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ANALYSIS OF THE STATIC BEHAVIOR OF A NEW LANDING GEAR MODEL BASED ON A FOUR-BAR LINKAGE MECHANISM

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ABSTRACT

A landing gear model using a four-bar linkage mechanism is proposed in this study. The simulation study was conducted to evaluate the effect of the link dimension variation and coil spring constant on the equivalent stiffness and static deflection of the landing gear. The simulation results show that increasing the landing gear dimension affects the static deflection of the landing gear. However, the linear stiffness of the landing gear system is not much affected by the landing gear dimension variation. Furthermore, the landing gear stiffness characteristic is nonlinear for large landing gear displacement.

Keywords: Dynamic; Impact; Landing gear; Simulation; Vibration

1. INTRODUCTION

Unmanned aerial vehicles (UAVs), also known as drones, are pilotless aircraft controlled remotely using a computer or radio controller (RC). They are created with various sizes, designs, and purposes and can fly autonomously using a pre-flight path planning program (Yao et al., 2015; Yang et al., 2016; Sutresman et al., 2017). Given their sophistication and technological ease, UAVs are widely used in areas such as monitoring, mapping, search and rescue operations, goods shipping, civil infrastructure inspection, and military weapons (Jha, 2009; Sung, 2014).

One of the most important components in UAVs is the landing gear system. Generally, a landing gear system consists of shock absorbers, steering, a shimmy control, wheels, and brakes (Prasad & Gangadharan, 2015). The landing gear system is used to hold the UAV load during parking and taxiing (Bahkali, 2013) as well as to reduce the force transmission and acceleration of a UAV body during landing. Furthermore, it must keep the UAV wheel in contact with the ground for steering stability. These important features should be considered in designing an optimum UAV landing gear system.

Different types and characteristics of UAV landing gear systems depend on a number of factors, including UAV weight, stiffness, and vibration characteristics. Several studies have been conducted to evaluate UAV landing gear system performance in reducing impact-induced vibration during landing. An interesting feature is landing gear stability during braking and maneuvering on the ground, which can be improved by using longer axles, stiffer springs, a smaller wheel mass, and lower aircraft landing speeds (Sadrey, 2012).

Although high stiffness in the landing gear system is very necessary for aircraft stability, this

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condition also has the side effect of increasing the shock force transmission to the UAV structure during landing. This large shock load increases UAV acceleration response and causes damage to the electronic components inside the UAV body (Mikulowski, 2008; Son et al., 2018).

Effective shock isolation performance in a landing gear system is normally achieved by increasing the energy storage capacity of the landing gear elastic element; however, the significant energy storage requires large deformations of the landing gear, and space is normally limited. In addition, the landing gear structure must be able to dissipate the impact energy to reduce residual vibrations. An alternative method to reduce vibration response is to increase the structural damping using fiber reinforced materials (Murali et al., 2014). Active vibration control methods have proposed by researchers to attenuate vibration response occurred in mechanical systems. Mohebbi and Hashemi (2016) proposed an active vibration control technique for reducing the vibration response of an unbalanced rotary engine. In his study, the unbalanced rotary engine was modeled by a one-degree of freedom vibration system. The application of the active vibration control to a two-degree of freedom unbalanced engine model was also proposed by Mohebbi and Hashemi (2017).

Shock vibration isolation systems with nonlinear elements have been used by several researchers to improve shock isolation performance. Snowdon (1963) was one of the first to investigate the shock isolation characteristics of nonlinear elements. Much later, Carrella et al. (2008) proposed a high-static and low-dynamic stiffness isolator using a combination of linear springs. Meanwhile, Son et al. (2019) have found that the stiffness nonlinearities could be advantageous in reducing impact induced vibration in terms of rebound displacement and acceleration response in comparison with linear elastic elements.

In this study, the static analysis of a landing gear system based on a four-bar linkage mechanism is performed. The simulation study was conducted to evaluate the effects of spring stiffness and the landing gear dimension variation on the nonlinear characteristic and the static deflection of the landing gear system.

