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MAGNETORHEOLOGICAL DAMPERS IN LANDING GEARS: DYNAMIC ANALYSIS FOCUSED ON SHOCK ABSORPTION AND VIBRATION COMFORT

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Abstract. *This article investigates the use of Magnetorheological (MR) dampers in aircraft landing gear, aiming to improve safety, efficiency and comfort during the landing. MR dampers can adjust the damping force in real time, adapting its behavior to specific needs during this critical phase of the flight. The study considers the Spencer dynamic model, which includes non-linear characteristics, such that the hysteretic effect, and the decrease in the damping force if the velocity approaches zero. The work introduce force decomposition to the actuator into hydraulic, pneumatic and active components. The landing gear system is modeled with two degrees of freedom, taking into account the vertical oscillations. The analysis is conducted by numerical simulations using the fourth-order Runge-Kutta integrator method. The results are evaluated in terms of shock absorption efficiency and vibration comfort. The results obtained demonstrate the potential of the technologies based on MR dampers to improve flight safety and efficiency. Furthermore, these technologies have the potential to make aircraft landings more comfortable for passengers.*

Keywords: *MR Damper, Landing Gear, Dynamics Analysis, Vibration Comfort*

1. INTRODUCTION

In recent decades, innovative and promising technologies have emerged regarding the attenuation of vibrations using dampers, such that different applications involving Magnetorheological (MR) dampers. MR dampers are different from standard devices, and they are designed to take advantage of the MR fluid properties, whose characteristics can be controlled through a magnetic field. Discovered in the mid-1940s by Jacob Rabinow, these fluids are able to vary their resulting viscosity, presenting a semi-solid behavior in a magnetic field and an aspect similar to a Newtonian fluid in the absence of the applied magnetic field (Schwartz, 2008). In the automotive and aeronautical industries, these dampers are gaining notoriety, mainly in car suspension applications (Masa'id *et al.*, 2023) and in landing gears (Laporte *et al.*, 2020).

Landing gear is part of a typical aircraft that plays an extremely important role in aviation, providing a safe connection between the aircraft and the ground during landings, takeoffs, and even in ground maneuvers. This component supports the weight of the fuselage as well as contributes to attenuate the vibrations that occur during the landing. Typically, aircraft are equipped with passive oil-pneumatic landing gear that provides high-efficiency shock absorption (Currey, 1988). However, it is difficult for passive landing gear to attend performance specifications in different various landing conditions that are outside the designed conditions (Jo *et al.*, 2021). Then, an alternative to these problems is found in semi-active dampers, which offers the advantages of passive and active characteristics (WU *et al.*, 2007).

The active dampers can adjust their damping force through control based strategies (Dyke *et al.*, 1999). They also can ensure stability by reverting to the passive mode if electric voltage is not applied on it. This behavior between passive and active from semi-active dampers offers more precise and efficient control of vehicle dynamic behavior, resulting in an improved stability and comfort while driving vehicles or aircraft. The performance and stability of the developed landing gears are evaluated through impact tests, in which they are validated by numerical simulations. Numerous impact test simulations are performed using a simplified dynamic model, to evaluate the behavior and investigate the supported loads, during the landing, known as touchdown. This simplified model consists of a 2 degrees of freedom (2DOF) system (Batterbee *et al.*, 2007).

A dynamic model with high fidelity is commonly necessary to design controllers if MR dampers are employed in a particular application. Then, several models for this type of shock absorber have emerged over time, such as the Bingham model, Gamota and Filisko model, and the Bouc-Wen model (Spencer *et al.*, 1997). Although each one of these models has some disadvantages, such accurate hysteretic response representation, the change in force magnitude in relation to low speeds, and numerical instability in computational simulations, they provide interesting insight when investigating dynamics with dissipation devices. In this context, this article considers the dynamic analysis of the landing gear of a light aircraft, considering an MR damper instead of a conventional damper. The Spencer model is considered since it includes the non-linear behavior, which allows one to investigate the hysteretic effect, and exhibits the force-decreasing behavior if the involved velocity approaches zero. A landing gear model with 2 degrees of freedom is considered, which takes into account the vertical oscillations. The MR damper is applied between the first and second mass. The shock absorber force is rewritten and presented in terms of pneumatic, hydraulic, and active components (due to the acting magnetic field). The shock absorption efficiency is computed, as well as the Jerk parameter, which is used to evaluate the vibration comfort.

