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RESEARCH PAPER

Shock absorber system dynamic model in model-based environment

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Abstract

This paper addresses the mathematical modelling of aircraft landing gear based on the shock absorber system's dynamics and examination of results depending on different touchdown scenarios and design parameters. The proposed methodology relies on determining an analytical formulation of the shock absorber system's equation of motion, modelling this formulation on the model-based environment (Matlab/Simulink), and integrating with an accurate aircraft nonlinear dynamic model to observe the performance of landing gear in different touchdown or impact velocities. A suitable landing performance depends on different parameters which are related to the shock absorber system's working principle. There are three subsystems of the main system which are hydraulic, pneumatic, and tire systems. Subsystems create a different sort of forces and behaviors. The air in the pneumatic system is compressed by the impact effect so it behaves like a spring and creates pneumatic or air spring force so the most effective parameter in this structure is determined as initial air volume. Hydraulic oil in the receptacle of the hydraulic system flow in an orifice hole when impact occurs so it behaves as a damper and creates damping or hydraulic force. The same working principle is acceptable for the air in the tire. The relationship between tire and ground creates a friction force based on dynamic friction coefficient depending on aircraft dynamics. As a result of this study effect of the impact velocity and initial air volume parameters on the system are examined and determined by optimization according to maximum initial load limits of aircraft and displacement of strut and tire surface.

Key words: Shock absorber; landing-touchdown performance; oleo-pneumatic and strut; aircraft landing loads
AMS 2020 Classification: 37M05; 37N35; 93C10; 93C35.

1 Introduction

Shock absorber systems have essential roles in aircraft structure. Accidents occur during both landing and takeoff. Shock absorber systems in landing gear can absorb the touchdown loads. This system needs to be designed and controlled as it can provide a health touchdown condition before the manufacturing process. There are two controlling ways observe the system's qualification. The first one is an empirical way that needs to test apparatuses [1]. Applying this way is expensive because there is a mechanic system to observe touchdown condition. The second way is the analytic or simulation method. In this method, the dynamics of shock absorber systems, equations of motions, tire behaviors etc. are simulated in computer programs (Matlab/Simulink) [2, 3, 4, 5].

In addition, according to international regulations and literature, there are a few landing conditions (three-point landing, two-point landing) [6, 7, 8]. These conditions directly affect the response of the system. In one-gear landing conditions, the aircraft is in the level

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attitude. In this condition aircraft contact the runway on one main landing gear and touchdown velocity is the most important parameter for the shock absorber to healthy landing. In two-point landing conditions, load factors and pitching accelerations are changed by time. Main gear landing loads are critical in this condition. Changes in load factors are caused to differences in landing gear systems design parameters. Examples of these parameters are hydraulic characteristics and oleo length. In three-point landing conditions, pitching acceleration is equal to zero. the nose gear system and its structures are generally critical in this condition and the nose landing gear carries %15 of the total weight of the aircraft in the static position [9]. One of the main function of the landing gear systems is the compensation of the maximum critical load. The critical parameter which is the most important input to the model is a vertical component of touchdown velocity. It directly affects the motion. Some experiments show the critical touchdown velocity is between the $3-5\ m/s$ [10].

The discharge coefficient which is determining the buffer damping force is generally determined between 0.8-0.82 which is related to the hydraulic flow motion [1]. The oleo-pneumatic shock absorber system has a few subsystems. In this system, the air is directly used to store the impact energy. Air works like a spring and produces a spring force (air spring force). Air spring force depends on a few parameters. For instance, the initial pressure of air which is generally determined firstly is can be calculating if the air vehicle mass is known. So, initial pressure is a main design parameter. Desired air spring deflection is observed in static position of the air vehicle may determine this parameter. The other store part for impact energy is the hydraulic damping. The behavior of hydraulic oil during corresponding impact force is the product of hydraulic force. The tire which is working as a spring is needed to bear all produced forces. The tire spring characterize is the most important parameter that can directly affect the tire behavior [11].

Different coefficients of friction in different runway conditions cause frictional force variation between the aircraft and the runway. Change in friction force affects the friction force which is normal to the axis of the shock strut and friction force at the tire in the horizontal direction. The dynamic friction coefficient between the tire and the runway is not a constant value and can be expressed as a dependent function of forward velocity (u), the forward speed of the aircraft in the x direction. There is an inverse proportion between forward speed and dynamic friction coefficient.

the shock absorber landing gear system is simulated with the integration of aircraft non-linear dynamic model in this paper. The most important parameter that is impact velocity, is considered when landing maneuver scenarios creates. In this study, we want to develop a generical model of the nose and main landing gears.

2 Methodology

In this section, the oleo-pneumatic shock strut system dynamic is explained and modelled. Figure 1 shows the schematic view of the oleo-pneumatic shock strut where A_a is the net pneumatic area, A_n is the net orifice area, A_h is the net hydraulic area.

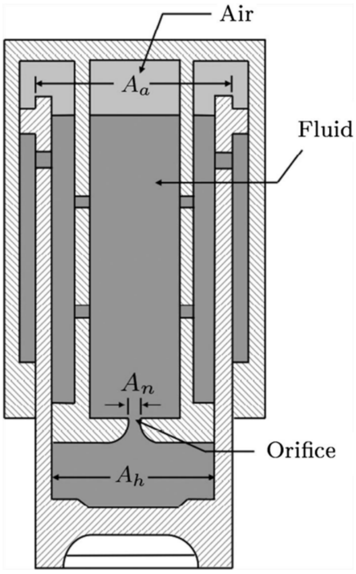

Figure 1. Schematic view of the oleo-pneumatic shock strut [15].

