Investigation of active intelligent shock absorber system performance for oscillation control of quarter aircraft model during touchdown phase

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Abstract. The main function of an airplane suspension system is to isolate the airframe from airstrip disturbance in order to keep wheels in contact with runway surface and to maximize passengers comfort. The aim of this paper is to design Proportional Integral Derivative (PID) controller for the model of an active landing gear system that chooses the shock-absorbing force of the suspension system as a controllable variable. The parameters of the controller are adjusted according to bees Intelligent algorithm by minimizing acceleration and load induced to aircraft as the objective function of the optimization technique. This research utilizes a nonlinear mathematical model to describe oleo-pneumatic shock absorber. The results of numerical Simulation indicate that the air spring force as impact load and the vertical vibration of body have good compromise compared with passive performance by decreasing of 50% and 75% averagely which conduce to increase in quality of landing, improvement of passengers comfort and betterment of structures fatigue life during touchdown phase with two various sink speeds and half sine wave runway disturbance. According to numerical simulation, the active suspension increases the comfort of the ride for passengers and the fatigue life of the structure. This is achieved by decreasing the impact force, displacement and acceleration significantly. The results of numerical analysis for this airplane model demonstrate that the active shock absorber system in accordance with the bee multi-objective algorithm has good performance in comparison with the passive approach to minimize the bounce displacement and momentum, the pitch displacement and momentum, the suspension travel and impact force in time-domain, that results in improvement of passenger ride comfort importantly. As well as, enhancement of structures fatigue life is a likely case as a consequence of study applicable to the industry.

Keywords: PID controller, Bees intelligent optimization algorithm, Oleo-pneumatic landing gear, Active performance

1 Introduction

The most aircraft utilize landing gears with a passive performance that are designed by the producers [1]. The impact loads experienced are large, because the character design parameters of a shock-absorbing device in a passive system can not adapt to encounter different landing and runway environments. In very bad landing conditions, large impact loads can result in the design limitations of the airframe and landing gear structure to cause a possible flight accident.

From the 1970s, the semi-active and active control performances began to be popular and famously-used in vibration control of vehicle suspensions. Compared with the passive control, the active and semi-active controls have excellent adjustability due to their pliable structure.

[2] demonstrated that the advantages of applying active control force for the suspension system to restrict the loads induced to the fuselage. The benefits of active landing gears in decreasing touchdown loads and oscillations under runway disturbances was deduced by [3, 4] by means of analysis and experimentation.

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[5] implemented a mathematical model with nonlinear characteristics for main landing gear improved with an external hydraulic system. A6 intruder landing gear system has been surveyed based on analysis and test method [6].

According to studies of [7] for automotive applications, compared with the passive control, the semi-active and active control has excellent tunability due to flexible structure.

Maemori [8] proposes an optimization method for a semi-active landing gear to handle variations in the maximum vertical acceleration of an aircraft during landing caused by the variation of the aircraft mass.

Ghiringhelli [9] builds a complete aircraft landing simulation model in ADAMS software. Semi-active PID control method is used to control the orifice area and tests a semi-active landing gear control system of a generic aircraft.

Dong-Su [10] constructs a semi-active GA-based nonlinear model predictive controller for landing gear system at touchdown. Drop tests are carried out on an experimental passive landing gear system to validate the parameters of the simulation model.

Investigations have shown that active control greatly reduces vertical displacements, impact and fatigue loads experienced by the aircraft. This is achieved by tuning the systems stiffness and damping values [11]-[14].

Previously, NASA studied the behavior of an active nose landing gear using A-10 and F-106B airplanes [15] [16]. In the latter, drop tests were performed. These two studies focused on observation and experimental data but lacked a theoretical analysis to support the tests.

J.T. Xing [17] develops a mathematical model to control aircraft vibrations caused by runway excitation using an active landing gear system and focuses his paper on optimization of the performance of the active landing gear system.

Liu Hui [18] selects parallel high-speed solenoid valves as an actuator for the semi-active controlled landing gear. The simulation results indicate that the semi-active control based on fuzzy PD control rule can effectively improve the control performance and reduce impact load during landing. M. Zarchi et al [19] surveyed active shock absorber efficiency with optimization objective function of displacement and speed of aircraft and suspension system according to bees algorithm. M. Zarchi et al [20] studied semi-active landing gear performance in three landing conditions with half sine wave profile for runway using PID controller based on bees algorithm. In reference [21], A. Toloei et al designed LQR controller for full aircraft model in order to analyze the vibrational model.