2. SPENCER MODEL

Figure1 shows a representation of an MR damper with a circular piston. The magnetic field is applied radially to the fluid, perpendicular to the direction of its displacement. The modeling of this system is carried out with the Spencer model, which is a phenomenological model, that presents responses that realistically describe the experimental observation of the physical responses of the system. This type of modeling describes physical phenomena from empirical data. The model is useful to represent physical phenomena in a realistic way, it is able to perform consistent analysis, and it describes a good relation between measured data and system responses (Mcmullin, 1968).

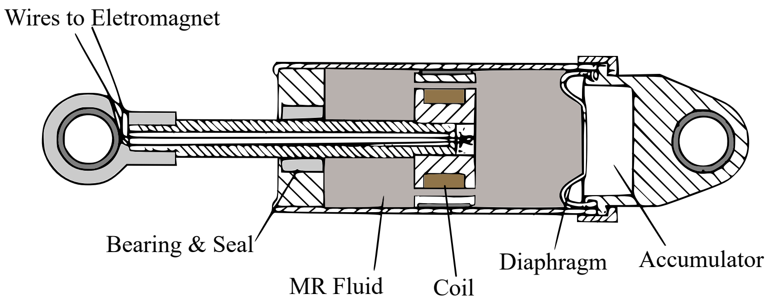


Figure 1. MR damper (adaptado de Dyke *et al.* (1999)).

Spencer *et al.* (1997) observed the force response and noted that when no electric voltage is applied to the coil (no magnetic field), the damper response behaves as a purely viscous device, but if the voltage is applied, a Bingham plastic behavior parallels the behavior of a viscous fluid arises, and for a certain voltage level, the increase of this force is nearly linear. The model proposed by Spencer is a modified Bouc-Wen model, which manages to better represent the real response of this type of damper device. In the modified model, the classic Bouc-Wen model is placed in series with a linear damper to model the response of the device when its velocity is close to zero, and this is in parallel with a spring which is added to take into account the accumulator from the device Spencer *et al.* (1997). A schematic representation of the model is presented in Fig.2.

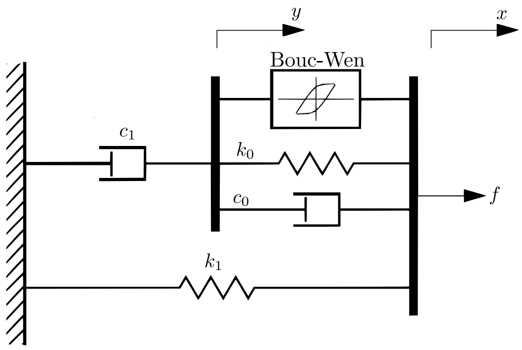


Figure 2. Schematic representation of the Spencer MR fluid damper model, where x and y are respectively the displacements of the rightmost and leftmost bar, f is the strength of the system, and c_1, c_0, k_1 and k_0 are model parameters.

2.1 Equation of MR Damper

The force exerted by the damper is given by Eq.(1) as follows

$$f = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) + k_1(x - x_0) \tag{1}$$

where z is an evolutionary variable (Wen, 1976), and $\dot{y}$ is obtained from a sum of forces in the upper region of the schematic model, and it is given by,

$$\dot{z} = -\gamma(\dot{x} - \dot{y})|z|z|^{n-1} - \beta|\dot{x} - \dot{y}|z|^n + A(\dot{x} - \dot{y}) \tag{2}$$

$$\dot{y} = \frac{1}{(c_0 + c_1)}\{\alpha z + c_0\dot{x} + k_0(x - y)\} \tag{3}$$

the parameters change their values based on the applied electric voltage and consequently with the change in the magnetic field, Spencer *et al.* (1997) proposed a first-order filter that varies in terms of the electric voltage, such that,

$$\dot{u} = -\eta(u - v) \tag{4}$$

in which the value of the parameters varies linearly with its response, as shown below by Eq.(5),

$$\alpha = \alpha(u) = \alpha_a + \alpha_b u, \qquad c_1 = c_1(u) = c_{1a} + c_{1b}u, \qquad c_0 = c_0(u) = c_{0a} + c_{0b}u \tag{5}$$

The stiffness term in the model due to the accumulator is represented by k_1 and x_0 represents an initial deflection in the spring, while the viscous damping observed at high speeds is represented by c_0. The c_1 component refers to a dashpot, which introduces a non-linear decrease in the force-velocity relationships observed at low speeds, and the parameter k_0 is used to control stiffness at high speeds. By manipulating the parameters γ, β, and A, it is possible to control the linearity of the unloading and the smoothness of the solidification of the fluid. These adjustments allow controlling the gradual progression and the transition from the liquid to the solid phase, ensuring the desired behavior. At last, x describes the piston displacement.