2. METHODS

The conventional type of landing gear system for UAVs consisting of a linear spring and damping system has some limitations. Significant stiffness in the landing gear system can improve the steering stability; however, the transmission force becomes significant, thus increasing the acceleration response of the UAV body. This side effect can cause damage to the landing gear structure and UAV components. Conversely, a low-stiffness landing gear system can reduce the force transmission and acceleration of the UAV. However, the UAV static deflection becomes large and the steering stability reduces. Practically, the landing gear's static displacement is limited by the landing gear’s space and dimensions.

In this research, a new concept of a landing gear system that has high stiffness for small deflection and low stiffness for large deflection is proposed. These landing gear behaviors are realized using a four-bar linkage mechanism, as shown in Figure 1. This research begins by modeling the landing gear system. Next, the system equations of motion are calculated based on kinematic and static analysis. The last step consists of evaluating the landing gear parameters, such as spring stiffness and landing gear dimensions, on the landing gear equivalent stiffness characteristic.

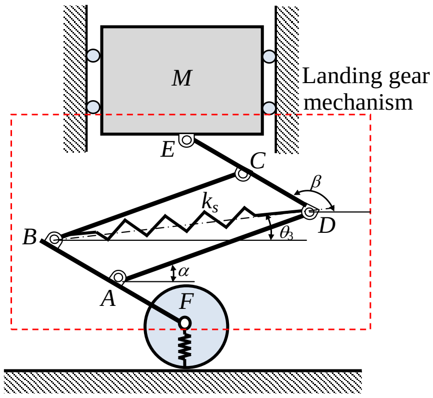


Figure 1 Four-bar mechanism landing gear system

2.1. Kinematic Analysis of the Four-bar Linkage Mechanism

Kinematic analysis of the four-bar linkage mechanism of the landing gear system was derived as shown in Figure 2. In this analysis, it was assumed that the landing gear is only allowed to move in the vertical direction. Therefore, the system is considered as a one degree of freedom (one DOF) vibration model. By assuming the dimension $DE = BF = a$ and $BC = AD = b$ then,

$$\alpha + \beta = 180 \tag{1}$$

$$L^2 = \left(\frac{1}{2}a\right)^2 + b^2 - 2\cdot\frac{1}{a}\cdot b\cdot\cos\left(180-2\alpha\right) \tag{2}$$

$$Xx^2 = \left(\frac{1}{2}a\right)^2 + \left(\frac{1}{2}a\right)^2 - 2\cdot\frac{1}{2}a\cdot\frac{1}{2}a\cdot\cos\left(180-2\alpha\right) \tag{3}$$

$$Xx^2 = L^2 + \left(b-\frac{1}{2}a\right)^2 - 2\cdot L\cdot\left(b-\frac{1}{2}a\right)\cdot\cos\left(\theta_4\right) \tag{4}$$

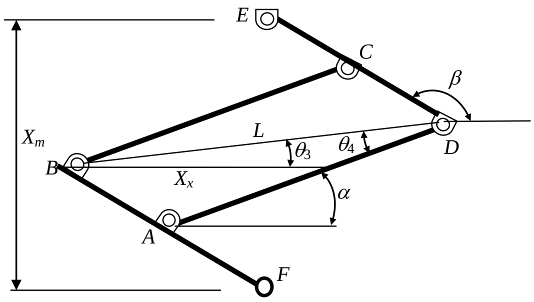


Figure 2 Four-bar mechanism landing gear system

The relationship between α and θ_3 can be expressed as:

$$\theta_3 = \alpha - \cos^{-1}\left(\frac{L^2 + \left(b-\frac{1}{2}a\right)^2 - Xx^2}{2\cdot L\cdot\left(b-\frac{1}{2}a\right)}\right) \tag{5}$$

According to Figure 2, X_m depends on α, β, and θ_3; therefore, X_m and the static deflection of the landing gear (x) can be expressed as follows:

$$X_m = DE\sin\left(\beta\right) + BD\sin\left(\theta_3\right) + BF\sin\left(\beta\right) \tag{6}$$

$$x = X_{m0} - X_{mi} \tag{7}$$

where X_{mo} and X_{mi} are the initial and final value of X_m after loading.

2.2. Static Analysis of the Landing Gear System

The UAV landing gear system supports the aircraft weight when stationary (parking) and moves on the ground (taxiing). During the static condition, the landing gear system was deformed due to the UAV gravitational force. Figure 3 shows the static forces acting on the UAV main mass. F_{Ex} and F_{Ey} are forces relating to the interaction between the UAV mass and the landing gear mechanism.