Mathematical model

Pneumatic force

The mathematical model of the pneumatic force in shock strut is given as:

$$F_a = A_a P_{a_0} \left(\frac{v_0}{v_0 - S_s A_a} \right)^n , \tag{1}$$

$$S_s = \frac{Z_1 - Z_2}{cos\phi} , \tag{2}$$

where F_a is the pneumatic force (air-spring force), A_a is the pneumatic area, p_{a_0} is the initial strut air pressure, v_0 is the initial air volume, n is the effective polytropic exponent for the nitrogen-compression process, S_s is the deflection of the shock strut, Z_1 and Z_2 are the vertical displacement of sprung (aircraft structure) and the unsprung mass respectively and α is the anteversion angle of the strut [12, 13].

There are many reasons why nitrogen is used instead of air in the damper system. Firstly, since the air contains oxygen and hydrogen, moisture formation may be observed during operation and this may increase the risk of cavitation. Therefore, using nitrogen is more advantageous. Secondly, during operation, the nitrogen internal pressure is more consistent than the air internal pressure. Thirdly, since the density of nitrogen is greater than the density of air, it can keep the damper pressure longer period of time. Finally, since nitrogen is an inert gas, it does not react with other damper components [14].

Hydraulic force

The main orifice hydraulic force is:

$$F_h = \rho \left(\frac{A_h^3}{2A_0^2 C_d^2} \right) |\dot{S}|\dot{S}, \tag{3}$$

$$\frac{1}{C_d} = \frac{1}{0.827 - 0.0085\frac{l}{d}} + \frac{20}{Re}\left(1 + 2.25\frac{l}{d}\right), \tag{4}$$

where F_h is the hydraulic force, ρ is the density of the fluid, A_h is the hydraulic area, A_0 is the sectional area of the orifice inlet, C_d is the discharge coefficient, $\dot{S}$ is the stroke telescoping velocity, R_e is the Reynold number, l is the orifice length, d is the orifice diameter. Hydraulic force is the measurement of the pressure loss between the ends of the shock absorber. The discharge coefficient is calculated to find the relationship between the shock absorber hydraulic force and the strut telescoping velocity. In this paper, the l/d ratio was assumed as greater than 2. In line with the assumptions, the formula in Eq. 4 was used. According to the researches, C_d value was determined approximately 0.8 and the C_d value was assumed as 0.8 in [1, 15].

Friction force

The internal friction force in shock strut is;

$$F_f = \frac{\dot{S}}{|\dot{S}|}|F_{N\alpha}|\left[(\mu_1 + \mu_2)\frac{l_2 - S}{l_1 + S} + \mu_2\right], \tag{5}$$

$$F_{N\alpha} = \frac{w}{g}\ddot{Z}_1 \sin\alpha + F_{vg}\sin\alpha - W_2\sin\alpha - F_{hg}\cos\alpha, \tag{6}$$

$$F_{hg} = F_{vg}\mu_{gr}, \tag{7}$$

where F_f is the friction force, $\dot{S}$ is the stroke telescoping velocity, $F_{N\alpha}$ is the force normal to the axis of the shock strut applied at axle, μ_1 is the friction coefficient between inlet cylinder and stroke surface above the orifice area, μ_2 is the friction coefficient between inlet cylinder and stroke surface at below the orifice area, l_1 is the distance between the axle and orifice area, l_2 is the distance between orifice area and upper of landing gear, α is the anteversion angle of shock strut, F_{vg} is the vertical force of tire, F_{hg} is the horizontal force of tire, μ_{gr} is the friction coefficient between ground and tire. There are two sources of friction which are tightness of seal and deformation of shock strut. The friction forces acting on the direction of strut were considered [16].

Tire force

Vertical tire force which is acting during the landing progress results from the tire compression is given by:

$$F_{vg} = (1 + \dot{Z}_2 C_T) f Z_2, \tag{8}$$

where $\dot{Z}_2$ is the tire hub vertical velocity, C_T is the vertical damping coefficient of the tire, fZ_2 is the tire static compression curve. Figure 2 shows the tire footprint. Where P is the internal tire pressure, R_L is the loaded radius, D_0 is the diameter of tire, d is the collapse distance. The dynamic friction coefficient changes depending on the forward speed of the aircraft in the x direction. The equation for the variable dynamic friction coefficient is given in below;

$$\mu(\lambda, \nu) = e^{C_4 \lambda \nu}[C_1(1 - e^{-C_2\lambda}) - C_3\lambda], \tag{9}$$

where C_1 is the friction curve maximum value, C_2 is the friction curve shape, λ is the slip ratio, μ is the aircraft forward speed, C_3 is the difference between the maximum value at $\lambda = 1$ and the maximum value of the friction curve, C_4 is in the range of $0.02 - 0.04 s/m$. For dry concrete condition parameters which used in this paper are: $C_1 = 1.2801$, $C_2 = 23.99$, $C_3 = 0.52$ and $C_4 = 0.03 s/m$ [17]. Figure 3 shows the relationship between slip ratio and friction coefficient.

