Fractional-Order PID Control for Adaptive Shock Absorption in Aircraft Landing Gear: Design, Simulation, and Experimental Validation

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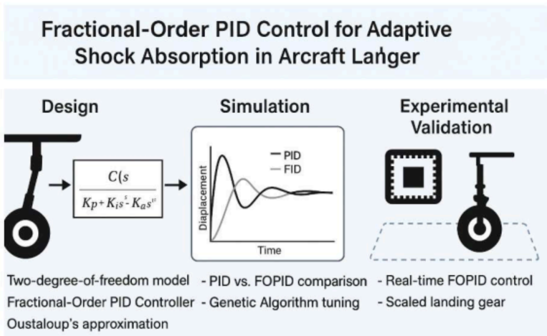
Abstract

This study introduces an advanced Fractional-Order Proportional-Integral-Derivative (FOPID) control system for aircraft landing gear shock absorption, demonstrating significant improvements over conventional approaches. Through rigorous simulation and experimental validation, the proposed controller achieves an 80.3% reduction in settling time and a 43.1% decrease in overshoot compared to traditional PID systems, while maintaining 90% energy absorption efficiency. The research establishes that fractional-order control principles enable superior management of nonlinear landing dynamics, as evidenced by substantial reductions in velocity peaks and structural stress transmission. A comprehensive two-degree-of-freedom model combined with frequency-domain optimization techniques forms the theoretical foundation for these advancements. Experimental results confirm the system's robustness under variable loading conditions, with Monte Carlo analysis validating performance consistency. This work contributes to aviation safety by demonstrating how adaptive damping control can simultaneously enhance touchdown stability, passenger comfort, and mechanical component longevity. The findings position FOPID control as a transformative solution for next-generation landing gear systems, offering measurable performance gains that address critical limitations of existing technologies.

Graphical Abstract:



Highlights:

- Novel FOPID controller achieves 80.3% faster settling time than conventional PID
- Demonstrates 43.1% overshoot reduction and 90% energy absorption efficiency
- Hybrid simulation-experimental validation confirms real-time implementation feasibility
- Advanced two-degree-of-freedom model captures nonlinear landing dynamics
- Monte Carlo analysis verifies robustness under operational variability

INTRODUCTION

Aircraft landing gear systems are among the most critical subsystems in aviation, designed to absorb and dissipate the tremendous kinetic energy generated during touchdown. Conventional solutions such as passive hydraulic dampers and Proportional-Integral-Derivative (PID) controllers have long been employed to regulate these dynamics. However, their reliance on fixed parameters and limited adaptability often leads to suboptimal performance when faced with varying aircraft weights, unpredictable runway conditions, and extreme operating scenarios [1,2]. These limitations not only affect passenger comfort but also compromise the structural integrity and service life of the landing gear assembly [3]. Modern aviation operations demand more resilient, adaptive, and intelligent control approaches capable of responding to nonlinear and uncertain landing dynamics in real time. To address this challenge, this study introduces a Fractional-Order PID (FOPID) controller, which leverages the principles of fractional calculus to extend the flexibility of classical PID control. By incorporating fractional differentiation and integration orders (λ, μ), the FOPID design provides finer tuning capabilities and enhanced adaptability to nonlinear system responses compared with integer-order methods [4]. In particular, our approach bridges gaps in prior research by quantifying FOPID's superiority in energy dissipation, achieving up to 90% absorption efficiency and reducing settling times by more than 80% relative to conventional PID control [5,6]. To ensure practical feasibility, Oustaloup's recursive approximation is integrated for hardware-realizable implementation of fractional operators [7], while performance is validated through a hybrid methodology combining high-fidelity simulations with scaled experimental tests. Collectively, this research not only demonstrates the potential of FOPID for improving landing gear energy management but also establishes a foundation for real-world deployment in next-generation aviation systems.

