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Abstract

The design of modern aircraft systems involves creating complex, adaptable systems with high performance. However, meeting these standards while keeping costs down poses a significant challenge for engineers. Traditional design methods that rely on trial and error lack efficiency and can lead to increased development expenses, especially for safety-critical systems. To tackle this issue, industries are turning to model-based techniques and optimization methods instead of traditional design methods. This paper presents a case study on the design of a pressure regulator for an aircraft, showcasing how model-based approaches and optimization have significantly reduced design costs while maintaining optimal performance. The pressure regulator is designed to meet various objectives across different operational points, requiring the solution of a multi-point, multi-objective optimization problem. Unlike solving traditional optimization problems, this necessitates a progressive, multi-layered approach to obtain a unique design solution. The paper demonstrates a progressive optimization approach to solve such complex design optimization problems and emphasizes the importance of using model-based techniques to identify critical design parameters in streamlining the optimization process. It also presents the validation of the proposed design approach using test data.

Keywords

Design Optimization, Multi Point Multi Optimization, Model-Based Design, Sensitivity analysis.

Introduction

Optimization is a powerful technique that helps engineers build systems that are optimum not only in performance but also in cost, weight, etc. However, the implementation of these methods requires parametric design models and powerful computing infrastructure to provide accurate and faster design solutions. With the adoption of model-based approaches and the availability of High-performing Computers, these methods are being widely accepted now across industries. Despite the advantages that these methods have there are certain limitations in terms of applying these methods to systems that operate across a wide range of operating conditions, which is a typical scenario of systems in the Aerospace Industry. The design optimized for one operating point cannot guarantee the optimum performance at a different operating point. To overcome such challenges this paper presents an approach where a progressive optimization technique has been adopted to size a Pressure Regulator Valve (PRV) that has a wide range of pressure and flow requirements across its operating envelope. A parametric physics-based model of the PRV has been developed in SIMSCAPE. The model has been validated using test data and the validated model has been used to perform optimization and arrive at a cost-effective design.

Case Study: Design of a Pressure Regulator Valve (PRV)

Problem Statement

This study aims to scale up an existing PRV to match new program requirements. The PRV was scaled up using the conventional approach. But even after numerous trials and errors, meeting its pressure and flow requirements proved to be difficult due to its wide operating range. PRV to be designed for minimum weight and cost and it should satisfy the performance requirements from operating point 1 to operating point 2.

Literature review

Optimization is a very well researched field, so detailed literature study was carried out with an objective to identify the best suitable method for PRV design problem that is Multi-Point, Multi-Objective Optimization (MPMO) problem. But we couldn't find any direct method for MPMO problem In Many design optimization problems have been dealt with in the literature that is either Single-Objective Optimization (SOO) or Multi-Objective Optimization (MOO) at a specific operating point. As the name suggests, the SOO problem has only one objective to be optimized like performance, cost, or weight. Whereas the MOO problem has more than one objective to be optimized for like performance and cost or performance, cost and weight, etc. MOO problems are solved in the literature using Weighted Sum and Pareto methods. In the Weighted Sum approach, a multi-objective problem is transformed into a single-objective problem by assigning weights to each objective and summing them up. The authors have established the groundwork for MOO in [1]. In [2] the authors have provided a comprehensive overview of multi-objective decision-making methods, including the weighted sum method, and discussed its theoretical underpinnings. The Pareto-based methods follow the principle of Pareto optimality, where a solution is considered Pareto optimal if no other solution can improve one objective without worsening at least one other objective. The Pareto front represents the set of all Pareto optimal solutions. The concept of Pareto efficiency was first introduced by Vilfredo Pareto in his work on economic theory, which laid the foundation for multi-objective optimization [3]. In [4] the authors have provided a comprehensive introduction to MOO optimization using evolutionary algorithms, with a significant focus on Pareto-based methods. It is a key reference for understanding the theoretical basis of Pareto optimality. With the advent of Model-Based Design (MBD), industries started adapting the optimization methods during early design phases. The benefits of MBD over conventional design methods have been a topic of interest across various engineering disciplines. Many engineers and researchers have investigated and published the benefits that these methods are bringing to the industry while also sensitizing the challenges in implementing these approaches. In [5] the authors provided a thorough comparison between conventional design methodologies and model-based design practices specifically within the aerospace engineering domain. Using case studies and simulations, the authors evaluated factors like design efficiency, cost-effectiveness, and overall design quality. The study emphasized the advantages of model-based design, such as early validation, integration, and enhanced collaboration, while addressing challenges like model complexity and barriers to adoption. In [6] the authors presented how industries can overcome a few critical