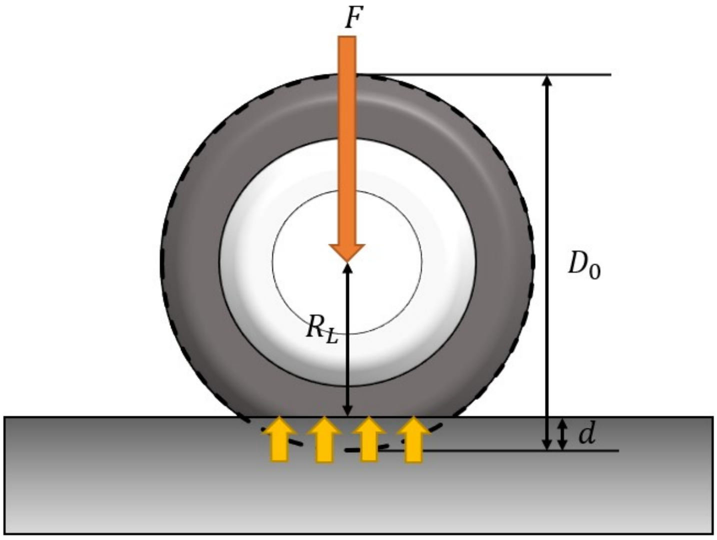

Figure 2. Tire footprint.

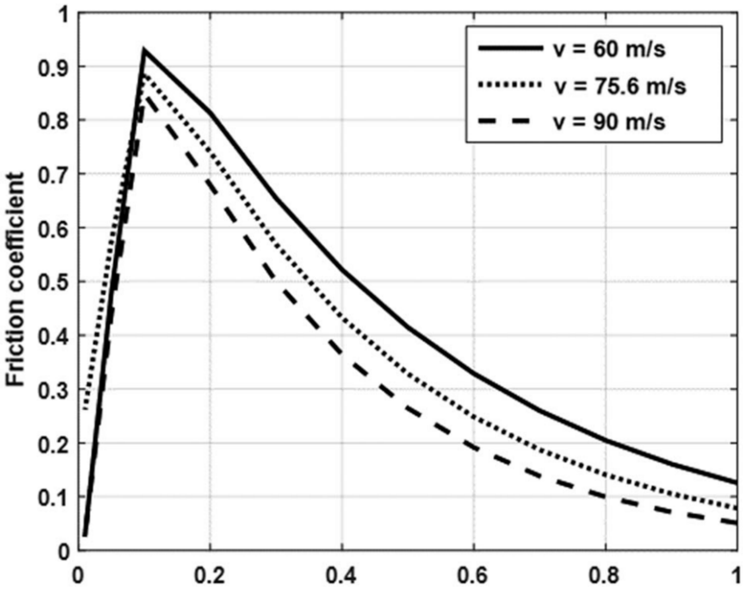

Figure 3. Relationship between λ and μ at different horizontal landing speeds [17].

Equations of motions

Tire rotation and deformation in horizontal direction are not considered, the nonlinear equations of motions are given below;

$$m_1\dot{Z}_1 = m_1 g - (F_a + F_h + F_f)\cos(\alpha), \tag{10}$$

$$m_2\dot{Z}_2 = m_2 g + (F_a + F_h + F_f)\cos(\alpha) - F_\mu, \tag{11}$$

where Z_1 and Z_2 are the vertical displacements of sprung (aircraft structure) and unsprung mass respectively [1]. Figure 4 shows the landing gear forces. $R_{(l,u)(x,y)}$ is the bearing reaction force at lower and upper, F_H is the hydraulic force, F_A is the air spring force, F_f is the friction force, F_{vg} and F_t are vertical and horizontal forces, α is anteversion angle of shock strut [18]. Figure 4 shows the free body diagram of the total system as two degrees of freedom.

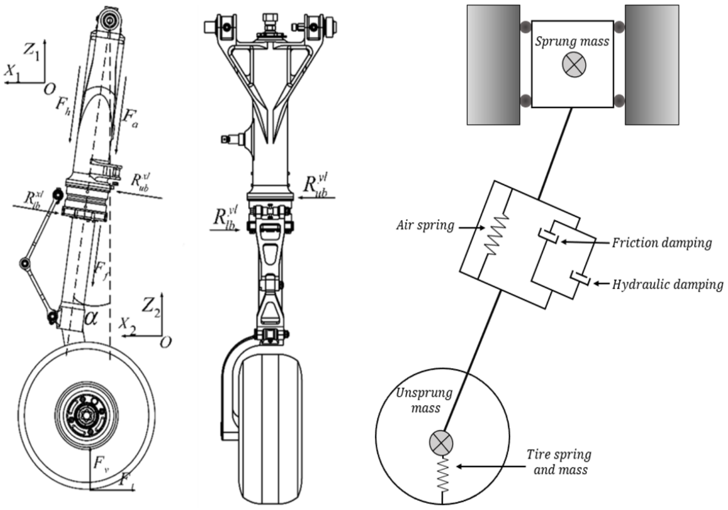

Figure 4. Forces on landing gear [1] and free body diagram of landing system.

3 Plant model development

Figure 5 shows the schematic of Simulink model. There is not any pneumatic force effect on aircraft at the initial time because there should be a reaction force of the pneumatic system to hold the airspring force. There is a pneumatic force but it does not affect aircraft force equilibrium. So, the initial force of the pneumatic system subtracts from the total strut force which directly affects the equations of motion. Figure 5 also shows the schematic of the flight dynamic model and dynamic friction coefficient connection. Since the forward speed of the aircraft v is a parameter that affects the dynamic friction coefficient function, the aircraft non-linear dynamic model is also considered in this paper. Figure 6 shows the results of dynamic friction coefficient's results depends on aircraft dynamics.

