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Research Article

Active Vibration Control of the Landing Gear System

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ABSTRACT

Vibrations caused by the dynamic interaction of the aircraft with the ground during landing and take-off can cause serious problems. Therefore, these vibrations should be reduced by means of active or passive methods. In this study, the active vibration control of an aircraft is investigated. The equation of motion of the aircraft is obtained by Newton's second law and simulated in MATLAB/Simulink environment. Proportional, integral derivative (PID) and Linear–quadratic regulator (LQR) control approaches are used for the active system. In the study, vertical acceleration of the vehicle body, pitching motion and control output of the controller were determined as performance criteria because of the negative effect on the pilot's capability. The simulation studies were conducted under the road profile defined in ISO 8608 and bump obstacles on the runway. LQR control performance is presented in comparison with the performance of PID control and a passive system. Based on the findings, under the bump road, 36.4% and 26.7% improvements are achieved in the vertical acceleration of the vehicle body in the case of LQR and PID controller, respectively. Similarly, under the A-grade road profile, it has been observed that the LQR control provides a 27% improvement in vertical acceleration by using 60% less force when compared to passive systems.

Keywords: *Landing gear, Active control, Vibration control.*

İniş Takımı Sisteminin Aktif Titreşim Kontrolü

ÖZET

Uçağın iniş ve kalkış sırasındaki yerle dinamik etkileşimi nedeniyle oluşan titreşimler ciddi sorunlara neden olabilmektedir. Bu nedenle, oluşan bu titreşimler aktif yada pasif yöntemler ile azaltılmalıdır. Bu çalışmada bir uçağın aktif titreşim kontrolü incelenmiştir.. Uçağın hareket denklemi Newton'un ikinci yasası ile elde edilmiş ve MATLAB/Simulink ortamında simüle edilmiştir. Aktif sistem için oransal, integral türev (PID) ve doğrusal ikinci dereceden regülatör (LQR) kontrol yaklaşımları kullanılmıştır. Çalışmada, pilotun kabiliyet performansı üzerinde zararlı etkileri olduğu için gövdenin dikey ivmelenmesi, baş vurma hareketi ve kontrol kuvvet çıkışları performans kriteri olarak belirlenmiştir. Simülasyon çalışmaları, ISO 8608'e göre oluşturulan yol profili ve tümsek engel altında çalıştırılmıştır.

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LQR kontrol performansı, PID kontrol ve pasif bir sistemin performansı ile karşılaştırmalı olarak sunulmuştur. Sonuçlardan, tümsek yol uyarımı altında, LQR ve PID kontrolörlerinin gövde düşey ivme değeride sırasıyla %36.4 ve %26.7 iyileştirme elde edilmiştir. Benzer şekilde A sınıfı yol profili altında, pasif sistemlere kıyasla LQR kontrolcünün %60 oranında daha az kuvvet kullanarak düşey ivme değerinde %27 iyileşme sağladığı görülmüştür.

Anahtar Kelimeler: *İniş takımı, Aktif kontrol, Titreşim kontrolü*

I. INTRODUCTION

The purpose of the landing gear (LG) is to assist the aircraft during landing, taking off, and taxing. During these motions, the fuselage of the aircraft is under continuous dynamic load that comes from tire-road interactions. The dynamic load vibrates the whole body. This vibration gives rise to undesirable noise and has a negative effect on passenger comfort and ride dynamics. Furthermore, vibration reduces the vehicle's maneuverability and subsequently may cause undesirable effects on braking distance. Last but not least vibration due to runaway-tire interaction is recognized as a significant factor in causing fatigue damage to the landing gear frame [1]. Therefore, LG should be designed so that it can absorb and dissipate the induced vibration. Early aircraft had passive suspension systems in their landing gear systems. However, passive suspension systems cannot perform well under different road conditions. They can perform well only under conditions for which their parameters are tuned. Further, the parameters of the suspension system change as the LG is used. So, LG cannot perform well even in the condition it is designed to work after some usage of LG.

