ESKİŞEHİR TEKNİK ÜNİVERSİTESİ BİLİM VE TEKNOLOJİ DERGİSİ B- TEORİK BİLİMLER

Eskişehir Technical University Journal of Science and Technology B- Theoretical Sciences

2021, 9(2), pp. 37-46, DOI:10.20290/estubtdb.900786

RESEARCH ARTICLE

METERING PIN DIAMETER OPTIMIZATION OF AN AIRCRAFT LANDING GEAR SHOCK ABSORBER

Ali DINC *

College of Engineering and Technology, American University of the Middle East, Egaila, Kuwait

ABSTRACT

One of the most important components of an aircraft is the landing gear. In today`s modern landing gears, mostly oleo-pneumatic shock struts are used. Analytically, landing gear can be modeled as a mass-spring-damper system. The model used in the study included landing gear components such as the oleo-pneumatic shock strut, tire and wheel. Furthermore, a tapered metering pin was added to model in order to control the area of the orifice by which hydraulic oil flows during the act of landing impact force. Landing gear design usually aims to minimize two elements which are vertical acceleration and displacement of aircraft mass. The impact force during landing is indicated by vertical acceleration. Displacement of shock absorber should be minimum to decrease the size, weight and space needed for the landing gear system. An optimization problem was defined to minimize those two parameters within the range of given inputs. For this purpose, a composite objective function was created to include and optimize the two output parameters simultaneously with equal weight. Among many inputs, metering pin hub and tip external diameters were selected as variables for the optimization and other inputs were kept constant. For the optimization study, genetic algorithm method was coupled with the Matlab/Simulink model of the landing gear model. After some iterations, solution was converged to determine the two diameters of the metering pin where the vertical acceleration and displacement of aircraft mass are minimized as an objective. At the end of optimization process, vertical acceleration of aircraft mass was reduced from 2.433 g to 1.7828 g (-36.47%) within the given constraint of 2 g maximum. Displacement of aircraft mass X_1 was increased from 0.2982 m to 0.3682 m (+23.47%) which is in an acceptable limit of 0.4 m.

Keywords: System simulation, Optimization, Mass-spring-damper system, Shock absorber, Aircraft landing gear

1. INTRODUCTION

The landing gear arrangement is a crucial part of aircraft design. Landing gear system can be considered as a suspension system which absorbs and dissipates the kinetic energy during taxi, takeoff and particularly throughout landing of the airplane. Conway [1] explained the landing gear design in a practical way. Currey [2] presented a step by step approach in landing gear design. In today`s modern landing gears, mostly oleo-pneumatic shock struts are used. Wahi [3] conducted a complex analysis and real-time simulation of conventional oleo-pneumatic shock struts by including both aircraft and strut dynamics in the simulation with a good correlation between flight/drop test data. For aircraft design and research, Furnish and Anders [4] performed an analytical simulation of landing gear dynamics to demonstrate how landing gear dynamics affect aircraft taxi and landing loads by including both nose and main gear models in the total airplane equations of motion and presented test results for comparison with the analytical data. McBrearty [5] studied various cases of landing-gear structural failure. Yadav and Ramamoorthy [6] investigated nonlinear landing gear behaviour during landing impact for a heave-pitch model with telescoping main gear and articulated nose gear utilizing an oleopneumatic shock absorber was used to study landing gear dynamics for an airplane. Recent advances in the computational simulation of landing gear systems were presented and an overview of how numerical analysis methods may be used to solve vibration problems in landing gears was provided by Krüger and Morandini [7]. Dinc and Gharbia [8] investigated the impact of spring and damper elements by simulations on dynamics of aircraft landing gear. Paletta et al. [9] proposed an automatic procedure for the landing gear

*Corresponding Author: Ali.Dinc@aum.edu.kw
Received: 21.03.2021 Published: 30.08.2021