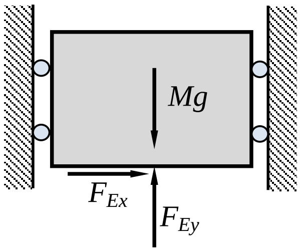


Figure 3 Static forces on the main mass

The vertical force balancing on the UAV mass in Figure 3 can be written as:

$$\begin{aligned} &Mg - F_{Ey} = 0 \\ &Mg = \left(\frac{\sin(180+\theta_3-\beta)\cdot\sin(\alpha)}{\cos(\beta-\alpha-90)} - \sin(\theta_3) \right)\cdot F_{kc} \\ &Mg = \left(\frac{\sin(180+\theta_3-\beta)\cdot\sin(\alpha)}{\cos(\beta-\alpha-90)} - \sin(\theta_3) \right)\cdot k_s \cdot \Delta L \end{aligned} \tag{8}$$

where,

$$\Delta L = L_i - L_o \tag{9}$$

The equivalent spring constant of the landing gear system is calculated from the relationship between the static vertical load and the vertical displacement of the UAV mass. This relationship is obtained by combining Equation 5 to Equation 9.

2.3. Landing Gear Model Parameters

The landing gear model consists of a main mass, four-bar linkage mechanism, a spring, and a wheel. The landing gear nominal parameters for simulation are depicted in Table 1. Kinematic analysis of the four-bar linkage landing gear mechanism was carried out using CAD modeling software. The landing gear positions were calculated for some values of vertical loads. The angular changes of each landing gear link were investigated from the position analysis of the landing gear mechanism.

Table 1 Nominal landing gear parameters

No.	Component	Dimension	Material
1	Main Mass	40 kg	Steel Alloy
2	Bar	a = 0.2 m	Aluminum
		b = 0.3 m	
3	Spring	L_0 = 240 mm	Steel Alloy
		k_{s0} = 100000 N/m	

To evaluate the effect of landing gear dimension variation on the stiffness and static deflection, the lengths of links *DE* and *AD* were varied in five categories, as depicted in Table 2. As shown in Table 2, the lengths of links *DE* and *AD* were varied from (1/2) *a* to (3/2) *a*.

Table 2 Landing gear bar length

Landing Gear Model	Length of *DE*	Length of *AD*
Model 1	(1/2)*a*	(1/2)*b*
Model 2	(3/4)*a*	(3/4)*b*
Model 3	*a*	*b*
Model 4	(5/4)*a*	(5/4)*b*
Model 5	(3/2)*a*	(3/2)*b*

3. RESULTS AND DISCUSSION

The CAD modeling result of the landing gear mechanism is shown in Figure 4. The CAD simulation model was used to evaluate the relationship between the mass position and the link angles on the mechanism. The simulation results obtained from the CAD model were compared with those obtained by analytical calculation using Equation 1 to Equation 5.

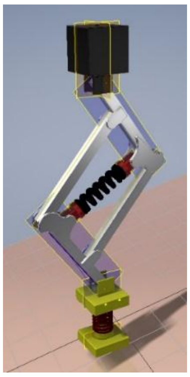
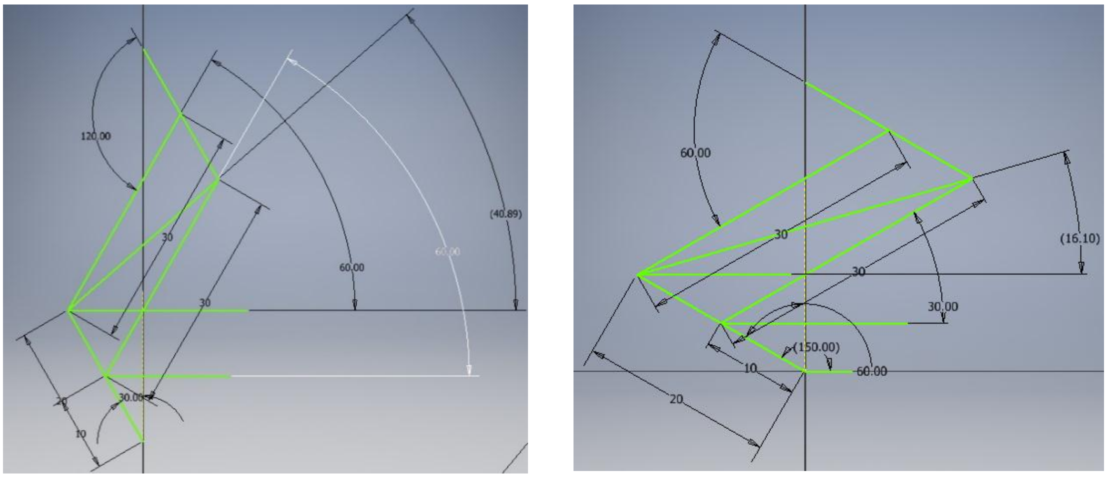