Active vibration control has been used to control the vibration of road vehicles, buildings, bridges, and so on. Active vibration control has been very popular in vibration control of LG design thanks to the availability of microelectronics used microcomputers and in controllers. After NASA developed the active landing gear system to overcome the limitation of the passive suspension system in 1976 many researchers applied active vibration control to LG [2]. For example, S. Sivaprakasam investigated the active control of aircraft to reduce bounce, pitch, roll accelerations, displacement, and shock strut travel when moving on random runways using a PID controller [3]. S. Sivaprakasam and A. P. Haran studied the active vibration control of LG. System variables are parameterized and active vibration control is applied using a PID controller [4]. More studies related to the active control of LG can be found in [5,6,7,8]. However, the fact that active-controlled LG performs better than passive suspension, and active vibration control systems gives rise to another problem. For example, the addition of a sensor and actuator to the active control system increases the weight. Also, failure of the sensor may cause a fatal accident. Lastly, the cost of an active control system along with maintenance costs may increase the total cost of aircraft. Recently, a magnetorheological fluid (MR) damper has been fitted to LG. The working principles of MR are similar to passive suspension systems. In MR damper damping is arranged according to requirements by external means. When a magnetic field is applied, MR fluid solidifies and resists the fluid flow in an orifice. By this means controllable damping force can be obtained. MR damper can work as a passive damper even if the sensor fails. Therefore, it is called a fail-safe controller. To get benefit from the advantages of MR damper researchers investigated the control performance of MR damper LG. For example, D. Y. Lee, Y. J. Nam, R. Yamane, and M. K. Park investigated the applicability of the MR damper to aircraft landing gear with a simplified skyhook controller. It is concluded in the study that the simplified skyhook controller can be used to dampen the vibration of the MR damper [9]. W. Liu, W. Shi, and H. Ya created a mathematical model based on the Bouc-Wen hysteresis model to predict the force-displacement behavior and complex, nonlinear force-velocity response of MR dampers. Compared to passive control, it has been found that the MR damper based on semi-active control can suppress the displacement and acceleration response of the landing gear system [10]. D. Saxena and H. Rathore compared the response of landing gear with MR damper by using PID and Fuzzy-PID controllers together with MR damper to reduce vibrations of an airplane during the landing phase [11]. B. Sateesh and D. K. Maiti conducted an open-loop response analysis at the piston end of the nose landing gear of an aircraft for different loading conditions. It has been observed that excessive vibration is caused by unbalanced loading and this vibration can be reduced with an MR damper [12]. Several other studies have explored the development of landing gear prototypes and conducted physical tests to assess landing motion. For instance, in [13], researchers utilized a prototype MR damper-equipped landing gear along with a drop test setup to enhance the impact energy absorption during aircraft landings. The implementation of Skyhook and Hybrid control on the MR damper equipped landing gear demonstrated significantly improved impact damping performance during landing conditions. Additionally, [14] examined an intelligent controller based on supervised neural network control to minimize the impact during aircraft landings. The results obtained from drop tests using the MR-equipped landing gear indicated that the proposed controller outperformed the hybrid controller, even without requiring information about the aircraft mass or force inputs.

Motivated by these observations, in this study, the performance and effectiveness of different controllers fitted to LG are investigated under B grade and bump road excitation. Although numerous researchers have discussed the design and simulation of active suspension systems for LG systems, the performance of controllers has not been sufficiently highlighted. The study focuses on the design and simulation of active systems. The passive and active system of aircraft is modeled and simulated using MATLAB/Simulink. The performance of controllers is evaluated in terms of the vertical displacement and vertical acceleration of the fuselage.

II. MATERIAL AND METHOD

A. MATHEMATICAL MODELING OF ACTIVE LANDING GEAR SYSTEM

The aircraft landing gear system used in the study is illustrated in Figure 1. The system has 6 degrees of freedom. These degrees of freedom are the bounce, pitch, and roll motions of the fuselage and the displacements of the front and rear landing gears. The equation of motion is obtained by using Newton's second law.

