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Modeling a Hydraulically Powered Flight Control Actuation System

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Featured Application: This approach is suitable for diagnostics of other systems in terms of real-time fault identification and mitigation. It will also be useful in the field of digital twin applications.

Abstract: Many different types of aircraft designs have flight control systems (FCS) powered by hydraulic systems. With respect to the torques, moments, surface areas, and opposing forces to be acted upon, components introduce faults into the hydraulic system when these components are aging or degrading. The diagnostics of a hydraulically powered flight control actuation system (HPFCAS) rely on the faults produced within the subsystem components as well as the entire system's mechanism itself. In this paper, a model for an HPFCAS is developed to analyze faults where the HPFCAS was approached as a system of systems (SOS). The identified faults were injected into the system. It is established that some of the faults from the different subsystems had similar characteristic effects and were propagated with attendant consequences. For instance, a measured decrease in the pressure value is observed because of the decrease in the pump speed. A similar characteristic is observed if there is leakage on the line or if there is a clogging valve. These form complex integrated responses in determining where the fault is coming from if only one component is analyzed since it involves components serving different subsystems. Results show that only models that can describe the real characteristics or attributes of the specific systems, due to their defined components, are sufficient for effective diagnostics. This is because the data obtained are more accurate at predicting the behavior of components.

Keywords: aircraft systems; fault detection; diagnostics; classification; algorithm; flight control actuation system

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1. Introduction

The HPFCAS is used for the flight control and management of some aircraft. This controls the main primary control surfaces like the aileron, elevator, and rudder. Sometimes the secondary control surfaces, involving the trim systems, slats, flaps, slits, and spoilers, regarded as auxiliary control surfaces, are also involved. In fact, hydraulically powered control is also used for heavy lifts like the undercarriage of the aircraft due to the power-to-weight ratio advantage of hydraulic systems. The authors of Ref. [1] stated that, with a little hydraulic fluid in a cylinder, an enormous amount of load is moved with the hydraulic pressure, if it is properly channeled without leakage.

Apart from the leakage mentioned, there is loss of pressure in the system through different component faults like valve sticking, corrosion or erosion, filter clogging, the loss of pump speed, bearing noise, pipe leakage or blockage, the loss of electric power to the motor, fluid temperature increases, cavitation, and many more [2–4]. These are regarded as symptom vectors that cause many faults within the system. Thus, these faults

were viewed as mechanical, electrical, and hydraulic faults obtained from the different subsystems. However, the subsystems make up the entire system by virtue of the operating principles of the components used. The effects of these faults, grouped as mechanical, electrical, and hydraulic, are interwoven, where the fault triggered by the symptom vectors of one component may propagate a fault in another component, thus making the SOS fault approach suitable.

It is established that fault propagation from one aircraft subsystem to another has become more frequent due to the increased interactions between the aircraft systems [5]. Although some of these faults are addressed during maintenance activities, if a fault takes an unexpected propagation path, its cascading effects are difficult to troubleshoot. Models of aircraft systems were used in the past for diagnostics, for example, in an environmental control system model, an electrical power system model, and an engine system model [5,6], but these were not broken down into SOS. Since fault propagation occurs due to faults of one aircraft subsystem affecting other interacting systems, in modeling HPFCAS faults, the HPFCAS is broken into subsystem models. It is noted that only a few research works consider subsystem/system interactions at the top aircraft vehicle level [7]. With the trend of increasingly integrated systems in the aircraft industry, the complexity of interactions between aircraft systems is increasing. This has resulted in the necessity of monitoring aircraft systems' health both within the subsystems and across the systems.

To investigate these effects, a study of two aircraft HPFCASs was carried out. The working principles of the HPFCAS for the different aircraft in relation to hydraulic system performance were the same. To compare their performances against related flight conditions and identify what appear to be observed root causes and effects on the HPFCAS, it was noted that demand for responses is channeled to a hydraulic reservoir through transducers. The hydraulic reservoir is then used to power the required actions. To obtain the required data that would be useful in supporting fault findings and can be used for diagnostics of such complex systems, an experimental model as an analogy of the two aircraft's HPFCASs was developed as a test rig in the laboratory based on the functions of their different components. The two system cases provided a fair representation of the HPFCAS and mimicked the functions of a baseline HPFCAS for any aircraft. To ensure a robust representation, experimental data were collected to establish the basis for component functional behavior or characteristics. These data were obtained under healthy and degraded scenarios. Using the same conditions of operation, faults were introduced on the components based on the symptom vectors earlier described. The data for unhealthy cases were collected. Thereafter, a system-by-system breakdown of the component models was made and integrated. A simulation model of the experiment was developed in MATLAB Simulink and Simscape version 2023a using the experimentally defined conditions. Simulations were completed for the healthy cases, and results were obtained. After these, the faults were injected into the components to establish the unhealthy cases and simulated. Different values were established in both the healthy and unhealthy situations, respectively. The comparison between the experimental data and the simulated model data obtained provided verification and validation results of the developed model. These provided the requirements needed for the expected diagnostic of the aircraft's HPFCAS, as different conditions of operations of the components were altered with the different data results obtained.

It should be noted here that access to repository data of the HPFCAS was not readily available, and manufacturers of the two aircraft types were not ready to volunteer their data to the public domain. However, the suitable data needed for future work on HPFCAS diagnostics were generated by the developed model. The discussion on the HPFCAS diagnostics using the developed SOS model will be presented in a different paper. Perhaps, one of the vital benefits of this approach is that the data required for a system diagnostic can be generated from the simulations of the subsystem models as useful performance data of the system. These data can be used for the development of digital twin capabilities in the modeling of aircraft systems, whereby useful system performance data is needed.

It is well understood that one of the main requirements for good system fault analysis is the availability of sufficient data. These data must be richly obtained in a manner suitable for the diagnostics analysis. For many years, efforts regarding data acquisition have been intensified through sensor technologies for extracting useful information. For more robust data, the sensors were enhanced through calibrations for optimum performance [8,9]. Thus, the extraction of the sensor information and the processing of this information into quantifiable and qualitative data for usage in system diagnostics involve the development of the right models. The authors of Ref. [10] stated that, in recent times, there has been a quantum volume of repository data available that can be accessed. However, whether such a repository of data has a good generic bearing on the system and component degradation experience is still under investigation. This is because, although the data may exist, obtaining the exact or right data that correlate with the performance of a system and are specifically required for the proper diagnostics of faults or failures in a particular system is difficult.

Although passive fault management tools for maintenance and monitoring of system models are put in place to support maintenance processes and arrest the breakdown of systems, these do not assure the users of their regular availability. This means fault management tools must be designed for each individual subsystem that makes up the entire system. This is because the modes of failure of the subsystems would not be the same in all cases. In their research, Refs. [11,12] collaborated in making these statements. They stated that the results displayed to interpret the presence of faults in a physical system must relate to the simulated system's model type. That is, from the system data used in carrying out an analysis, both the generated data obtained when the physical system is deployed and the simulated data obtained must be sufficient in comparison. This will also depend on the type of algorithm to be deployed or used for the data analysis. The authors of Refs. [6,10–12], in their separate research works, asserted clearly that the different models of systems are used to generate the basic diagnostic requirements. These requirements are peculiar to the functions or workings of a system. Hence having a complete model of a system that mimics its functionality will provide the needed data. These data can be compared with other repository data of similar features if they can be used as a validation or verification process. In situations where the information is incomparable, the sole responsibility would fall on the credibility of developing a model of the system, where data can be obtained and used for analyzing its failures. In fact, of critical importance in modern-day diagnostics is the emergence of the system-level diagnostic approach. System-level diagnostic targets, aim at assessing accurately a system's health state and detecting and identifying faults in the system's faulty components. These make the development of models essential because, without the subsystem model's data, a system-level integration for carrying out diagnostics will increase the burden. In [13], a model for fault simulations and diagnostics of a Boeing 747 auxiliary power unit was created. Meanwhile in research work [14], a model to investigate automation and communication methodology for data exchange was developed. Similarly, in working on the simulation of an aircraft environmental control system, the authors of Ref. [5] created a model of the system for simulating the behavior of the components, integrated into the system. Thus, the authors of Ref. [15], in developing and implementing a framework for aerospace vehicle reasoning, utilized many models of aircraft systems. These indicate that developing models for diagnostics and other analyses is important. As a result, the authors of Ref. [16], in their review work on model-based and data-driven diagnostic methods, targeted hardware system diagnostics. This used separate models of the hardware. The authors of Refs. [17–20], in their development works and use of models, all agreed that models are advantageous since they do not require historical knowledge of the system in operation. Secondly, the rate of false alarms to misdetections can be adjusted especially in situations where faults from different systems have similar fault signals. However, the development of models requires knowledge of the engineering of the system or component under examination.

Therefore, the novel contributions of this paper are as follows:

- The development of a model to provide sufficient data on hydraulically powered flight control actuation systems using an SOS approach targeting the subsystems, not just the components involved. Past attempts at HPFCAS fault findings were based on specific components, like a pump, bearing, and seal of an actuator. Hence, only the data and diagnostics of a specific component out of the many components are analyzed.
- Although other forms of models for diagnostics have been in the past, they do not consider the effects of the propagated or cascaded faults in a system. They are only good for isolated faults.
- The proposed development of the HPFCAS shows that a complex system can be broken down into subsystem models to obtain the rich data required for fault analysis due to the non-availability of the required data. This helps to analyze faults under different conditions of operation, where symptom vectors of different faults are grouped according to how they affect the subsystems.

2. Literature Review

A literature review on fault and diagnostic processes for different FCASs shows variations in approaches. Of particular interest was the HPFCAS [21] in one study, which established a suitable approach where the fault-finding challenges of multisystem configurations or integrations on an aircraft are separated into different systems. This is for a model-based diagnostic method and for a principal understanding of the physics of the HPFCAS system. That is, the models of the system will be developed with the physics-based knowledge of the separated subsystems. This must be well understood. However, accessing the historical data was problematic. Adequate data and algorithm development to match the HPFCAS diagnostic model were lacking. For hydraulic systems, any single system or component failure is a principal failure mode, as well as any combination of failures. Therefore, common-mode failures that can affect multiple systems are usually principal failure modes. These were designated as research gaps.

This paper is a follow-up part of the review of the HPFCAS to develop a model of the system [21]. It was initiated by simple experiments to determine the characteristics of the components. Also, it was used to obtain initial data that are used to create the model and subsequent simulations of faults. Some parts that constitute a build-up process have been documented and are shown in the Venn diagram of Figure 1. A brief recap of the previous work is given to explain the overall scale of the literature review work. The outcomes and the current contributions that enabled the scope of this paper were already published in a journal paper titled "A Review of Diagnostic Methods for Hydraulically Powered Flight Control Actuation Systems" [21].

A holistic view of past FCS research shows that limited experimental works have been completed on the simulation of system faults. There is a lack of historical functional data to validate how an HPFCAS interacts with other aircraft systems. Most model-based diagnostics of HPFCAS systems presently do not account for fault injection and degradation severity as a threshold of propagated or cascaded effects.

Coming from the above literature review experience, it was important to have a training data range suitably specific to the system. These data were to be obtained for detecting faults at both normal and faulty operations. It was necessary to have a similar data range from a model of the system when it operates without faults and when it operates with faults.

Limited research work has been reported on the quantification of the effects of degradation severities on the overall actuator system performance. Studies on their propagation to the different components of the HPFCAS are still ongoing. Most works, including Ref. [22], consulted and dwelt more on the quantification of effects that affect the electrical and mechanical actuator systems of aircraft. These are attributed to common effects like vibration, bearing's wear out, and other symptoms, where many techniques have been used to analyze their fault diagnostics. For instance, processes like signal processing have been used to achieve favorable results. This cannot be said for HPFCASs with the irregular

properties of fluids in their performance. Thus, a simple HPFCAS model was proposed to be developed for use in fault injection and simulations.