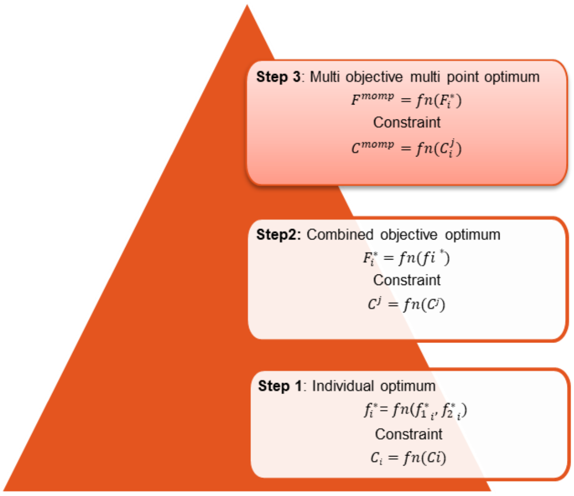


Figure 1. General Description of Multi-Objective Optimization

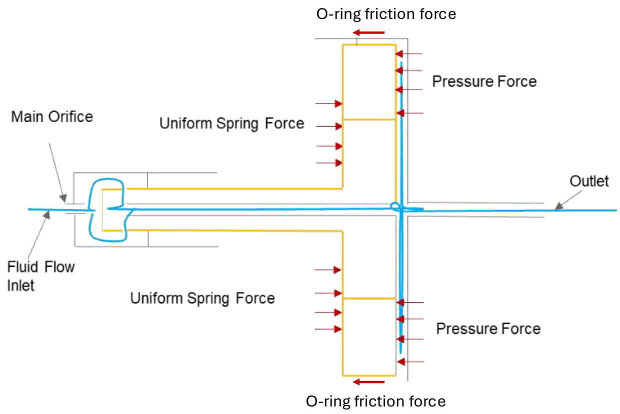


Figure 2. Free Body Diagram of Regulator

challenges facing today in terms of high-fidelity model development by developing reusable physics-based models and presented the use case of Model-based diagnostics highlighting the versatility and the benefits of using model-based approaches in the Aerospace industry.

Progressive Optimization

The design of PRV is a Multi-Point, Multi-Objective Optimization (MPMO) problem. This essentially means we must fulfill multiple objectives simultaneously by meeting different requirements at different operating points. Through literature study it was found there is no direct method for MPMO problem, so multi objective optimization methods were taken as baseline and extended MPMO problem with few additional steps. Figure 1, gives a general idea of MPMO, where all the non-dominated solutions give the same optimized value depending on the objective weights given. It gives us the flexibility to choose from the most practically implementable solution.

The multi-point part in MPMO refers to the optimization at two operating conditions, for this work, the lowest and highest supply pressure limits. So essentially the whole idea of optimization being used in this paper is optimizing for multiple objectives, multiple constraints, and multiple operating conditions for the design of a pressure regulator problem.

Model Development & Validation

Model Development

The PRV model has been built in SIMSCAPE using basic library blocks. Force balance on the moving piston is the fundamental principle for developing the model of the pressure regulator. It impacts the outlet pressure and flow of the fluid. Figure 2 shows the free-body diagram of the piston inside the PRV with various forces acting on the piston. The model is developed as a parametric model to perform component sizing study. The PRV being designed and developed is a spring-loaded valve. The fluid is moist air whose properties are taken from the SIMSCAPE library. Due to the difference in magnitude of forces acting on different surfaces of piston, there will be piston movement before it reaches a steady state. The model is developed to capture these dynamics due to fluid pressure acting against friction and the spring forces.