Furthermore, the relationship between force and velocity does not show significant deviations when acceleration and velocity have opposite signs and the magnitude of the velocities is small. Then, the model is able to maintain a consistent response, even when changes in velocity direction or magnitude occur. The 14 model parameters, c_{0a}, c_{0b}, k_0, c_{1a}, c_{1b}, k_1, x_0, α_a, α_b, γ, μ, A, n and η need to be adjusted from experimental data for different voltage values v. For the application of the model in the system of two degrees of freedom of the landing gear, there is only the need to change the displacement x, where this is considered the relative motion between the two masses, i.e., $x = s$ where $s = x_1 - x_2$ and the velocity is given by $\dot{s} = \dot{x}_1 - \dot{x}_2$.

2.2 Simplified Model of a Landing Gear

The modeling of the landing gear considers that, the instant in which the system touchdown occurs. In that instant, the horizontal energy is absorbed by the aircraft brakes, and the vertical energy is absorbed by the landing gear through the tire. Figure 3 presents a system of 2 degrees of freedom that represents a landing gear with an MR damper, which is inspired by the simplified model of 1/4 of the vehicle, where m_2 represents the tire mass, m_1 represents the mass of the fuselage supported by the actuator Spencer *et al.* (1997), and f the actuator force given by the Spencer model Fig.2. The tire reaction force is given by $F_{tire} = k_t \cdot x^b$ where k_t is the stiffness of the tire and b is an exponent for including nonlinearity in the force, and x_1 and x_2 are the masses displacements from m_1 and m_2, respectively.

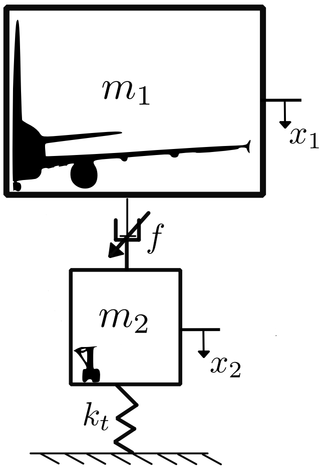


Figure 3. Two degrees of freedom landing gear model.

The model presented above has its dynamics described by a system of 2nd-order equations given by,

$$\begin{cases} m_1\ddot{x_1} = -f + m_1 g \\ m_2\ddot{x_2} = f - k_t x_2^b + m_2 g \end{cases} \tag{6}$$

The force of the shock can be rewritten in the form of Eq.(7) to present the force components in terms of the pneumatic force (F_p) and the MR fluid (F_{mr}) force.

$$f = F_p + F_{mr} \tag{7}$$

If the system is not influenced by a magnetic field (i.e, v = 0 V), the forces acting on the system are the hydraulic force of the MR fluid (F_h) and the pneumatic forces due to the accumulator (F_p) such that.

$$\begin{cases} F_p = k_1(x - x_0) \\ F_{mr} = F_h, & \text{if } v = 0. \\ F_h = \alpha z + c_0(\dot{x} - \dot{y}) + k_0(x - y) \end{cases} \tag{8}$$

On the other hand, if a magnetic field is applied to the system ($v \neq 0$ V), the MR fluid in contact with the field solidifies, presenting in parallel with the viscous damping, a damping similar to that provided by a Bingham fluid. In this model, the variation due to the magnetic field is projected into the variables c_0, c_1, and α, where they vary linearly with the voltage. The increase in hydraulic force relative to the fluid with no field applied is the active force (F_a), and it can be obtained computing the difference between the forces F_{mr-on} (condition with magnetic field, $v \neq 0$) and F_{mr-off} (condition without the magnetic field, v=0), as presented in Eq.(9).

$$\begin{cases} F_{mr} = F_h + F_a, & \text{if } v \neq 0. \\ F_a = F_{mr-on} + F_{mr-off} \end{cases} \tag{9}$$

The impact absorption efficiency is given by Eq.(10), where s is the relative displacement associated to the spring and F_s is the ground reaction force ($k_t \cdot x_2^b$), which is also the force at the support.

$$E[\%] = \frac{\int_0^{s_{max}} F_s ds}{F_{s,max} s_{max}} \tag{10}$$

The device efficiency is computed based on the energy dissipated by the landing gear in relation to the total mechanical energy of the aircraft immediately before its contact with the ground (Jo *et al.*, 2021). This parameter is essential to evaluate the performance of the MR fluid in comparison with other types of dampers, such as those purely hydraulic and pneumatic devices.