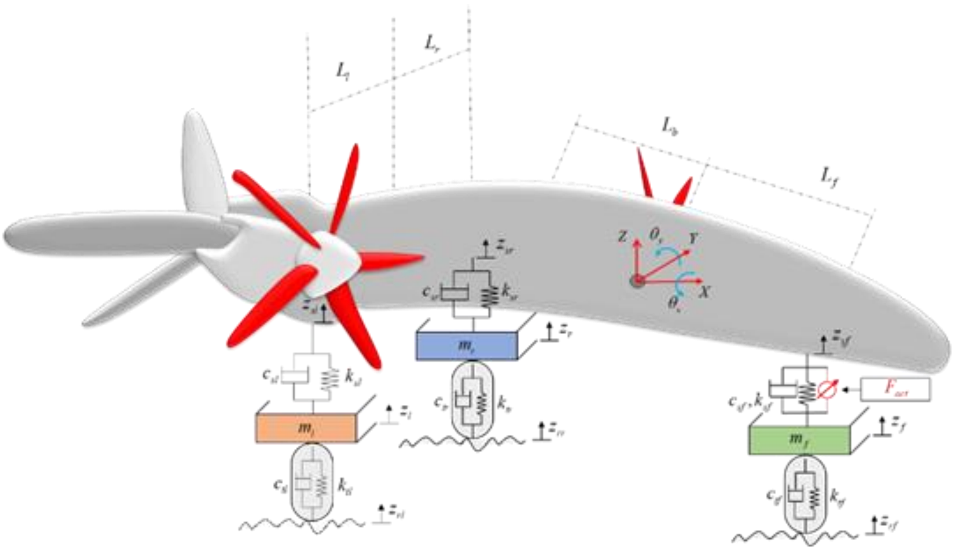

Figure 1. *Physical model of aircraft used in the study.*

The dynamics of the system are obtained mathematically as follows:
Suspension working space (rattle space):

$$\begin{aligned} z_{sf} &= (z + \theta_y L_f - \theta_x h - z_f) \\ z_{sl} &= (z + \theta_y L_b - \theta_x L_l - z_l) \\ z_{sr} &= (z - \theta_y L_b + \theta_x L_r - z_r) \end{aligned} \tag{1}$$

Equation of vertical motion, pitch motion, and roll motion of the fuselage is given in equations 2-4 respectively. Equation 5 to 7 are the equations of front wheel motion, rear left wheel motion, and rear right wheel motion respectively. h is the eccentricity of the center of gravity in -y axis.

$$M_b\ddot{z}_b = -k_{sf}z_{sf} - k_{sl}z_{sl} - k_{sr}z_{sr} - c_{sf}\dot{z}_{sf} - c_{sl}\dot{z}_{sl} - c_{sr}\dot{z}_{sr} - f_{act} \tag{2}$$

$$I_y\ddot{\theta}_y = -L_f k_{sf}z_{sf} + L_b k_{sl}z_{sl} + L_b k_{sr}z_{sr} - L_f c_{sf}\dot{z}_{sf} + L_b c_{sl}\dot{z}_{sl} + L_b c_{sr}\dot{z}_{sr} - L_f f_{act} \tag{3}$$

$$\begin{gathered} I_x\ddot{\theta}_x = hk_{sf}z_{sf} + L_l k_{sl}z_{sl} - L_r k_{sr}z_{sr} + hc_{sf}\dot{z}_{sf} + L_l c_{sl}\dot{z}_{sl} - L_r c_{sr}\dot{z}_{sr} + hf_{act} \\ h = L_l - L_r \end{gathered} \tag{4}$$

$$m_f\ddot{z}_f = k_{sf}z_{sf} + c_{sf}\dot{z}_{sf} - k_{tf}(z_f - z_{rf}) - c_{tf}(\dot{z}_f - \dot{z}_{rf}) + f_{act} \tag{5}$$

$$m_l\ddot{z}_l = k_{sl}z_{sl} + c_{sl}\dot{z}_{sl} - k_{tl}(z_l - z_{rl}) - c_{tl}(\dot{z}_l - \dot{z}_{rl}) \tag{6}$$

$$m_r\ddot{z}_r = k_{sr}z_{sr} + c_{sr}\dot{z}_{sr} - k_{tr}(z_r - z_{rr}) - c_{tr}(\dot{z}_r - \dot{z}_{rr}) \tag{7}$$

