

Research Article

Mathematical Modelling and Simulation of a Two-Stage Nozzle Flapper Electro-Hydraulic Servo Valve for Aircraft Landing Gear Operation

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Abstract

Electro-hydraulic servo valves (EHSVs) are extensively used in aerospace actuation systems due to their capability to provide precise and rapid control of hydraulic flow. However, accurate mathematical modeling is essential to capture their complex nonlinear dynamics for purposes of simulation, analysis, and control system design. This paper presents a comprehensive mathematical model of a two-stage nozzle flapper EHSV applied to aircraft landing gear operations. The servo valve is divided into five key subsystems: the servo amplifier, voltage-current converter, torque motor, nozzle flapper mechanism, and spool valve integrated with a feedback sensor. Transfer functions are derived for each subsystem and subsequently combined to form an overall system model. The model's accuracy is validated through simulations conducted in MATLAB/Simulink, enabling detailed performance analysis under various input conditions. Simulation results are used to evaluate system stability, transient response, and overall accuracy. The findings reveal a rapid settling time of 0.85 s, negligible overshoot, and a fine spool displacement of 1.43×10^{-4} m (0.143 mm), demonstrating the model's capability to achieve stable and precise hydraulic control. These findings highlight the significant potential of the proposed mathematical model to enhance the dynamic performance of aircraft landing gear systems by providing more accurate, stable, and responsive control of hydraulic actuation.

Keywords

Electro-hydraulic Servo Valve, Landing Gear System, Nozzle Flapper, Spool Displacement

1. Introduction

Aircraft landing gear systems play a critical role in ensuring safe take-off, landing, and taxiing operations. They must withstand complex loading conditions, shocks, and vibrations while maintaining structural integrity and operational reliability [15, 22]. Previous aircraft landing gear systems used basic control methods operated by the pilot through a system

of cables and pulleys. This technique continued to be used for small airplanes. However, this method makes use of muscular effort of the pilot not sufficient to combat aerodynamics hinges while take-off and landing. In commercial aeroplanes the architecture of the flight control system has significantly changed throughout the years [7, 22]. As aircraft became

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larger and more complex, hydraulic systems were introduced to provide a more efficient and reliable method of deploying and retracting the landing gear.

The solenoid-valve were used in fluid power application. The solenoid valve is only an on-off valve without an intermediate position; therefore, the performance was not good for a fast-hydraulic control system to provide retraction of landing gear. Because of a great limit of its performance, a new concept servo valve of control valves was developed [6].

The development of hydraulic servo valves in the mid-20th century brought significant improvements to aircraft control system [24]. Based on the advancement in electronics and control systems, the aviation industry sought ways to integrate electrical control with hydraulic systems, leading to the emergence of electro-hydraulic servo-mechanism [15, 20]. Proper design of a landing gear system allows aircraft operations that dampen the impact force during the landing phase of an aircraft by absorbing and dissipating the kinetic energy, acting as a suspension system during taxi and takeoff [8].

By using a servo valve, the flow is controlled by controlling the position of a moving landing gear in the valve. In certain classes of valves, like check valves or solenoid on/off valves, the purpose is to allow the fluid to flow or not, but the flow rate is not controlled. In servo valves, the purpose is to control the flow rate precisely and bidirectionally [1].

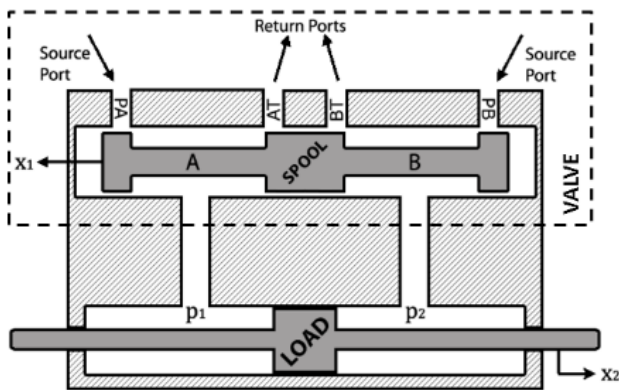


Figure 1. Simple sketch of servo valve spool and its load [1].