In section 2, the model of active landing gear is introduced. Then in sections 3 and 4, PID control technique and bees intelligent optimization algorithm are developed. In section 5, the numerical simulation with MATLAB software is performed and the conclusion of this investigation is summarized in section 6.

2 Model of active landing gear system

The shock absorber is the main component of a passive system. Active control consists of a servo valve, a low-pressure (LP) reservoir, a high-pressure (HP) accumulator, a hydraulic pump, an electronic controller and feedback transducers. When an aircraft lands, the shock absorber stroke is influenced by the aircraft’s payload and varies depending on runway excitation. The stroke is measured by the transducers and their signals input into the electronic controller. Fig. 1 illustrates a model of an active landing gear system with a typical oleo-pneumatic shock absorber [23, 24].

Using Newton’s second law of motion and the system model in Fig. 1, the dynamic equilibrium equation for the active system is represented in Eq. 1.

2.1 Dynamic equilibrium equations of active landing gear system

Damping effect is produced by compacting the compressed oil through the orifice. It produces an oleo damping force. In the pneumatic chamber, the air is compressed by the movement of the piston, thus it provides an air spring force. Friction forces are generated from two principal sources. One force is caused by the tightness of the seal and the other is due to the offset wheel.
Fig. 1: Model of landing gear with an active control system [17, 19]

\[ m_1 \ddot{y}_1 = m_1 g - L - F_a - F_O - f - F_Q \]
\[ m_2 \ddot{y}_2 = m_2 g - F_t - F_a + F_O + f + F_Q \]  \hspace{1cm} (1)

2.2 Oleo damping force

\[ F_O = \frac{\rho A^3}{2 C_O^2 A_O^2} (\dot{y}_1 - \dot{y}_2)^2 \text{sgn}(\dot{y}_1 - \dot{y}_2) \]  \hspace{1cm} (2)

2.3 Air spring force

\[ F_a = P_0 A (1 - \frac{y_1 - y_2}{y_0})^{-n} \]  \hspace{1cm} (3)

2.4 Friction force

\[ f = k_m (\dot{y}_1 - \dot{y}_2) + \text{sgn}(\dot{y}_1 - \dot{y}_2) k_n (\dot{y}_1 - \dot{y}_2)^2 + \mu \left( \frac{F_l}{y_s + B} \right) \]  \hspace{1cm} (4)
2.5 Active control force

\[ F_Q = k_a Q + k_b Q^2 \text{sgn}(Q) \]
\[ Q = C_Q wx \sqrt{|P_{sh} - P_{sl}| / \rho} \]  

(5)

\( k_a \) and \( k_b \) are two constants measured for the servo valve actuator. \( Q \) is flow quantity. \( P_{sh} \) and \( P_{sl} \) are pressure in the HP and LP storages, respectively. \( C_Q \) represents a non-dimensional discharge coefficient, \( w \) and \( x \) define the orifice area gradient and the movement of the servo valve spool [17, 19].

2.6 Tyre force

The tire is acted as a combination of a linear spring and a linear damper.

\[ F_t = c_t(y_2 - \dot{y}_g) + k_t(y_2 + y_g) \]  

(6)

3 Design of pid control

Proportional, Integral and derivative (PID) controller is the most widely used controller in the automotive and aerospace industries because of its simplicity, robustness and successful practical application. The PID controller tuning methods are classified into two main categories. Closed loop and Open loop methods. The purpose of this study is an investigation of Minimum error criteria method for single input single output (SISO) system using computer simulation. The spool displacement of servo valve as the actuator is controlled according to Eq. 7, as shown in Fig. 2. Input error to the controller \( (e(t)) \) is the difference between shock absorber stroke and desired output.

\[ X(t) = k_p e(t) + k_i \int e(t) dt + k_d \dot{e}(t) \]  

(7)

![Fig. 2: Schematic sketch of the PID controller in the closed-loop system](image)

4 Design of bees algorithm

This intelligent algorithm uses flowchart shown in Fig. 3 for tuning of PID classical controller parameters. The algorithm requires a number of parameters to be set. Namely, number of scout bees \( (n) \), number of sites