Accordingly, the dynamic equation of the total system that includes the mass, spring, and damper can be arranged as follows.

$$M\ddot{x}_s = C\dot{x}_s + Kx_s + Hf_{act} + E_1 d + E_2\dot{d} \tag{8}$$

$$x_s = [z \quad \theta_x \quad \theta_y \quad z_f \quad z_l \quad z_r]^T \tag{9}$$

In equation (8), M, C, and K represent mass, damping, and stiffness matrices, respectively. H represents the force vector that gives the location of the controller. E_1 and E_2 represent the force vector that stands for the road input to the dynamic model. f_{act} is the control force of the actuator. The runway disturbances are referred by d and finally, $\dot{d}$ is the velocity input due to the runway profile as given in equation (10) - (11).

$$d = [z_{rf} \quad z_{rl} \quad z_{rr}]^T \tag{10}$$

$$\dot{d} = [\dot{z}_{rf} \quad \dot{z}_{rl} \quad \dot{z}_{rr}]^T \tag{11}$$

Then the system can be written in state space format as

$$\begin{gathered} \underbrace{\begin{bmatrix}\dot{x}_s\\ \ddot{x}_s\end{bmatrix}}_{\dot{x}} = \underbrace{\begin{bmatrix}0_{6x6} & I_{6x6}\\ M^{-1}K & M^{-1}C\end{bmatrix}}_{A}\underbrace{\begin{bmatrix}x_s\\ \dot{x}_s\end{bmatrix}}_{X} + \underbrace{\begin{bmatrix}0_{6x1} & 0_{6x3} & 0_{6x3}\\ M^{-1}H & M^{-1}E_1 & M^{-1}E_2\end{bmatrix}}_{B}\underbrace{\begin{bmatrix}f_{act}\\ d\\ \dot{d}\end{bmatrix}}_{u} \\ \dot{x} = Ax + Bu \end{gathered} \tag{12}$$

B. LINEAR QUADRATIC REGULATOR (LQR)

LQR is one of the most common linear controllers among the model-based optimal control methods. In the LQR control, the control input is calculated in a way that minimizes a quadratic performance index formed by the system's state variables and control inputs. This structure is given in Figure 2. The state-feedback control signal that minimizes the cost function can be written as given in equation (13), here, P can be obtained by solving algebraic Riccati equations.

$$K = R^{-1}(B^T P + N^T) \tag{13}$$

The LQR control aims to find a transfer matrix $K(s)$ that will minimize the cost function given in equation (14).

$$J_{LQR} = \int_0^\infty \rho_1\|(\ddot{z})(t)\|^2 + \rho_2\left\|z_{sf}(t)\right\|^2 + \rho_3\left\|(\theta_y(t)\right\|^2 + \rho_4\|F_{MR}(t)\|^2 dt \tag{14}$$