Modern landing gear systems integrate hydraulic actuators controlled by electro-hydraulic servo valves (EHSVs), which provide precise motion and force regulation essential for extension and retraction cycles [8, 12].

Electro-hydraulic servo valves, particularly the two-stage nozzle-flapper type, have become the standard in aerospace applications due to their sensitivity, fast response, and capability to handle high-pressure flows [16, 21]. In these systems, a torque motor generates flapper movement, creating differential pressure that drives the spool displacement, thereby

regulating hydraulic fluid flow [10, 13].

Mathematical modeling of these valves is vital to predict system dynamics, stability, and performance under varying operating conditions. Prior studies have applied nonlinear system modeling, including fluid compressibility, leakage, and hysteresis effects, to better understand EHSV dynamics [19]. Recent research has also highlighted the importance of simulation tools such as MATLAB/Simulink in optimizing design parameters for servo amplifiers, torque motors, and nozzle-flapper stages [17, 18].

Despite significant progress, challenges remain in capturing the coupled electro-mechanical-hydraulic interactions in two-stage nozzle-flapper EHSVs, especially when applied to safety-critical systems like aircraft landing gear. This study addresses these challenges by developing and validating a comprehensive mathematical model tailored for landing gear actuation, aiming to improve accuracy, responsiveness, and reliability of EHSV-based systems [5, 11].

1.1. Landing Gear System

Landing gear system is a vital structural system of an aircraft, typically consisting of two or more main undercarriage units located in the wings or fuselage, and an auxiliary unit at the nose or tail for steering and balance [22, 23]. Its main functions are to support the aircraft during ground operations, absorb landing shocks, provide steering, enable braking, and ensure overall stability [15, 25].

Landing gear arrangements exist in three primary configurations: conventional, tandem, and tricycle types. Conventional gear (tailwheel type) positions the main wheels ahead of the center of gravity, with a tail wheel or skid at the rear. Early aircraft widely used this arrangement as it enabled longer propellers, improved clearance on unpaved runways, and reduced weight due to the light tail assembly [2, 3]. Tandem gear, found in some military aircraft and sailplanes, aligns the main and tail gear along the fuselage's longitudinal axis. This reduces drag and allows flexible wing designs, sometimes supplemented with outrigger wheels or skids for stability [22]. Tricycle gear combines a main landing gear behind the center of gravity and a nose landing gear. Common in modern aircraft, it improves forward visibility, enhances braking, prevents ground looping, and ensures better stability during taxiing and landing [23].

The design of landing gear systems is complex, requiring careful attention to constraints such as minimum weight, compact volume, stability, stiffness, and cost efficiency. Designers must also consider ground clearance and the ability to dampen impact forces during various landing conditions [22, 26].

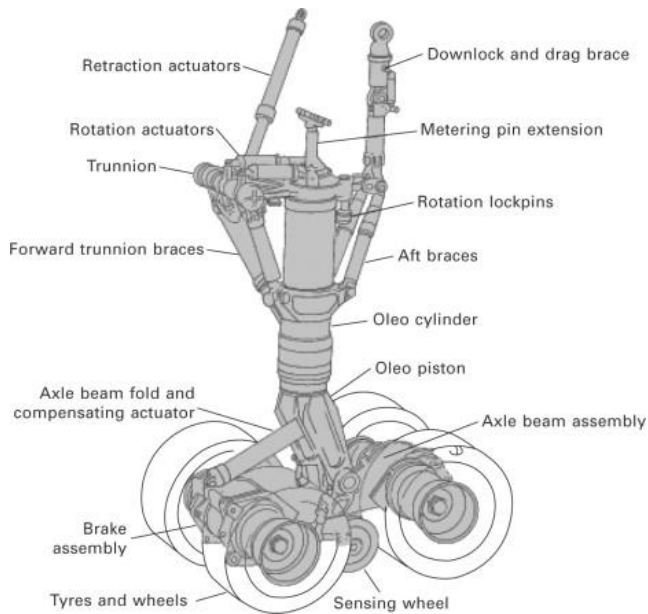


Figure 2. Landing gear system [15].