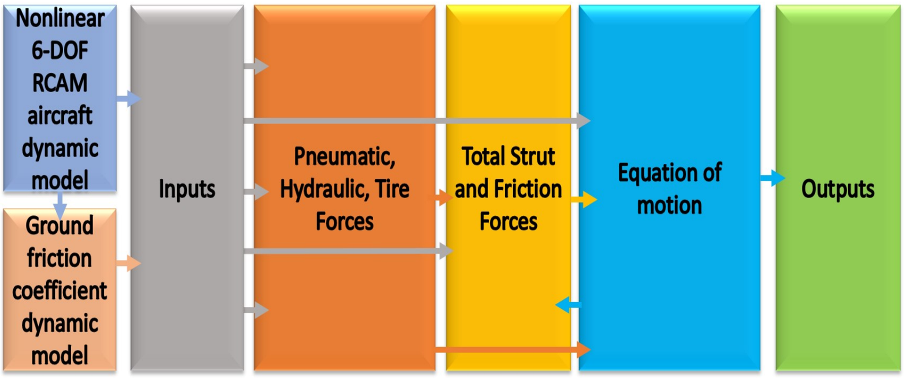

Figure 5. Schematic of Simulink model.

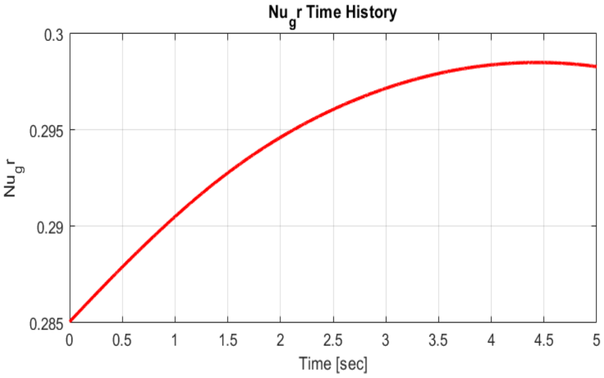

Figure 6. Dynamic friction coefficient results.

Table 1 shows the values of shock absorber system parameters.

Table 1. Parameter values and units

Parameters	Values	Units
A_a	0.014	m^2
A_h	0.013	m^2
A_n	0.0006412	m^2
n	1.6	–
ϕ	0	deg
k	950000	N/m
C_T	25000	Ns/m
μ_1	0.006	–
μ_2	0.006	–

4 Simulation results

To assess the optimum landing performance of an aircraft without any structural damage this section presents a series of simulation results that illustrate the behavior of the shock absorber system reacting to different impact velocities and initial air pressure in pneumatic system. According to the results of applying different impact velocities (2 m/s, 3 m/s, 4 m/s) to system, the displacement of sprung and unsprung mass increase proportionally with increase of impact velocities. Maximum displacement in sprung (strut) mass determined as 37.55 cm and displacement of unsprung (tire) mass determined as 15.31 cm in 4 m/s condition. Maximum loading on sprung mass that is critical structure was determined as -5.6 g and loading on unsprung mass was determined as -11.85 g. The passing time of damping of systems is inversely proportional to impact velocities because higher impact velocity creates more energy to absorb as shown on Figure 7 and Figure 8. According to the examination of these results, optimum impact velocity is determined as 3 m/s. Because, according to the design limits of sprung mass, the maximum load should be under -4.5 g. To reach the optimum performance, the impact velocity should be determined according to minimum damping time, maximum load below structural limits. Forces acting on the system according to different impact velocities as shown in Figure 9 and Figure 10.

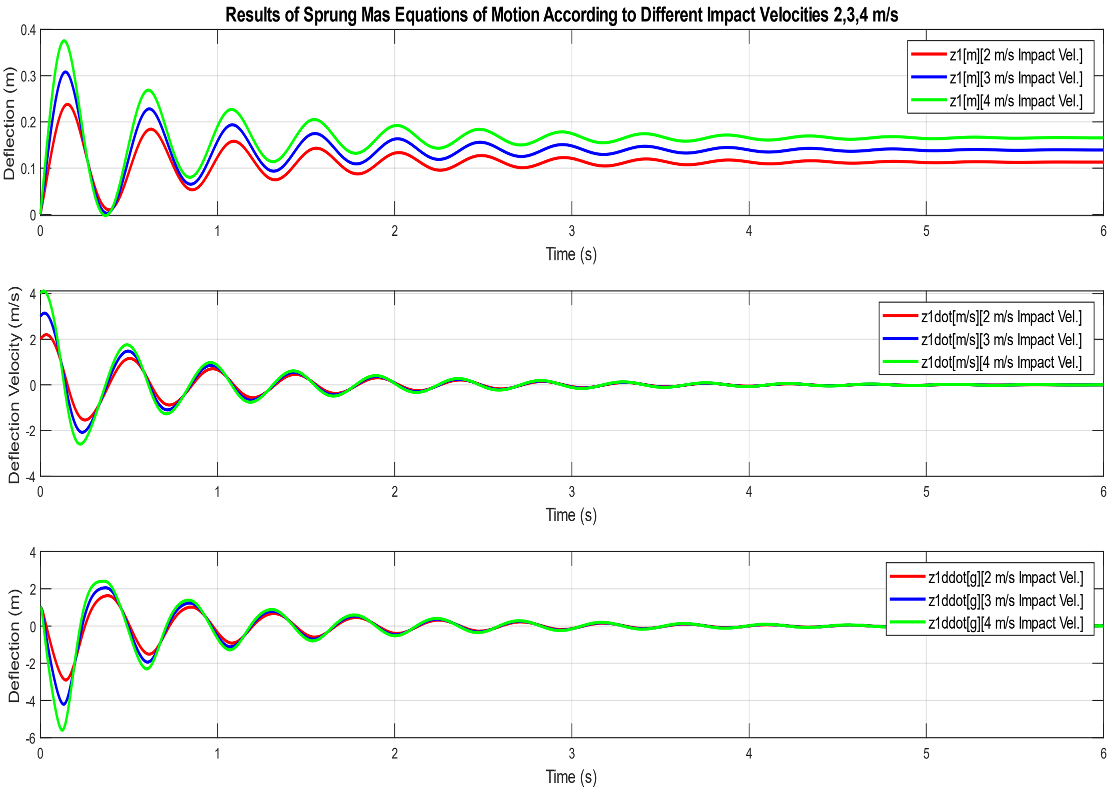

Figure 7. Sprung mass equations of motion results according to different impact velocities.