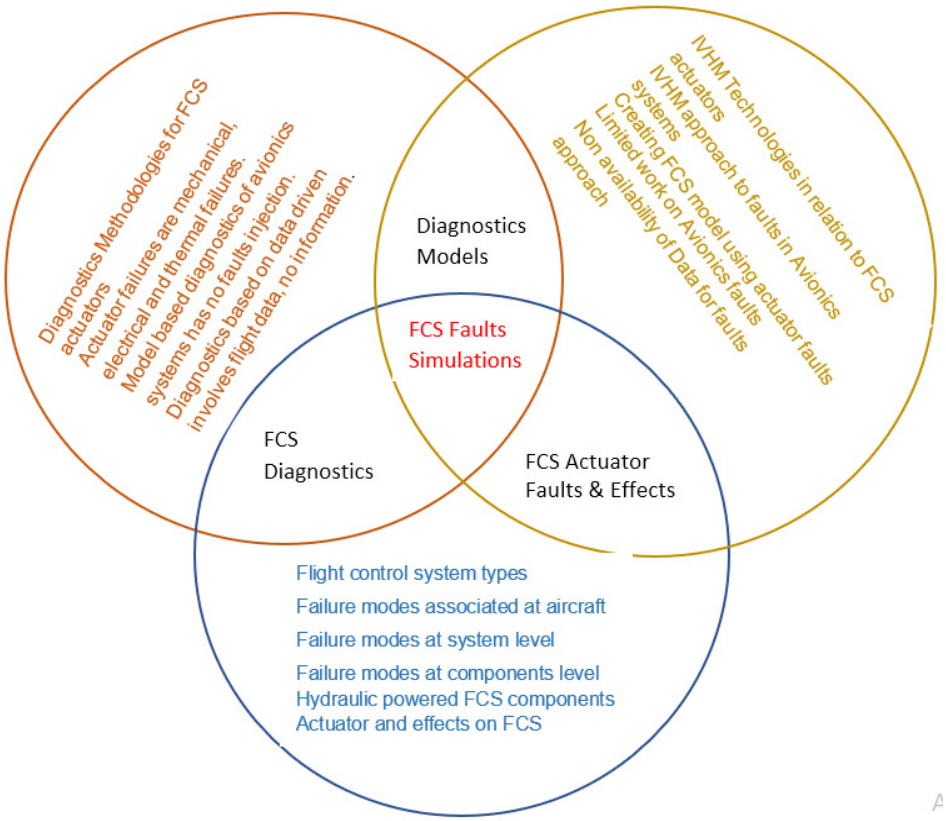


Figure 1. Venn diagram of the scope of the literature review.

3. Simulation Model for a Hydraulic Powered FCAS

The proposal for the development of a simulation model of an HPFCAS was approached in a systematic manner, and the experimental schematic of the HPFCAS was built in the laboratory to demonstrate its functionality. This was possible having obtained a block diagram of how the model should be and what it will do. Hence, a schematic of the algorithm to be utilized was also formed in terms of the relationships and performance algorithms that would exist among the components or subsystems when put to use. This is chronologically shown as follows:

i. A proposed system block diagram depicting the subsystems.
ii. An experimental block schematic showing how the various components were connected in the IVHM Laboratory.
iii. The identified fault modes, causes, and effects.
iv. The formation of the functional model elements and fault injection schematic.
v. Simulations

3.1. Methodology and System Model Blocks

In Figure 2, the HPFCAS is viewed as an SOS block model with four subsystems and their individual models integrated. These are designated as the hydraulic, mechanical, electrical, and control subsystems. The model functions are grouped under a control system with the input, the plant/process, and the output. The main idea is to ascertain how the inputs obtained from any of the subsystems must be controlled and channeled into a hydraulically controlled circuit [23]. The hydraulic components basically are mechanical in nature. These are the fluid, the pipes, the valves, and the actuator and all its accessories used to generate the output.

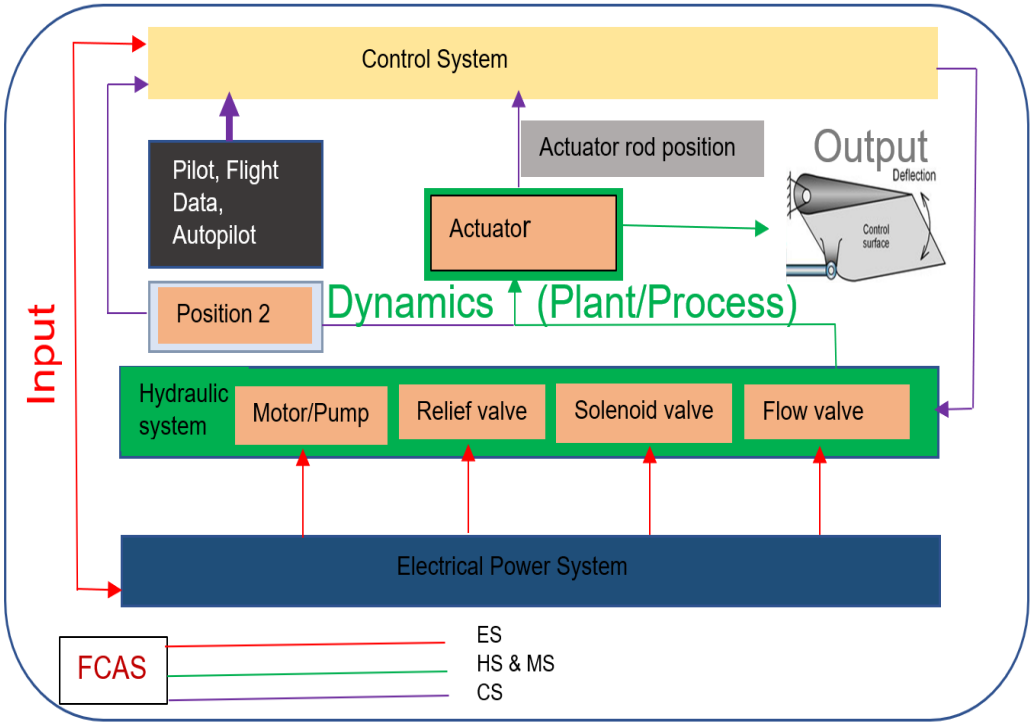


Figure 2. The FCAS fault detection block models for the subsystems.

Thus, in Figure 2, the inputs come from different sources. For instance, commands come from the operators by mechanical/analog means using the control yoke and by digital means through the flight director/autopilot signals sent to the control system. The control is powered by the electrical system, and it provides selected signal commands for the hydraulic control unit. This sequence of control events at the control command and the hydraulic control unit helps by channeling the inputs obtained in the right directions and regulates the output performance. The regulation of the hydraulic components is used to power the output of the HPFCAS.

Therefore, the HPFCAS is a multi-system comprising subsystem components with dissimilar features working for a common goal. An adequate knowledge of the causes or symptoms of degradations, faults, and unhealthy conditions is required [24,25]. It is noted that the electrical power is supplied to all the components of the hydraulic unit; hence, the possibility of adding more faults to the system is observed. Ideally, the possible faults envisaged are the ones produced by the mechanical subsystem (MS) due to mechanical components (MCs), the electrical subsystem (ES) due to electrical components (ECs), the hydraulic subsystem (HS) due to hydraulic components (HCs), and the control subsystem (CS) faults, respectively. Figure 3 shows a clear representation of the different subsystem faults.

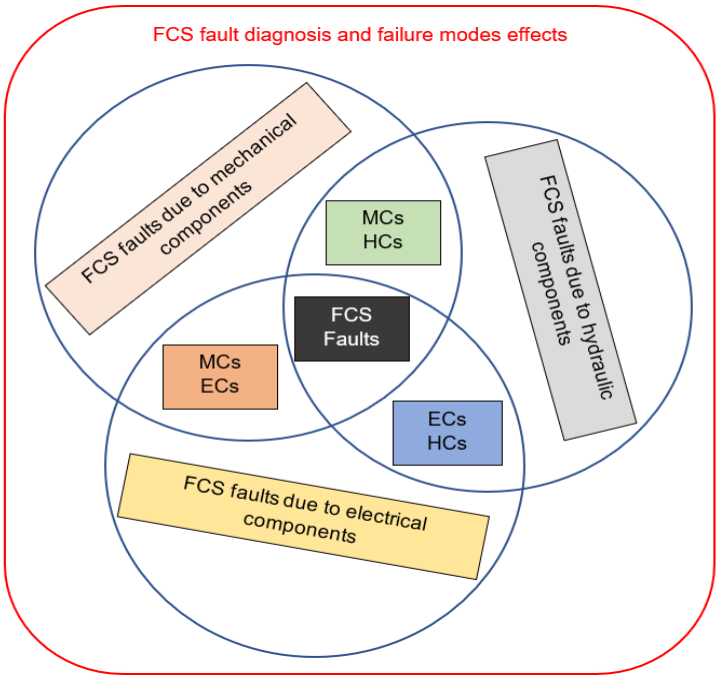


Figure 3. Fault mode classifications based on the interacting systems.

3.2. FCAS Experimental Process Block Schematic

In the experimental process schematic, details of the component's performance characteristics are required following the specifications provided by the component manufacturers. Therefore, the design of component integration and connection was made based on the interactions and conditions under which they would affect one another. This is developed as a process shown in Figure 4. This formation was created and integrated into computer graphical user interface (GUI) by the Software LabVIEW Version 2 provided by National Instruments (NI), which also serves as the platform for the main control subsystem. A hydraulic tank with liquid at atmospheric pressure was connected to a fixed displacement electric pump via pipes and connectors. A pressure relief valve and a four-way directional proportional valve (DPV) were connected to an actuator to complete the circuit with flow meters and pressure sensors attached to the connections. The details of these are explained in the section under simulations.

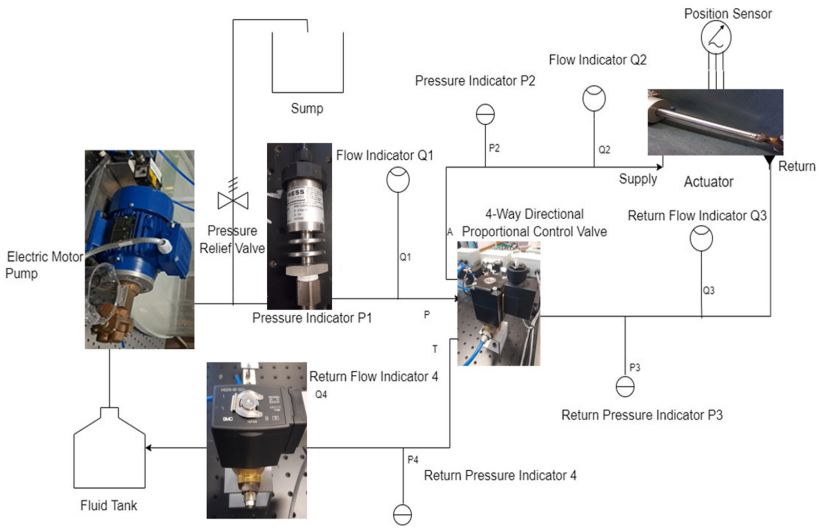


Figure 4. The experimental process schematic.