Throughout its service life, landing gear endures significant stress from repeated landings, exposure to dirt, ice, spray, and grit. This harsh environment necessitates regular servicing and lubrication to prevent corrosion, seizure of parts, and electrical failures [8, 14]. Landing gear plays a central role in safe aircraft operation, with configurations tailored to aircraft type and operational requirements. Its durability, reliability, and proper maintenance are essential for the performance and safety of any aircraft.

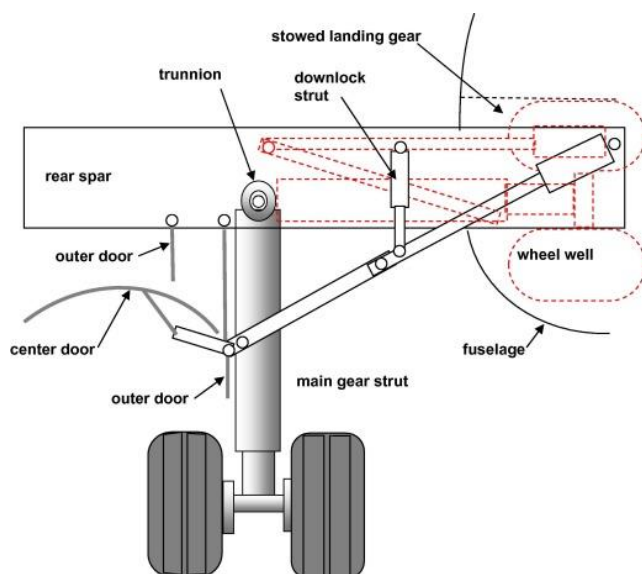


Figure 3. Retractable landing gear [23].

Beyond the aircraft landing gear wheel arrangement are classified further as either fixed or retractable landing gear. Fixed (non-retractable) landing gear hangs underneath an

aircraft during flight where is used with slow, light aircraft and some larger aircraft on which simplicity is of prime importance, reduced maintenance, however fixed landing gear reduces the performance of an aircraft caused by the drag which act on it during flight [15, 22].

Retractable landing gear is used in higher performance aircraft, where drag becomes progressively more important, which during the flight aircraft wheels are retracted into the wings or fuselage [14]. This type of landing gear is believed to deliver effective aircraft wheels operations during landing and after take-off and offer a cruising performance by reducing aerodynamics drag forces.

1.2. Two-stage Nozzle Flapper Electrohydraulic Servo Valve

This design types the pilot pressure is applied to both ends of the main spool and linked by orifices to small jets playing to a flapper which can be moved by the electrical control signal. Pressure at each end of the main spool (and also spool movement) is determined by the flow issued out of each jet which, in turn, is determined by flapper position and electrical control signal [12, 21]. The flapper-nozzle system converts the flapper motion, driven by a low-power electrical torque motor, into a hydraulically powered motion of the spool. The small spool motions control relatively large oil flows through the spool ports, which is the second power amplification [16].

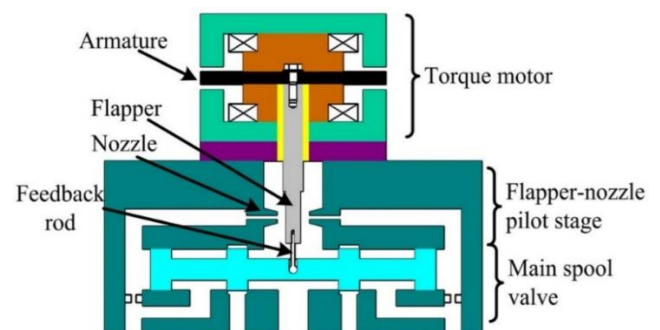


Figure 4. Flapper servo valve [21].

The performance of electro-hydraulic servo valves (EHSV) is fundamentally influenced by spool displacement, which regulates fluid flow and determines system accuracy, stability, and responsiveness [15].