Another important performance indicator is the Jerk (j), which is the rate of acceleration over time, which can be determined by the following equation

$$j = \frac{d}{dt}\ddot{x}_1 \tag{11}$$

This parameter is computed in relation to the displacement of the mass m_1 (fuselage) and it provides interesting information to evaluate the level of comfort caused by the system acceleration over time.

2.3 System parameters

The proposed methodology is investigated by considering the parameters of the landing gear previously considered by Jo *et al.* (2021). They are presented in Tab.(1). The MR damper device is described by the Spencer model, in this paper optimal parameters for a landing gear design were not considered, since this, being a phenomenological model, has the need that, after being built, it has its values adjusted in the model through algorithms of optimization, such as done by Spencer *et al.* (1997) and WU *et al.* (2007). However, the authors sought from empirical methods to obtain values for the parameters so that the scale of the force generated by the shock absorber is close to the results presented by Jo *et al.* (2021). The adjusted parameters are shown in Tab.(2).

Table 1. Landing Gear Parameter (Jo *et al.*, 2021).

Parameters	Values
m_1	245 kg
m_2	15 kg
k_t	412 kN/m
b	1.13

Table 2. Parameters of the Spencer's MR damper model.

Parameters	Values	Parameters	Values
c_{0a}	4737.6 N . s /m	α_a	0.056 N/m
c_{0b}	197.4 N . s / V . m	α_b	2820.513 N /V . m
k_0	31025.641 N/ m	γ	363 m^{-2}
c_{1a}	2000.32 N . s /m	β	363 m^{-2}
c_{1b}	987 N. s / V . m	A	301
k_1	19743.59 N/ m	n	2
x_0	0 m	η	190

3. RESULTS AND DISCUSSION

Numerical simulations were carried out using an implemented Python-based algorithm. The integration of the system differential equations over time was performed using a fourth-order Runge-Kutta integrator from the SciPy library, where t is taken into the range $0 < t \leq 2$ s, with a total of 65536 points. Three different cases were evaluated considering different electric voltages, i.e., 0, 1.5, and 3 Volts, for applying passive control on and off. The analysis considers the time instant of the system touchdown, that is, at the exact moment that contact with the ground occurs, the initial conditions for the landing gear system were used equal to zero for the mass displacements and 3 m/s as sink speed, which is a commonly used standard as presented by Yoon *et al.* (2020). The damper initial conditions were taken equal to zeros.

Figure 4 presents the results for the case with 3 different electric voltages. Note that Figs.(4a-b) show a reduction in the piston stroke and velocity, from the relative displacement and its velocity between the masses (s, $\dot{s}$) with increasing voltage and, consecutively, increasing the magnetic field. Figure (4c) shows that an increase in the applied electric voltage, the ground reaction force also has growth, but this also causes greater damping of the oscillations in time, followed by the application of smaller forces in the next stages of compression and expansion. On the other hand, the Fig.(4d) shows the strut force by piston displacement. The force exerted by the structure has two distinct peak moments during compression (in v=0 V).

The first peak is a result of hydraulic force (around 15 mm, $v = 0$ V), while the second peak is caused by the compressed air force (the region between $150 < s < 290$ mm, $v = 0$ V), which is better seen in the model presented by Yoon *et al.* (2020), where the pneumatic force is given by an ideal gas. The efficiency is given by the area below the curve, where the distance between the peaks takes an important role, that is, the smaller the disparity between these two peaks implies to a more efficient system. Regarding the MR fluid, it can be seen that a higher system voltage, presents itself as more fluid solidified. The results show that the first peak is amplified due to the increase in electric voltage, consequently causing the graph to present a larger amplitude in the strut force direction. However, the pneumatic force is pulled to the left and the valley is suppressed, compelling the two peaks more parallel with each other, such that the area below the curve increases, and improves the landing efficiency.