Figure 4 Landing gear CAD model

3.1. Relationship Between α, β, and θ_3

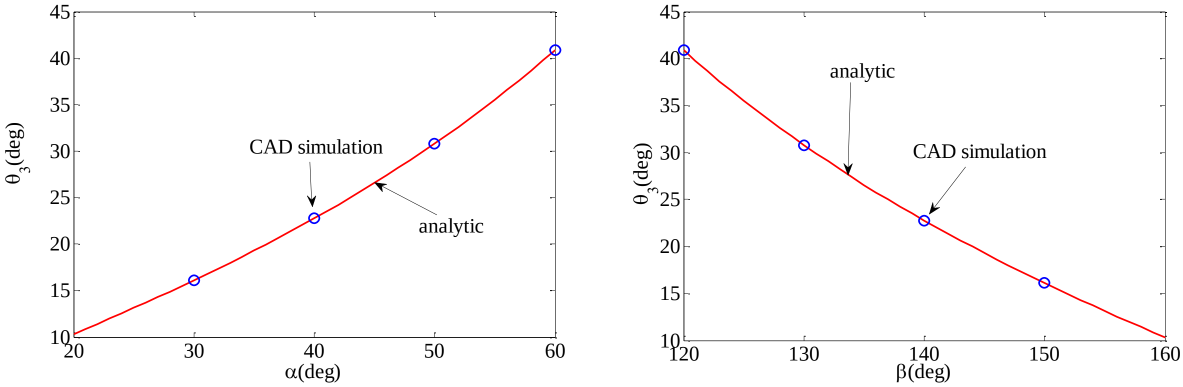
The relationship between α, β, and θ_3 was evaluated by increasing β from 120^o to 150^o. Meanwhile, lengths *a* and *b* were selected as 20 cm and 30 cm, respectively. Figure 5 shows the variation of the landing gear links orientation for $\beta = 120^o$ and $\beta = 150^o$.



(a) $\beta = 120°$ (b) $\beta = 150°$

Figure 5 Relation between α, β, and θ_3

Figure 6 shows a comparison of the landing gear angle obtained from CAD modeling and analytical results. It can be seen from Figure 6 that the results obtained from the CAD simulation are similar to those obtained by the analytical method.



(a) α vs θ_3 (b) β vs θ_3

Figure 6 Relationship of bar angle a) α vs θ_3 b) β vs θ_3

The results depicted in Figure 6 indicate that increasing the landing gear load will increase the spring length and decrease the mechanism level (X_m); therefore α and θ_3 decrease and β increases.

3.2. Spring Rate

The spring rates of the landing gear system were obtained from the relationship between the static load (Mg) and deflection (x) of the main mass. The static deflection was calculated using Equation 8. The relationship between the vertical load and landing gear deflections for five models is shown in Figure 7. It can be seen from Figure 7 that the relationship between landing gear weight and deflection is linear for small displacements and becomes nonlinear for large displacements. Furthermore, the static deflection is large when the landing gear dimension is increased.