In order to obtain structural insight into the behavior of electro-hydraulic servo-valve, with respect to relevant dynamics as well as relevant non-linearities, the procedure usually starts with the theoretical, physically based modelling of the complete servo-valve. Mathematical model is constructed from basic equation which using and combining available contributions on modelling of electro-hydraulic servo valve found in relevant literature [12]. The result is usually a non-linear dynamic (simulation) model of the hydraulic ser-

vo-valve which used to perform various simulations, with realistic physical parameters in application extension and retraction of landing gear of an aircraft, so that structural insight into the relevant dynamics and non-linearities of the system can be gained [16]. These are the basic known equations employed in a mathematical model of the electro-hydraulic servo valve system

1) Continuity equation

The flow of continuity equation obtains as [16]

$$Q = A V_e$$

2) Newton second law of motion

The newton second law of motion obtained as [9]

$$P = \frac{F}{A}$$

3) Bulk modulus

The quantity β is called the bulk modulus and it is defined as the ratio of change in pressure to the change in volume at constant temperature. Different hydraulic fluids have their own values of K_B which is a constant value property. It has the units of pressure (N/m², in SI system) [12].

K_B = change in pressure/change in volume per unit volume

$$\beta = \frac{\Delta P}{\frac{\Delta V}{V}}$$

2. Methodology

The modeling approach follows a system decomposition strategy, breaking down the EHSV into subsystems.

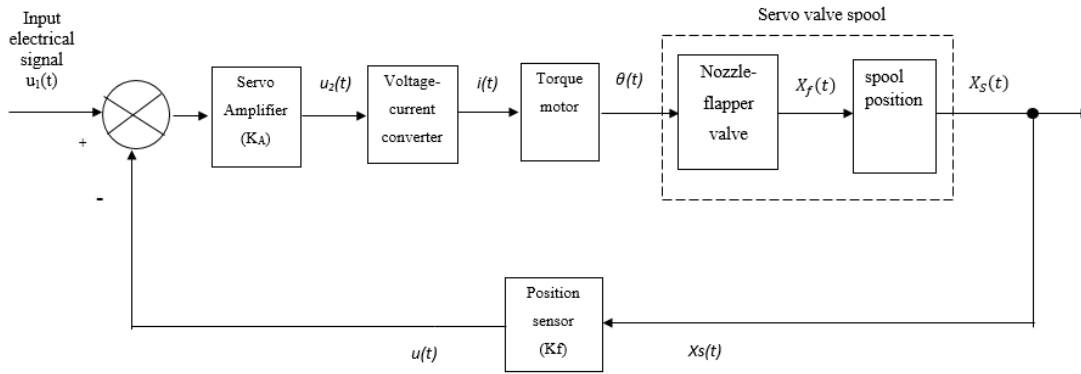


Figure 5. A Conceptual block diagram of electro-hydraulic servo valve mechanism.

The operation mechanism is conducted using an initial electrical input signal provided by the pilot to the servo valve. The servo valve is a critical system composed of the following components: Servo amplifier which receives an input voltage signal required to actuate torque motor. Torque motor receive current through use of a voltage-current converter in which the resulting current flow in the solenoid of the torque motor produces magnetic field causing the flapper connected to the spool valve to be deflected causing the servo valve spool to moves. During the movement of the spool hydraulic fluid passages, regulating the landing gear actuator to extend or retract during aircraft landing or takeoff approach.

2.1. Servo Amplifier

Based on pilot's action, servo amplifier receives an input signal in form of a voltage $u_1(t)$. The expected output is $u_2(t)$ as shown in a corresponding circuit diagram see Figure 6.

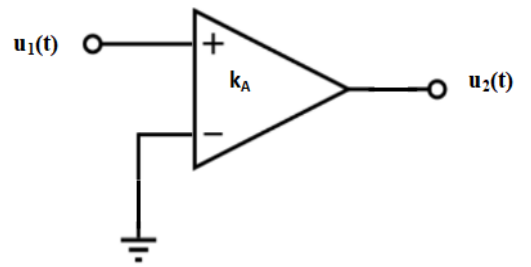


Figure 6. Circuit diagram of the servo amplifier.

The mathematical equation describing servo-amplifier output voltage is

$$u_2(t) = k_A u_1(t) \quad (1)$$

The equation (1) when expressing into a form of Laplace transform obtain as;

$$u_2(s) = k_A u_1(s) \quad (2)$$

By expressing equation (2) it into a form of a transfer function, after performing Laplace transforms which obtain as;

$$\frac{u_2(s)}{u_1(s)} = k_A \quad (3)$$

2.2. Voltage-current Converter

Since the torque motor type used in this study requires an input signal in form of a current a converter has been incorporated. The corresponding circuit diagram is presented in Figure 7.