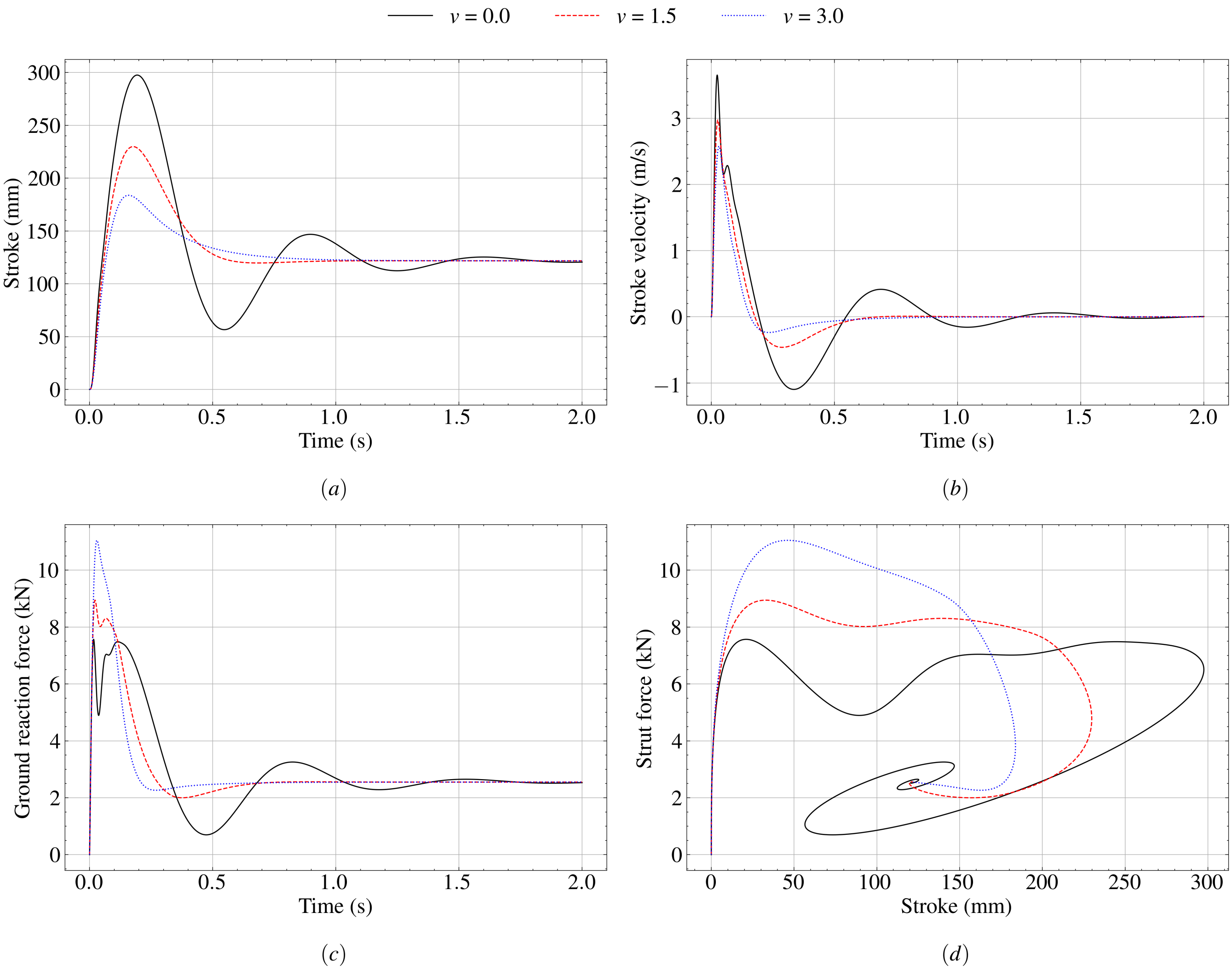
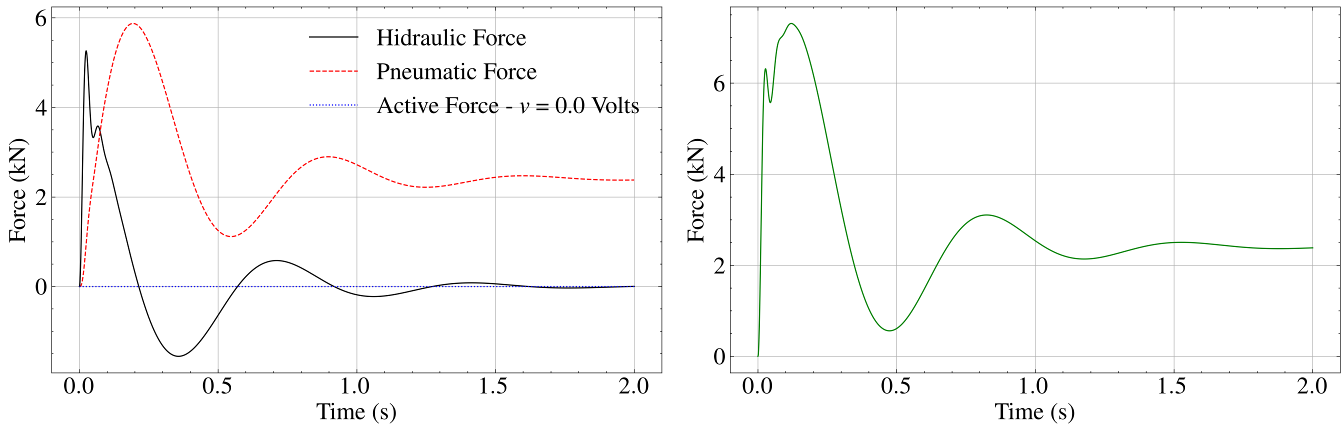


