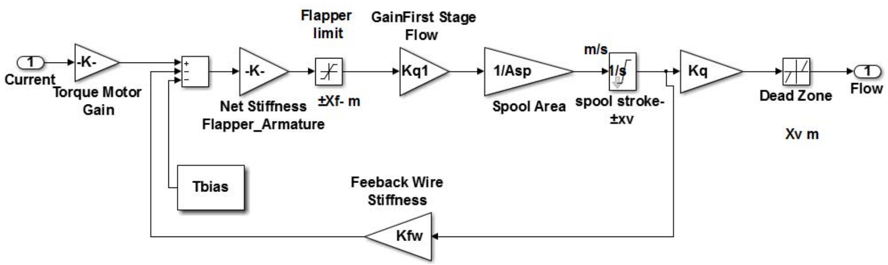


Reduced Order Model for HILS

Servo Valve Model



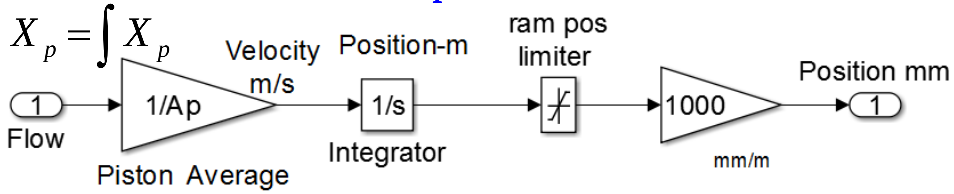
Simulink Implementation



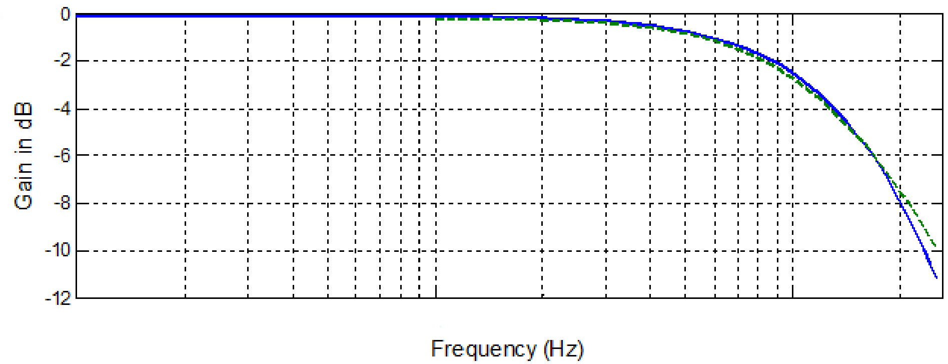
$$X_p = Q / A_p$$