Figure 7. Circuit diagram of the servo amplifier.

The relevant mathematical equation representing the relationship between the amplifier output voltage and output current shown as;

$$\frac{1}{R} u_2(t) = \frac{L_i}{R} \frac{di(t)}{dt} + i(t) \quad (4)$$

The equation (4) when expressing into a form of Laplace transform obtain as;

$$\frac{1}{R} U_2(s) = I(s) \left(s \frac{L_i}{R} + 1 \right)$$

By expressing it into a form of a transfer function, after performing Laplace transforms which obtain as;

$$\frac{I(s)}{U_2(s)} = \frac{1}{L_i s + R} \quad (5)$$

2.3. Torque Motor

A torque motor consists of upper and lower pole pieces, armature, two coils, flapper and flexure tube. The two pole pieces, one polarized 'North' and the other polarized 'South', provide paths for the magnetic flux. The armature is mounted on a pivot and is suspended in the air gaps of the magnetic field. Torque motor converts the input signal to a proportionate semi-rotary movement of the armature, either clockwise or anti-clockwise, depending on the magnetic polarity.

2.3.1. Electromagnetic Torque Motor

The electromagnetic torque motor transforms a low-level electric input signal into a mechanical torque that is proportionate to it. The net torque is influenced by the flapper rotational angle and effective input current. The following torque expression can be derived by ignoring the impact of magnetic hysteresis.

$$T = K_i i + K_\theta \theta \quad (6)$$

2.3.2. Armature Equation of Motion

Under the influence of the torque caused by electromagnetic forces, an armature assembly (consisting of the armature and the flapper) moves. In order to cancel the negative influence of the torque motor electromagnetic spring constant, the armature assembly was required a flexure tube as an elastic support. The armature assembly and the flexure tube move and deform together. Applying the law of angular momentum change to armature motion with presumption that the mass of the flexure tube can be neglected since the thickness of its wall is thin the following is differential equation that represents the armature dynamics can be expressed as:

$$T = J \frac{d^2 \theta}{dt^2} + B \frac{d\theta}{dt} + K_T \theta \quad (7)$$

Rearranging the equations (6) and (7) in a Laplace transform equation, we can obtain the transfer function of the torque motor:

$$G(s) = \frac{\theta(s)}{I(s)} = \frac{K_i}{(Js^2 + Bs + (K_T + K_\theta))} \quad (8)$$

This transfer function represents the ratio of the angular displacement $\theta(s)$ of the torque motor to the input current $I(s)$ in the Laplace domain. It describes the dynamic behavior of the torque motor in an electro-hydraulic servo valve system.

2.4. Nozzle Flapper

In order to model the angular displacement of the flapper use has been made of the following schematic diagram based on pendulum displacement

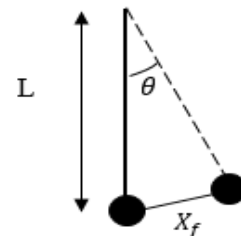


Figure 8. Angular displacement of the flapper.

Following flapper displacement is obtain from

$$\tan\theta = \frac{x_f}{L} \quad (9)$$

For small angle $\theta \approx 0$

$$X_f = \theta L \quad (10)$$

After rearrange equation (11) it in a transfer function

$$\frac{X_f(s)}{\theta(s)} = L \quad (11)$$

2.5. Servo Valve Spool

2.5.1. Flow Rate at the Flapper Across the Spool Valve

The flow rate affecting on the flapper and make a pressure differences between both sides of the spool is obtained by equation

$$Q_L = K_q X_f - K_c P_L \quad (12)$$

2.5.2. Continuity in the Flapper Chamber

By application of continuity equation as governing equation in the system the modeling for the nozzle-flapper stage dynamics taking into account of effects due to inertia and fluid compressibility effect are given by

$$Q_L = Q_{in} - Q_{out} = A \frac{dX_s}{dt} + \frac{V}{\beta} \frac{dP_L}{dt} \quad (13)$$