3.2.1. Identification of Fault Modes, Causes, and Effects

The development of the aircraft HPFCAS model for simulations was centered on ways to approach the data-generating mechanism for system health diagnostics and to enhance fault detections in this complex asset. This is because the approach is concerned with accurately detecting faults in the components of the system and generating corresponding and representative data of these faults. Thus, if the known faults are injected and their data are collected thereafter, the injected faults are replaced to restore the system to a healthy state [26,27] during the simulations.

Hence, a component database was created for the HPFCAS that contains the system's components and their possible fault modes and physical parameters that capture these fault modes. Based on the system structure of each component created, it was observed that each element of the functional model correlated with one or more fault modes. These fault modes are associated with two condition indicators: pressure drop or gain. These are shown in Table 1. It is interesting to note that many fault modes that occur in this system type were identified, but for this analysis, not all the fault modes were chosen.

Table 1. The functional elements, fault modes, and condition indicators.

Failure Modes	Causes of Faults	Effects	Failure Types
HPFCAS1	Filter Clogging	Decrease in pressure	Mechanical, Hydraulic
HPFCAS2	Pipe Leaking	Decrease in pressure	Mechanical, Hydraulic
HPFCAS3	Motor (demagnetization) loss of output to the pump	Decrease in rpm	Mechanical, Electrical
HPFCAS4	Low power to the electric pump	Decrease in rpm or no pressure	Electrical
HPFCAS5	Clogged nozzle/malfunction (flow control valve NRV)	Decrease or no pressure, damage to the flow line	Mechanical, Hydraulic
HPFCAS6	Low power to the flow control valve (Solenoid valve)	No pressure, damage to the flow lines	Electrical, Hydraulic
HPFCAS7	Temperature rise (windings, heat)	More power required, pressure decrease	Thermal, Mechanical, Electrical
HPFCAS8	Vibrations (electrical connections, position sensor measurements)	Actuator components, electrical cables,	Electrical, sensors

The fault analysis method most suitable for a hydraulic-powered FCAS would be a good combination of the different types of modes, that is, the hybrid modes, involving all the different techniques for the failure mode capabilities to be used. However, to investigate the healthy and degraded behavior of the main components in the HPFCAS, under a multisystem level, the main concern is not the root cause of the component's fault but the root causes that affect the entire system [28].

Two major features are identified, the structural and functional interconnections of the system's principal components or subsystems [29,30]. Thus, if a fault is identified, the fault detection mechanism should be more detailed to identify the root cause of the fault and the consequences for the entire system. In this case, the system is functioning as a system of systems (SOS).

3.2.2. Experiment and Component Connections

The experiment and component connections involve the modification of a fuel rig in the laboratory to form the HPFCAS system by attaching an actuator. To carry out analysis on the basic components for their characteristics, sensor data measurements from the transducers like the flow meter, the pressure gauges, and the laser sensor for the flow rates,

the pressure gains or drops, and the pump speed, respectively, were used. This is shown in Figure 5.

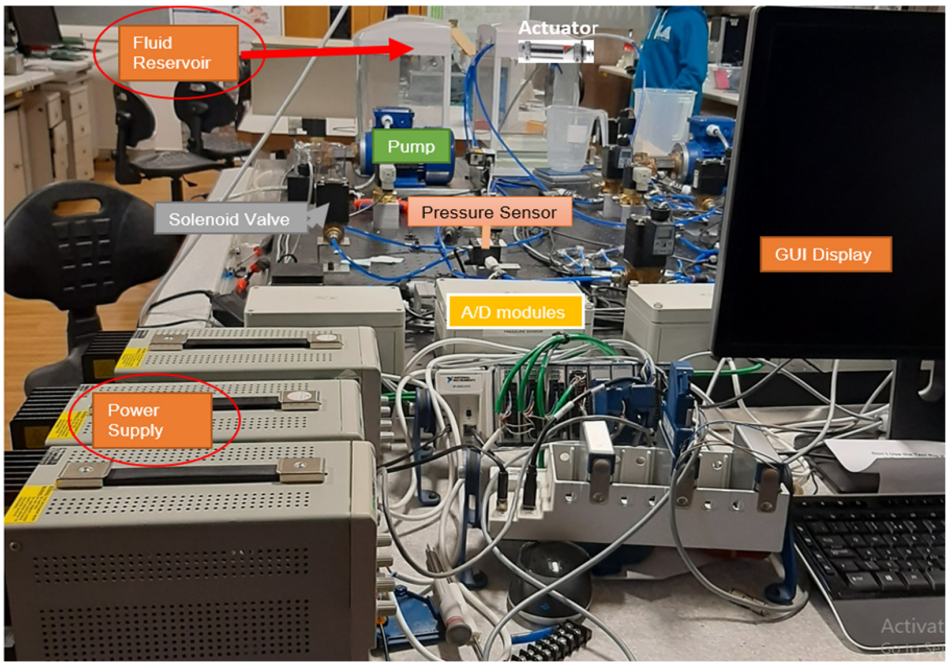


Figure 5. The laboratory modification of the Fuel Rig for PCA.

3.2.3. Operating Procedure of the Preliminary Experiment

The rig contains two main tanks, each tank contains 30 L of fluid. One is the reservoir tank and another is a sump tank placed under the bench. Three gear pumps are driven by external motors, where only one is used at a time. One of the pumps was used to create fault injections during experimental simulations. A shut-off valve, a directional proportional valve (DPV), a laser sensor, four pressure sensors, and two flow meters are used. A National Instruments LabVIEW application is installed on the PC positioned in front of the rig to provide the control system as well as the GUI.

1. Before the rig was operated, the operator ensured the following:
   - The power supplies were switched on.
   - The main tanks were filled to the required quantity of fluid by visually inspecting the tanks for their integrity and that the tanks were intact.
   - Two converters, CDAQ-9172 devices, were switched on.
   - The button for the motor drives situated below the emergency button was switched on.
2. The PC was switched on and LabVIEW launched (this allows the Modified Fuel Rig System file in the Fuel Rig system project folder to be created):
   - Experiments were run and stopped at intervals of 10 s each.
   - Readings were taken and saved for healthy cases.
   - Then faults were injected for unhealthy scenarios, and the procedures were repeated.

4. Derivation of Boundary Conditions for Steady-State Simulation Model Parameters

By analogy, inputs to the HPFCAS system come in different forms, like the pilot control stick, which is a mechanical push–pull or electrical system, and the trim system switches. Another means is the digital computation of inputs through the autopilot/flight director, based on the Nav/Comm conditions. All these are channeled to a reservoir control unit irrespective of the means of input used for the system. Thus, the corresponding input sensing revolves around the type of inputs to the hydraulic system. These are interpreted

by different transducers. The transducers convert the inputs delivered into a form that can be utilized by the hydraulic system to provide the output.

Hence, a simple mathematical model formation of the hydraulic principle was formed with its associated components in two stages. These later assisted in the buildup of the HPFCAS simulated model.

A mathematical calculation was applied from the Bernoulli principle [30]. Initially, a replacement for the linear actuator was completed with a fluid tank under atmospheric pressure to estimate the value of P4, and these provided two values of known pressures P1 and P4, respectively. The two remaining unknown pressure values, P2 and P3, were obtained using Bernoulli's equation. Thereafter, the fluid tank was replaced with a suitable actuator that could withstand the pressure values at P4 for the simulation model.

In the second stage as shown in Figure 6, the boundary conditions were established for the experiment, and the actuator was integrated upon successful completion of the mathematical calculations. Successive and repeated simulations were completed. Additional data were generated. The actuator rod displacement position, the pressure-changing values for a fixed pump speed, and the different values of pump speeds were noted. Both the experimental and the developed model simulations were run at intervals of 10 s in each case.

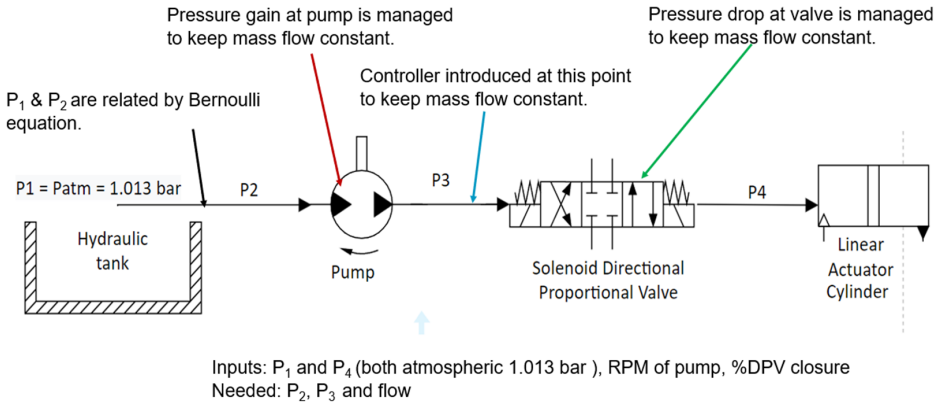


Figure 6. The second stage of the mathematical model relationship with actuator integration.

Developing Subsystem Models for Fault Injection

In this stage, a unified model of the FCAS at all stages showing the contributions of the faults from all subsystems was harmonized. These were obtained with the ideal knowledge of the individual components and their roles in the fault initiations or propagations in the system. A matrix or algorithm was established to show how the process can be achieved. As depicted with summary block explanations in Figure 7, stages 1 and 2 represent the contributions of earlier work published as a review paper, which enhances the significant development of this work [21]. It was established that HPFCASs are nonlinear complex systems with strong fault concealment [31,32]. As a result of degradation caused by the component wearing out, there was a lack of knowledge of the critical failures known from available data.

In their research work, the authors of [33] also concluded that a vibration signal approach would have been nice for fault-finding in HPFCASs, but there was a complex vibration transmission mechanism and nonlinear time-varying signals associated with the HPFCASs. These made the diagnostic approaches based on signal processing and vibration techniques difficult. Thus, the diagnostics of HPFCASs should be approached as an SOS. The blocks from stages 3, 4, 5, and 6 show how these are implemented.

Based on the relationship between the fault modes and the condition indicators, a fault symptom matrix is created. Using this matrix, the faulty components can be uniquely identified. Their contributions to the entire system are known as fault injections. The details are shown later.

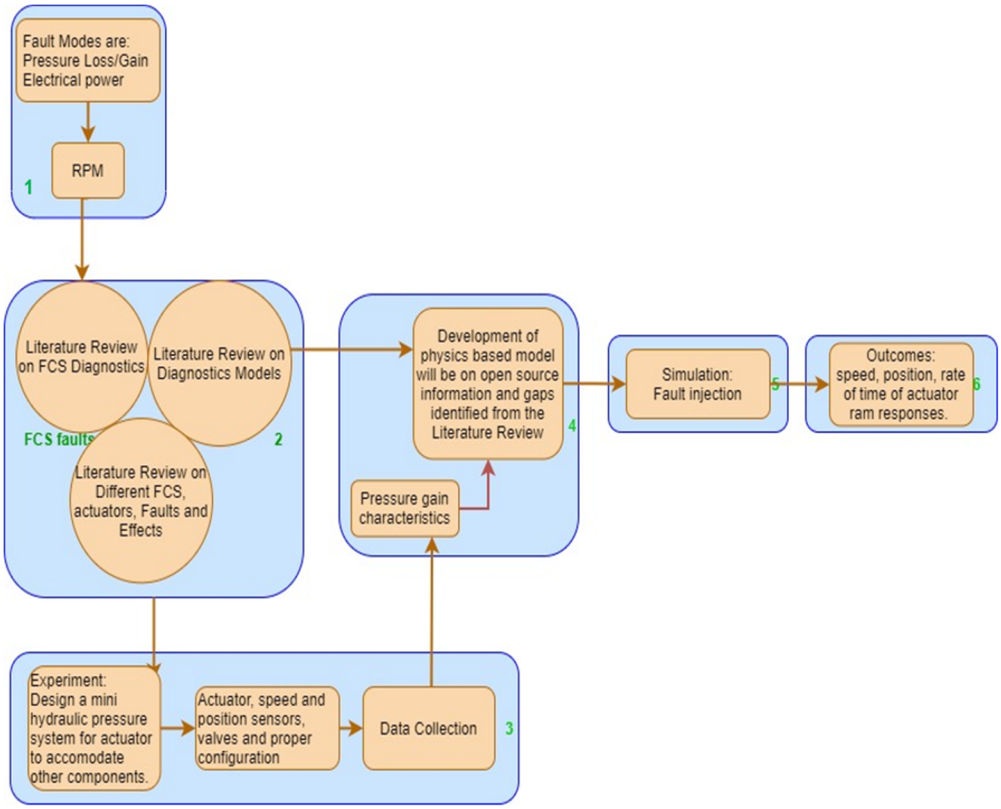


Figure 7. FCAS fault detection block models for the subsystem matrix.