Figure 4. Landing gear responses over time: a) Stroke , b) Stroke velocity , c) Ground reaction force , d) Strut force.

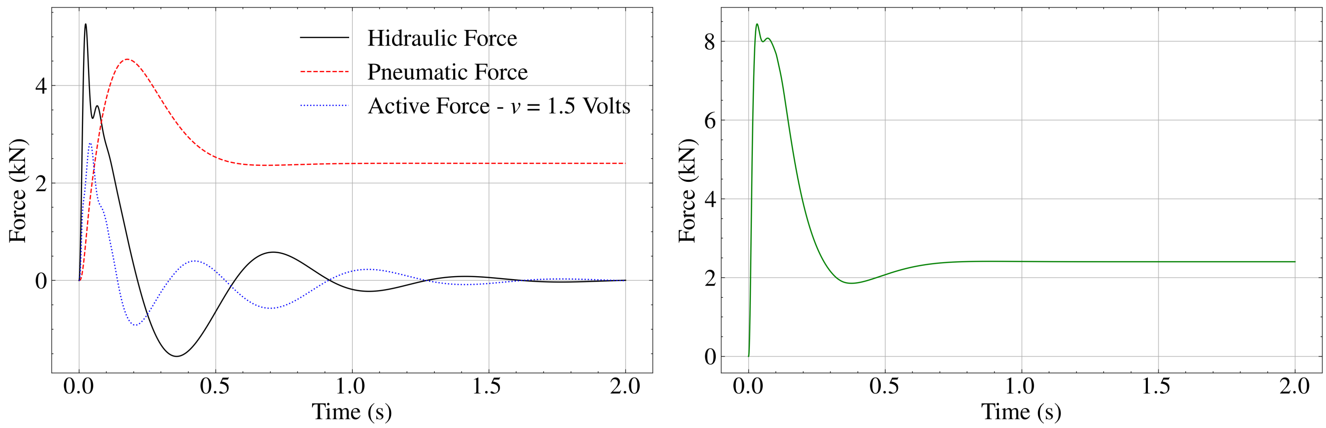
Figures (5-7) present the force exerted by the damper considering different elements to compose it, i.e., the terms hydraulic, pneumatic, and magnetic with the three components to allow a visualization of the scale of their forces and the action of the tension in the total response of the system. The results show that if no voltage is applied (Fig.5), the system response to the model used responds similarly to that observed by alternative models as presented by Jo *et al.* (2021); Yoon *et al.* (2020). Figure (4a) shows that the initial stage of the first compression is dominated by the hydraulic term due to the high velocity of the stroke, and at the end of the compression the pneumatic force acts due to the large displacement, the two peaks can be seen in Fig.(4b).