2.5.3. Equation of Motion of the Spool

The motion of the spool valve is described by the following

$$AP_L = M \frac{d^2 X_s}{dt} + u \frac{dX_s}{dt} + k_s X_s \quad (14)$$

Combining equations (9) and (12) mathematical model of the servo valve spool can be described as

$$K_q X_f - K_c P_L = A \frac{dX_s}{dt} + \frac{V}{\beta} \frac{dP_L}{dt} \quad (15)$$

Subsisting P_L in equation (13) into equation (14) it becomes

$$K_q X_f - K_c \left(\frac{M}{A} \frac{d^2 X_s}{dt} + \frac{u}{A} \frac{dX_s}{dt} + \frac{k_s}{A} X_s \right) = A \frac{dX_s}{dt} + \frac{V}{\beta} \frac{d \left(\frac{M d^2 X_s}{A dt} + \frac{u dX_s}{A dt} + \frac{k_s X_s}{A} \right)}{dt}$$

After rearrange it become

$$K_q X_f = \frac{VM}{\beta A} \frac{d^3 X_s}{dt} + \left(\frac{K_c M}{A} + \frac{Vu}{\beta A} \right) \frac{d^2 X_s}{dt} + \left(A + \frac{K_c u}{A} + \frac{V k_s}{\beta A} \right) \frac{dX_s}{dt} + \frac{k_s}{A} X_s \quad (16)$$

According to the equation (15) the transfer function after performing Laplace transforms obtained as;

$$\frac{X_s(s)}{X_f(s)} = \frac{K_q}{\frac{VM}{\beta A} s^3 + \left(\frac{K_c M}{A} + \frac{Vu}{\beta A} \right) s^2 + \left(A + \frac{K_c u}{A} + \frac{V k_s}{\beta A} \right) s + \frac{k_s}{A}}$$

After rearrange it becomes

$$\frac{X_s(s)}{X_f(s)} = \frac{K_q \frac{\beta A}{VM}}{s^3 + \left(\frac{K_c \beta}{V} + \frac{u}{M} \right) s^2 + \left(\frac{\beta A^2}{VM} + \frac{K_c u \beta}{VM} + \frac{k_s}{M} \right) s + \frac{k_s \beta}{VM}}$$

2.6. Feedback Sensor

The feedback sensor is used to convert into an equivalent electrical signal of the output using (sensor or transducer). The position sensor has been used to measure the exact position of spool. The mathematical equation of feedback sensor representing the relationship between input flow rate to the output voltage;

$$u(t) = X_s(t) K_f \quad (17)$$

By expressing equation, it into a form of a transfer function it's become the constant gain which obtains as;

$$H(S) = \frac{U(s)}{X_s(s)} = K_f$$

2.7. Overall Transfer Function of Electro Hydraulic Servo Valve

Overall transfer function of the system has derived through the block diagram reduction which simplifies complex block diagrams by combining multiple blocks of the components included amplifier, voltage-current converter, torque motor, Nozzle flapper, spool valves and feedback sensor into single equivalent blocks. By employing this technique, the simplification aids have been made in the analysis and design of electro-hydraulic servo valve for assisted aircraft landing gear systems and allows making informed decisions to achieve desired system performance and stability.

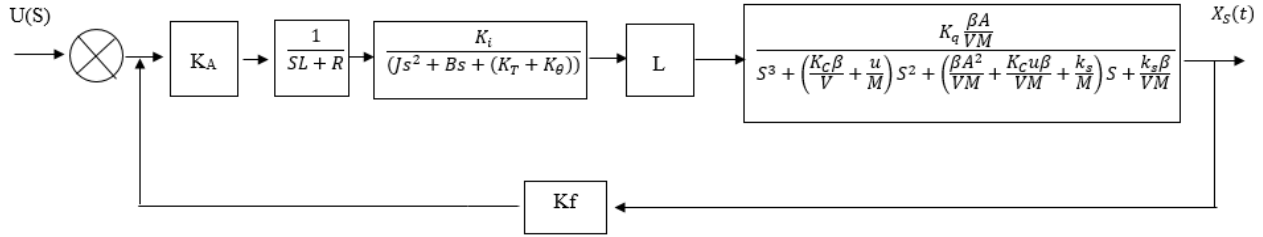


Figure 9. Block diagram of EHSV with transfer function of multiple components.