Thus, for the development of subsystem fault models, Figure 9 shows how the fault can be injected into the mechanical system functional model using principal component elements.

The mechanical system involves parts like a filter, valves, a motor pump, sensors, pipes, and an actuator. A combination of two subsystems, the mechanical and hydraulic failure models, exist such that the failure modes of these subsystems constitute the faults observed with the mechanical components. These may either be due to mechanical or electrical effects. For example, if the Ac power supply to a motor pump is reduced in the system, though electrical, it will cause a reduction in the power to the motor, and the pump revolutions per minute (RPM) will also drop. This fault origin is electrical but has been propagated to a mechanical fault. This same cascading effect is observed if the bearing of the motor degrades, whereas the causative effect is from mechanical components and not electrical.

Hence, Figure 8 shows the structural and functional HPFCAS model interconnections involving mechanical and hydraulic elements. The hydraulic system is identified with the thick, green-colored lines and dotted green lines signifying the hydraulic supply and return lines, respectively.

The main system for fault injection and diagnostics is the hydraulic system shown in green-colored lines. It consists of mechanical parts as components and a reservoir from which the fluid is pumped by an electrically powered motor pump at the required RPM. The fluid passes through the flow lines and a filter to the pump. This goes to the directional proportional valve (DPV). If control for opening the DPV is not initiated, excess pressure builds up due to the fluid flow; hence, a pressure relief valve is connected across the DPV to reduce excessive pressure. This allows flowback to the reservoir and acts as a safety measure for the pump.

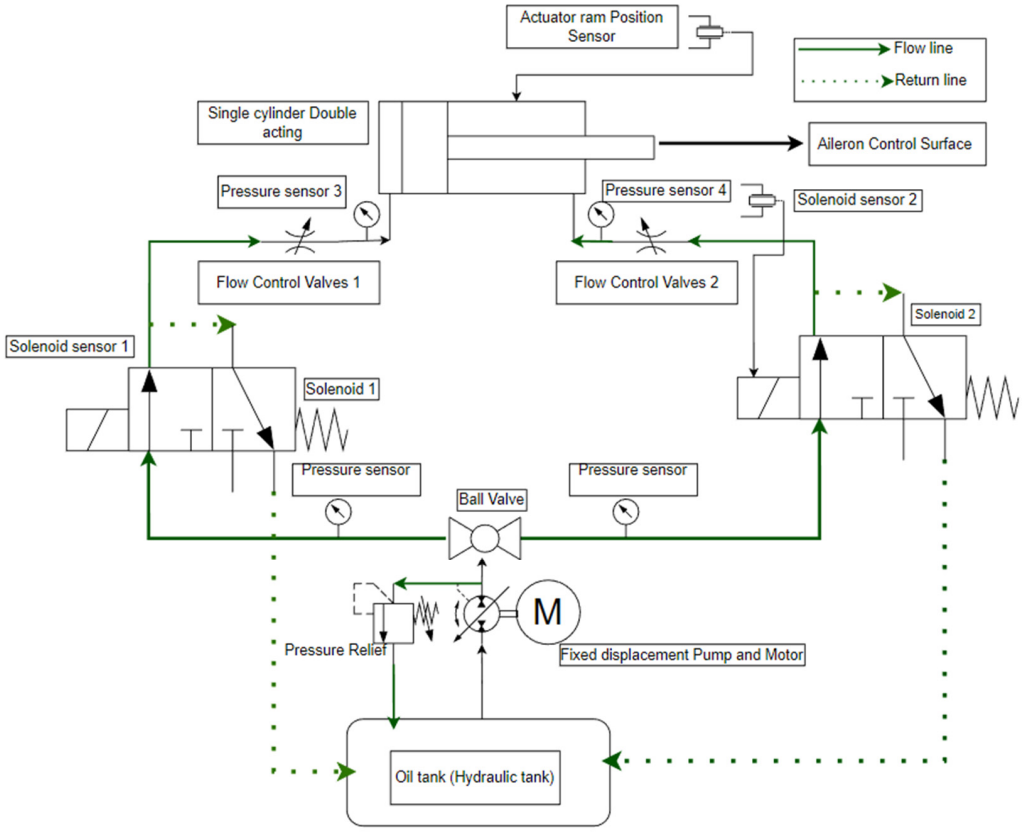


Figure 8. Components of the mechanical subsystem model.

In another system model development, the model of the mechanical and hydraulic systems was augmented by control logic that aided the fault injections as shown in Figure 9.

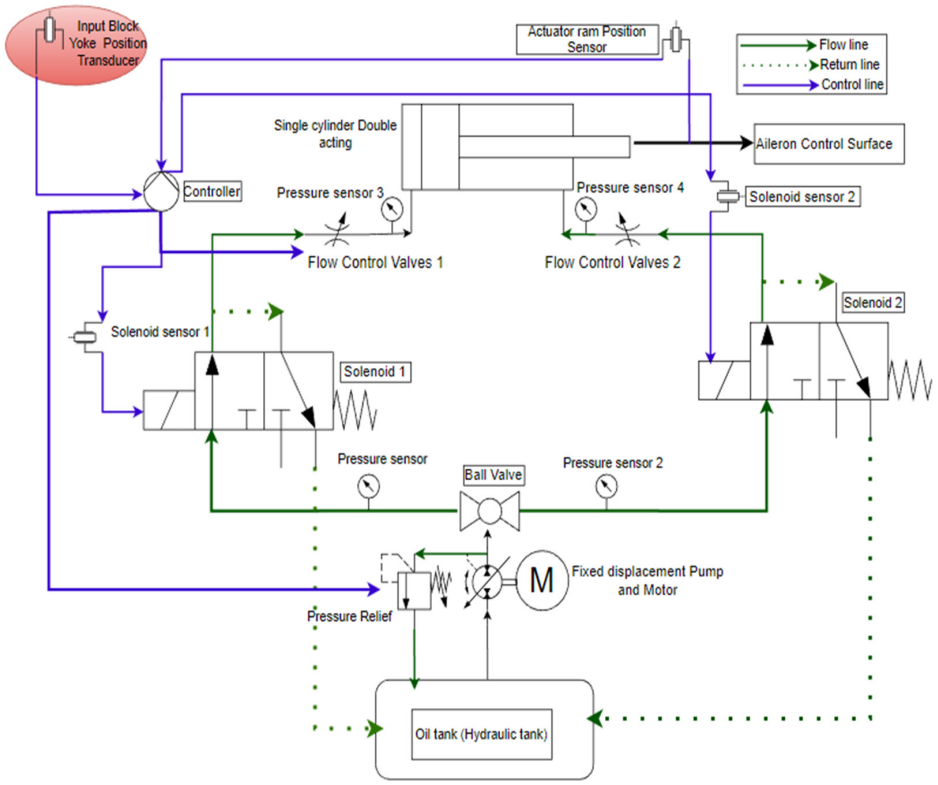


Figure 9. Faults introduced in the subsystem's functional model using control logic.

In the diagram, the control logic circuit is determined by the connections shown in purple-colored lines and represents the control actions for the entire HPFCAS model. They consist of the control functions, the pump speed (RPM), valve opening positions, pressure sensor measurements, actuator position sensor measurements, and feedback, respectively. Besides these, the control system is used to introduce metering-in and metering-out on both sides of the actuator to obtain the sensor measurements for displacements at different values of the RPM. This is one of the important variables in the measurement process. It describes the relationship between the flow rate and the pressure gain/drops as the major characteristics of the valve opening settings.

In applying the SOS approach, other subsystem models were implemented to accommodate the effects of the electrical system model's faults. This was identified based on the failure causes of the principal components. This is important since some of the faults are caused by electrical component failures. Therefore, a demonstration of electrical system fault propagations in the system was shown on the components. Figure 10 illustrates this.

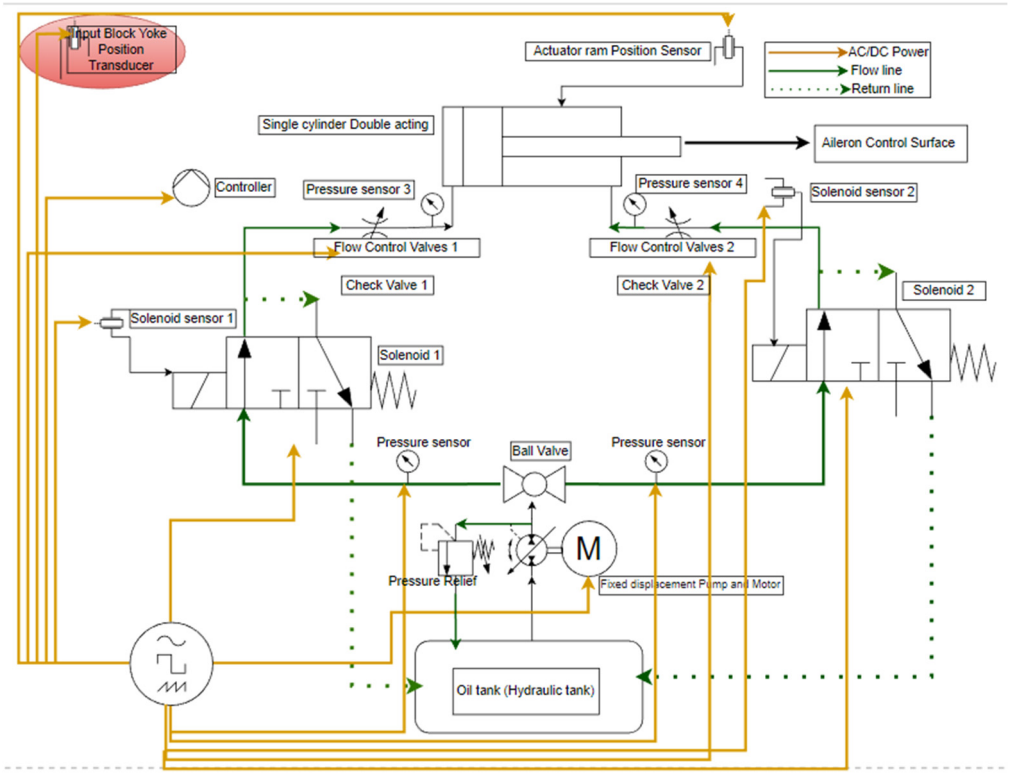


Figure 10. Electrical subsystem model connections.