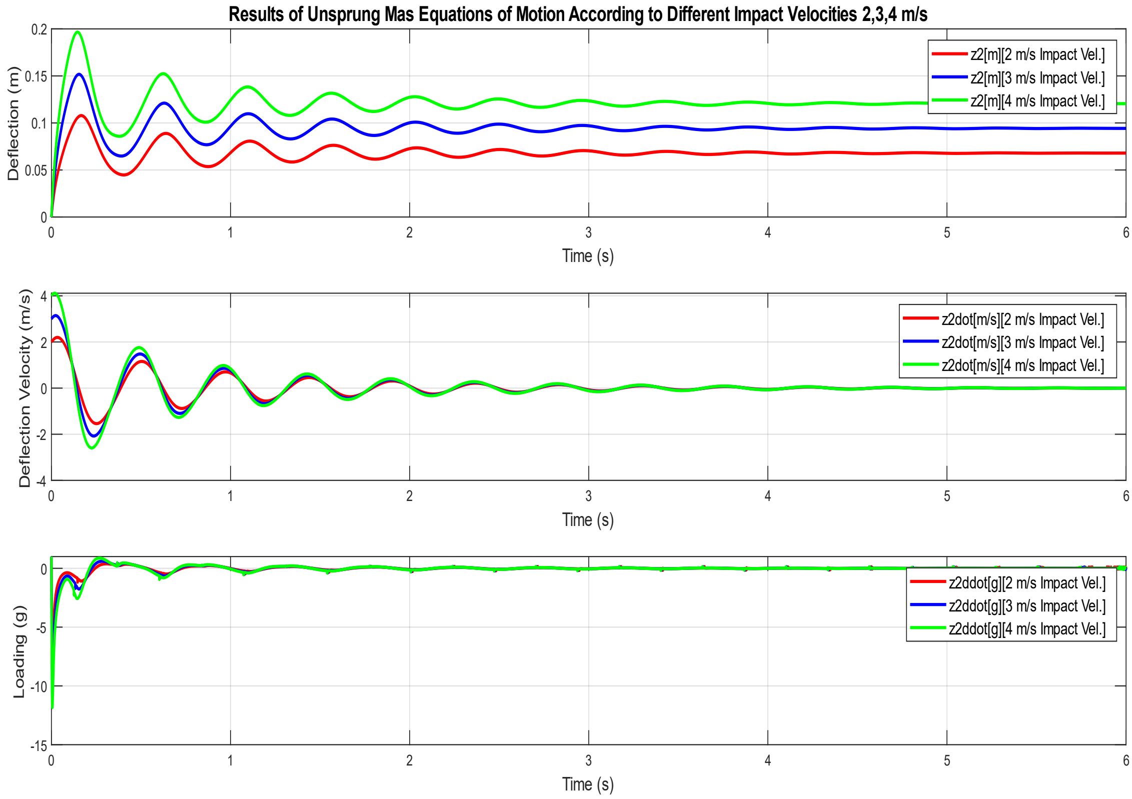

Figure 8. Unsprung mass equations of motion results according to different impact velocities.

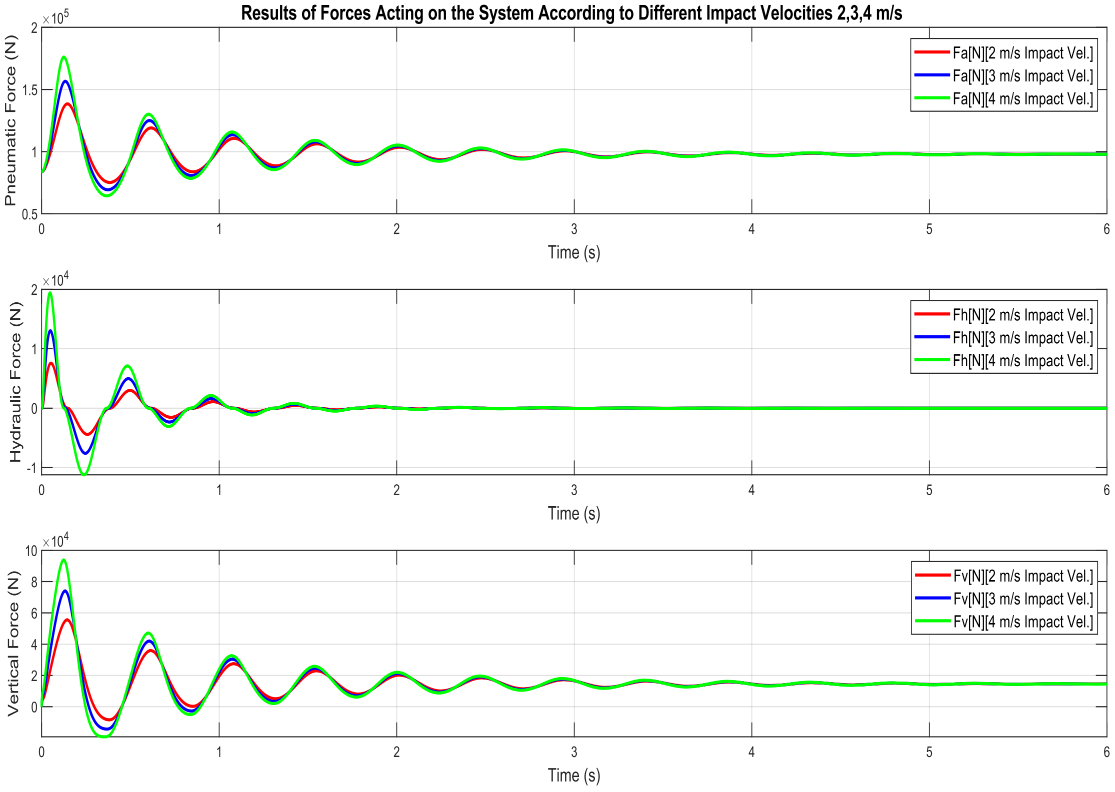

Figure 9. Forces acting on the system results according to different impact velocities.