conceptual design of a light unmanned aircraft and simulated the drop test for two cases which are single orifice with constant area and single orifice with variable area (metering pin), showing increased efficiency in the case of variable area with metering pin. Nuti et al. [10] demonstrated the conceptual design and multibody dynamics analysis of an innovative fuselage-mounted main landing gear for a civil transport aircraft with a passenger capacity of about 300. Chester [11] employed a parametric method to simulate landing impact, determining the reaction of the main and nose gears by pitching and heaving degrees of freedom of the aircraft motion. Shi [12] and Shi et al. [13] performed single and multi-objective optimization studies of passive shock absorber for landing gears by considering four types of metering pins including conventional taper pin, multi-taper, single-parabolic and multi-parabolic configurations. Asthana and Bhat [14] proposed a novel design of landing gear oleo strut damper using magnetorheological fluid for aircraft and UAVs. Liu et al. [15] performed an optimization study on shock absorber based on magnetorheological (MR) damper with a metering pin and presented drop test results on the damping characteristics of the shock absorber and damping effect. Heininen et al. [16] studied the behavior of the equations of state in fighter aircraft oleo-pneumatic shock absorber modelling and concluded that verifies that the ideal gas law should not be used. Zhu et al. [17] proposed a mathematical model that takes into account the thermal effect of landing gear which is based on a single operating oleo-pneumatic shock absorber. Karam and Mare [18] proposed an advanced model for landing gear shock struts which explicitly treats the heat exchange between gas and oil and also takes into account physical phenomena such as chamber compliance, gas dissolution, and gas/oil mixed flow between chambers. Bharath et al. [19] developed a simple oleo pneumatic (shock absorber) model using computational fluid dynamics (CFD) program to understand how various parameters influence the performance of the undercarriage shock absorber.

The originality of this paper comes form the fact that the study focuses on and optimizes the geometry of the metering pin which is very seldom in literature. Additionally, this study employs a coupled genuine genetic algoritm optimization code developed by the author.

2. MATERIAL AND METHOD

2.1. Dynamic System Model

A landing gear was modelled as a mass-spring-damper system in this analysis as depicted in Figure 1 where m_1 represents aircraft mass distributed to each landing gear and m_2 represents the total mass of wheel and tire group respectively. In this model there are two spring elements which are k_1 shock absorber spring and k_2 tire spring elements. Last element of the model is b damper of the shock absorber. The aim of this model is to calculate F_1 force acting on the aircraft mass and displacement of the aircraft and shock absorber. Equations of motion can be written as follows [20]:

$$F_1 = m_1\ddot{x}_1 = W_1 - F_{spring,\ shock\ absorb} - F_{damping} \quad (1)$$
$$F_1 = m_1\ddot{x}_1 = W_1 - kx - b\dot{x} \quad (2)$$
$$x = x_1 - x_2 \quad (3)$$
$$m_1\ddot{x}_1 + k_1\,(x_1 - x_2) + b(\dot{x}_1 - \dot{x}_2) = W_1 \quad (4)$$
$$W_1 = m_1 g - L \quad (5)$$
$$m_1\ddot{x}_1 + k_1\,(x_1 - x_2) + b(\dot{x}_1 - \dot{x}_2) = m_1 g - L \quad (6)$$

Similarly, F_2 force acting on the mass m_2 (wheel and tire group) can be written as given below:

$$F_2 = m_2\ddot{x}_2 = F_{spring,\ shock\ absorb} + F_{damping} - F_{spring,\ tire} \quad (7)$$
$$m_2\ddot{x}_2 = k_1 x + b\dot{x} - k_2\, x_2 \quad (8)$$
$$x = x_1 - x_2 \quad (9)$$
$$m_1\ddot{x}_1 + k_1\,(x_1 - x_2) + b\,(\dot{x}_1 - \dot{x}_2) = W_1 \quad (10)$$
$$m_2\ddot{x}_2 - k_1\,(x_1 - x_2) - b\,(\dot{x}_1 - \dot{x}_2) + k_2\, x_2 = 0 \quad (11)$$

where:

b : shock absorber damping coefficient
F_1 : net force on m_1
F_2 : ground reaction force
g : gravity
k_1 : shock absorber spring constant
k_2 : tire spring constant
L : lift force acting on aircraft
m_1 : aircraft mass (per landing gear)
m_2 : total mass of wheel, tire and axle
V : aircraft vertical speed (descent velocity)
W_1 : aircraft weight minus lift force
x : displacement of shock absorber
x_1 : displacement of aircraft
x_2 : displacement of wheel