The overall transfer function becomes,

$$G(s) = \frac{z}{aes^6 + (af + be)s^5 + (ag + bf + ce)s^4 + (ah + bg + cf + de)s^3 + (bh + cg + df)s^2 + (ch + dg)s + (dh + w)}$$

Where;

$$z = K_q K_A K_i L \frac{\beta A}{VM}$$

$$a = L \times J$$

$$b = (L \times B) + (R \times J)$$

$$c = (L \times (K_T + K_\theta)) + (R \times B)$$

$$d = R \times (K_T + K_\theta)$$

$$e = 1$$

$$f = \left(\frac{K_C \beta}{V} + \frac{u}{M} \right)$$

$$g = \left(\frac{\beta A^2}{VM} + \frac{K_C u \beta}{VM} + \frac{k_s}{M} \right)$$

$$h = \frac{k_s \beta}{VM}$$

$$w = K_q K_A K_f K_i L \frac{\beta A}{VM}$$

Simulation has been made based on specialized software MATLAB of a version 2023Ra to simulate diverse and dynamic operational conditions, providing an understanding of the electro-hydraulic servo valve's behavior in landing gear system. The simulation determines the design parameter of the servo valve in the landing gear extension and retraction system.

3. Results

The modeling of the two-stage nozzle flapper electro-hydraulic servo valve required the determination of several component parameters, including the amplifier, voltage-current converter, torque motor, nozzle flapper, spool valve, and feedback sensor. These values were obtained from manufacturer data and previous studies [10, 11, 18].

Table 1 summarizes the consolidated parameters used in the mathematical modeling.

Table 1. Design parameter value of electro-hydraulic servo valve.

Parameter	Symbol	Value
Amplifier gain	k_A	10
Resistance	R	100Ω
Inductance	Li	0.02H
Current torque Gain	K_i	0.556Nm/A
Armature rotation angle gain	k_θ	5 x 10 ⁻⁷ Nm/rad
Stiffness of flexible tube	K_T	10N/m
Moment of inertia	J	0.0058kgm ²
Damping coefficient	B	0.25Nms/rad
Flapper length	L	0.009m

Parameter	Symbol	Value
oil density	ρ	867 kg/m ³
bulk modulus	β	1.4 x 10 ⁹ N/m ²
Total mass being moved	M	0.0035 kg
Spool diameter	d	0.02m
Length of the spool	L	0.08m
Volume of the fluid	V	3.250 x 10 ⁻⁵ m ³
Viscous friction coefficient	μ	3.8 x 10 ³ N/(m/s)
Discharge coefficient	C _d	0.65
Flow gain constant	K _q	10 m ³ / s/V
Flow pressure coefficient	K _c	0.02m ³ /(s.pa)
Feedback spring coefficient	K _s	900 N/m
Feedback gain	K _f	70

The combined dataset demonstrates consistency across all subsystems and provides the necessary input for formulating the overall transfer function of the servo valve.

The individual transfer functions of each subsystem were integrated to obtain the overall transfer function of spool displacement. This represents the dynamic response of the complete servo valve as it converts an electrical input into precise spool movement, thereby regulating hydraulic flow to the actuator.

The resulting Plot showing the relationship between input voltage from the pilot action and output spool displacement is presented in Figure 9. The input voltage used was 10 volts.

The simulation results show that the spool displacement settles at 1.43×10^{-4} m (0.143 mm), the settling time is approximately 0.85 seconds, small overshoot is observed, but the system stabilizes rapidly with minimal oscillation. The relationship between input voltage and spool displacement is proportional, confirming the validity of the developed model. These results are consistent with the general behavior of electro-hydraulic servo valves reported in earlier studies [1, 15], which emphasize precision control of hydraulic flow under varying load conditions.

4. Discussion

The simulation results demonstrate that the developed two-stage nozzle flapper electro-hydraulic servo valve model achieves a rapid stabilization time of approximately 0.85 seconds, with the spool displacement converging to 0.143 mm. These findings indicate a highly responsive system capable of delivering fine control of hydraulic flow. Such precision is critical for landing gear systems, where smooth extension and retraction directly influence aircraft safety during landing and take-off operations.