The electrical power supply system provides the required power for the individual components to function as shown in yellow in Figure 10. The model shows Ac and Dc power supply sources. The primary source is Ac, which is used for the pump-coupled electric motor. Part of the Ac power is converted by a Dc converter to supply Dc power to sensors and valves. That is, it provides two sources of power supply; a Dc power of a rated amount in VDC to components like the valves, sensors, controller unit, and VAC power to the motor (M) that drives the pump.

This forms the electrical subsystem model of the HPFCAS model. Thus, the failure modes associated with electrical systems are those that would affect the electrical components' functions.

Finally, the fault injection for generating diagnostics data is the red dotted lines targeting component performance indicators. These performance indices are appropriate physical variables that capture a component's degradation and indicate the baselines or

thresholds for healthy historic data or boundary conditions. Deviations from them signify unhealthy or faulty scenarios.

However, if the DPV component is initiated depending on the direction, it allows fluid to flow to the actuator for both extension and retraction. The pressure is measured at different points by the three pressure sensors (S1, S2, and S3).

Possible faults to the hydraulic system are known as single faults and propagated faults injected at the system level due to the mechanical and electrical systems. Fault injection or allocation is targeted at the root causes of the faults. There are many failure modes of the HPFCAS. For analysis, eight were selected for injection both at the experimental level and at the simulated level. The simulated model mimics the experiment, hence the development of Figure 11. The principal component elements were identified, and the HPFCAS faults were injected. For example, HPFCAS1, HPFCAS5, and HPFCAS6 were injected through the valves, depending on the conditions selected. The condition selection is achieved using the controller that controls the flow meters and pressure sensors. Similarly, HPFCAS3, HPFCAS4, and HPFCAS7 were injected through the motor and pump. HPFCAS2 and HPFCAS8 were injected through all components since the most common symptom vector is vibration. Despite these, single faults are injected if other faults are suppressed within the same subsystem. The faults defined in Table 1 as HPFCAS 1, 5, and 6 were observed after injecting stickiness on serviceable flow control valves and ball valves. These are represented by the values of FCV1, BV, and FCV2. For HPFCAS 3, 4, and 7, a low voltage, a reduced pump speed, and a temperature increase are represented by PS1, PS2, M, S1, S2, and C. Meanwhile, HPFCAS 2 and HPFCAS 8 represent injections of leakage in the pipes and vibrations, respectively.

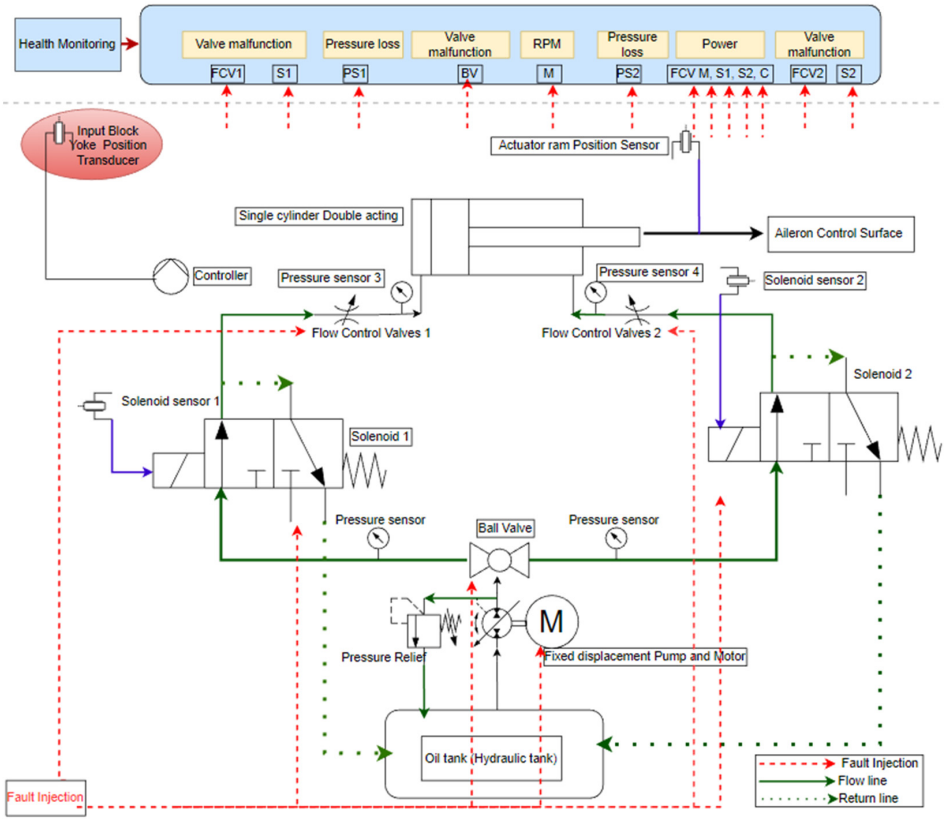


Figure 11. A fault injection model is shown in red dotted lines.

Some other fault properties were observed as effects like the change in the linear positions of the actuator ram, which may not correspond to the expected displacement of the primary control surfaces attached to the actuator ram. These are due to pressure drops/gains after each simulation.

For effective functioning, monitoring, and analysis of the model, essentially all the dependent systems, i.e., the mechanical system, the electrical power system, and the control system work simultaneously if required. This is also alongside with the sensors that are connected for feature extraction. Hence, the fault modes are injected into the HPFCAS model via the control system as can be seen in Figure 12.

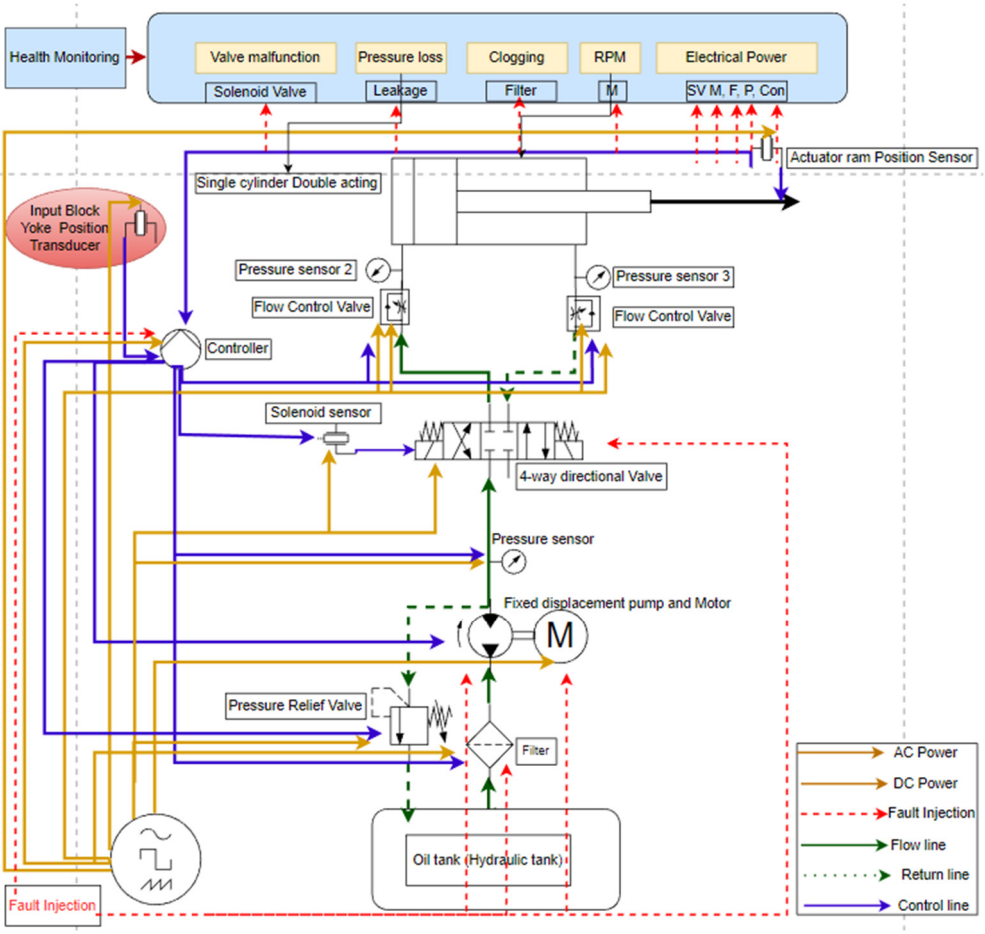


Figure 12. How faults were injected into the subsystem's functional model using the system's components elements.

5. HPFCAS Model Development and Simulations

The HPFCAS model that was created has all its inputs channeled to a hydraulic control unit. The unit converts the information into a hydraulic power supply using a fluid rate (mass flow) and the corresponding pressure delivered to the actuation system, mainly through the pump speed and the flow control valves.

5.1. Simulations at Steady State

To facilitate the simulation of the HPFCAS model, a build-up of the model in MATLAB Simulink was completed using the basic principles, equations, and characteristics of the main components. For instance, using Bernoulli's equation, the basics and fundamentals were used to establish the flow quantities within the system [3].

$$P_T = p_2 + ½ \text{ rho } v^2 \quad (1)$$

That is, Total pressure = static pressure + dynamic head

$$V = Q/A \quad (2)$$

where the velocity of flow is equal to the quantity of flow per area.

Comparing the values obtained from the experimental measurements and plotting the data, the characteristics of the key components, that is, the pump and the directional (proportional) control valve, were noted as a baseline condition for the iterative processes of the simulations. This also assisted in determining the relationships between the parameters measured by the sensors used. These were the flow meters and pressure sensors. Figure 13 shows the characteristics or behavior of the pump.

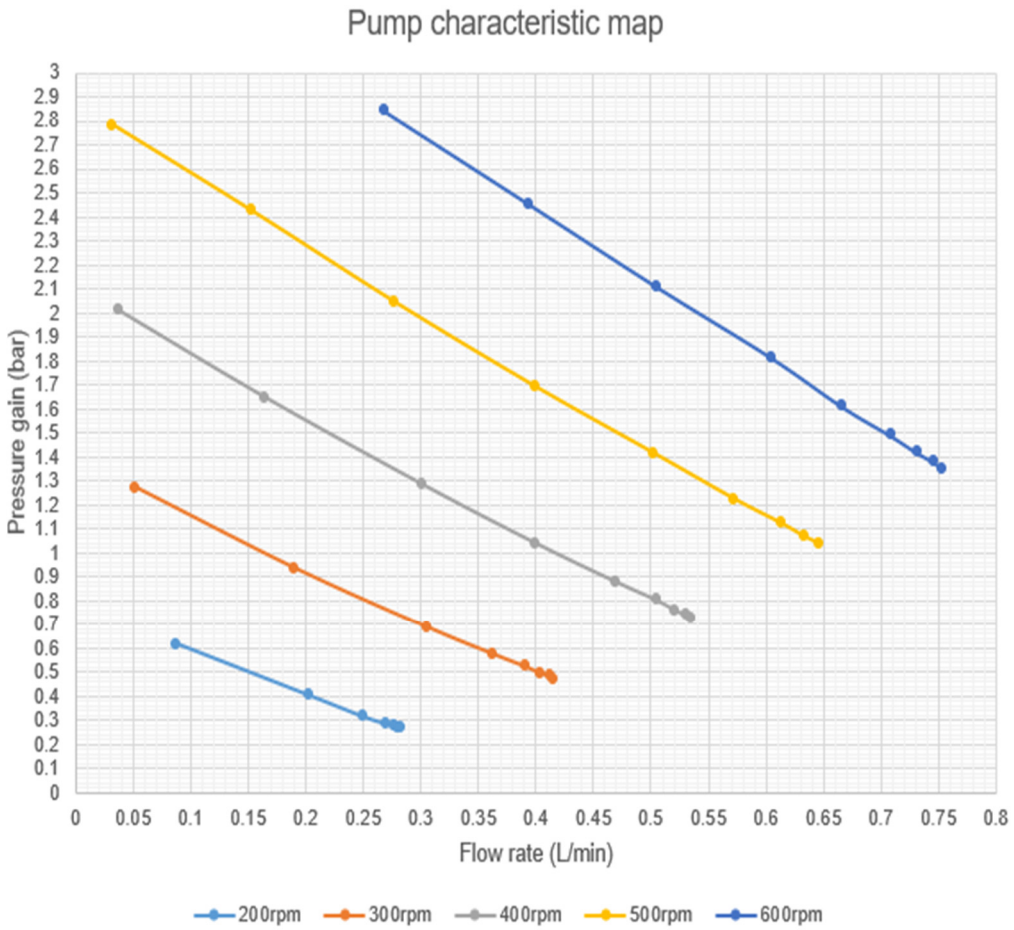


Figure 13. The experimental values show the characteristic map for the pump.