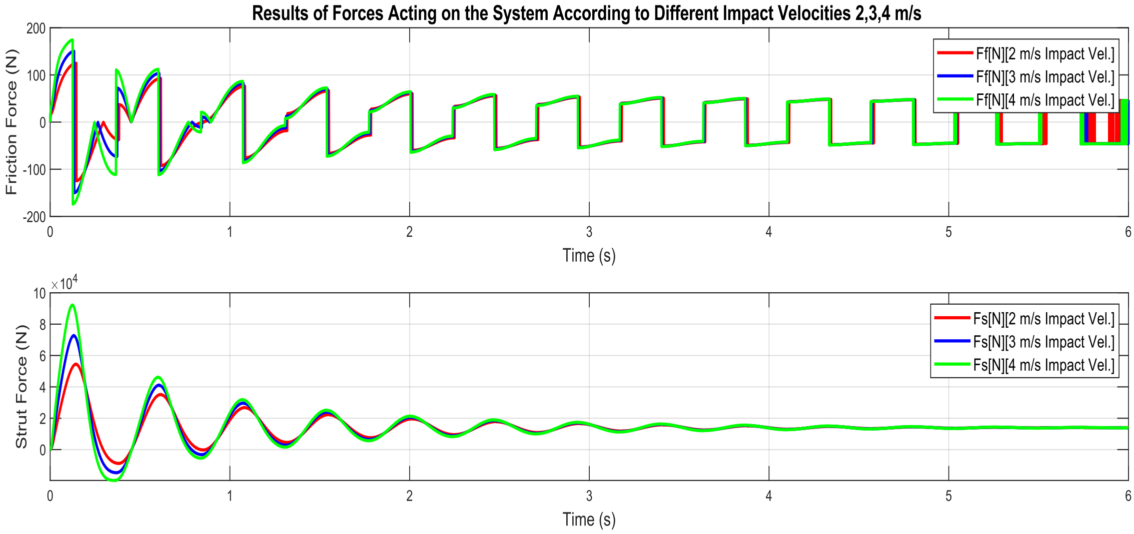

Figure 10. Forces acting on the system results according to different impact velocities.

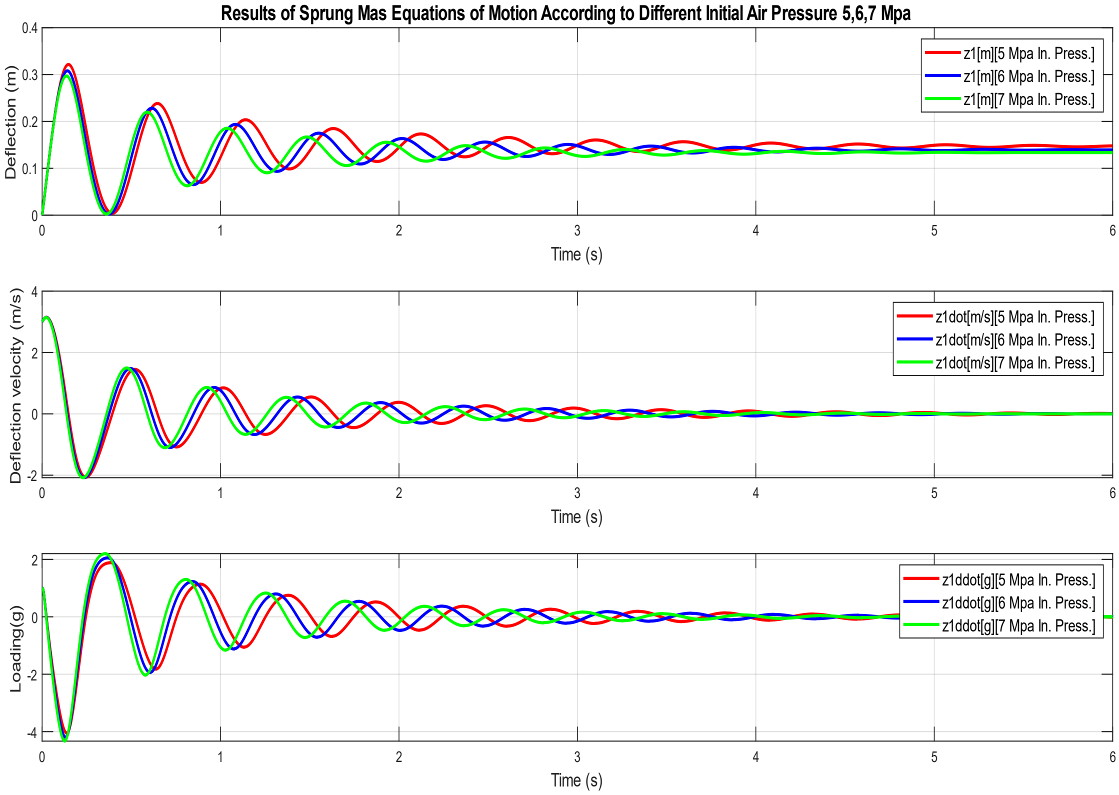

Figure 11. Sprung mass equations of motion results according to different initial air pressure.