Model Validation

The PRV is used in baseline program so experimental test data and component parameters were available. So, the model was parameterized for baseline program and validated against the baseline experimental test data. The Experiments were carried out for different outlet flow rates and four test units. Outlet flow conditions were determined by the flow restrictor downstream of the PRV. The PRV has been tested for the rated flow, 75% flow, 50% flow, and 25% flow conditions. During this whole experiment, supply pressure decreased from the rated pressure to 2.5% of the rated pressure. For validation output pressure was compared between simulation and experiment data. The correlation observed during validation for different operating conditions varies from 89% to 98%.

Sensitivity study

The objective is to update baseline PRV parameters to meet the new program requirements. Redesign using traditional methods or with trial-and-error methods couldn't produce the PRV that satisfy constraints at all operating points. Optimization based design is the best option in this scenario. As PRV has many parameters, optimization will be time consuming process. But all parameters may not be equally significant. So less critical parameters can be excluded from optimization.

Sensitivity analysis is carried out to identify the critical parameters. Sensitivity is defined as how change in an input parameter affects the output of system. Based on system understanding six parameters were identified for sample generation and sensitivity analysis.

The critical parameters identified are reported in **Table 1**. For Input parameter sample generation, the SOBOL Sampling Technique is used.

Based on system understanding and previous sensitivity, the study range for various parameters was defined as shown in **Table 2**.

The SOBOL Sampling Technique was leveraged with 500 Samples (100 Samples per Parameter) being generated for the Sensitivity Analysis. At end of study Compliance Report congaing the output results of Flow Rate and Regulated Pressure and Explained Variance Compliance (EVC) is generated which is shown in Table 3.

Parameter Name	Parameter Description
Kspring	Single Spring Stiffness
DV	Inlet Valve Opening Diameter
DOri	Pressure Regulator Outlet End Adaptor Diameter
X0	Initial Spring Compression (changes Spring Preload Force)
DPiston	Piston Base Diameter at the Outlet end of the Pressure Regulator

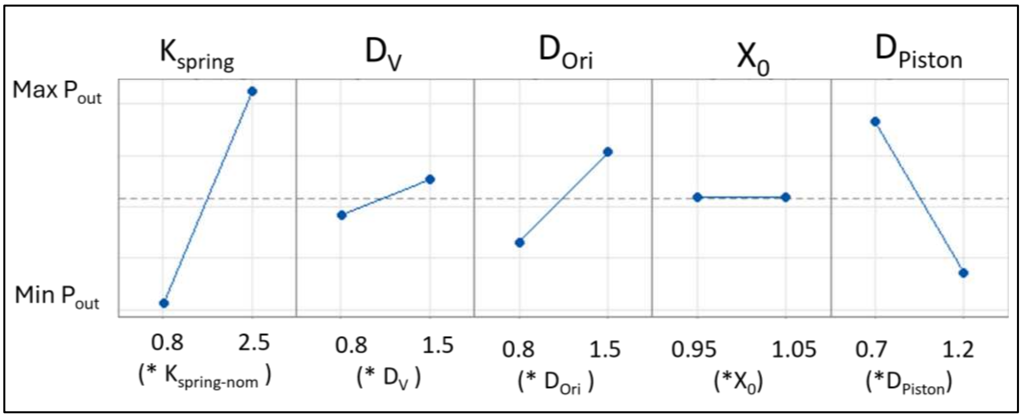
Table 1. Critical Parameters for Sensitivity Analysis of Pressure Regulator

Model Name	Distribution Type	Nominal	Range
Kspring	Uniform	Kspring-nom	Kspring-nom *[0.8 2.5]
DV	Uniform	DV-nom	DV-nom *[0.8 1.5]
DOri	Uniform	DOri-nom	DOri-nom *[0.8 1.5]
X0	Normal	X0-nom	X0-nom *[0.95 1.05]
DPiston	Uniform	DPiston-nom	DPiston-nom *[0.7 1.2]