Figure 13 shows the pressure gains or drops as the flow rate changes at different values of the pump RPM. Similarly, the characteristics or behavior of the DPV was obtained as a relationship between the pump's RPM and the different percentage openings of the DPV.

In the plot of Figure 14, the measurements were taken, indicating the characteristics of the DPV. These were traced for each value and at a constant RPM of 400. After setting a constant RPM, to obtain values for the DPV, pressure drop values as well as the corresponding mass flow rates were obtained, unlike in the case of the pump characteristics, where the pressure ratios were the measured parameters. Hence, the corresponding pressure drops were obtained while the flow rate was adjusted.

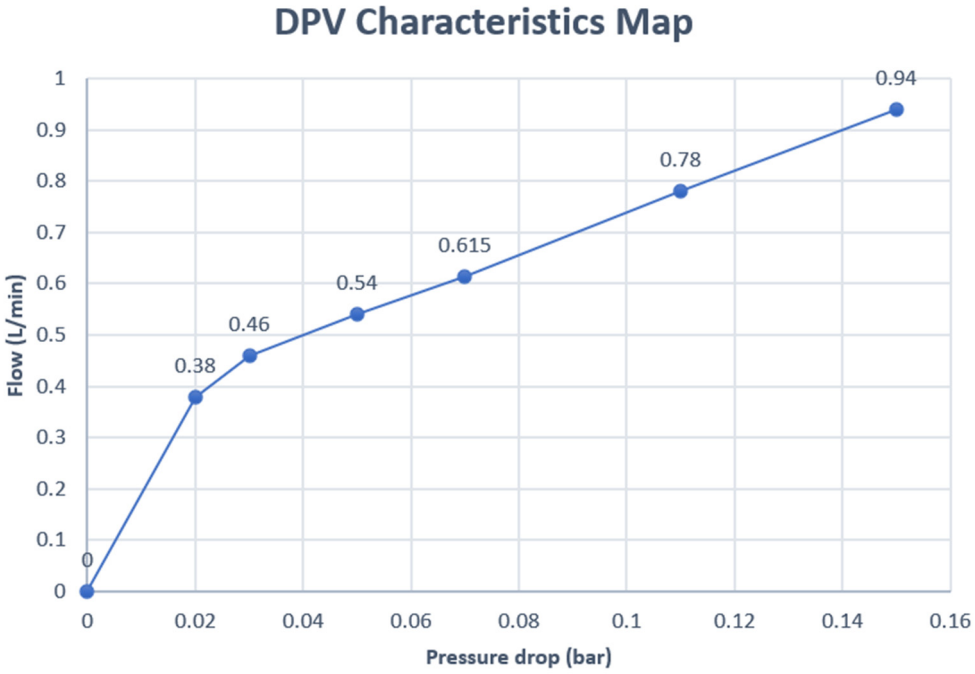


Figure 14. The experimental values show the characteristic map for the DPV.

5.2. Procedures for Actuator Integration with the Model

Though the boundary conditions were chosen in developing the HPFCAS model, the building blocks were built with the basic equations and the characteristics of the components embedded in all the model blocks. Thus, the block model for the actuator needed the sizing for the principal parameters of the actuator like the stroke length, bore, cylinder length, piston length, and areas of the actuator chambers. These were chosen considering the pressure and the Bernoulli equation's boundary conditions. The maximum pressures that can exhibit pressure forces to drive the actuator and the maximum external force as loading on the actuator were calculated. Hence, the actuator was designed to fit into the system by adjusting the parameters of a double-acting linear actuator block from Simulink libraries and replacing most parameters with the calculated ones. These showed its suitability to be used and integrated with the Simulink and Simscape models. Figure 15 shows some of the calculated actuator simple parameter values.

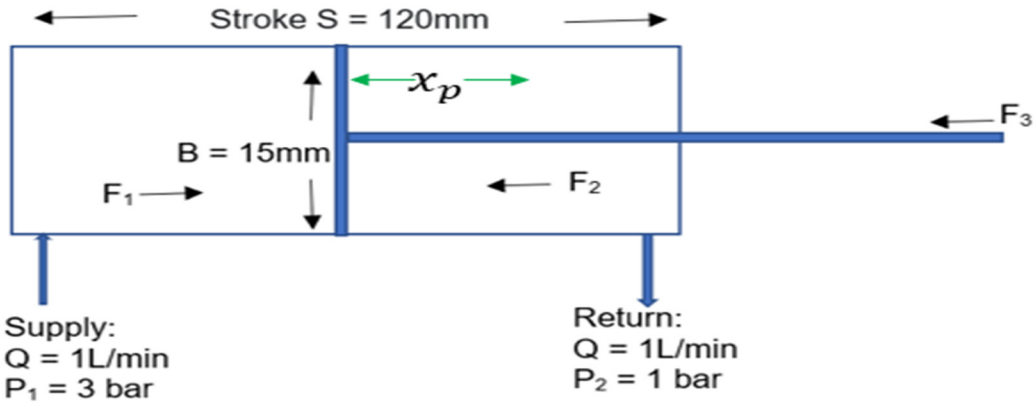


Figure 15. The designed actuator dimensions and simple properties.

The loading, work done, or power relationship of the actuator was calculated for the steady-state flow into the actuator equation as follows [34]:

$$F_L \dot{x_p} = P_1 Q_1 - P_2 Q_2 \delta \quad (3)$$

where $F_L\dot{x_p}$ = External load and piston velocity, $P_1 - P_2\delta$ = Load pressure, and $Q_1 - Q_2$ = Load flow.

Combining these with other parameters, the actuator was tested at a steady state. This implies, there is a constant velocity of the actuator piston to observe its steady-state response before being integrated.

The model in Figure 16 was used for all simulations whether at a steady state of the actuator or at a transient state. However, the equations embedded in the actuator blocks had changes in the parameters. Also, the model was tested without actuator integration to obtain the values for healthy scenarios before the fault injections. Here, a tested flow rate amount of 0.5 L/min and percentage changes in the flow rate for the full opening of the DPV at a constant speed of 400 rpm of the pump were used to run the first simulation in a period of 10 s. This served as the solution process for all other simulations because the initial conditions of the inputs were generated and could simulate any value of mass flow that was not more than 2 L/min for all the changing parameters of the pressure and flow rates. This was simply because the maximum pump speed was 1000 rpm, which was to produce a maximum flow rate of 2 L/min.

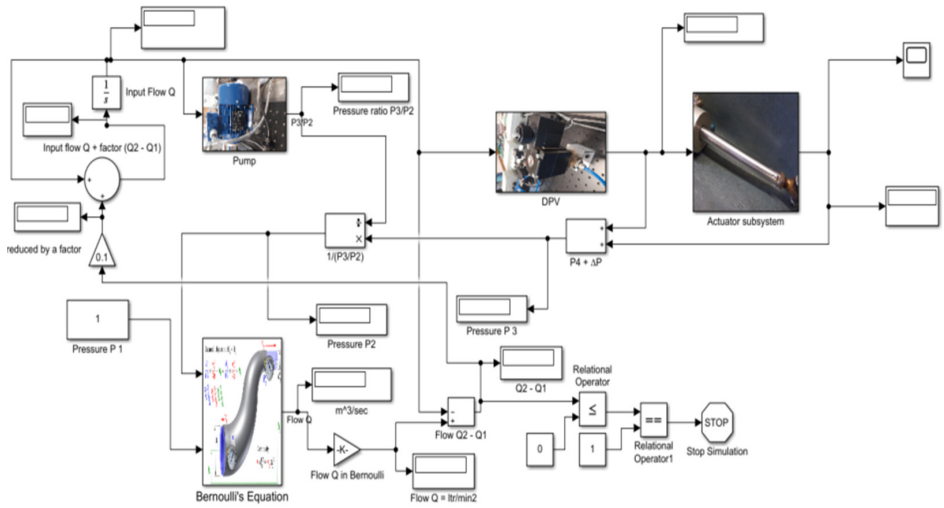


Figure 16. The developed Simulink model of the HPFCAS for simulations with actuator integration.

The solution process and Simulink simulation algorithm started with identifying the initial inputs and boundary conditions. The iterative processes continued in each case until both the input designated value and the final value are same where P2 and P3, the unknowns are measured. Table 2 illustrates the solution process for the HPFCAS model.

Table 2. The solution process and simulation algorithm.

Inputs	**Initial Boundary Conditions**	**Descriptions**
i (Pressure values)	P1 and P4	both atmospheric
ii (Rpm settings)	400	RPM of pump
iii (DPV opening)	100%	RPM of pump
Iv (Pressure values)	P2 and P3	Unknowns
Process		
i (Flow rate values)	0.5 L/min	Guess mass flow
ii (Pressure values)	P3	Obtained from DPV curve
iii (Pressure ratio values)	P3/P2	Obtained from pump curve
iv (Flow rate values)	Flow	Obtained from Bernoulli using stations 1 and 2
v (Flow rate values)	Mass flow	Adjust the flow rate and repeat the process.

5.3. Simulations of Model in a Transient State

Simulations in a transient state were completed with fault injection conditions, hence the equation of the steady-state flow changed to Equation (4) to give the force balance for the piston movement of the integrated actuator [35].

$$mv_a = (P_a A_a - P_b A_b) - (\beta_\gamma + F_{fr}) - F_L \quad (4)$$

where mv_a = mass of the piston and the double derivative of the piston displacement, respectively.