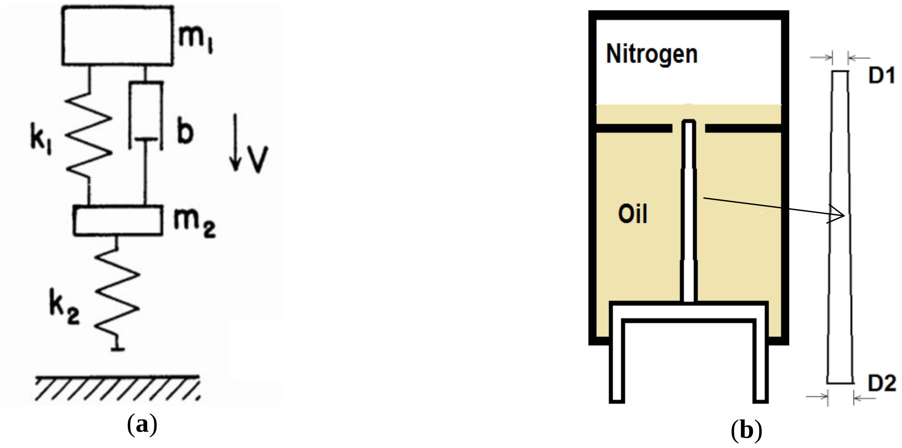


Figure 1. (a) Mass-spring-damper model for landing gear; (b) Shock absorber cross section and metering pin diameters.

2.2. Genetic Algorithm

The Genetic Algorithm (GA) optimization technique was used in this analysis. GA is a powerful mathematical algorithm used for solving complex problems and optimization tasks. GA is based on the evolution theory, and is used to find a solution to a problem called an objective function using a numerical algorithm. In physics, engineering, industry, economics, and finance, GAs have been used as a computational algorithm in various fields including aerospace [21–26]. In the genetic algorithm, the steps and processes are all mathematical operations. Chromosomes, generation, mutation, and crossover are all terms that refer to mathematical operations of binary numbers. Genetic algorithm optimization can be applied to a well specified problem using the steps below [27]:

- *Step 1. Pick and presume genetic parameters*
- *Step 2. Generate chromosomes of the original population randomly in chosen intervals and accuracy*
- *Step 3. Calculate the objective function to evaluate the fitness value of the chromosomes*
- *Step 4: Chromosome selection*
- *Step 5: Chromosome crossover*
- *Step 6: Chromosome mutation*
- *Step 7: New generation of chromosomes (offspring)*

It is needed to repeat steps from 3 to 7 for a number of iterations which are called “generations” until a converged solution is obtained.

3. RESULTS AND DISCUSSION

A computer model was constructed to solve the equation of motions simultaneously in Matlab/Simulink. A geometry given in Figure 1 was used in the simulation with a specific feature of tapered metering pin. The flowchart of the model is given in Figure 2 which uses a set of inputs to calculate hydraulic, pneumatic and tire forces in an iterative manner to determine displacements, velocities and accelerations of the sprung mass (airplane) and unsprung (tire&wheel assembly) mass. Calculated accelerations are related with the forces acting on sprung and unsprung masses which are required for structural calculations in the design process later on. Similarly, Matlab/Simulink model is given in Figure 3. A set of input parameters were collected mostly from [20] and is tabulated in Table 1.

Table 1. Landing gear baseline input parameters (adopted from [20])

Parameter	Value
Aircraft sink speed (m/s)	3.05
Shock absorber hydraulic area (m^2)	0.0256774
Aircraft mass per landing gear m_1 (kg)	18103
Tire & wheel mass m_2 (kg)	59.43
Oil density (kg/m^3)	870
Orifice diameter (mm)	28.6
Discharge coefficient	1
W_1 : Weight minus lift (N)	0
Baseline metering pin constant diameter (mm)	24

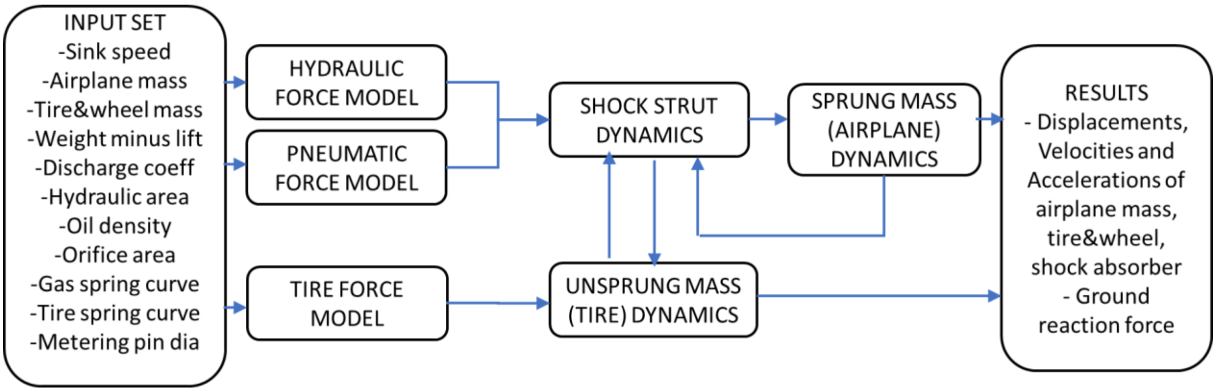


Figure 2. Flowchart of landing gear simulation (adopted from [3]).