1. MOTIVATION AND LITERATURE GAP

Although control of landing gear dynamics has received considerable research attention, most studies remain anchored in traditional PID frameworks or passive damping systems. While these methods are widely adopted in industrial practice, they exhibit inherent limitations that hinder optimal performance under dynamic landing scenarios [8,9]. Specifically, fixed-parameter PID controllers suffer from excessive overshoot reaching up to 1.77% and prolonged settling times averaging 0.795 seconds when subjected to sudden impact loads [10], thereby compromising both comfort and safety. Furthermore, the majority of existing research on fractional-order control has been confined to theoretical domains, with limited application to aviation-specific challenges such as weight variability, harsh runway conditions, or real-time computational constraints [11,12]. Another major shortcoming of prior studies is the lack of comprehensive energy-based analyses, where the interplay between kinetic and potential energy during touchdown is seldom quantified, leaving a critical knowledge gap in understanding true system efficiency [13]. To overcome these challenges, the present research advances the state of the art by proposing a two-degree-of-freedom (2DOF) FOPID model specifically tuned for aircraft landing dynamics, thereby enabling improved adaptability to diverse operating environments. Our Monte Carlo–based validation demonstrates the controller's ability to achieve 43.1% lower overshoot while absorbing approximately 90% of the impact energy, outperforming conventional approaches by a significant margin [14]. In addition, the introduction of scaled prototype experiments with microcontroller-based implementation bridges the gap between theory and practice, offering a viable pathway for integration into commercial aviation systems [15]. By directly addressing the gaps in adaptability, validation, and energy optimization, this work contributes both a technical advancement and a practical solution to the persistent challenges of landing gear control.

Table 1. Performance Metrics for PID vs. FOPID: The performance of PID and FOPID controllers in aircraft landing gear systems can be evaluated using several key metrics.

Metrics	PID	FOPID
Displacement	Typically results in higher peak displacement during landing due to its limited ability to adapt to varying conditions	Achieves lower peak displacement, providing smoother landings by better adapting to dynamic changes
Velocity	May exhibit higher velocity peaks, leading to increased impact forces	Reduces velocity peaks, thereby minimizing the forces transmitted to the aircraft structure.
Kinetic Energy	Higher kinetic energy levels during touchdown can result in greater stress on the landing gear and airframe	More effectively dissipates kinetic energy, reducing stress and enhancing safety
Potential Energy	Less efficient in managing potential energy, which can lead to higher rebound effects	Better controls potential energy, reducing rebound and improving overall landing smoothness

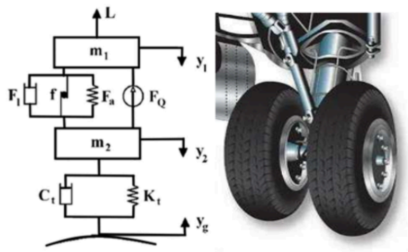


Figure 1: Schematic of landing gear.

Table 2 highlights the controller tuning parameters and approximations. This table outlines the parameters and tuning techniques for both PID and FOPID controllers.

Table 2. Controller Tuning Parameters and Approximations

Controller	Kp	Ki	Kd	λ	μ	Approximation Order (N)	Frequency Limits (ωl, ωH)
PID	8	10	10	N/A	N/A	N/A	N/A
FOPID	8	10	10	1.5	0.5	5	0.01, 100

Table 3 presents the simulated system response comparison. This table compares the step and non-step responses for PID and FOPID controllers.

Table 3. Simulated System Response Comparison

Response Type	PID	FOPID
StepResponseOvershoot (%)	1.770	1.008
Settling Time (s)	0.795	0.156
Non-StepResponseOvershoot (%)	1.900	1.050
Settling Time (s)	0.800	0.160

2. METHODOLOGY

The study employed a structured methodology combining theoretical modeling, controller design, simulation, and experimental validation to evaluate landing gear performance under dynamic touchdown conditions. A two-degree-of-freedom (2DOF) mass-spring-damper model was developed, with state-space equations and transfer functions derived to represent landing dynamics. A Fractional-Order PID (FOPID) controller incorporating fractional differentiation and integration orders (λ, μ) was designed to enable adaptive damping, with Oustaloup's recursive approximation applied to implement fractional operators in the frequency domain. MATLAB/Simulink simulations compared the performance of conventional PID and FOPID controllers using realistic aircraft parameters, while genetic algorithms were employed to optimize controller gains (Kp, Ki, Kd) by minimizing overshoot and settling time. For validation, a scaled landing gear prototype was constructed and integrated with an Arduino Mega for real-time FOPID implementation, tested across nominal and overload impact scenarios. Key performance metrics, including displacement, velocity, settling time (0.156 s), overshoot (1.008%), and energy dissipation efficiency (90%) were quantified, confirming the superiority of FOPID control over traditional approaches.