(a) (b)

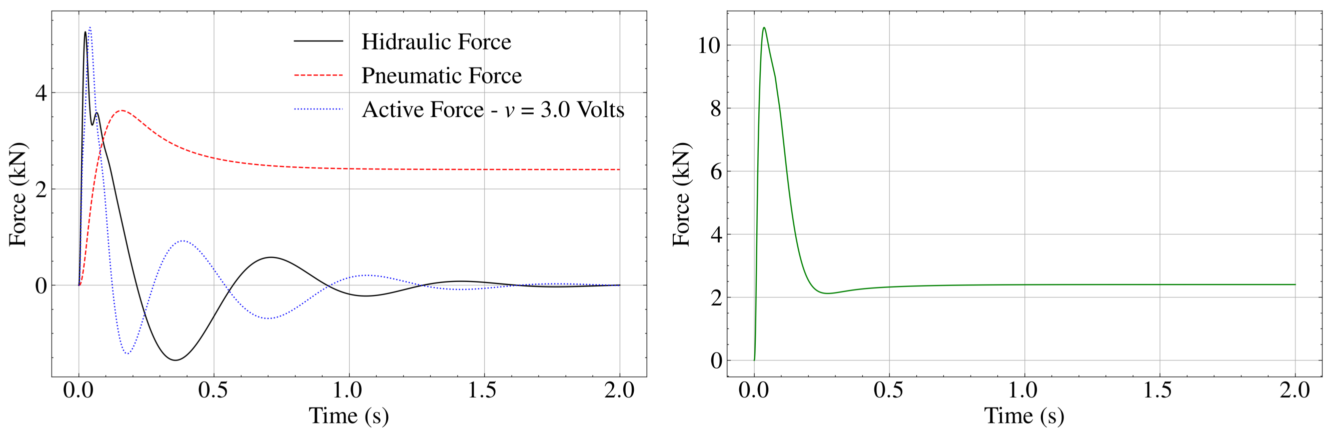
Figure 5. Forces acting on the system: a) Force components, b) Actuator force (v = 0 V).

Figures (6-7), show a similar behavior, if an electric voltage is applied. However, this time decreasing the scale of force related to the pneumatic part, since the system has enough damping to reduce the displacement of the stroke in the first stage of compression due to the activation of the force provided by the action of the magnetic field, causing the system to oscillate with a small displacement and thus making the force produced by this term almost constant, the reduction of this force can be seen most prominently in Fig.(4d).



(a) (b)

Figure 6. Forces acting on the system: a) Force components, b) Actuator force (v = 1.5 V).



(a) (b)

Figure 7. Forces acting on the system: a) Force components, b) Actuator force (v = 3.0 V).

Figure (8a) represents the displacement of the mass of the fuselage. It is possible to observe its movement at the time of landing, therefore, it is noted that the higher displacement level in the first impact that the aircraft experiences. Figure (8b) presents the aircraft acceleration, and it becomes an important parameter in relation to the comfort of the passengers. So, it is possible to observe that in the first seconds, the acceleration is high, which suggests an important potential discomfort to the passengers. In addition, Fig.(8c) shows its time variation rate, i.e., the system jerk, from which is possible to observe that the jerk decreases over time, thus the system comfort increases, since the disturbances are minimized.

The drop in the peak at the first contact is due to the wheel with the ground, with the increase in voltage there is a more sudden drop, due to the MR fluid causing the system to stabilize faster, as the energy dissipation at the first contact is bigger than the other ones. On top of that, Fig.(8d) presents the efficiencies for each voltage applied to the system, in the case of 0V the system efficiency is given only by the hydraulic and pneumatic forces. If the electric voltage is applied, the MR fluid starts to act, consequently increasing the efficiency of the system, presenting an efficiency of 69.5 % for 0V , 76.3 % for 1.5 V, and 77.2 % for 3 V.