Initially, the model was prepared with a different geometry metering pin as described in [20] and model validation was performed with the results given in [20]. Then the model was updated with a tapered metering pin which is the focus point of this study. Apart from the embedded GA optimization functions in Matlab, a new genuine optimization code was written by authors to optimize two parameters at the same time for a composite objective function and multiple constraint equations. Then, Simulink model of landing gear (Figure 3) and the new Matlab optimization code were integrated to work together. Once initial results were obtained, exhaustive optimization studies were conducted. For the optimization study, a composite objective function was defined to minimize two elements which are vertical acceleration and displacement of aircraft mass. The impact force during landing is indicated by vertical acceleration. Displacement of shock absorber should be minimum to decrease the size, weight and space needed for the landing gear system. Therefore, the composite objective function was created to include and optimize the two output parameters simultaneously with equal weight. Among many inputs, as the main focus of this research, metering pin hub and tip external diameters were selected as variables for the optimization and other inputs were kept constant. Resulting composite objective function was defined as follows:

$$Z = \left[\frac{1}{0.5\left(\frac{\text{Acceleration}}{c_1}\right) + 0.5\left(\frac{\text{Displacement}}{c_2}\right)} \right] \tag{12}$$

where Z is objective function, c_1 and c_2 are constants. Those two constants are used to normalize "Vertical Acceleration" and "Displacement" parameters. Since vertical acceleration (indicating landing impact force) and displacement of aircraft mass has different orders of magnitude, normalization by constants c_1 and c_2 is needed. There are also 0.5 multipliers applied in Eq. (12) to make "Vertical Acceleration" and "Displacement" equally important for the objective function with a 50% weight. As a result, the objective function should be maximized around 1.

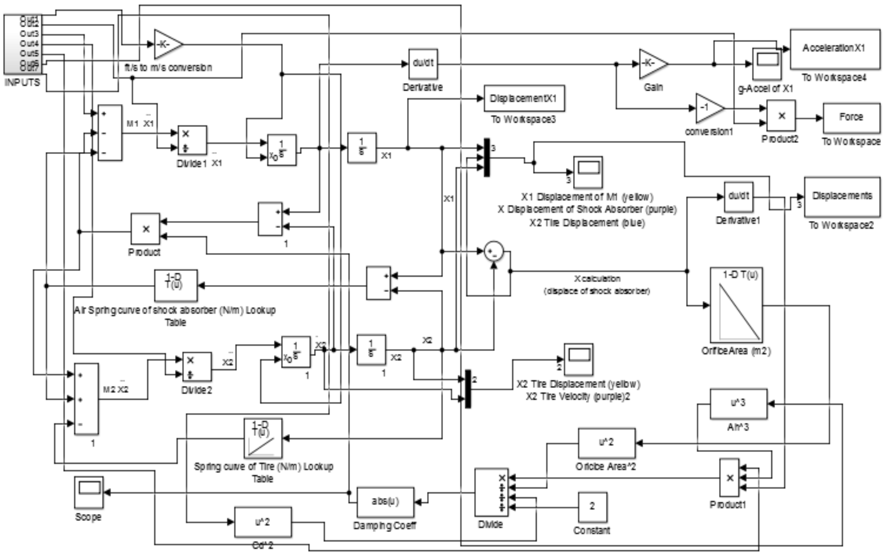
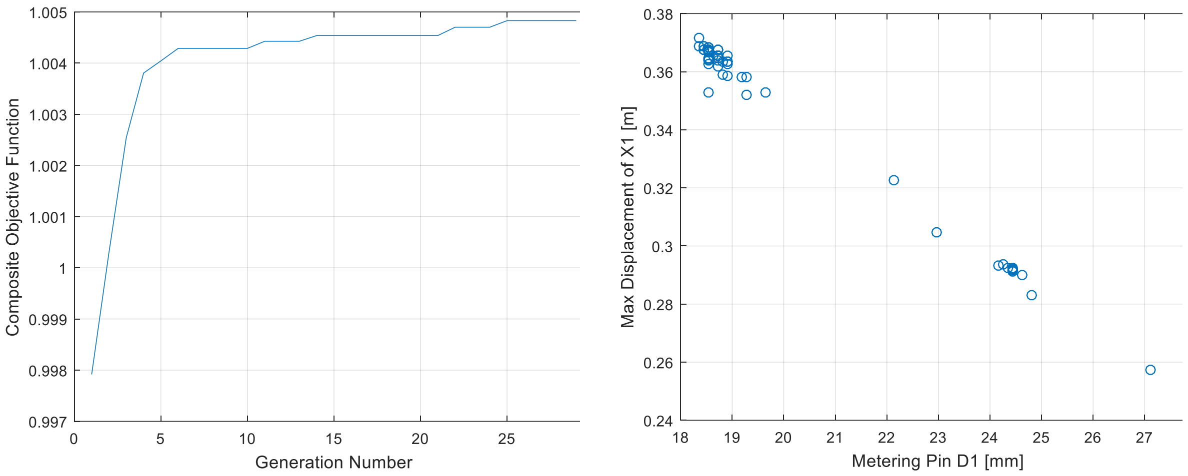