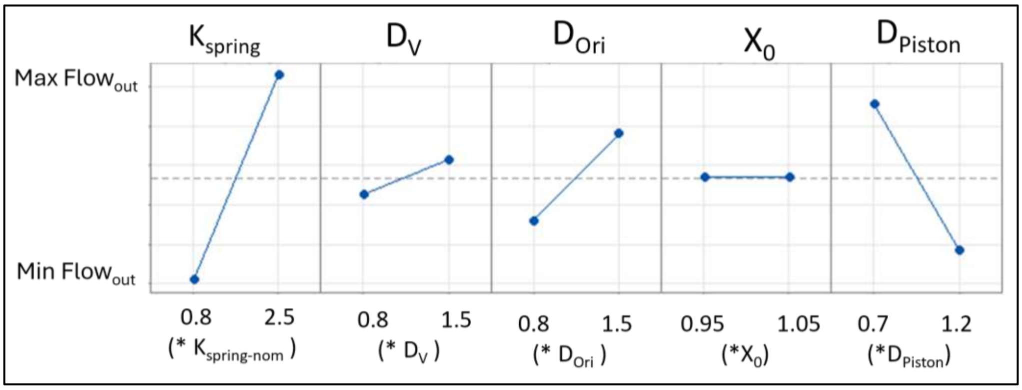
Table 2. Input Parameters with Relevant Parameter variations of Sensitivity Study

Parameter	Output 1 : Flow Rate	Output 2 : Regulated Pressure
	EVC	**EVC**
Kspring	56.9%	56.8%
DV	1.5%	1.5%
DOri	10.9%	10.8%
X0	0.0%	0.0%
DPiston	30.8%	30.8%

Table 3. Sensitivity Analysis Output



(a)



(b)

Figure 3. Mean Plots for Input Parameters for (a) Regulated Pressure and (b) Flow Output

Additionally, by using Minitab a fitted mean plot to understand the effect of each input parameters from the analysis, Flow Rate and Regulated Pressure are generated.

Based on EVC values and Slop of fitted mean plots it is observed out of 5 parameters chosen for sensitivity study analysis for Supply pressure case of P_{rated}, K_{spring}, D_{Ori} and D_{Piston} are more critical and flow rate and regulated pressure are more sensitive to them.

The results obtained from the sensitivity brought out an interesting observation that by changing supply pressure to 0.16 P_{rated}**, Valve Seat Diameter ending up influencing the low supply pressure cases, a possible reason could be that for some of the samples the parameters would have started dropping off the ideal operation zone of the pressure regulator.** Same as previous case, a characteristic curve is generated to get a better understanding near fully closed position of pressure regulator.

Tool Used	Multi Point Multi Objective Optimization Tool
Operating Points	Supply Pressure (P_IN) = Prated
	Supply Pressure (P_IN) = 0.1Prated
Optimization Constraints (feasibility is the objective)	PLim1(psig) < Regulat ed Pressure < PLim2 (psig)
	Flow Rate > 2Flowrated
Optimization Solver	Particleswarm (MaxStallIterations=20)

Table 4. Optimization Run Inputs and Constraints

S. No.	Parameter Name	Initial Value for Optimization	Range	Optimized Value
1	Kspring	Kspring-initial	Kspring-initial *[0.8 1.2]	1.1 Kspring-initial
2	DV	DV-initial	DV-initial*[0.8 1.9]	1.3 DV-initial
3	DOri	DOri-initial	DOri-initial*[0.8 1.4]	1.35 DOri-initial
4	X0	X0-initial	X0-initial*[1 1.1]	1.04 X0-initial
5	DPiston	DPiston-initial	DPiston-initial*[0.8 1.25]	1.04 DPiston-initial

Table 5. Initial Value Range of Parameters of Optimization and Optimized Values

Optimization

Post sensitivity analysis, for optimizations for P_{rated} and 0.16 P_{rated} psi supply pressure cases were chosen. Here optimization problem should satisfy two sets of operating conditions and flow constraint requirements.