$P_a A_a - P_b A_b$ = Pressure derivative equations from two chambers,

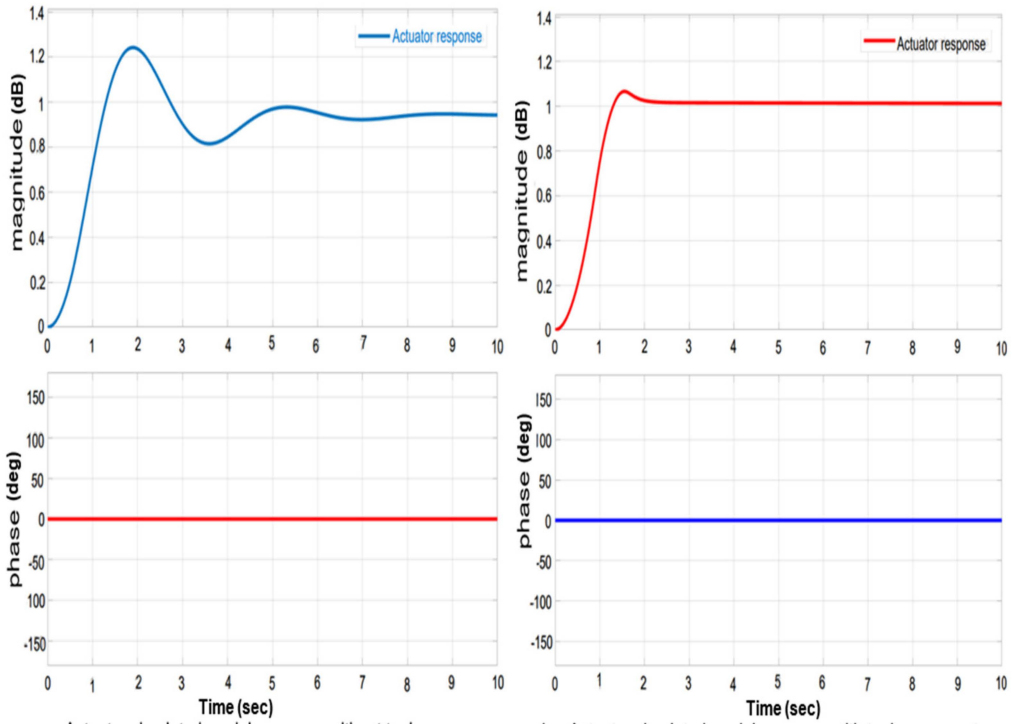
$\beta_\gamma + F_{fr}$ = Viscous and frictional forces in the actuator cylinder,

F_L = External load.

This represents a dynamic model of the actuator, which contains pressure derivative equations from two chambers expressed by a continuity mass equation and a double derivative equation for the motion of the actuator piston [36].

From the developed HPFCAS model, a significant quantity of data was generated from the various conditions of operations considered for all the principal components. For instance, the pump speed was adjusted for five different conditions of speed from 200 rpm to 600 rpm, and the valves were adjusted from 10 to 100% operations. The model itself was set to run in two ways. These were either "Run to flow", where you set a flow rate and run all simulations, or "Run to rpm", in which case, a specific rpm of the pump is set at a constant value. In this work, the run-to-flow option was used because, in practical terms, the engine-driven pump or electric-driven pump expects the fluid supply to be at a preset flow rate, to maintain a constant flow [37]. Thereafter, the Simulink model was transformed into Matlab/Simscape to observe the responses of the actuator as follows:

The first step was to test the frequency response characteristics of the actuator system model using a control approach without tuning and with tuning to establish how the actuator vibration would be managed on the Simulink model, as shown in Figure 17a,b.



a. Actuator simulated model response without tuning parameters.

b. Actuator simulated model response with tuning parameters.

Figure 17. The responses of the actuator in Simulink without tuning and with tuning in (**a**,**b**), respectively.

In Figure 17a without tuning of the actuator, the magnitude of the actuator frequency responses, when simulated for 10 s oscillates, take a longer time to settle and show the nature of the vibrations in the actuator before settling down, while the phase margin does not change. These are established faults associated with HPFCAS. However, with the right tuning parameters after a series of iterative processes in Figure 17b, the actuator responses dampened in a short period of just 2s, which shows that the actuator overcomes vibrations within a short time. This makes its parameters suitable for integration in the Simscape model. Meanwhile, the phase margin was still unaffected.

Secondly, the actuator was tested for its saturation limit and its high gain despite the result obtained in the first instance before it was used to develop the Simscape model. Thus, in the Simscape model simulation, the result of the actuator response was obtained by different sensor measurements for the piston position, velocity, acceleration, and force. This was required to verify and observe the behavior of the actuator as its parameters were adjusted. Figure 18 shows the Simscape integration of the actuator.

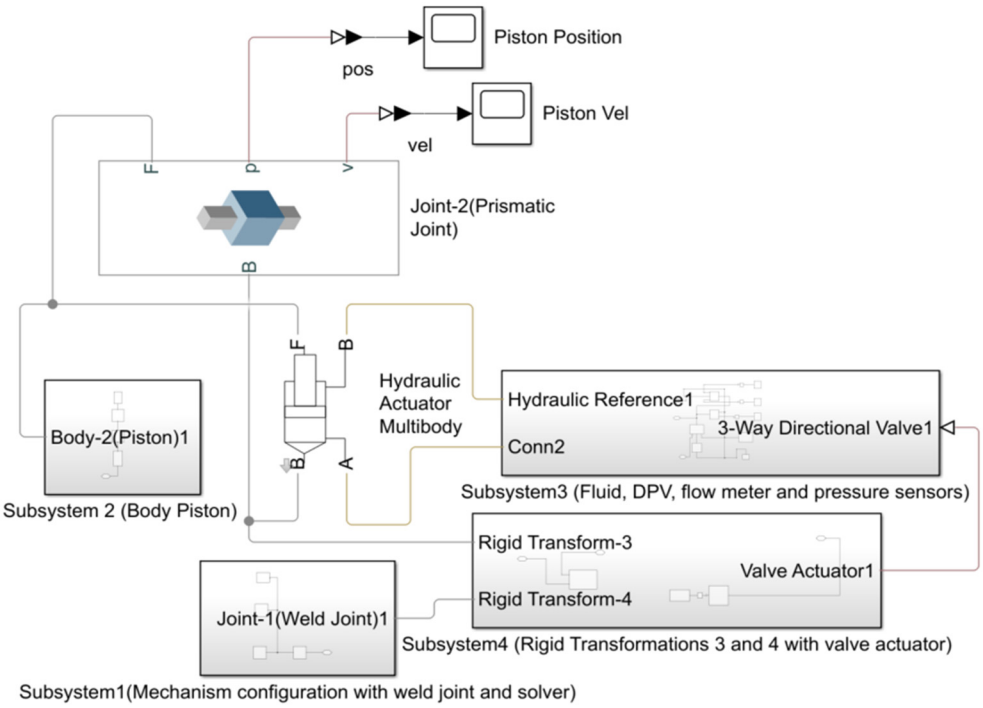


Figure 18. The Simscape integration of the actuator to verify its behavior.

The result was a video clip animation of the dynamic movement of the actuator piston, as it extends and retracts which was captured on the simulation of the Simscape integration model, shown in Figure 19.

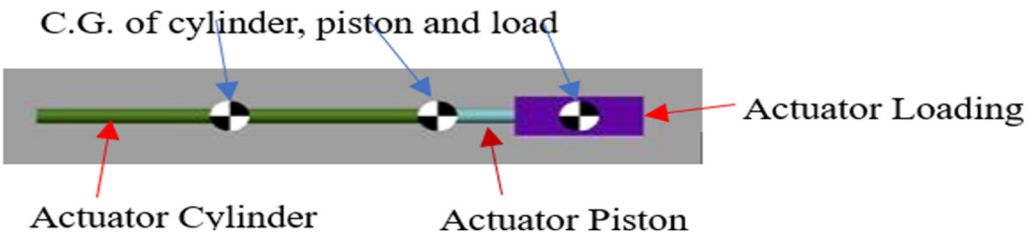


Figure 19. The responses of the actuator in the Simscape model showing extension and retraction.

In Figure 19, the horizontal linear response of the actuator is captured during the simulation of an extension. The green color is the cylinder, the blue-colored block is the piston, and the violet color represents the loading due to forces. The black and white cycles

are the center of gravities of the cylinder, piston, and loads, respectively. At full retraction, the center of gravities of the cylinder and the piston coincide at a steady state.

6. Results and Discussions

6.1. Healthy Cases

In considering the healthy cases of the HPFCAS system, a comparison of the experimental values from a laboratory test rig and the simulated values of the model developed using the SOS approach under the same defined conditions of operation were obtained. These were completed under different conditions. The results show that there were no significant differences. Hence, for the 100% condition, the DPV is fully opened, and there was no clogging, and this is presented alongside the initial state consideration for the actuator response. This is shown in Figure 20.

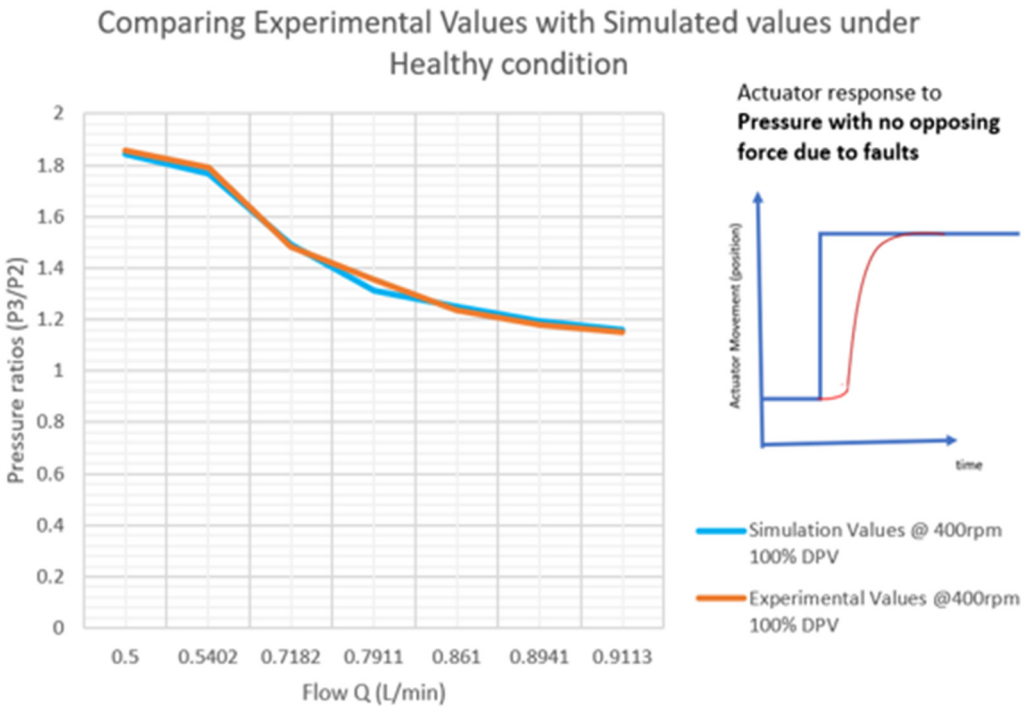


Figure 20. The verification and validation plot of the healthy cases of the components.

Figure 20 illustrates the results obtained for the healthy cases of the components without identified failure modes for the pump, valves, pipes, seals, as well as the actuator response. This was observed for both the experimental values and the Simulink simulated model values. The orange color represents the experimental results and the blue color the simulated results at a constant speed of the pump at 400 rpm. This is an indication of no degradation for both the experimental model without actuator integration and the simulated developmental model without fault injection.

At 70% DPV opening, the experimental values were compared with the simulated values. The results show a remarkable similarity. This confirmed that under healthy cases, both the experimental and the simulated results are achieved as shown in Figure 21.

The orange color represents the experimental results and the violet color stands for the simulated results. Figure 21 implies that there are no faults found under healthy conditions if there is no fault propagation even under component degradation. The variation in the simulated results was simply because of an attempt to test at a flow rate value higher than the experimented values. As soon as fault propagation occurs in a component's degradation, an unhealthy case is established. This is noticed under the unhealthy cases considered.