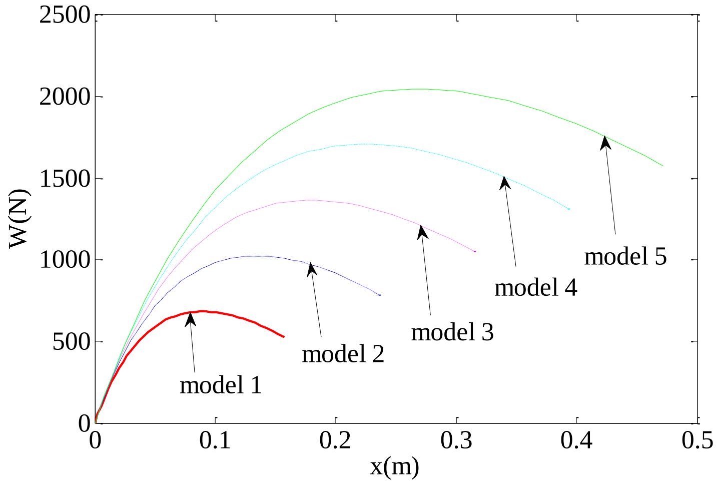


Figure 7 Spring rate variation of each model

Table 3 shows the equivalent linear stiffness obtained for each model. The linear stiffness is calculated in the linear region of the spring rate curve. As shown in Table 3, the equivalent linear stiffness is almost constant with the landing gear dimensions variation.

Table 3 Linear spring equation for each model

Landing Gear System	Linear Spring Equations
Model 1	y = 3425.8x+284.86
Model 2	y = 3425.8x+427.29
Model 3	y = 3425.8x+569.72
Model 4	y = 3425.8x+712.15
Model 5	y = 3425.8x+854.57

Based on the results shown in Table 3, it can be concluded that variations in the dimensions of *DE* and *AD* (for each model) do not significantly affect the magnitude of the equivalent linear spring constant of the landing gear system. However, increasing the values of *DE* and *AD* will increase the static deflection of the landing gear (x), as shown in Table 4. The largest static deflection is obtained from Model 5, and the smallest static deflection occurs in Model 1.

Table 4 Static deflection of the landing gear

Landing Gear System	X_m Maximum (m)	Static Deflection, x (m)
Model 1	0.26	0.157
Model 2	0.39	0.236
Model 3	0.52	0.314
Model 4	0.65	0.393
Model 5	0.78	0.472

A variation of the landing gear spring rate vs k_s for Model 1 is depicted in Figure 8. In this simulation, k_s is varied from 0.6 k_{s0} to 1.4 k_{s0}. It can be seen from Figure 8 that the larger values of k_s result in a large value for the equivalent landing gear linear stiffness. The results shown in Figure 8 indicate that the equivalent linear stiffness increases with the increase of k_s.

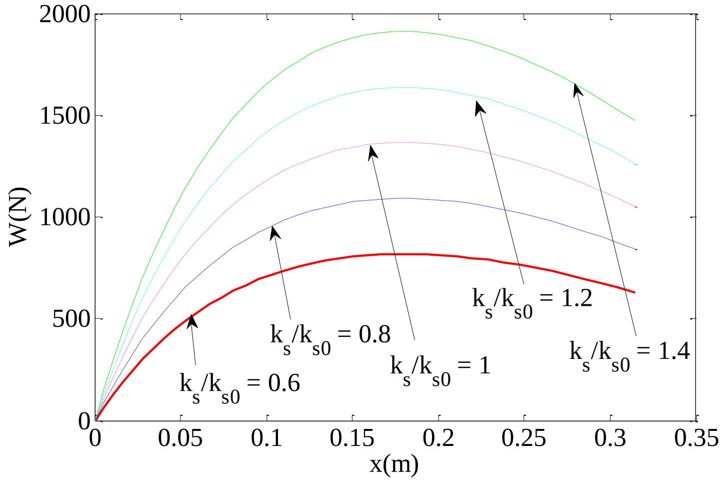


Figure 8 Relationship between static displacement and load

4. CONCLUSION

A new model for a UAV landing gear system using a four-bar linkage mechanism has been proposed here, and static analysis was conducted to evaluate the stiffness characteristic and static deflection of the landing gear. Several conclusions were obtained as follows: (1) The stiffness characteristic of the four-bar linkage mechanism landing gear system is nonlinear; (2) The nonlinear behavior of the landing gear system with a high-static stiffness and low-dynamic stiffness characteristic can improve the dynamic response of the landing gear; (3) Increasing the landing gear dimension does not much affect the linear stiffness. However, it can increase the static displacement of the landing gear.

5. ACKNOWLEDGEMENT

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