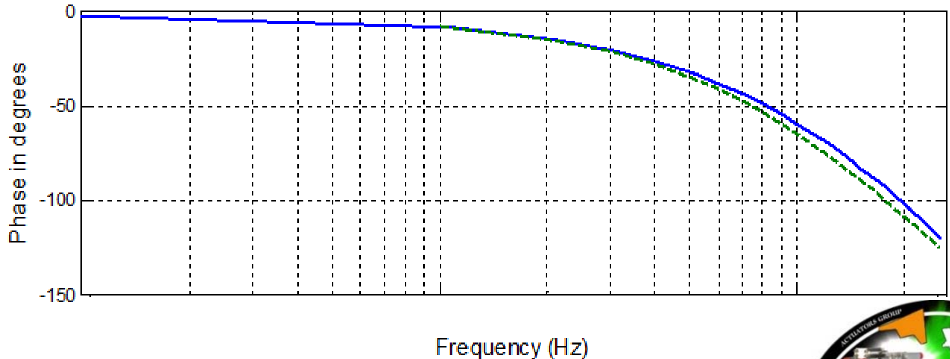
Actuator Flow Displacement Model

$$X_p = \int \dot{X}_p$$

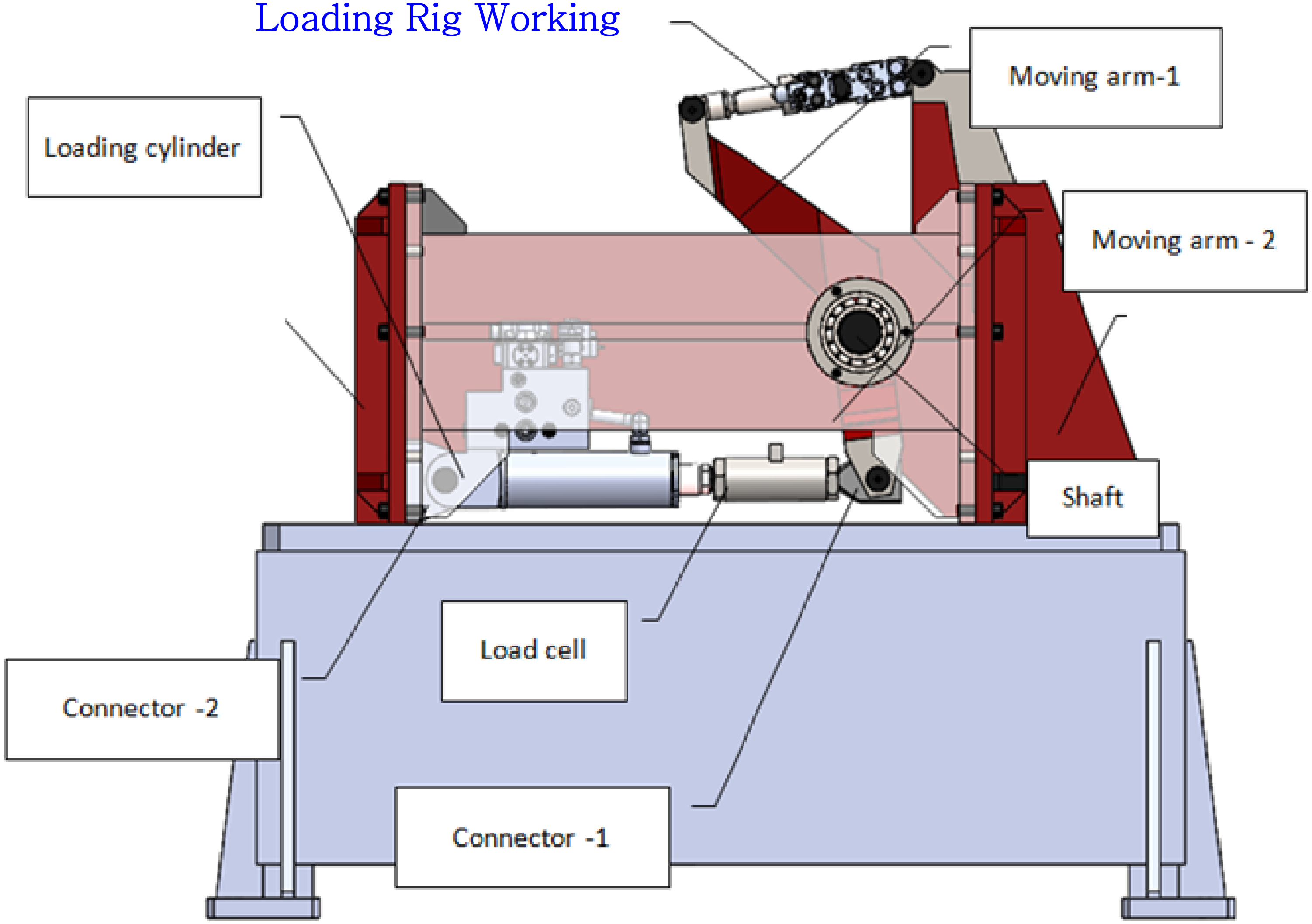


Frequency Response Data Match





Loading Rig Working



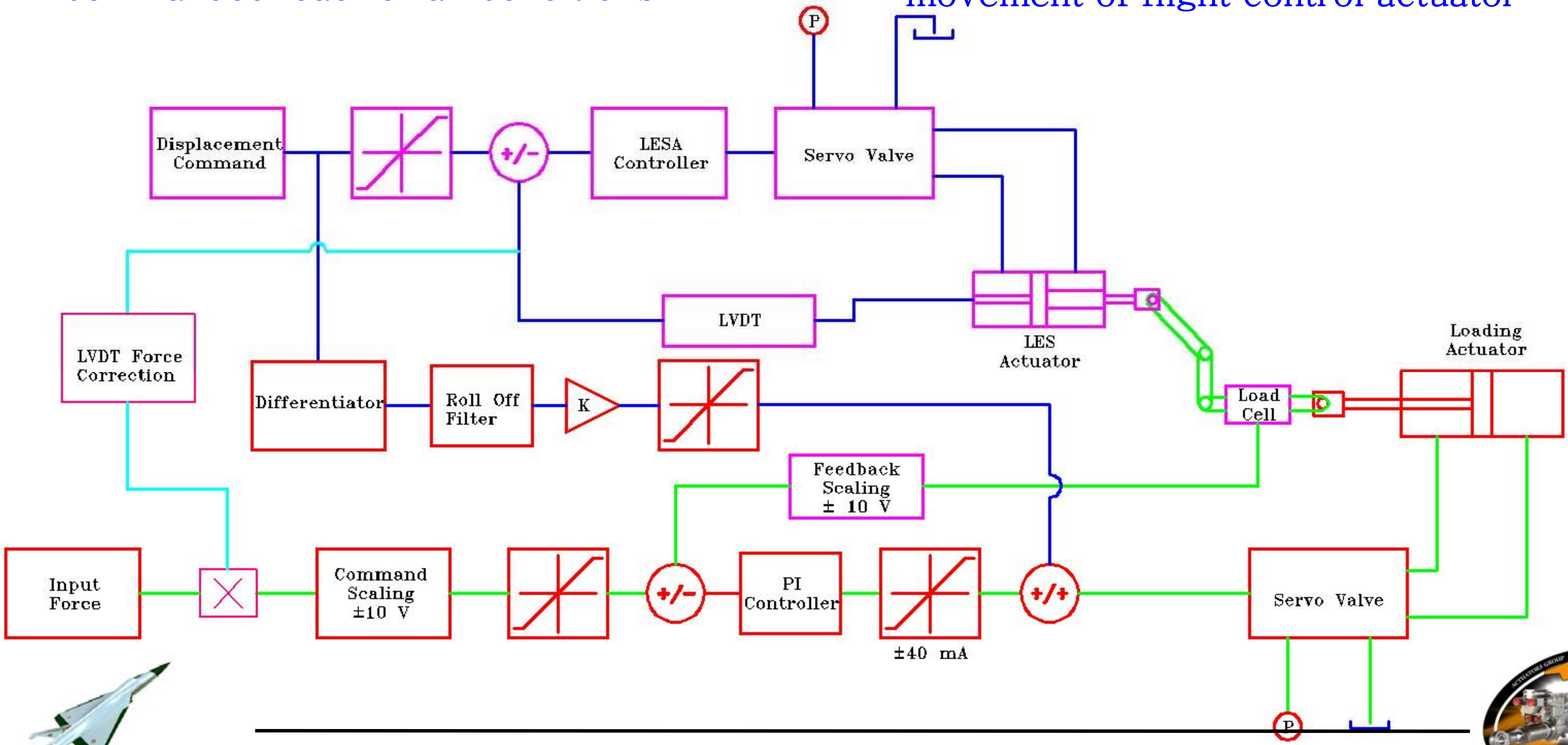
Loading Rig Configuration

Key Features

- Flight Control Actuator in Position Loop
- Loading Actuator in Force Control Loop
- Force correction due to angle change
- Force control within ± 10 % of commanded load for all conditions