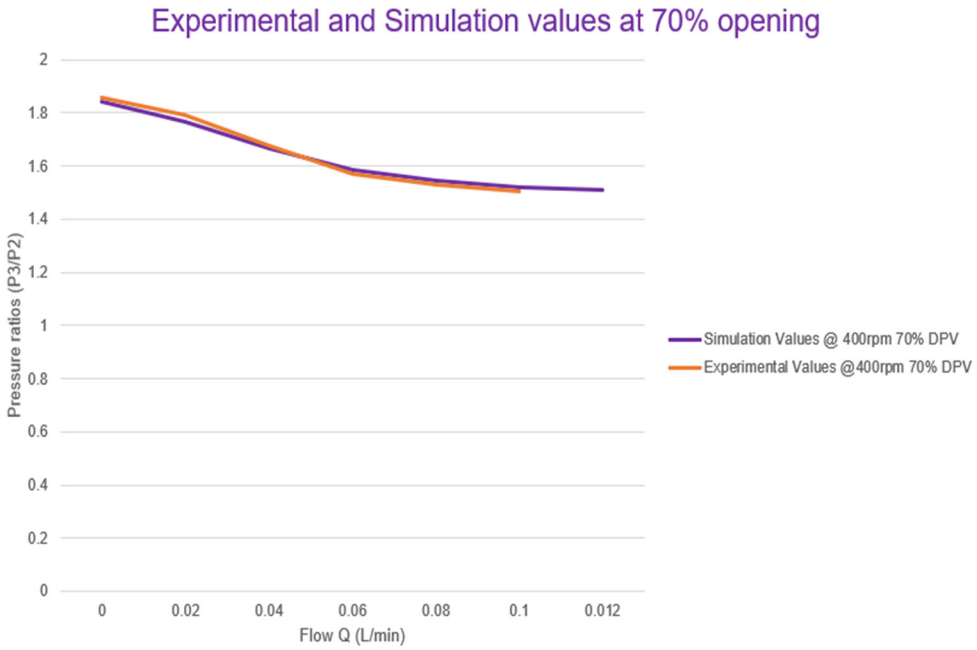


Figure 21. The verification and validation of the healthy cases of both the experimental and simulated valve opening.

6.2. Unhealthy Cases

In analyzing unhealthy cases, faults like leakage, clogging valves, ram seal deterioration, and many other failure modes were identified. Some of these were injected into the model, and the responses were measured. The results were grouped and plotted for the degradation effects as shown in Figure 22.

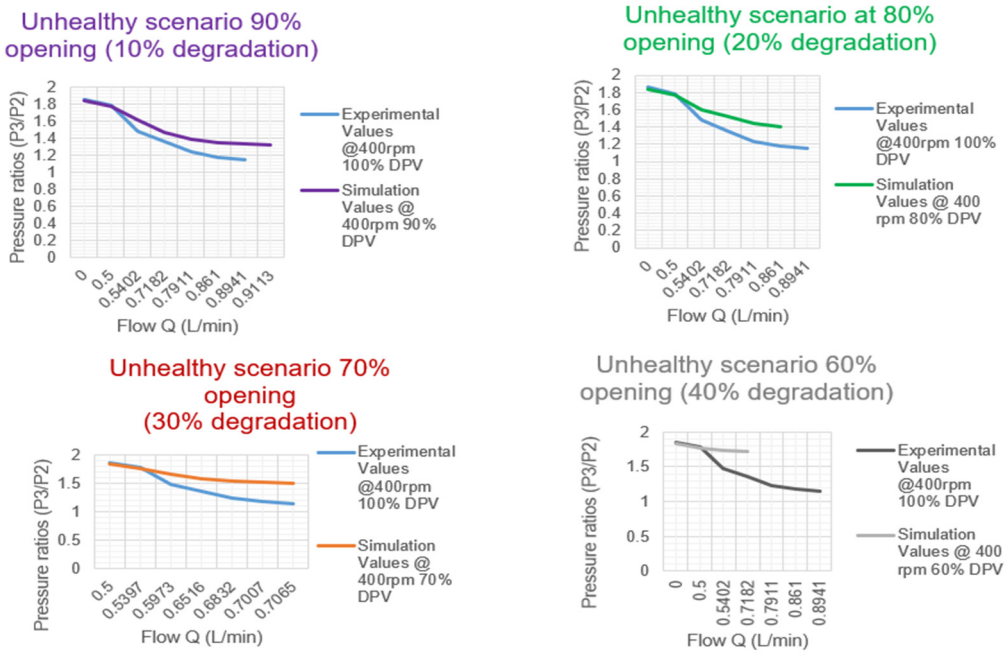


Figure 22. Unhealthy scenarios for four failure mode categories.

The results are observed in each case by comparing the experimental results in the blue color and the simulated results in other colors, as in the healthy case. Thus, due to the degraded effects occasioned by propagated faults, there has been a sharp disparity in the various results considered for the percentage degradation and the severities. These were

also due to the different sources of the faults injected during the simulation to represent the propagated faults. In the physical experiment, those propagations were not easily observed from all the components of the system. For a component that has a way of correcting some abnormalities due to the feedback produced by the sensors, if the channel sensors are blocked, the cascaded effects of faults are no longer sensed. Hence, the propagated faults are observed with noticeable signatures. For example, the adjustment of the pump speed to compensate for a loss of power of the motor cannot be achieved if the laser sensor is shut off or blocked.

Using the DPV as the main component that controls the flow of fluid and a fair representation of the effects of other symptom vectors for faults, the more it clogged, the more the severities were occasioned by the sharp and drastic deviations from the experimental healthy values.

Thus, using control commands, the pump, and the four-way DPV, different conditions were observed as deviations from the healthy scenarios with their various degrees of severity.

The results were also felt during the actuator's dynamic responses as a shift in its steady-state response due to saturation. This was captured as a shift in the transition response of the actuator based on the degraded performance of the DPV. It is represented by the time rate of change and overshooting in the transient responses, shown in Figure 23. The blue lines indicate the actuator response subjected to a unit step function or input. At initiation, the pressure builds up with in the inlet chamber A of a double acting cylinder causing the pressure to rise maximum while the pressure in the outlet chamber is reduced to minimum and extend the piston. At retraction, the reverse is the case, thus chamber A become opened to allow fluid to flow back reducing the maximum pressure to minimum.

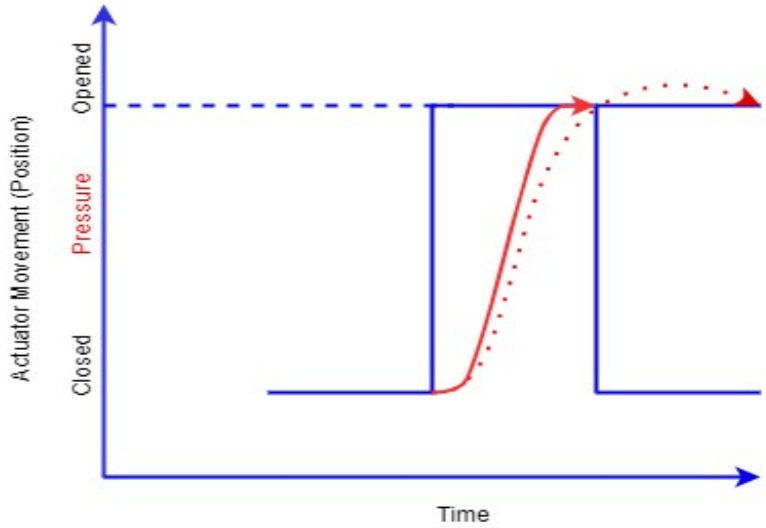


Figure 23. Pressure with opposing forces due to a fault injection causes a shift in the steady-state behavior of the actuator, represented by the red dotted line.

Although there are many failure modes, eight failure modes were profiled as shown in Table 1. These modes were conscripted into four categories based on the subsystem components involved by looking at SOS effects. Also, for easy analysis and possible classification during the diagnostics, the overall resultant effect on the system model was in terms of effects on the pressure within the subsystem.

Thus, the measures of observances in the severities of the faults are qualitatively and quantitatively obtained in percentage degradations. Classifications were made, and it is proposed that these could assist in the training algorithms that will aid diagnostics from the simulated data that were generated.

7. Conclusions

The actuation process uses a linear actuator, a vital link between the FCS inputs and hydraulic systems providing the motive force necessary to move FCS surfaces. It is noted here that though the actuator has its own individual components, the failures of those components, like actuator seals and other elements, were grouped under subsystem fault conditions. This is because the HPFCAS model was taken as a composition of all its components but must be broken down into subsystems known as an SOS and not at the level of the individual components. This was an approach at the subsystem level and the subsystem level's contributions to the faults of the hydraulic system for the HPFCAS. The faults, therefore, attributed to the components, whether mechanical or electrical, were analyzed in terms of how they contribute to or affect the hydraulic system and not in terms of the individual subsystems themselves.

- In the hydraulic system, any single system or component failure, e.g., an actuator, valve, or leakage, is a principal failure mode and can trigger multiple faults.
- Any combination of failures (e.g., dual electrical and hydraulic system failures or any single failure in combination with any probable hydraulic or electrical failure) are principal faults.
- Common-mode failures/single failures (e.g., leakage) are principal failure modes that can affect multiple systems.
- In the absence of the required data, the development of suitable models for the HPFCAS for the different performance conditions generated sufficient data that were used to carry out the analysis.
- The data generated were classified and are to be used to train algorithms for diagnostics. It is proposed that this model approach can be completed appropriately for all systems.

Therefore, developing an accurate model of an HPFCAS produces more precise simulations that generate the required data. This can be used for diagnostic capabilities. This is because suitable fault detection thresholds may be selected. A diagnostic algorithm would be formed and applied based on an understanding of the physics of the system. The method is useful because it does not require the fault history of the system or component. That is, through classification of the data generated from the simulated data, more features will be analyzed within the limits of the complexities of the hydraulic system. The system must be separated into different subsystems and the physics-based knowledge of the separated subsystems must be well understood.

8. Future Work and Challenges

For a multisystem like the hydraulic-powered FCAS, the principal knowledge of the system for a model-based diagnostic method is crucial.

Although data were collected from a simulation model and experimental test rig under healthy and faulty conditions, there is a need to validate the results of the research work with a known aircraft. That is, there is a need to conduct fault analysis using different data analytical tools on a real aircraft to validate the HPFCAS model.

The proposed model-based method is a hybrid involving a physics-based simulation model and a highly dependent data-driven model. Its modeling accuracy is useful for OEMs to understand the system's behavior [38,39].

Long-term observation of an HPFCAS physical asset is needed to generate event features, which correlate with the healthy and faulty functioning of the system [40,41]. This will indicate the occurrence of fault modes under various operational conditions as a validation process.

For the fault analysis of the hydraulic-powered FCAS, it should be broken down into individual subsystems contributing faults to the entire system to caterfor the multiple faults. Although the authors of Ref. [42] recently proposed a framework that can diagnose

multiple faults in hydraulic systems and identify the different degradation levels of the components, it still requires validation for the FCAS models.

More future work is required in terms of using this approach for many more experimental test rigs to obtain data for analysis and verification.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

AP	Autopilot
AC	Alternating Current
CBM	Condition Based Maintenance
CND	Can Not Display
DPV	Directional Proportional Valve
DC	Direct Current
ECs	Electrical Components
FC	Flight Controls
FCAS	Flight Control Actuation System
FCS	Flight Control System
FDI	fault Detection and Isolation
FF	Fault Found
FMECA	Failure Modes Effects and Criticality Analysis
FTA	Fault Tree Analysis
HCs	Hydraulic Components
HPFCAS	Hydraulically Powered Flight Control Actuator System
IVHM	Integrated Vehicle Health Monitoring
KF	Kalman Filter
MCs	Mechanical Components
MFCAS	Mechanical Flight Control Actuation System
NFF	No Fault Found
PFCAS	Primary Flight Control Actuation System
PHM	Prognostics Health Monitoring
SOS	System of systems
RPM	Revolution Per Minute
RUF	Remaining Useful Life
VAC	Volt Alternating Current
VDC	Volt Direct Current

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