Current Limitation

The available optimization toolbox in MATLAB seemed not to fully be equipped to counter the problem of having Multi-Point Multi-Objective Optimization (MPMO). To overcome these issues, Progressive Optimization explain in previous section is used. Here optimization is done for two operating conditions of highest supply pressure limit of P_{rated} and lowest supply pressure limit of $0.16P_{rated}$ and two constraints of flow rate (>$Flow_{max}$ LPM) and Regulated [1] Pressure (**P_{lower}<Reg_Press< P_{upper}**).

Multi Point Multi Objective Optimization Tool

To overcome the limitations mentioned in the previous section, in-house tools are used to carry out MPMO optimization. The tool developed based on the progressive Optimization methodology explain in previous section. The inbuilt particle swarm solver given in MATLAB is chosen for optimization solver.

For the optimization, the range of parameters is increased to get a wider design space and to have very stable regulator characteristics as mentioned in **Table 5**.

With this parameters range and Constraints and Objective functions mentioned in **Table 4**, optimization was carried out and optimum parameters were obtained as shown in **Table 6**.

To validate, if this result meets required constraints for High Pressure Regulator the characteristic curve for different supply pressure is simulated using SIMSCAPE model and plotted. MBD Validation Through Prototyping.

MBD Validation Through Prototyping

Based on MPMO results PRV prototype was developed. PRV performance requirements were verified using the prototype. And the prototype satisfies all the performance requirements.

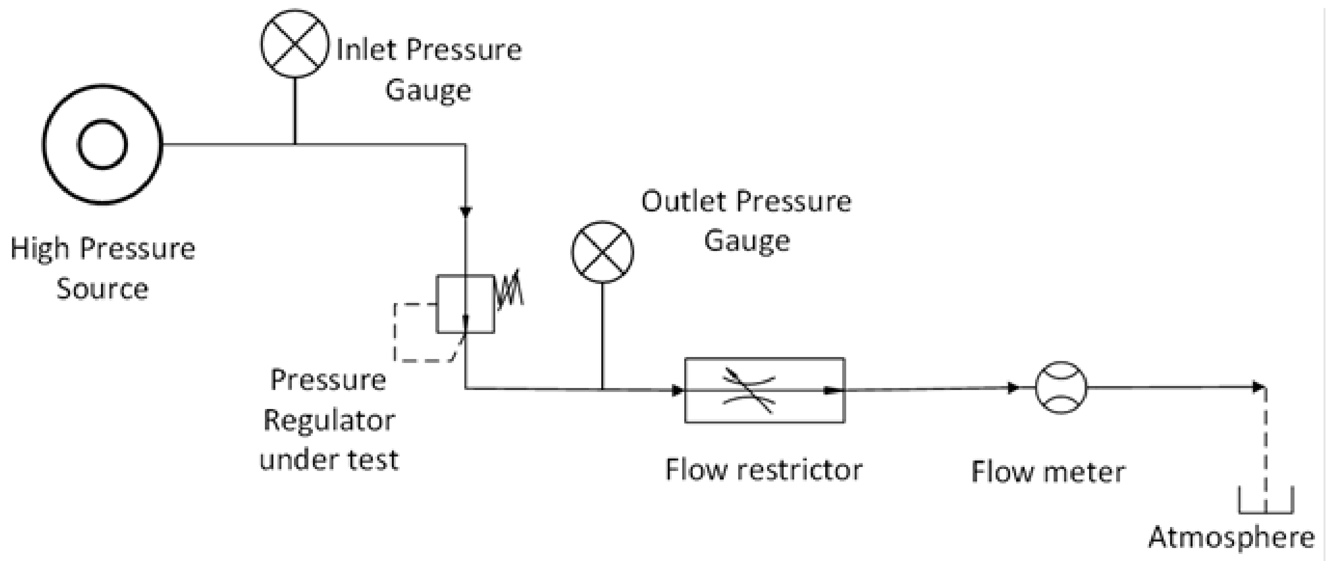


Figure 4. Test Setup for Pressure Regulator

The Model to Prototype correlation study was also carried out and a very good correlation ~95% was found between model and Prototype. The following are the details about correlation study.