Figure 3. Simulink model of landing gear.

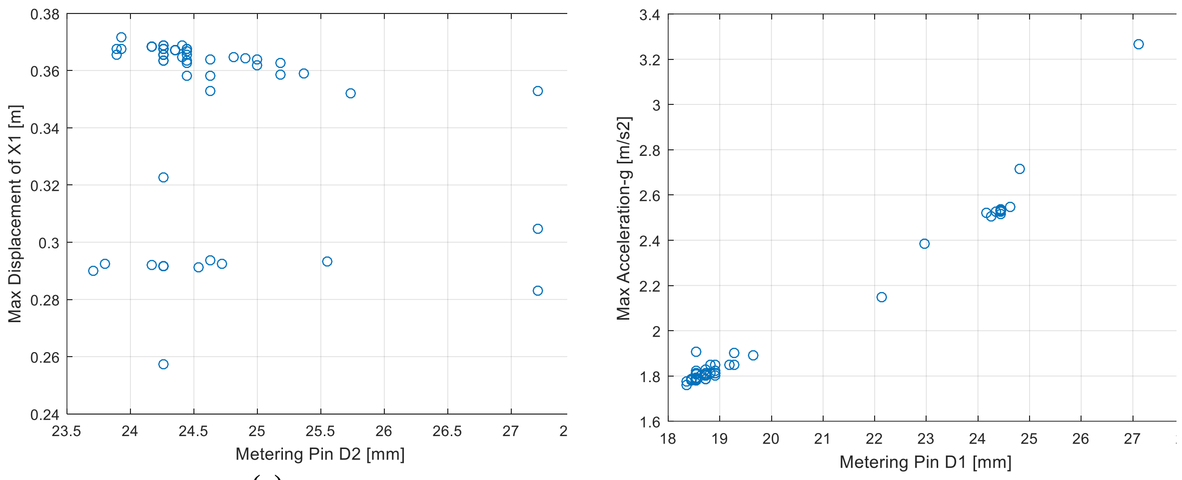
After determination of objective function, a set of constraints were defined in the problem. Constraint for max vertical acceleration (indicating landing impact force) was assumed as 2 g and max displacement of aircraft mass was assumed as 0.4 m. Those two output parameters need to be controlled within their constraints or limits. Additionally, those two output parameters are inversely proportional to each other, in other words when vertical acceleration is reduced, the displacement of aircraft mass increases and vice versa. Increase in displacement of aircraft mass leads to longer landing gear causing weight increase and also structural problems.

Figures 4-7 shows the general results. Objective function was converged after 25 generations (iterations) and reached its maximum value (Figure 4a). The effect of D1 and D2 metering pin diameters on displacement of aircraft mass is seen in Figure 4b and Figure 5a respectively. Similarly, the effect of D1 and D2 metering pin diameters on vertical acceleration (g-force) is seen in Figure 5b and Figure 6a respectively. Finally Figure 6b and Figure 7 depicts the effect of D1 and D2 metering pin diameters on composite objective function respectively. It is noticeable that optimum values are around the more populated areas as a result of genetic algorithm in Figures 4-7.



(**a**) (**b**)

Figure 4. (a) Objective function vs. generations (iterations); (b) Displacement of aircraft mass vs. D1.



(**a**) (**b**)

Figure 5. (a) Displacement of aircraft mass vs. D2; (b) Vertical acceleration vs. D1.

At the end of optimization process, metering pin diameters D1 and D2 were obtained as optimum values for a balanced composite objective function of vertical acceleration and displacement of aircraft mass as given in Table 2. After optimization, vertical acceleration of aircraft mass was reduced from 2.433 g to 1.7828 g (-36.47%) within the given constraint of 2 g maximum. Displacement of aircraft mass X_1 was increased from 0.2982 m to 0.3682 m (+23.47%) which is in an acceptable limit of 0.4 m. Additionally, time response solutions are given in Figures 8-9 for initial unoptimized geometry pin (constant 24 mm diameter) and also for optimized geometry pin (tapered) respectively.