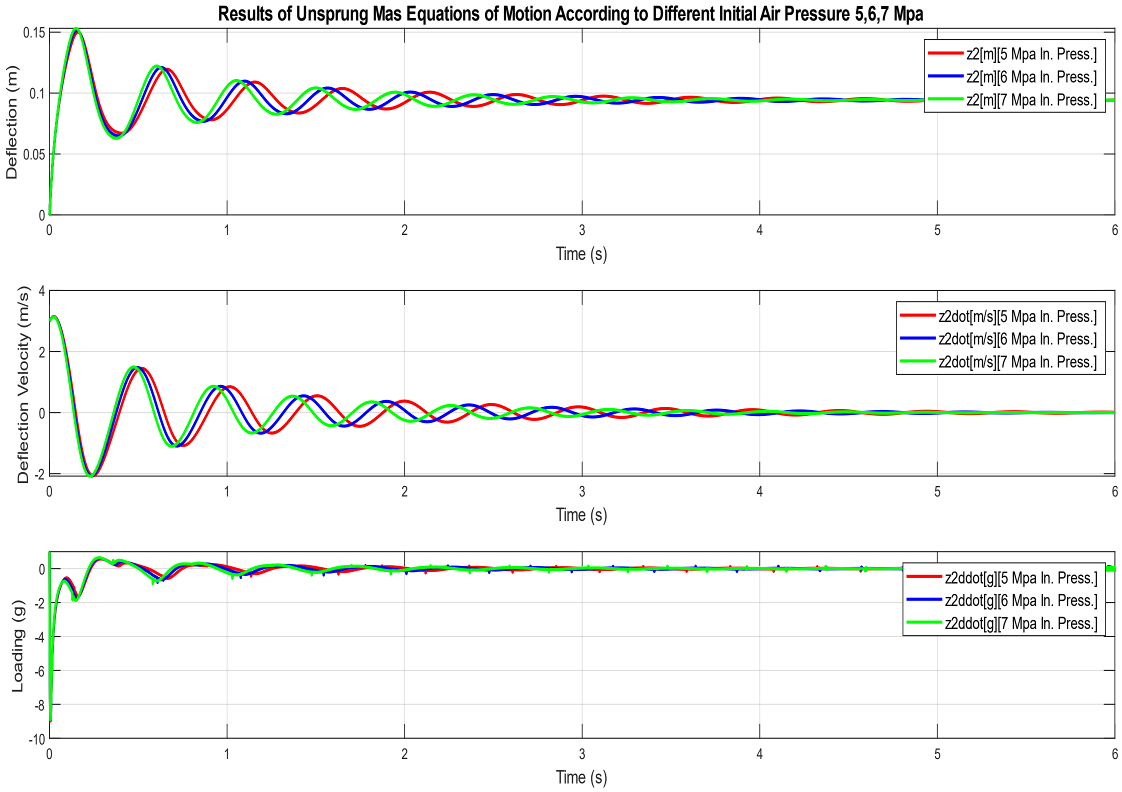

Figure 12. Unsprung mass equations of motion results according to different initial air pressure.

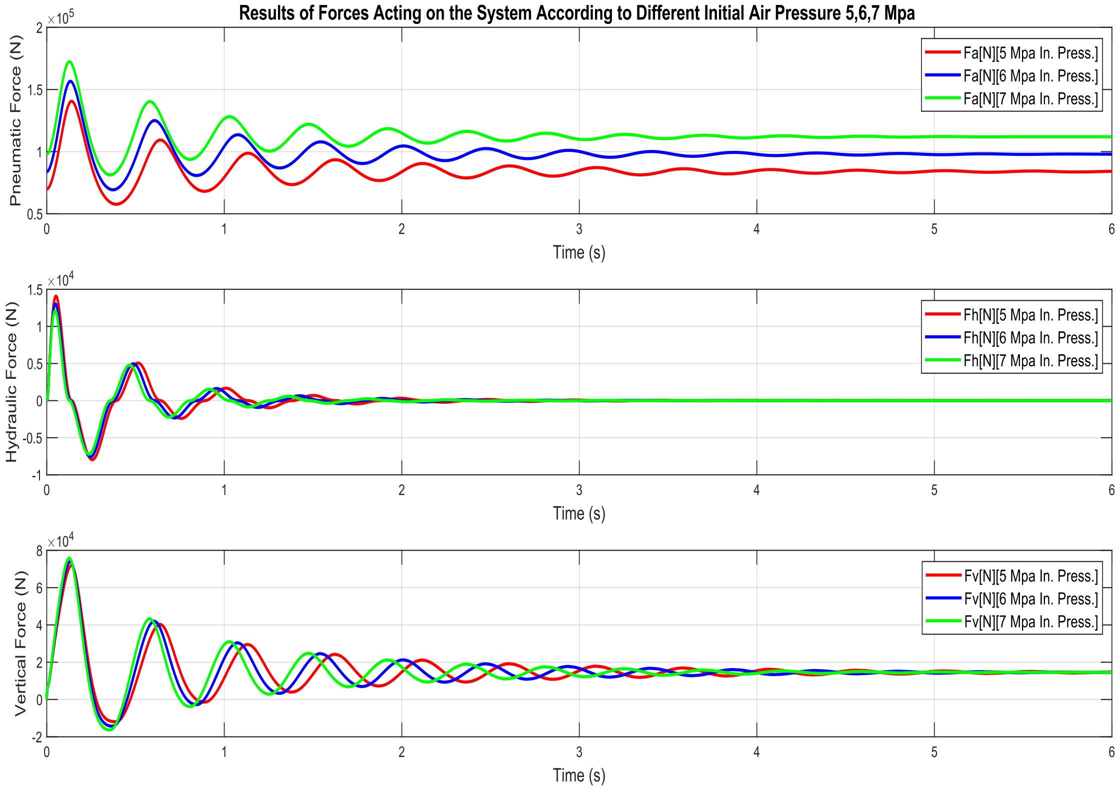

Figure 13. Forces acting on the system results according to different initial air pressure.