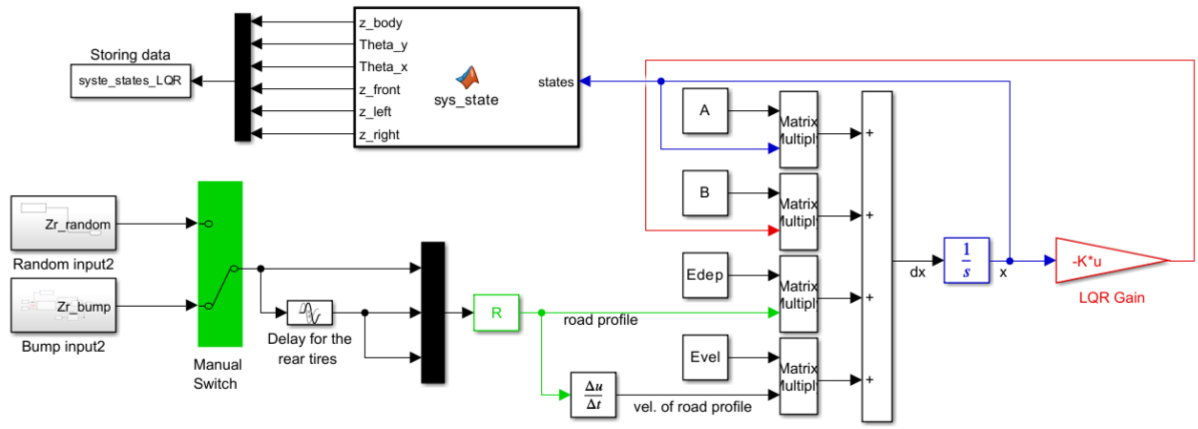

Figure 2. *LQR state variable feedback structure*

The weighting coefficients ρ_1, ρ_2, ρ_3 and ρ_4 provide the trade-off between the terms of the cost function. In MATLAB, the continuous time cost function is computed in the form of equation (15)

$$J_{LQR} = \int_0^{\infty} \{x(t)'Qx(t) + u(t)'R\,u(t) + 2x(t)'N(t)\,u(t)\}\,dt \tag{15}$$

By utilizing a generated code in MATLAB, Q, N and R matrices were obtained automatically. The trial-error method was used in the specifying the weighting coefficients, the actuator capacity was considered for the ρ_4. The selected parameters are $\rho_{i=1:4} = [2 \quad 0.05 \quad 5\times10^5 \quad 5\times10^{-7}]$. The resulting control gain is calculated as:

$$K = 10^5 \times [-0.0668 \quad -0.9751 \quad 0 \quad -0.1482 \quad -0.2055 \quad -0.2055 \quad -0.0266 \quad -1.2252 \quad 0 \quad -0.0042 \quad -0.0041 \quad -0.0041] \tag{16}$$

C. PID CONTROLLER

The PID control is frequently encountered in feedback control design especially in industrial applications because of its simplicity and effectiveness. The control system of a PID is shown in Figure 3 schematically. The desired performance of the PID is obtained by tuning of control parameters which are the proportional (K_p), the integral (K_i), and the derivative (K_d) of the system error. PID controller can be expressed mathematically in equation (18). Here, f_{act} is the actuator force. The parameters are set by trial and error methods until the desired output is obtained. In this study, K_p , K_i and K_d are set to 66000, 2000 and 500 respectively.

$$e(s) = r_i(s) - y(s) \tag{17}$$

Here, $y(s)$ is the deflection of the front suspension and the $r_i(s)$ is set to zero. The resulting control force can be calculated by equation (18).