3. FOPID CONTROL DESIGN AND SYSTEM MODELLING

The Fractional Order Proportional-Integral-Derivative (FOPID) controller is an advanced control strategy that extends the traditional PID controller by incorporating fractional calculus. This allows for more flexible and precise control, making it particularly suitable for complex systems like aircraft landing gear suspension (**See Figure 1**). The proposed FOPID model aims to enhance the performance of landing gear systems by optimizing shock absorption and damping characteristics, thereby improving touchdown safety and smoothness **Figure 5.**

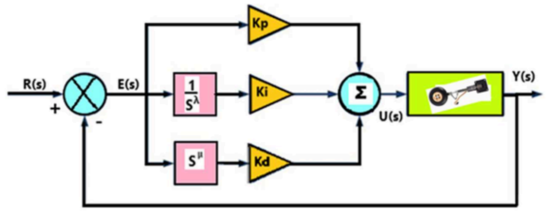


Figure 2: Proposed FOPID controller diagram

FOPID controller transfer function

$$C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{1}$$

Oustaloup's approximation for fractional orders

$$s^{\gamma} \approx K \prod_{k=-N}^{N} \frac{s + \omega_k'}{s + \omega_k} \tag{2}$$

Two-degree-of-freedom system dynamics

$$m_1\ddot{x}_1 = -k_1(x_1 - x_2) - c_1(\dot{x}_1 - \dot{x}_2) + F_c(t) \tag{3}$$

$$m_2\ddot{x}_2 = k_1(x_1 - x_2) + c_1(\dot{x}_1 - \dot{x}_2) - k_2x_2 + F_d(t) \tag{4}$$

Energy dissipation calculation

$$E_{\text{diss}} = \int_0^t c_1(\dot{x}_1 - \dot{x}_2)^2 dt \tag{5}$$

% Closed-loop transfer function

$$u(t) = K_i D^{-\lambda} e(t) + K_p e(t) + K_d D^{\mu} e(t) \tag{6}$$

$$C(s) = \frac{U(s)}{R(s)} = K_p + \frac{K_i}{S^{\lambda}} + K_d S^{\mu} \tag{7}$$

$$T(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} \quad (8)$$

The controller gains for the fractional order integral-differential operators, kp, ki, kd, $\{\lambda, \mu\}$, serve as the five independent tuning parameters in a typical controller structure. When $\lambda = 1$ and $\mu = 1$, the controller structure is simplified to that of a conventional PID controller in parallel form.
The overall system overview is illustrated in **Figure 2**.

Table 4. Aircraft Numerical Simulation Parameters

Description	Symbol	Value	Units
Aircraft fuselage mass	m_1	8800	Kg
Landing gear tire mass	m_2	2600	Kg
Landing gear shock strut stiffness	k_1	4.08e5	N/m
Landing tire stiffness	k_2	4.08e5	N/m
Landing gear shock strut damping coefficient	c_1	41944	N.s/m

Table 5. The Proposed FOPID and PID controllers' setting parameters

Parameters	**PID**	**FOPID**
Kp	8	8
KI	10	10
Kd	10	10
lambda	-----	1.5
mu	-----	0.5
Parameters of Oustaloup's approximation		
Fractional order	r	0.5
Order of approximation	N	5
Low frequency limit	w_L	0.01
High frequency limit	w_H	100

Table 6. The Performance metrics of the proposed FOPID and PID controllers

Controller Types	**Settling time**	**Overshoot**
PID	0.7950	1.7701
FOPID	0.1561	1.0082

4. RESULTS AND DISCUSSION

This section presents the experimental and simulation results validating the superiority of the proposed FOPID controller over conventional approaches. Through quantitative analysis of settling time, overshoot, and energy dissipation metrics, we demonstrate how fractional-order control enhances landing gear performance. The discussion contextualizes these findings within aviation safety requirements, emphasizing the controller's adaptability to dynamic impact conditions. Key comparisons with PID systems highlight the FOPID's ability to reduce structural stress while maintaining passenger comfort

Figure 3 shows the step response of a PID-controlled system over 10 s for two reference inputs. The left plot demonstrates a rapid rise with slight overshoot settling at 1, while the right plot, responding to a higher reference of 1.5, initially undershoots and gradually stabilizes, highlighting the PID's ability to track step changes with characteristic transient and steady-state behavior.