Table 2. Results

Parameter	Before Optimization	After Optimization	Change
Metering pin diameter D_1 at tip (mm)	24	18.5471	-29.4%
Metering pin diameter D_2 at hub (mm)	24	24.1686	+0.7%
Displacement of aircraft mass X_1 (m)	0.2982	0.3682	+23.47%
Vertical acceleration (g)	2.433	1.7828	-36.47%
Best composite objective function value	-	1.0048	-

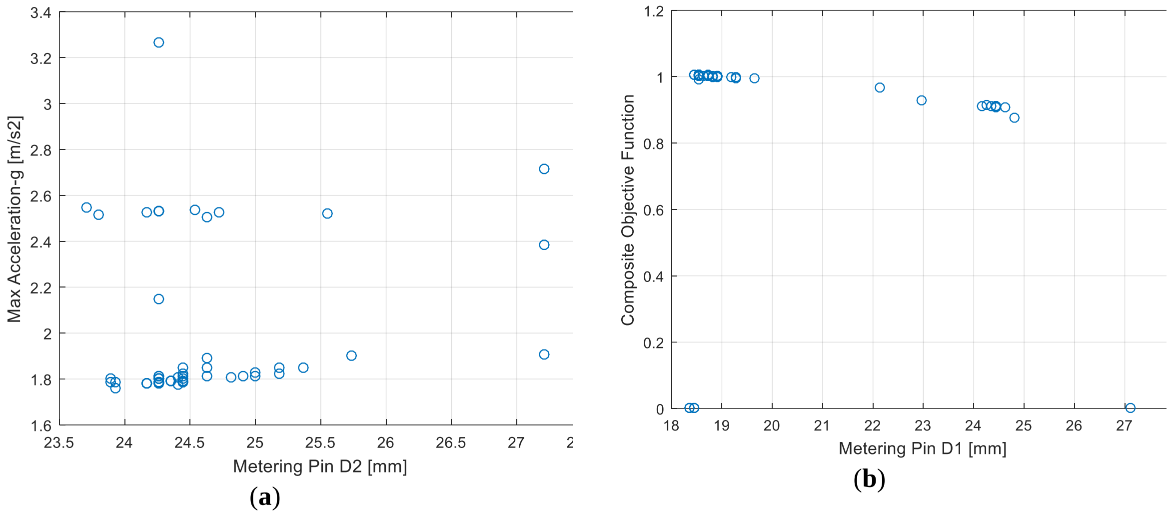


Figure 6. (a) Vertical acceleration vs. D2; (b) Objective function vs. D1.