The supply pressure range for the validation is Pmin -Pmax psi. Experimental data for 5 supply pressures viz. Pmin , 0.066* Pmax ,0.5* Pmax ,0.62* Pmax and Pmax for each volume flow rate is generated as shown in the following table The experimental data generated for this validation plan is shown in table 6.

For all supply pressures and volume flow rates, the maximum error between the pressure regulator model prediction ($P_{out_{model}}$) and experimental results ($P_{out_{exp}}$) are defined as per equation (1).

$$\% \, Max \, Error = \frac{\left|P_{out_{model}} - P_{out_{exp}}\right|}{P_{out_{exp}}} \qquad (1)$$

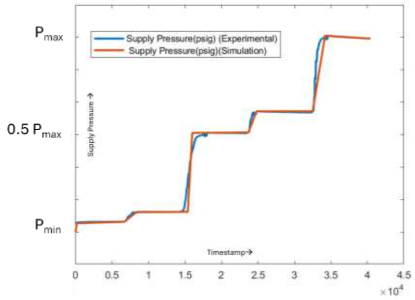
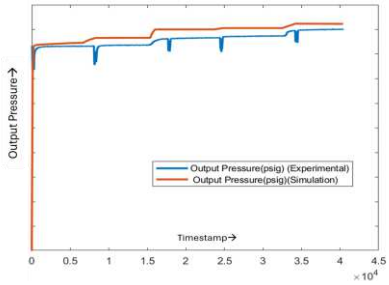
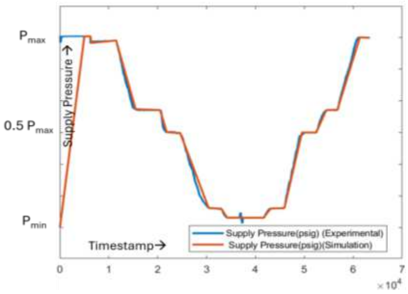
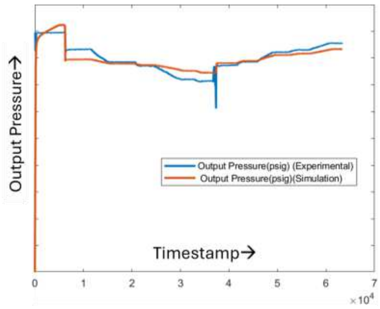
The Maximum error is found to be less than 5 %. This validates the design proposed by the MPMO tool with experimental data. **The important point to be considered here is the output pressure predicted by the model as well as the experimental data lies between the specified range of P1-P2 psi. Also, the flow that is extracted from the model > F LPM. So, this experiment validates the design that is provided by MPMO essentially satisfies the requirements put as the constraints to the MPMO tool.**

Benefits

Model Based Design (MBD) with progressive optimization technique reduces the design cycle time by 84% which includes both man hours and hardware iterations. Approximately 50 % cost reduction was achieved while doing this exercise through modelling and simulation techniques.

Conclusion

This work demonstrates the power of Model based design (MBD). It has reduced the PRV prototype development time to 1/6. The key highlights of this work are model development and design by optimization using the developed model. The model development is about transforming the real pressure regulator system into the model and obtaining the same response as real system. A high-fidelity model was developed by detailed study of real system and connecting behavior of each element with physical principals and then writing the equations for the same. The modeling activity was done in SIMSCAPE followed by detailed validation with >90% accuracy. The traditional design process was not suitable for pressure regulator design as the system operates at different operating conditions while having different constraints. For such scenario, design by optimization is a better method. This is a multi-operating point and multi objective problem (MPMO) though optimization is a well research field there is not much work done on (MPMO) problem, So Progressive optimization method developed during this work to handle MPMO problem. regulator design was done using this Progressive optimization method and validated through prototyping.