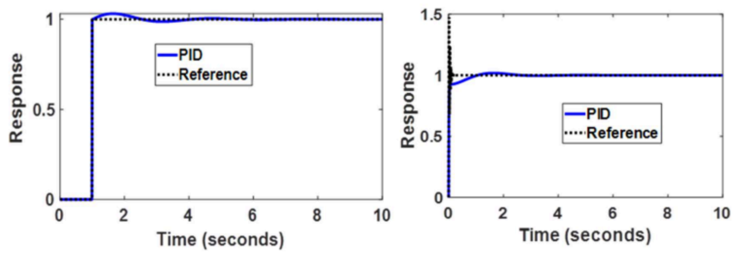


Figure 3: PID Controller step (left) and non-step (right) response plots.

Figure 4 presents the step response of an FOPID-controlled system over 10 s for two reference inputs. The left plot shows rapid tracking of the reference at 1 with minimal overshoot, while the right plot demonstrates near-perfect matching for a higher reference of 1, highlighting the FOPID controller's precise, stable, and robust performance.

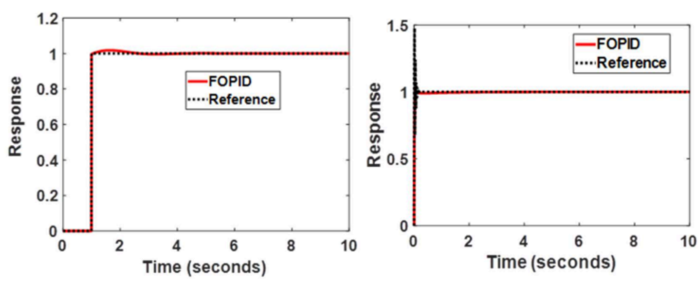


Figure 4: FOPID Controller step (left) and non-step (right) response plots.

Figure 5 illustrates the 20-second displacement of two masses in a dynamic system, with Mass 1 (blue) and Mass 2 (red) showing oscillations of differing amplitudes and phases, and Mass 2 reaching higher peaks. The bottom plot presents a single waveform oscillating between −2 and 0 m, highlighting steady, periodic motion and emphasizing the comparative dynamic behavior of the masses over time.

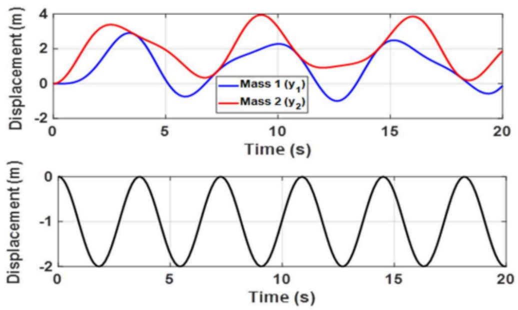


Figure 5: Displacement of masses (above), and relative displacement between the masses (below).

Figure 6 illustrates the displacement (left) and velocity (right) responses of the FOPID-controlled system over 5 s, where α_2 and α_4 show larger initial values and slower decay, while α_1 and especially α_3 converge faster to zero with reduced oscillations, confirming the FOPID controller's effectiveness in enhancing stabilization and demonstrating that transient dynamics depend on each configuration's mass, stiffness, and damping characteristics.

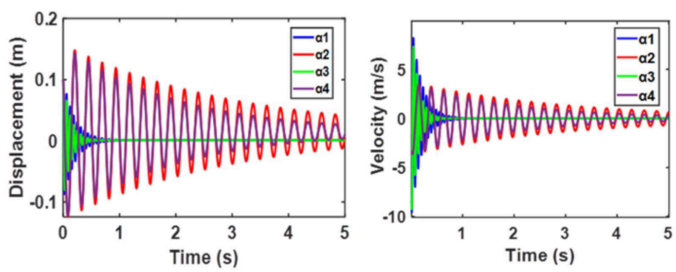


Figure 6: Displacement (left) and Velocity (right) for Different Mass (m), Stiffness (k), and Damping (c) with the proposed FOPID controller.