Compared with previous works, the results of this study are consistent with [1] and [15], who reported that nozzle-flapper servo valves provide accurate control of flow displacement under dynamic loads. [4] emphasized that small spool displacements strongly affect flow precision, which supports the present finding that a displacement of 0.143 mm is sufficient to regulate hydraulic actuation effectively. Similarly, [13] demonstrated that mathematical models based on fundamental mechanics can replicate experimental servo valve performance with satisfactory accuracy, further validating the reliability of the approach taken here.

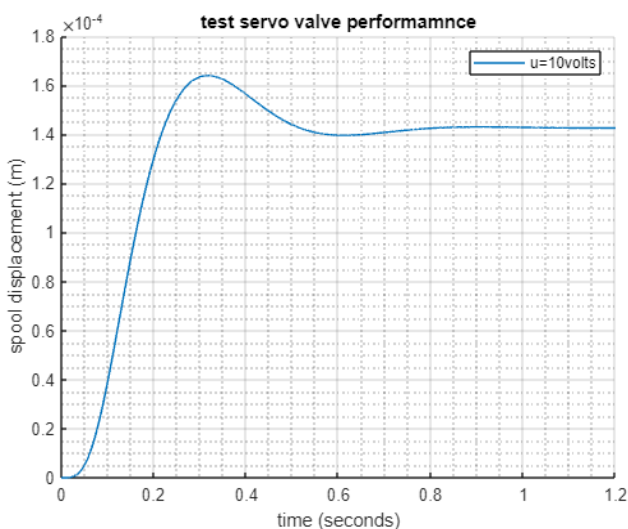


Figure 10. Performance of the servo valve.

An important aspect of the obtained response is the presence of a slight overshoot, which, while within acceptable limits, suggests areas for potential control refinement. [5] highlighted that temperature-dependent variations in oil viscosity can exacerbate overshoot and delay settling time. Likewise, [7] noted that environmental conditions, such as extreme temperature shifts in aerospace environments, significantly affect valve stability and wear. These comparisons suggest that although the developed model performs well under nominal conditions, its robustness under fluctuating environmental and load conditions must be carefully evaluated.

The broader implication of these results is that the proposed model provides a valid platform for predictive analysis and system optimization. Also, the simulated response of this study falls within the expected performance range of valves, validating both the parameter selection and modeling approach. Building on these directions, the present model demonstrates strong potential for integration with advanced monitoring and control strategies to enhance safety and reliability in aerospace applications.

Consequently, the model can serve as a reliable basis for future optimization integration with advanced digital controllers and robustness testing under varying environmental conditions (e.g., temperature, vibration, and pressure changes) to enhance applicability for real-world aerospace systems.

5. Conclusion

This study developed and simulated a mathematical model of a two-stage nozzle flapper electro-hydraulic servo valve for aircraft landing gear operation. The model incorporated the dynamics of the amplifier, voltage-current converter, torque motor, nozzle flapper, spool valve, and feedback sensor. A consolidated set of parameters was determined and applied to derive the overall transfer function of spool displacement.

Simulation results showed that the spool displacement stabilized at 1.43×10^{-4} m with a settling time of approximately 0.85 seconds, demonstrating the high responsiveness and precision required for safe and efficient landing gear actuation. The proportional relationship between input voltage and spool displacement confirmed the validity of the developed model.

The findings confirm that the proposed model accurately reflects the expected performance of aerospace-grade electro-hydraulic servo valves. The rapid stabilization and fine displacement capability highlight the potential of this approach to improve landing gear safety and reliability.

Abbreviations

EHSV Electro-hydraulic Servo Valve

Author Contributions

Isaac Itukulana Mwesigwa: Conceptualization, Data Curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft, Writing – review & editing

Benjamin William Ndimila: Formal analysis, Methodology, Resources, Supervision, Validation

Bakari Ramadhan Momba: Formal analysis, Methodology, Validation, Writing – review & editing

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Research Field

Isaac Itekulana Mwesigwa: aerospace, modelling, hydraulic, additive manufacturing, design, maintenance

Benjamin William Ndimila: Material analysis, Designing, Fatigue Analysis, Mechanics of materials

Bakari Momba Ramadhan: Material analysis, Designing, Mechanics of materials, Finite element method