The system has also been simulated by applying 5 MPa, 6 MPa and 7 MPa initial air pressures with the 3 m/s impact velocity scenario, damping occurs in a short time of the displacement of sprung and unsprung mass in 7 MPa initial air pressure condition. In addition, when initial air pressure increases, the pneumatic force dramatically increases. The maximum sprung mass displacement was observed in 5 MPa initial air pressure condition as value of 32.15 cm as shown in Figure 11. The maximum unsprung mass displacement is observed in 7 MPa initial air pressure condition as value of 15.32 cm shown in Figure 12. The maximum loading on sprung mass is measured as -4.3 g at sprung mass in 7 MPa initial air pressure condition. The loading on unsprung mass is measured as -8.99 g at unsprung mass in 5 MPa initial air pressured shock absorber. According to the result of applying different initial air pressure, low pressure is more effective for sprung mass, high pressure is more effective for unsprung mass. Because high pressure in the pneumatic system behaves high spring coefficient, it creates more force and more loading but low pressure creates more oscillations and high damping time as shown in Figure 13. To sum up of the results, the most effective parameter on loading is determined as impact velocity so it is determined firstly, initial air pressure is scaled for reach optimum loading, tire deflection and damping time.

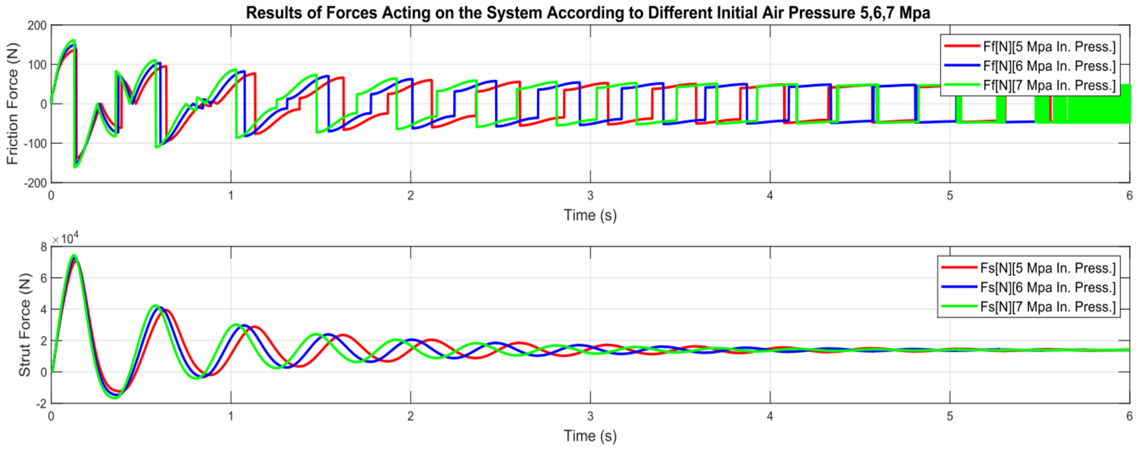

Figure 14. Forces acting on the system results according to different initial air pressure.

5 Conclusion

Landing gear shock absorber systems have a critical role in aircraft touchdown conditions. Because, there is an impact energy that needs to damping. It is important for safe landing condition. Landing gear shock absorber system dynamics have to be modelled before the manufacturing process to observe systems response. Thus, critical conditions can be predicted before a real flight and landing. Traditionally, landing gear characteristic observes with test apparatuses. This way takes a long time and more cost. However, landing gear dynamics which is modelled in model based environment such as Matlab/Simulink is cheaper and saves time. The paper has presented a perspective for shock absorber landing gear systems integrated to aircraft dynamics performance criteria. The proposed methodology relies on determining an analytical formulation of shock absorber system's equation of motion, modelling this formulation on model based environment (Matlab/Simulink) and integrating it with accurate aircraft nonlinear dynamic model to observe the performance of landing gear in different touchdown or impact velocities. Air spring force, hydraulic force, tire force, friction force and stroke position are the most important outputs of system to examine the results. The behavior of the system under different initial air pressure and impact velocities are investigated and determined with results for suitable landing gear performance. The relationship between tire and ground creates a friction force based on dynamic friction coefficient depending on aircraft dynamics. The quality of the result obtained clearly indicates that the approximation of founding optimum impact velocity and initial air pressure are suitable to aircraft and landing gear design limits. In this paper, the performance of the designed landing gear under different impact velocities and different design parameters has been investigated. In studies on landing gear design and optimization, the effect of changes in parameters such as air pressure and impact velocities on the system can be examined and system outputs can be compared with reference to this article. Therefore, this study will contribute to the developing and designing process of a landing gear for a new aircraft with decreasing time and economical aspects in the future.

Declarations

Consent for publication

Not applicable.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author's contributions

N.K.: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing - Review and Editing, Visualization, Supervision, Project Administration. S.C.: Methodology, Investigation, Resources, Writing - Review and Editing. Z.G.: Investigation, Resources, Writing - Review and Editing, Funding Acquisition. M.H.: Conceptualization, Methodology, Investigation, Resources, Visualization, Writing - Review and Editing. All authors discussed the results and contributed to the final manuscript.

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