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selected for neighborhood searching (m), number of top-rated sites among m selected sites (e), number of bees recruited for the best e sites (nep), number of bees recruited for the other selected sites (nsp), the initial size of each patch (ngh) (a patch is a region in the search space that includes the visited site and its neighborhood) and the stopping criterion [22]. In this paper, this algorithm is implemented by using Integral of the time-weighted absolute value of the error (ITAE) according to eq. 8 as the objective function. ITAE is applied to achieve acceptable stability and medium fastness of response for the control system due to the existence of time and error in this function. The stability conditions as adjustable parameters of the controller to utilize in Bees algorithm is presented in eq. 9 according to [17, 19].

\[
ITAE = \int_0^\infty t|e(t)|dt
\]

\[
\begin{align*}
&k_p < 1.680 \\
&1.23 \times 10^{-5} < k_i < 1.601 \\
&k_d < 1.042
\end{align*}
\]

**5 Numerical simulation**

A6 Intruder airplane with values according to Table.1 is investigated. Aircraft and Landing gear masses are 4832.7 kg and 145.1 kg, respectively. Lift Aerodynamic Force is 7500 N. Parameters of the bees algorithm are given in Table. 2. The runway disturbance is a half sin-type ramp of height 10cm and time 0.4s over which the airplane travels and is generated in Eq. 10. and Fig. 4. The damping and active control forces have nonlinear behavior without input constraint for the actuator of the suspension system and dynamic equations are linearized around stability point by using Taylor’s expansion [17]. The air spring force as the impact load is calculated in a nonlinear manner with constant and variable parameters according to Eq. 3.

\[
y_g = 0.1(1 - \cos 7.85t)0 < t < 0.4
\]
Table 1: Values of each parameter in the payoff matrix

<table>
<thead>
<tr>
<th>Shock Absorber</th>
<th>Value</th>
<th>Tire</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_0 (\text{pa})$</td>
<td>$1.6 \times 10^6$</td>
<td>$k_t (\text{N/m})$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td>$V_0 (\text{m}^3)$</td>
<td>$6.88 \times 10^{-3}$</td>
<td>$c_t (\text{Ns/m})$</td>
<td>$2.6 \times 10^6$</td>
</tr>
<tr>
<td>$A_n (\text{m}^2)$</td>
<td>$1.376 \times 10^{-2}$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$A_o (\text{m}^2)$</td>
<td>$6.412 \times 10^{-4}$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$\rho (Kg/m^3)$</td>
<td>$912$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_Q$</td>
<td>$0.1 \times 10^{-5}$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$C_O$</td>
<td>$0.3$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$K_n (\text{Ns/m})$</td>
<td>$0.7 \times 10^4$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$m (\text{Ns}^2/\text{m}^2)$</td>
<td>$0.1 \times 10^5$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$N$</td>
<td>$1.1$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$P_{in} (\text{pa})$</td>
<td>$20 \times 10^6$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
<tr>
<td>$P_{in} (\text{pa})$</td>
<td>$0.1 \times 10^6$</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 2: The bees algorithm Parameters

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>without disturbance</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>150</td>
</tr>
<tr>
<td>$M$</td>
<td>20</td>
</tr>
<tr>
<td>$E$</td>
<td>5</td>
</tr>
<tr>
<td>$N_{cp}$</td>
<td>15</td>
</tr>
<tr>
<td>$N_{sp}$</td>
<td>10</td>
</tr>
<tr>
<td>$N_{gb}$</td>
<td>40</td>
</tr>
<tr>
<td>with disturbance</td>
<td></td>
</tr>
<tr>
<td>$N$</td>
<td>120</td>
</tr>
<tr>
<td>$M$</td>
<td>12</td>
</tr>
<tr>
<td>$E$</td>
<td>8</td>
</tr>
<tr>
<td>$N_{cp}$</td>
<td>18</td>
</tr>
<tr>
<td>$N_{sp}$</td>
<td>5</td>
</tr>
<tr>
<td>$N_{gb}$</td>
<td>80</td>
</tr>
</tbody>
</table>

Fig. 4: Runway input with half sine wave profile [17]

5.1 Simulation without consideration of runway disturbance

Comparison of control performances including passive control, PID based on an experimental optimum set and PID based on Bees Algorithm for the active system is taken in terms of different sinking speed ($3 \text{m.s}^{-1}$ and $5 \text{m.s}^{-1}$) and Simulink model is presented in Fig. 5.
The vertical displacement of the aircraft is an important parameter in designing the landing gear system. The amplitude of the air spring force transmitted to the airframe and landing gear affects the structural strength. Fig. 6-9 show that these parameters are reduced significantly for this suspension system. Table 3 summarizes the results of these Figures and demonstrate that these variables are reduced using the PID-BA active system and finally these control systems indicate a significant improvement over the performance of the passive system.