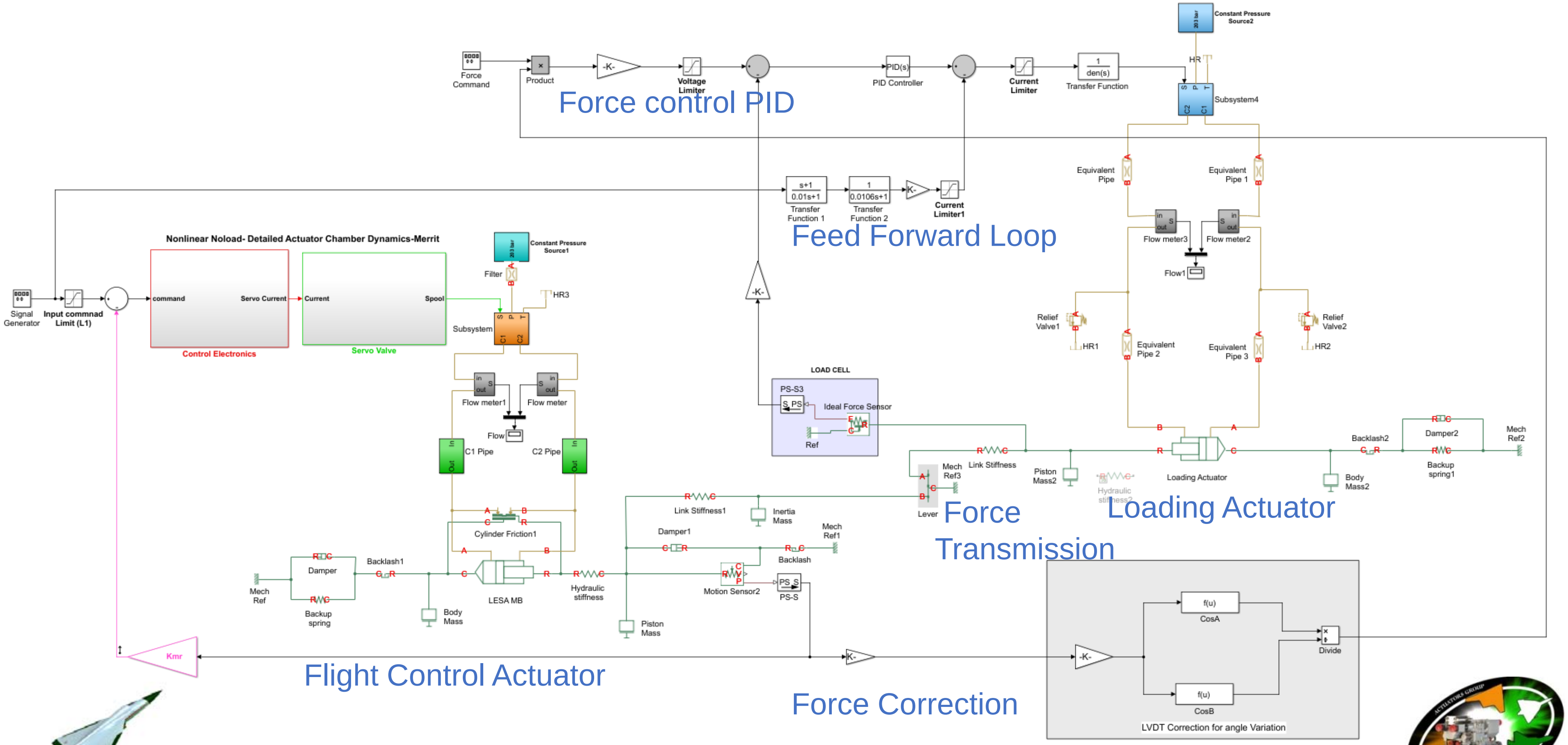
Design Challenges

- Modeling dynamic Characteristics
- Set point is changing with time
- Cater for various strokes, loads and frequencies
- Disturbance in the force caused by movement of flight control actuator