<table>
<tr><th>Flow condition</th><th>Supply conditions in the model</th><th>Output pressure
model vs experiment</th><th>Error</th></tr>
<tr><td>Lockup condition</td><td>
</td><td>
</td><td><4%</td></tr>
<tr><td>25 % Flow</td><td>
</td><td>
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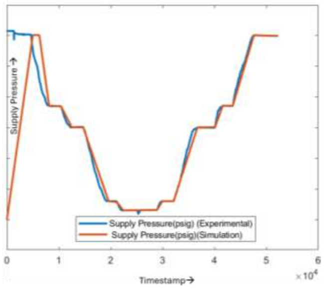
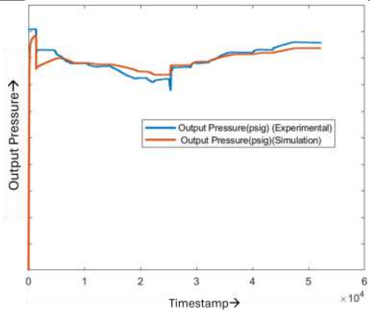
<tr><td>50 % Flow</td><td>
</td><td>
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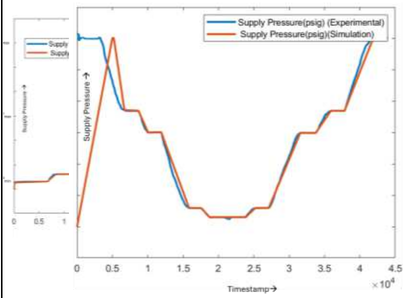
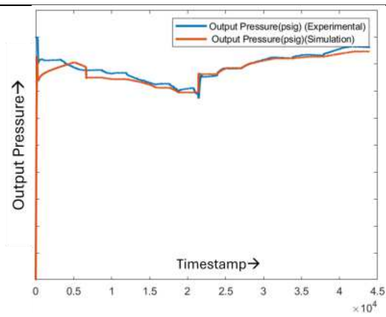
<tr><td>75 % Flow</td><td>
</td><td>
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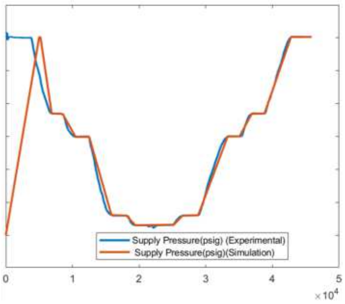
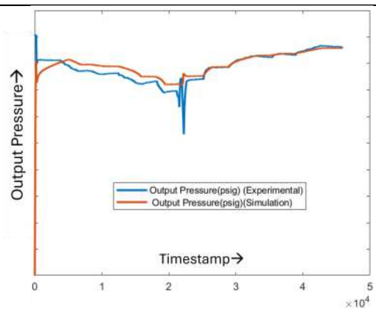
<tr><td>Full flow</td><td>
</td><td>
</td><td>< 4%</td></tr>
</table>

Table 6. Model performance for different pressure and flow conditions: Comparison with experimental results

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Biography

Venkateswaran Krishnasamy

Working as a Manager for Electromechanical systems at Collins Aerospace. Expert in physics-based plant model development over 14 years and expertise in modeling electrohydraulic, electro pneumatic, electromechanical systems. Lead young engineers to develop plant models with model-based design approach and guide them to use sensitivity study, optimization tools to improve the system design.

Shreyas Dixit

Lead Engineer in Collins Aerospace with professional experience in system modeling and simulation for over 2.5 years. Holds a Master's degree in mechanical Engineering from IISc. Worked in oxygen systems and optimization areas.

Hari Krishna Pavan Kumar Kollipara

H K Pavan Kumar Kollipara is the Principal Engineer at Collins Aerospace. He received his master's degree in Aerospace Engineering from Indian Institute of Technology Kanpur. He has 14 years of Industrial experience in System Modelling and Analysis.

Kadri Aejaj

Working as a Principal Engineer in Collins Aerospace with more than 10 years of professional experience in model-based product development. Holds master's degree in CAD/CAM. Worked in various projects like aircraft hydraulic systems, braking system, high lift system and cargo system.

Srinivasan S

Lead Engineer in Collins Aerospace with professional experience in system modeling and simulation for over 3 years. Holds a Master's degree in Aerospace Engineering. Worked on development of aircraft subsystems such as Emergency Oxygen System, Cargo Handling System and High Lift Actuation System.