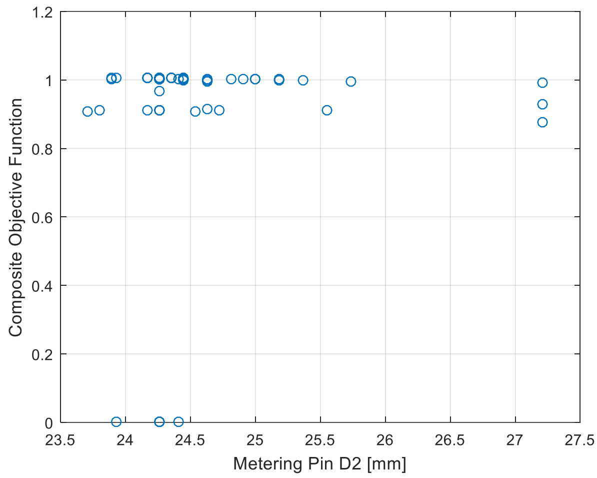


Figure 7. Objective function vs D2

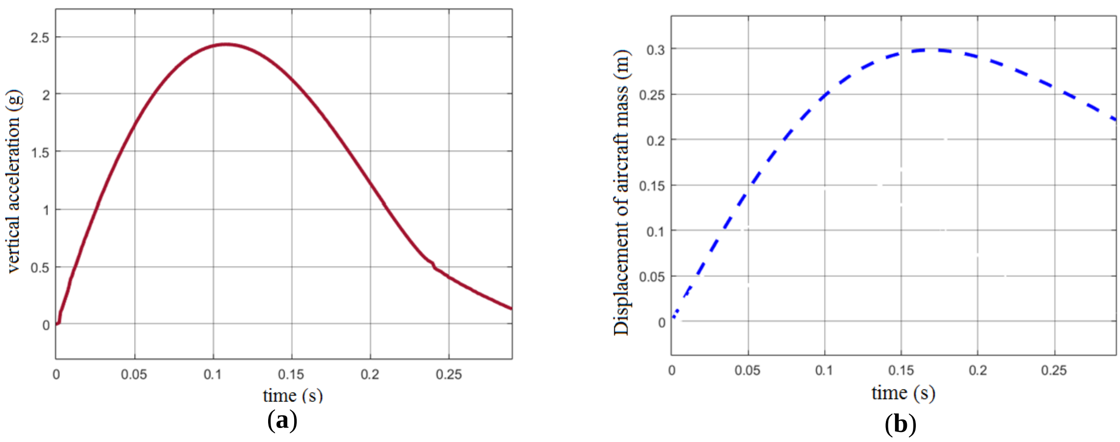


Figure 8. Initial unoptimized geometry (a) vertical acceleration (g) vs time (s); (b) displacement of aircraft mass (m) vs time (s)

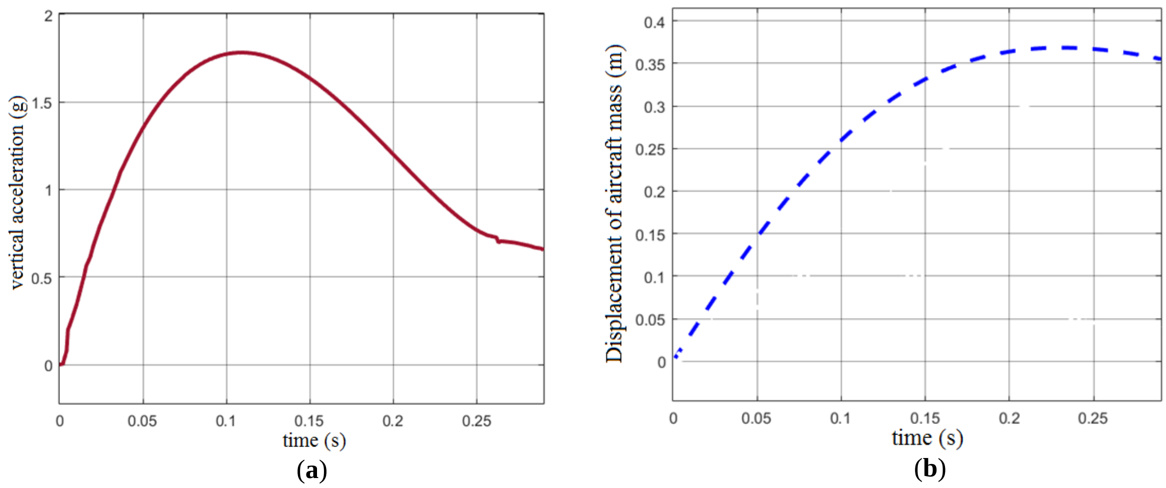


Figure 9. Optimized geometry (a) vertical acceleration (g) vs time (s); (b) displacement of aircraft mass (m) vs time (s)

4. CONCLUSION

In this study, an analytical model (spring-mass-damper) of landing gear was constructed with a special focus as tapered metering pin element in the shock absorber. Metering pin diameters D1 and D2 (tip and hub, see Figure 1b) were optimized for a balanced composite objective function of vertical acceleration and displacement of aircraft mass. After optimization, vertical acceleration of aircraft mass was reduced from 2.433 g to 1.7828 g (-36.47%) within the given constraint of 2 g maximum. Displacement of aircraft mass X_1 was increased from 0.2982 m to 0.3682 m (+23.47%) which is in an acceptable limit of 0.4 m. Genetic algorithm was successful in finding the optimum values and showed that it is a useful algorithm for optimization of this kind of problems in addition to many other application areas.

ACKNOWLEDGEMENTS

Author of this study would like to thank American University of the Middle East, Kuwait for the support on this research.

CONFLICT OF INTEREST

The author stated that there are no conflicts of interest regarding the publication of this article.

REFERENCES

[1] Conway HG. Landing Gear Design. Chapman & Hall; The Aeronautical Journal, 1958;62:569,pp.390.

[2] Currey NS. Aircraft Landing Gear Design: Principles and Practices . Washington DC: American Institute of Aeronautics and Astronautics; 1988.

[3] Wahi MK. Oleopneumatic shock strut dynamic analysis and its real-time simulation. J Aircr 1976;13(4):303–8.

[4] Furnish JF, Anders DE. Analytical simulation of landing gear dynamics for aircraft design and analysis. SAE Tech Pap 1971;0–8.