$$f_{act} = K_p e(t) + K_i \int_0^t e(t)dt + K_d \frac{de(t)}{dt} \tag{18}$$

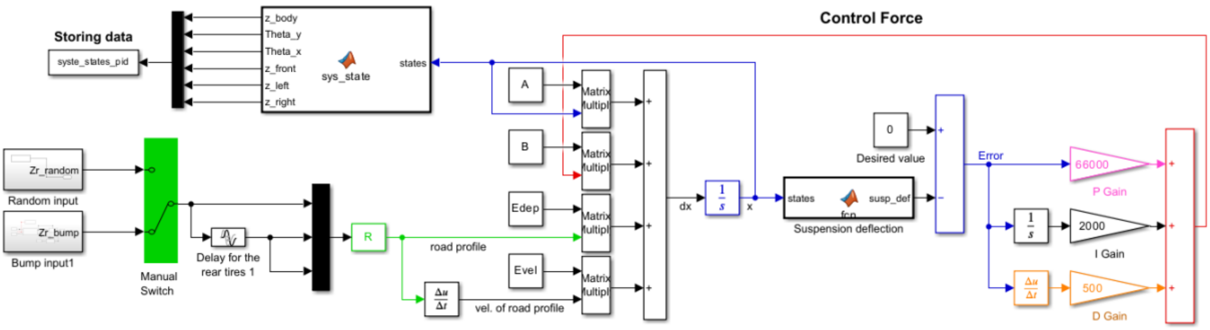

***Figure 3**. PID feedback structure*

D. NUMERICAL SIMULATION STUDY

In the simulation study, the landing gear LG that has no control (passive), LQR control, and PID control cases are modeled and simulated in the MATLAB environment. The parameters of aircraft used in this study are taken from [15] and given in Table 1. As shown in equation (19), the road roughness in this study is modeled as the sum of sinusoidal waves with variable amplitudes and frequencies. The velocity of the vehicle is constant and set to speed of 25 m/s.

$$z_r(x) = \sum_{i=0}^{N} \sqrt{2.G_{d0}.(\Omega/\Omega_0)^{-w}.\Delta n}\cos(2\pi.\Omega.x + \psi_r) \quad (19)$$

Here G_{d0} is the unevenness index that is selected as 1×10^{-6} m3/cycles that correspond to the A-grade road class defined in ISO 8608 [16]. Also, Ω is the spatial frequency, Ω_0 is reference spatial which is equal to 0.1 cycles/m, random phase angle is defined by ψ_r . The designed runway for a distance of 500 meters is given in Figure 4. After the random road, a bump input formed by equation (20) and in height of 20 mm is adopted to investigate the transient response of the system and evaluate the control performance under different road inputs.

$$z_r(t) = \begin{cases} 0.02(1+\cos 8\pi t)/2 & 0.875 \le t \le 1.125 \\ 0 & \text{otherwise} \end{cases} \quad (20)$$

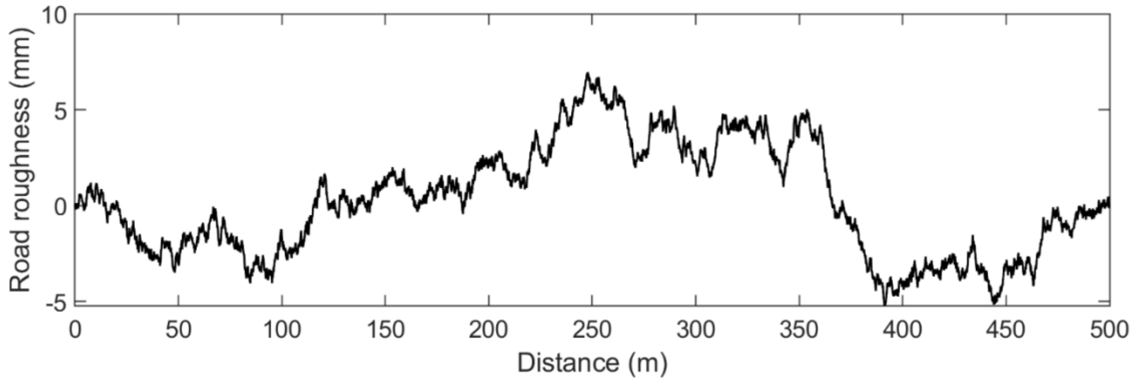

Figure 4. Designed A-grade runway roughness

Table 1. Parameters used in the study [13]