Fig. 5: Diagram of Matlab Simulink without runway excitation

Fig. 6: Displacement of aircraft under sink speed 3m/s with acceleration and impact load optimization objective

Fig. 6-9 show that the dynamic responses consist of displacement and load induced to fuselage are reduced significantly using PID-BA technique compared to passive performance. Table 3 is a comparison between passive and active methods for evaluation of suspension system.

The summarized results of Table 3 demonstrate that improvement percentage of PID-BA active system compared to passive performance is about 75% for displacement and force that leads to the comfort of rid and passengers and betterment of structure life.
Fig. 7: Air spring force under sink speed 3m/s with acceleration and impact load optimization objective

Fig. 8: Displacement of aircraft under sink speed 5m/s with acceleration and impact load optimization objective

Fig. 9: Air spring force under sink speed 5m/s with acceleration and impact load optimization objective

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Table 3: Comparison of time responses for active control without disturbance

<table>
<thead>
<tr>
<th>Touchdown</th>
<th>Controller</th>
<th>Overshoot (m)</th>
<th>Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sink speed 3m/s</td>
<td>Passive</td>
<td>0.2</td>
<td>9.6e+03</td>
</tr>
<tr>
<td></td>
<td>PID-NSE</td>
<td>0.2</td>
<td>9.6e+03</td>
</tr>
<tr>
<td></td>
<td>PID-BA</td>
<td>0.01</td>
<td>399.81</td>
</tr>
<tr>
<td></td>
<td>Improvement percentage</td>
<td>75%</td>
<td>76%</td>
</tr>
<tr>
<td>Sink speed 5m/s</td>
<td>Passive</td>
<td>0.25</td>
<td>1.19e+04</td>
</tr>
<tr>
<td></td>
<td>PID-NSE</td>
<td>0.25</td>
<td>1.19e+04</td>
</tr>
<tr>
<td></td>
<td>PID-BA</td>
<td>0.02</td>
<td>496.79</td>
</tr>
<tr>
<td></td>
<td>Improvement percentage</td>
<td>72%</td>
<td>76%</td>
</tr>
</tbody>
</table>

5.2 Simulation with consideration of runway disturbance

In the process of simulation, comparison of control methods including passive control, PID based on an approximate optimum set and PID based on Bees Algorithm adopting a wide range of control parameters for active system is performed in terms of various sinking speed (3m.s$^{-1}$ and 5m.s$^{-1}$) and Simulink model is illustrated in Fig. 10.

It is expected that an aircraft rapidly returns to its equilibrium state with runway disturbance. The amplitude of the spring force transmitted to the airframe and landing gear affects the fatigue life of them. The optimum set in Bees Algorithm produces the best control efficiency. Fig. 11-14 show that there is a decrease in the aircraft’s displacement response and impact force. Table 4 points out that active system results in improvements to the longevity of the airframe and landing gear and comfort to passengers.

Fig. 10: Diagram of Matlab Simulink with runway excitation

Fig. 11-14 show that the important parameters of displacement and force transmitted to fuselage are reduced importantly using PID-BA technique compared to passive performance.

The results of Table 4 point out that PID active system based on Bees Algorithm has good improvement percentage compared to passive control that deduces to increase in aircraft and landing gear fatigue life and ride and passenger comfort.
For example, the vertical displacement by using Bees Algorithm based PID technique for the active system has improvement percentage of approximately 40% and the force reduced up to 45% compared to passive performance that represents making better body and landing gear structure life.
6 Conclusion and discussion

In this work, the nonlinear characteristics of the mathematical model describing the active landing gear system, constant and variable parameters of the suspension system force are major problems to design of an appropriate controller. PID based on Bees Algorithm control strategy for active landing gear at touchdown with acceleration and impact load optimization objective function is proposed. It is remarked that the maximal overshoot of aircraft and load induced by the landing impact and runway disturbance can be significantly absorbed. It can be concluded that the efficiency of the landing gear is increased compared with work done in reference [19] that considered displacement and speed of aircraft and landing gear as optimization objective function according to bees algorithm. Future work will study the efficiency of other optimization algorithms for landing gear performances with input constraint for servo valve as an actuator of the suspension system in attendance intelligent and nonlinear control techniques.

References


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