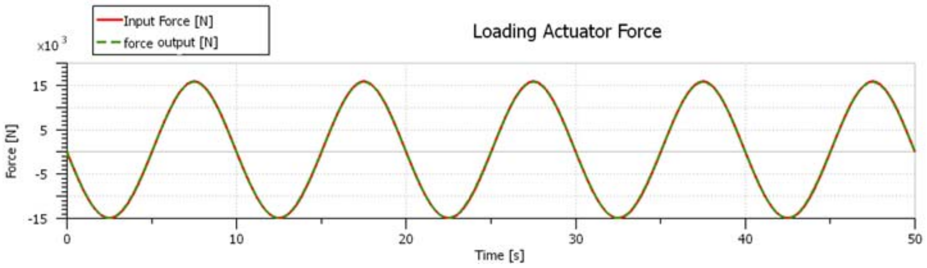
Loading Rig Control Design

- Optimum sizing of the servo valve- rated flow, pressure gain, dead band, response
- Optimum size of loading cylinder, pump and other components
- Accumulative pressure drop and power consumption at all operating conditions

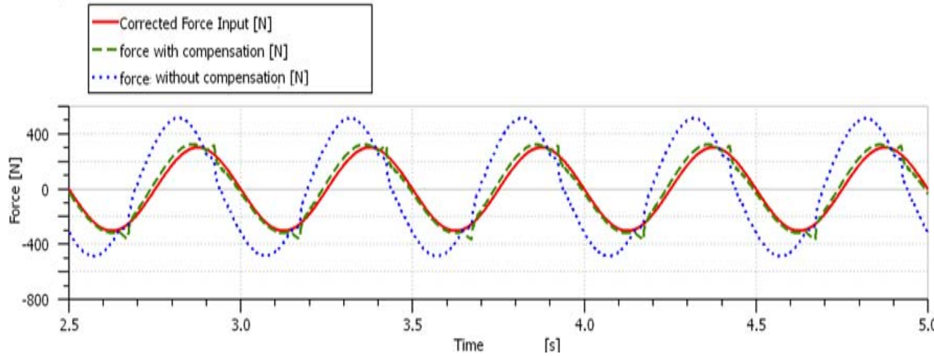


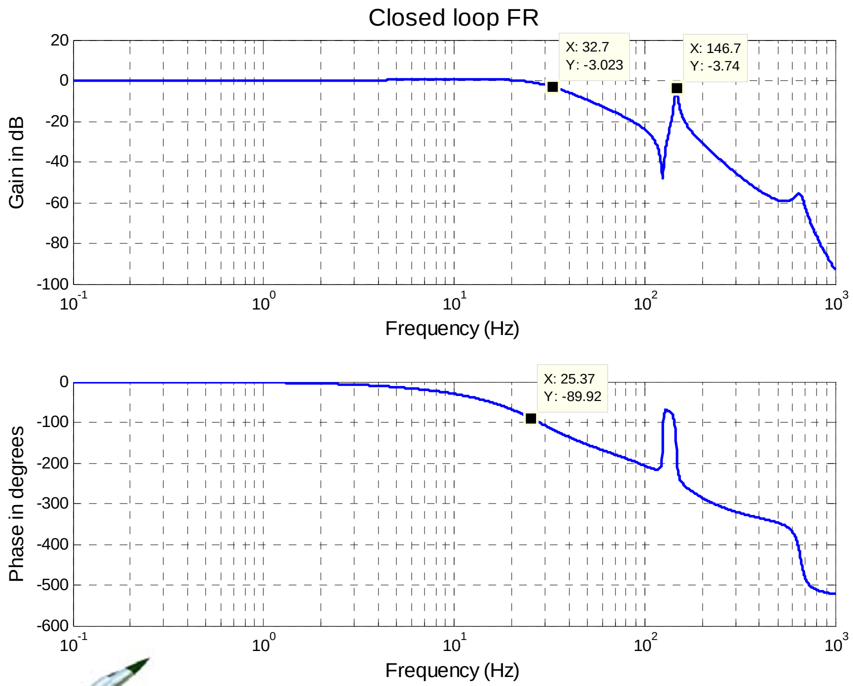
Loading Performance & Stability Analysis Results