Parameters	Value	Units	Parameters	Value	Units
M_s	3345	[kg]	k_{sl}	102095	[N/m]
m_f	100	[kg]	k_{sr}	102095	[N/m]
m_l	150	[kg]	k_{tf}	1590000	[N/m]
m_r	150	[kg]	k_{tl}	1590000	[N/m]
I_x	200879	[kgm^2]	k_{tr}	1590000	[N/m]
I_y	56465.3	[kgm^2]	c_{sf}	1.9822e4	[Ns/m]
L_f	11.6	[m]	c_{sl}	1.9822e4	[Ns/m]
L_b	1.2	[m]	c_{sr}	1.9822e4	[Ns/m]
L_l	5.2	[m]	c_{tf}	1500	[Ns/m]
L_r	5.2	[m]	c_{tl}	1500	[Ns/m]
k_{sf}	102095	[N/m]	c_{tr}	1500	[Ns/m]

II. RESULTS AND DISCUSSION

In this section, the dynamic model of aircraft explained in the previous section is simulated by using MATLAB/Simulink. The efficiency of the LQR controller algorithm is compared to PID control with regard to focused performance criteria which are vehicle body acceleration, body pitch motion (the rotation of an aircraft around its lateral axis) and the force output of front suspension. Figure 5 illustrates the comparison of passive suspension and active suspension systems considering the body pitching motion. As shown in Figure 5, the LQR control provides a better result in terms of overshoot on the random road and bump stages, also, the oscillations after the sudden input are absorbed faster than the PID control.

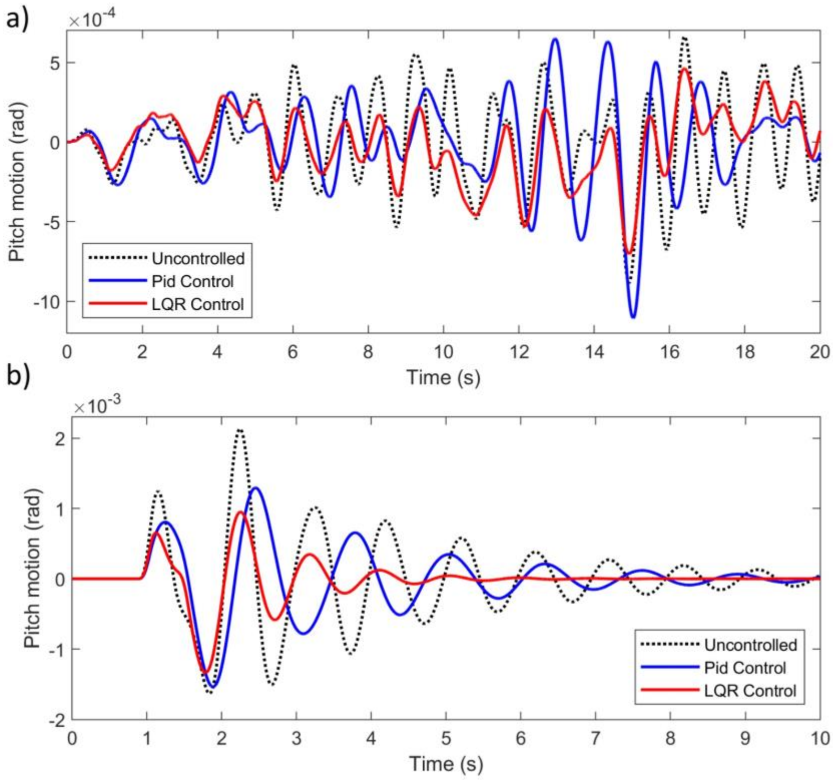

Figure 5. Pitch motion of the body, a) on the irregular runway, b) bump on the runway.

Another criterion for the performance evaluation, the force response of the designed controller should be considered. In addition, the peak value of the force is an indicator of the capacity of the actuator and the RMS (root-mean-square) value of the control force can be thought of as the average value of consumed energy. Figure 6 shows that the PTP (peak-to-peak) values of the controller both in the random and bump runway cases were decreased by 33.7% and 43.3% respectively. LQR control performs better than PID control besides it requires less energy than PID control.