[5] McBrearty JF. A Critical Study of Aircraft Landing Gears. J Aeronaut Sci 1948; May;15(5):263–80.

[6] Yadav D, Ramamoorthy RP. Nonlinear landing gear behavior at Touchdown. J Dyn Syst Meas Control Trans ASME 1991;113(4):677–83.

[7] Krüger WR, Morandini M. Recent developments at the numerical simulation of landing gear dynamics. CEAS Aeronaut J 2011;1(1–4):55–68.

[8] Dinc A, Gharbia Y. Effects of Spring and Damper Elements in Aircraft Landing Gear Dynamics. Int J Recent Technol Eng 2020; Jan 30;8(5):4265–9.

[9] Paletta N, Belardo M, Di Palma L. An automatic procedure for the landing gear conceptual design of a light unmanned aircraft. SAE Tech Pap 2013;7.

[10] Nuti A, Bertini F, Cipolla V, Di Rito G. Design of a Fuselage-Mounted Main Landing Gear of a Medium-Size Civil Transport Aircraft. Aerotec Missili Spaz 2018;97(2):85–95.

[11] Chester DH. Aircraft landing impact parametric study with emphasis on nose gear landing conditions. J Aircr 2002;39(3):394–403.

[12] Shi F. Multi-objective Optimization of Passive Shock Absorber for Landing Gear. Am J Mech Eng 2019;7(2):79–86.

[13] Shi F, Isaac Anak Dean W, Suyama T. Single-objective Optimization of Passive Shock Absorber for Landing Gear. Am J Mech Eng 2019;7(3):107–15.

[14] Asthana CB, Bhat RB. A novel design of landing gear oleo strut damper using MR fluid for aircraft and UAV's. Appl Mech Mater 2012;225:275–80.

[15] Liu XC, Zhu SX, Yang YG. Design and Drop Test of Aircraft Landing Gear's Shock Absorber Based on Magnetorheological Damper. Appl Mech Mater 2014; Oct;665:601–6.

[16] Heininen A, Aaltonen J, Koskinen KT, Huitula J. Equations of State in Fighter Aircraft Oleo-pneumatic Shock Absorber Modelling 2019; p. 64–70.

[17] Zhu Z, Feng Y, Pan W. The Improved Model for Landing Gear Dynamic Analysis Based on Thermodynamics. In: Proceedings of the 2018 International Conference on Service Robotics Technologies-ICSRT '18 New York, USA: ACM Press; 2018; p. 16–21.

[18] Karam W, Mare JC. Advanced model development and validation of landing gear shock struts. Proc Inst Mech Eng Part G J Aerosp Eng 2010;224(5):575–86.

[19] Bharath M, Singh P, Kantheti B. Determination of Influence of Parameters on Undercarriage Shock Absorber. SAE Int J Aerosp 2018;11(2):85–114.

[20] Flugge W. Landing Gear Impact, NACA TN 2743. 1952.

[21] Baklacioglu T, Turan O, Aydin H. Dynamic modeling of exergy efficiency of turboprop engine components using hybrid genetic algorithm-artificial neural networks. Energy 2015;86:709–21.

[22] Baklacioglu T, Turan O, Aydin H. Metaheuristic approach for an artificial neural network: Exergetic sustainability and environmental effect of a business aircraft. Transp Res Part D Transp Environ 2018;63:445–65.

[23] Kaba A, Aygun H, Turan O. Multi-dimensional energetic performance modeling of an aircraft engine with the aid of enhanced least–squares estimation based genetic algorithm method. J Therm Anal Calorim, 2021. 2021 Jun 26 [cited 2021 Jul 7];1–23. Available from: https://link.springer.com/article/10.1007/s10973-021-10922-z

[24] Dinc A. Optimization of turboprop ESFC and NOx emissions for UAV sizing. Aircr Eng Aerosp Technol 2017;89(3):375–83.

[25] Dinc A, Elbadawy I. Global warming potential optimization of a turbofan powered unmanned aerial vehicle during surveillance mission. Transp Res Part D Transp Environ 2020; Aug 1;85.

[26] Dinc A, Otkur M. Optimization of Electric Vehicle Battery Size and Reduction Ratio Using Genetic Algorithm. In: 2020 11th International Conference on Mechanical and Aerospace Engineering (ICMAE); IEEE 2020; p. 281–5.

[27] Kramer O. Genetic Algorithm Essentials . Springer International Publishing AG. Cham: Springer International Publishing; (Studies in Computational Intelligence; vol. 679), 2017; p. 11–20.