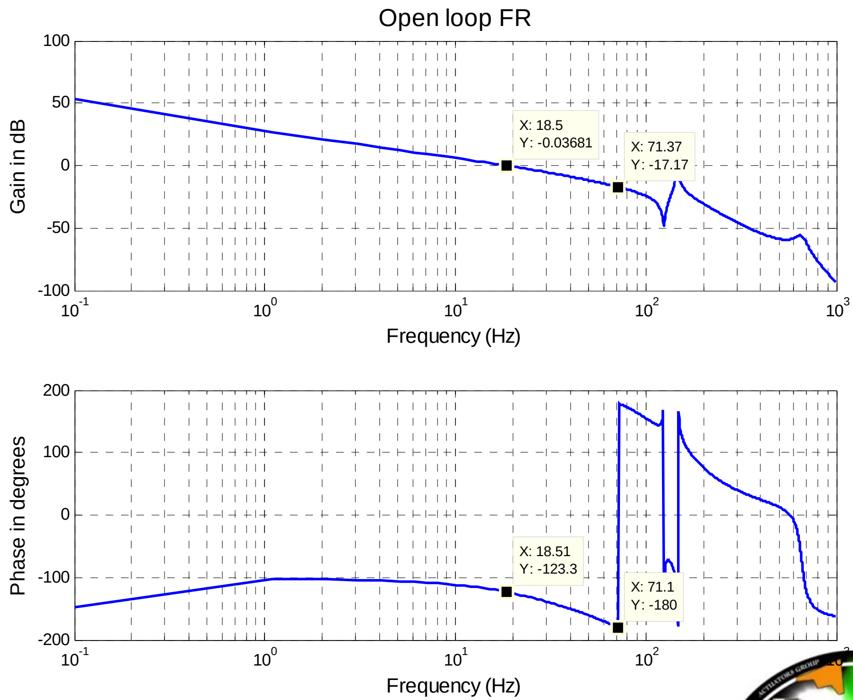
High Load, Low Frequency



Very Low Load, High Frequency

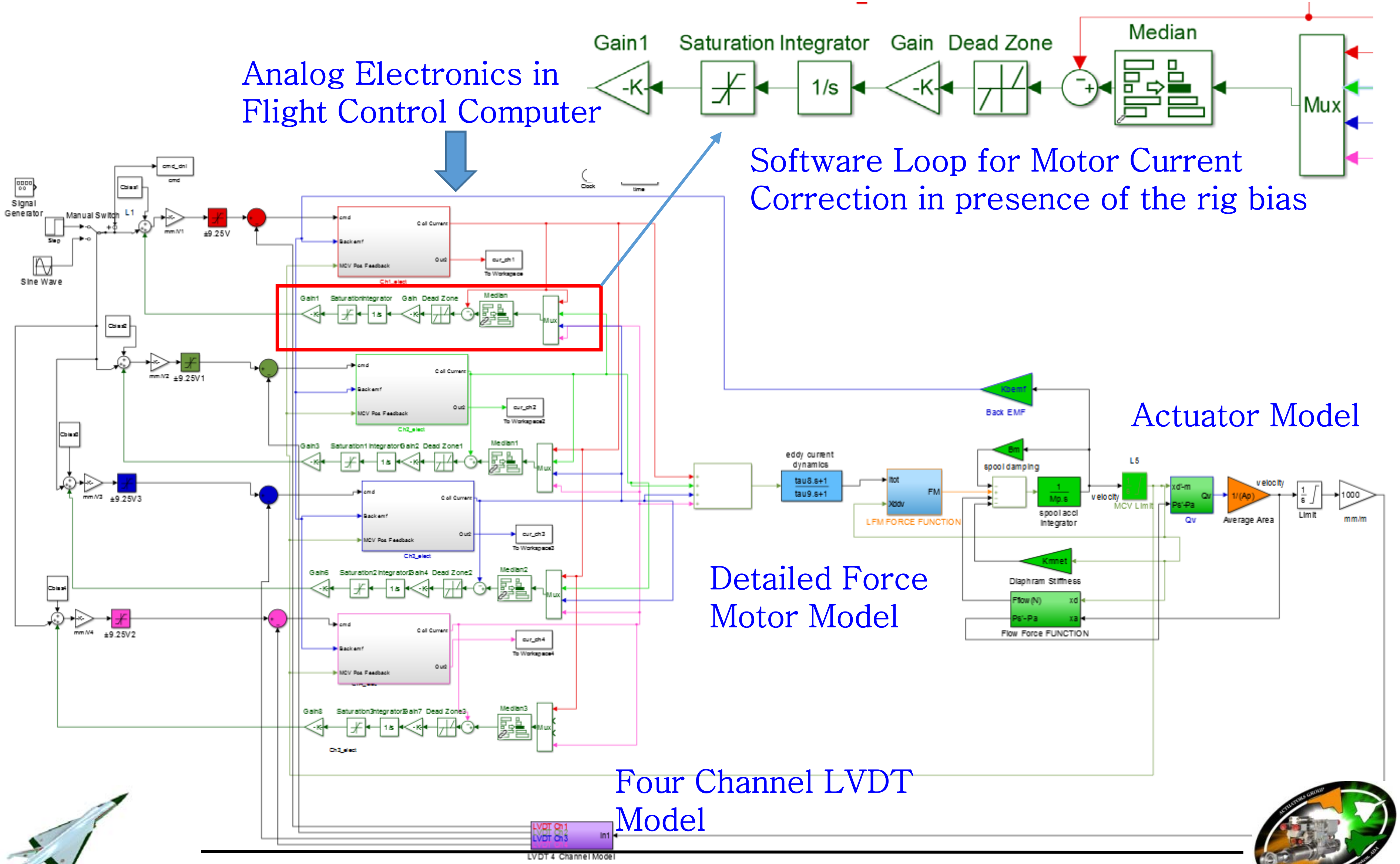






Software Thresholds & parameters- Multiple Loop System

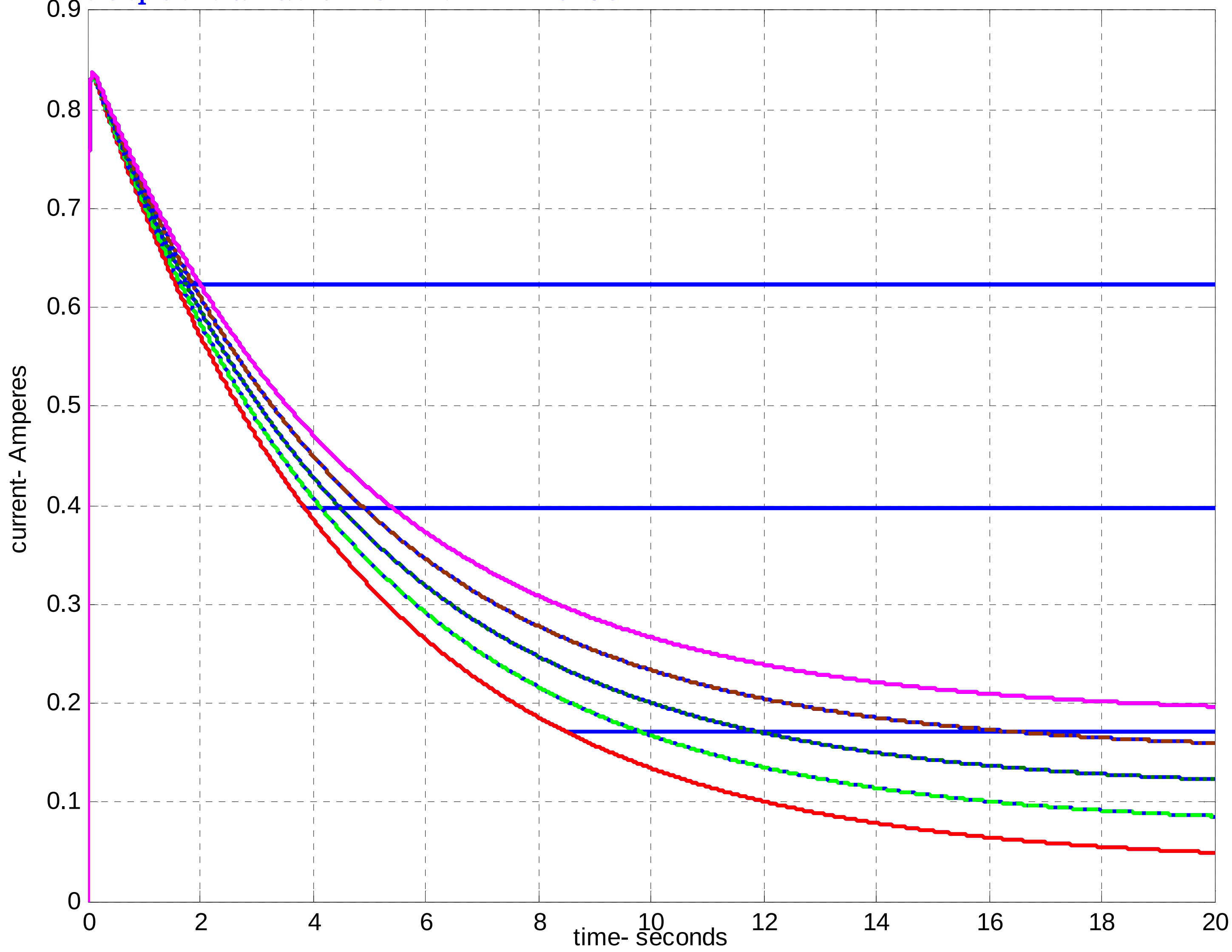
Four Channel DFCC Electronics & Actuator with Detailed Motor Model



Indigenous Actuators

Software Thresholds & parameters

Convergence of Coil Current under Rig bias, LVDT Voltage Output Variation & LVDT Noise



Conclusions

- ❑ Modelling and Simulation as an effective Design Tool
- ❑ MATLAB/Simulink are part of design process
- ❑ Modelling aspects and simulation results are of paramount importance for all design reviews related to actuators/test rigs

- ❖ Quick Verification of Preliminary Design with Model
- ❖ Estimation of System Parameters, which can't be measured easily
- ❖ Controller design for non linear model to meet dynamic requirement
- ❖ Excellent match with experimental data for all performance parameters
- ❖ Reduced order model for HILS – C Code

For The Loading Rig

- Prediction of actuator performance under load
- Prediction of Hydro Mechanical Resonant Frequencies
- Additional feed forward force control loop with adaptive gains based on dynamics of the disturbance caused by the movement of flight control actuator is essential for robust force control design of loading actuator.
- The design criteria to keep the force variation within ±10% of commanded force and keep the phase lag within ±10 degrees in the force control loop is achieved.

Thank You
Any Questions ??