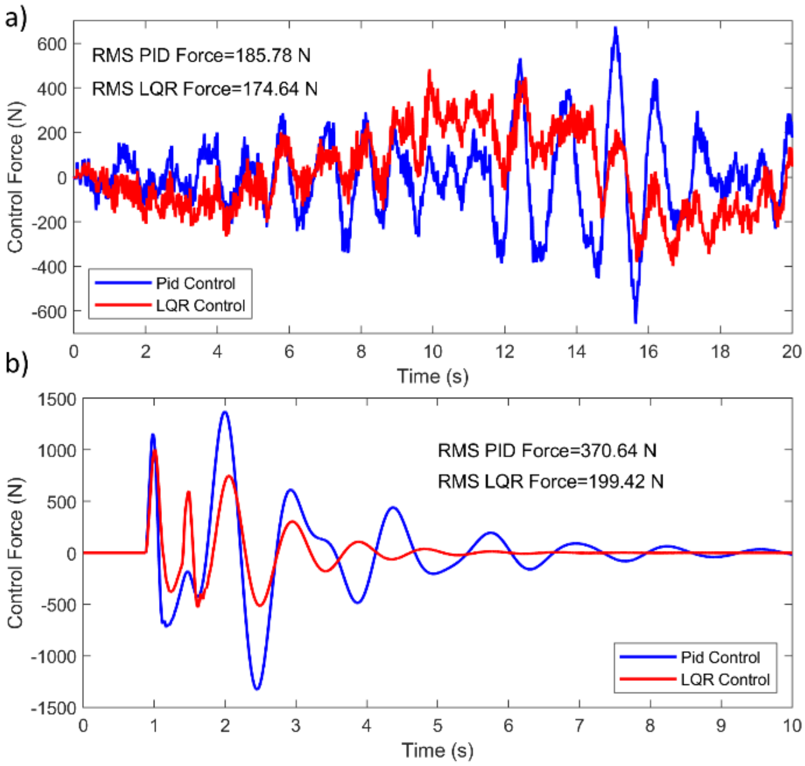

Figure 6. *Controller effort.*

Besides RMS values of the vertical acceleration of the body and the control forces, the PTP values of the focused performance criteria in the case of the random and the bump runway road profiles are summarized in Table 2. In the case of a bump on the runway, the RMS value of the passive system is 0.2985, and this value is reduced to 0.2186 and 0.1898 for PID and LQR control, respectively. Also, both PID and LQR controllers provide 22.7% reduction in vertical acceleration when compared to uncontrolled (passive) case. These results show that the LQR controller provides better control performance in terms of all the selected criteria by consuming less energy.

Table 2. *Comparison of simulation results.*

	A Grade runway			**Bump on runway**		
	Uncontrolled	PID	LQR	Uncontrolled	PID	LQR
RMS $\ddot{z}$ (m/s^2)	0.1072	0.0828	0.0774	0.2985	0.2186	0.1898
Improvement %		22.7	27.7	-	26.77	36.42
RMS Force (N)		185.78	174.64	-	370.64	199.42
Improvement %		-	60	-	-	46.2
PTP $\ddot{z}$	0.6913	0.5575	0.4593	2.9416	2.2230	1.9447
PTP θ_y	0.0015	0.0018	0.0012	0.0038	0.0028	0.0023
PTP Force	-	1332.3	883.5	-	2697.9	1530.1

III. CONCLUSIONS AND RECOMMENDATIONS

In this study, active vibration control of the aircraft landing gear mechanism is presented by using PID and LQR control. The study is performed under A grade road and bump road when the aircraft is taxing at a velocity of 25 m/s. The numerical simulations are utilized to demonstrate the feasibility of the proposed LQR control under various road conditions. LQR control requires up to 60% less force to achieve better performance in regard to considered indices when compared to the PID control. Also, peak to peak value of the vertical acceleration is decreased by 33.56% and 19.35% in the case of LQR and PID control, respectively. In physical application, LQR control needs all the system states but PID control can be implemented by only using suspension deflection. In physical application, PID control can be implemented by only measuring the suspension deflection but LQR control needs measurement of all system states. This condition increases the cost of the control implementation.

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