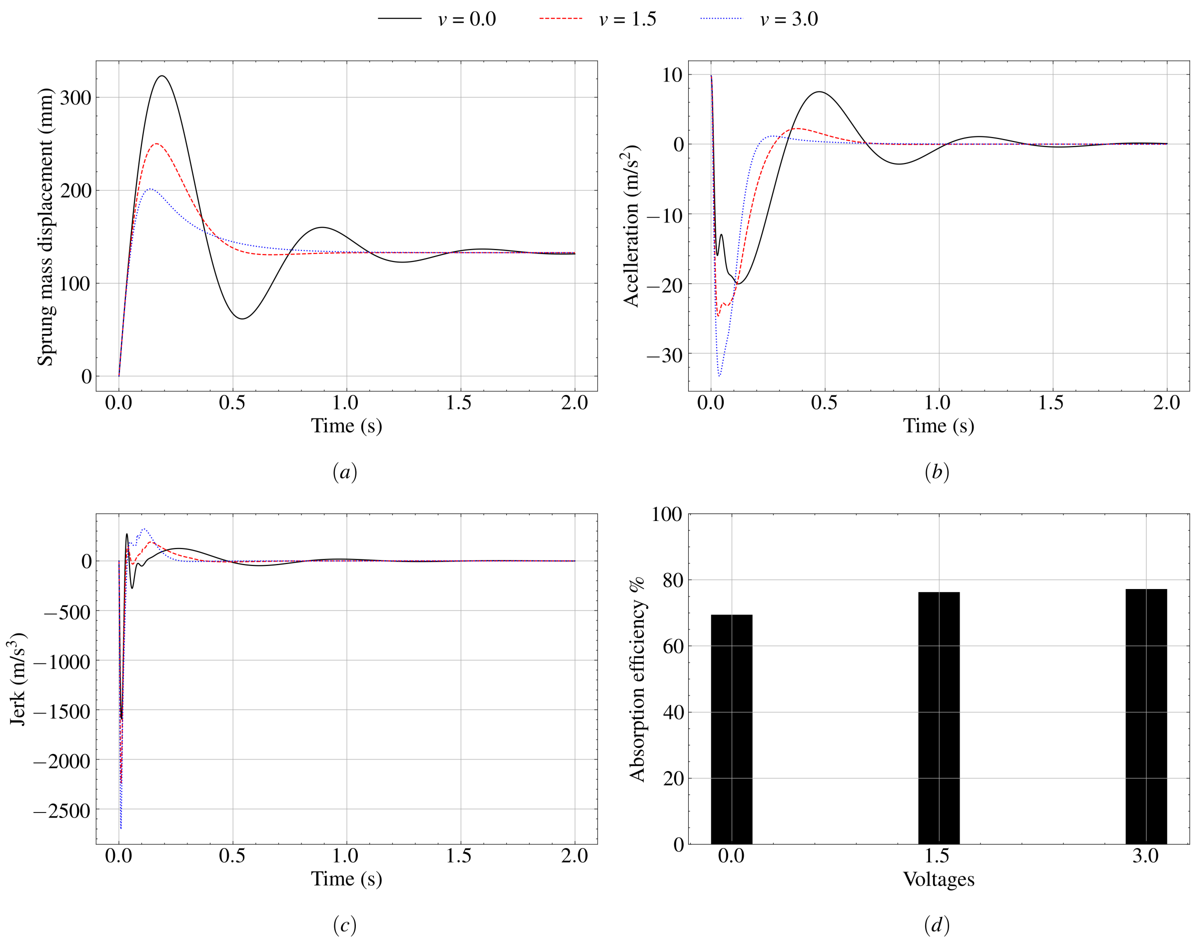


Figure 8. Efficiency and comfort parameters: (a) Sprung mass displacement, (b) Sprung mass acceleration, (c) Sprung mass jerk, (d) Absorption efficiency.

4. CONCLUSION

In this article, the Spencer MR damper model was used for modeling a magnetorheological damper device connected to a 2 DOF landing gear system. The model force components were evaluated to investigate the contributions of the pneumatic, hydraulic, and magnetic terms. Then, it was possible to understand the action of each one separately to each other. The Spencer model was used to adjust the geometric and physical parameters involved to obtain the MR force.

Numerical simulations were carried out focused on designing a passive controller. The response of the MR fluid in the landing gear system at the moment of landing due to an arbitrary voltage was obtained. In addition, three different electric voltages were used (0, 1.5 and 3 Volts). An increase in shock absorption was observed in comparison with the case of 0 V, such that 1.5 and 3 V of 9.8% and 11.2%, respectively. In relation to the jerk, this has a higher initial peak due to the deceleration in the initial instant provided by the active effect of the damper, but over time there is a decrease. Taking the area of the absolute value of the jerk over time, it is obtained that the jerk for the case of 1.5 and 3 V in relation to 0 V has a decrease of - 19.5 % and - 1.6%, which is an interesting result since the minimization of jerk is favorable to increase comfort in terms of the vibrations.

For future work, a parameter adjustment method to the Spencer model will be proposed and the use of a controller should be applied for a greater gain in efficiency and the minimization of jerk, where it can be observed that this last parameter of comfort, when having a higher voltage applied rises again, which can be improved using an active controller.

5. ACKNOWLEDGMENT

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7. RESPONSIBILITY NOTICE