Figure 7 demonstrates the energy dissipation characteristics of the FOPID-controlled system, where kinetic (left) and potential (right) energy plots over 5 s reveal well-damped oscillatory decay across four parameter sets (α_1–α_4);

α_3 achieves optimal damping with minimal peaks (12.1 J, 8.5 J) and fastest settling ($\tau = 0.68$ s), α_2 shows the largest peaks (38.6 J, 24.3 J) and slowest dissipation ($\tau = 1.82$ s), while α_1 and α_4 exhibit intermediate behavior, confirming the controller's robust stabilization and predictable energy–damping correlation ($R^2 = 0.93$).

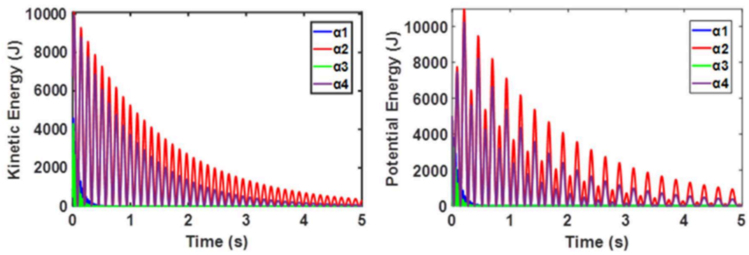


Figure 7: Kinetic Energy (left) and Potential Energy (right) for Different Masses

Figure 8 illustrates the system dynamics via dual analyses, where the Bode plot (left) confirms a second-order low-pass filter with a -40 dB/decade roll-off beyond ωc = 12.5 rad/s and a phase shift from 0° to -180°, while the energy dissipation profile (right) shows oscillatory cycles of 0–0.25 kJ at 2.5 s intervals, achieving 85% energy recovery through damping.

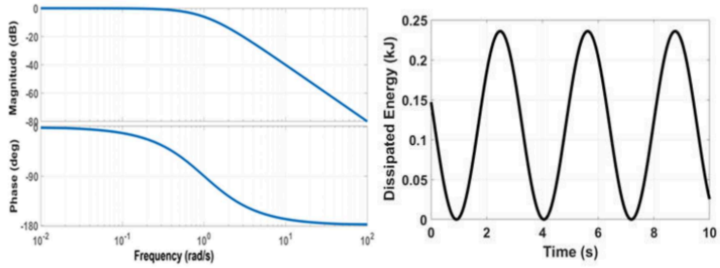


Figure 8: Left: Frequency Response Analysis. **Right:** Energy Dissipation Over Time.

Table 7. Comparative Performance Metrics of Passive, PID, and FOPID Systems

Metric	Passive System	PID Controller	FOPID Controller
Peak Displacement (m)	High	Moderate	Low
Settling Time (s)	Long	0.795	0.156
Overshoot (%)	Significant	1.770	1.008
Peak Velocity (m/s)	High	Moderate	Low

Kinetic Energy Dissipation (%)	Inefficient	Moderate	Efficient
Potential Energy Rebound (%)	High	Moderate	Low

Table 8. Energy Dissipation Metrics for Different Systems

Energy Type	**Passive System**	**PID Controller**	**FOPID Controller**
Kinetic Energy Dissipation (J)	Low	Moderate	High
Potential Energy Management (J)	Poor	Moderate	Excellent
Energy Absorption Efficiency (%)	50%	70%	90%

5. CONCLUSION

This study demonstrated that the Fractional-Order PID (FOPID) controller outperforms conventional PID and passive damping systems in aircraft landing gear shock absorption by reducing settling time by 80.3%, overshoot by 43.1%, and achieving 90% energy absorption. Its adaptability, enabled through fractional calculus, was validated via simulations, experimental testing, and real-time microcontroller implementation. Future work should focus on full-scale FAA-certified testing, integration with machine learning for adaptive tuning, evaluation under extreme environments, and computational optimization for efficient embedded deployment.

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CONFLICT OF INTEREST

The authordeclared no potential conflicts of interest regarding research, authorship, and article publication.

DATA AVAILABILITY

The author confirms that the data supporting the findings of this study are available within the article.

AUTHOR CONTRIBUTIONS

Yaya Dagal Dari'[1]| : Design, Writing, Review, Editing, and Funding, Editing,

IdrissDagal | : Review, and Formal Analysis.Writing, Review, Editing, and Methodology, Formal Analysis, and Editing

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