1146. Drop dynamic analysis of half-axle flexible aircraft landing gear

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Abstract. Landing gear shock strut binding problem occurred during an unmanned aircraft's flying test. The half-axle main landing gear of the unmanned aircraft was chosen to analyze the influences of shock strut flexibility on drop dynamics. The friction force was modeled based on the half-axle configuration and taking shock strut flexibility into account. Drop dynamic performances were analyzed and compared with those came from rigid strut model and drop test. Good correlation has been established between drop test data and the simulation predicated results. The results also showed that though the total axis force added merely 1 % when taking shock strut flexibility into account, the friction force added almost 45 %. A comprehensive deformation compatibility factor was presented to describe the actual deformation of shock strut bearings. Influence of deformation compatibility factor, flexibility of inner and outer cylinder were studied further.

Keywords: landing gear, drop, dynamics, half-axle, flexibility.

1. Introduction

There are four fundamental force elements, (air spring force, hydraulic force, friction force and structural limit force), in landing gear drop dynamic modeling usually [1]. For researches focus on whole aircraft or control performance, friction force is neglected or simplified frequently. In David H. Chester's research on aircraft landing dynamics with emphasis on nose gear landing conditions [2], Phil Evans's research on tricycle landing gear landing dynamics at normal and abnormal conditions [3], and David C. Batterbee's research on magneto rheological oleo pneumatic landing gear drop dynamics [4], friction force of the shock strut were neglected. Anthony G. Gerardi's landing gear model included friction force at first. However, the friction force was neglected when taking the symmetrical configuration of landing gear wheels into account [5]. Gu Hongbin simplified shock strut hydraulic damping and friction damping as a linear damping [6] and Yuan dong simplified them as a nonlinear damping [7]. Kapseong Ro [8], Jia Yuhong [9], Mu Rangke [10] mentioned that friction force were concluded in their dynamic models, but the friction force model were not presented in the articles.

For landing gear drop dynamics, friction force is usually taken into account. In Benjamin Milwitzky's landing gear drop dynamic model [11], shock strut outer cylinder and inner cylinder were assumed as rigid. Shock strut friction force was modeled as the function of reaction forces at upper bearing and lower bearing. Francis E. Cook adopted the same friction force modeling method as Benjamin Milwitzky's work [12]. Mahinder K. Wahi [13] and Wei Xiaohui [14, 15] inherited this model in their landing gear and aircraft landing dynamics.

Prashant Dilip Khapane neglected structural friction force and modeled the shock strut friction force as the function of inner air pressure, namely seal friction [16]. In fact, the more practical method is to add this seal friction force to structural friction force. James N. Daniels adopted this friction force model [17], and Archie B. Clark [18], Nie Hong [1], and Sui Fucheng [19] inherited this model in their researches respectively.

With the use of high-strength steel, such as 300M steel [20] and A100 steel [21], aircraft landing gear became more and more flexible. It seemed imperative that if the conventional rigid shock strut assumption still suitable for landing gear drop dynamics should be studied.

Frictional damping of the landing gear shock strut should be as small as possible, and it is usually no more than 5 percent of the shock strut axial force [22]. Shi Haiwen mentioned that tire longitudinal force has a great influence on the shock strut friction force [23]. But for the half-axle landing gear, tire vertical force also has an adverse effect on the shock strut friction force.

The shock strut of half-axle landing gear suffered more bending moment than the landing gear with symmetric layout of wheels. If the shock strut is not rigid enough, the influences of shock strut bending are non-ignorable. Gao Zejiong presented that the shock strut's bending deformation would add an additional moment on the bearings between inner and outer cylinder [22]. That would make the friction characteristic of the shock strut worse and possibly led to binding problem. But there are not any published researches of the effect of shock strut flexibility on the shock strut friction force and drop dynamics of landing gear. Then, the half-axle main landing gear of the aircraft was chosen to analyze the influences of shock strut flexibility on the shock strut friction force and drop dynamics.

2. Landing gear configuration and forces

The structural configuration of the main landing gear of the unmanned aircraft is a kind of half-axle shock strut. Figure 1 shows a schematic representation of the landing gear configuration. Figure 2 shows the forces on wheel and inner strut.

The ground coordinate system $Oxyz$ is fixed to the ground. The origin O is a point located on the ground, axis x is in the forward longitudinal direction, axis y is in the upward direction, axis z is followed the right-hand rule.

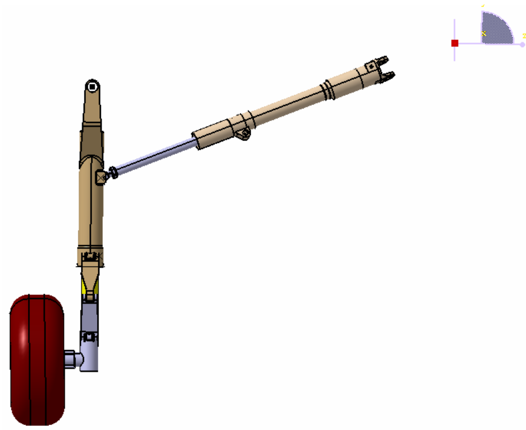

Fig. 1. Landing gear configuration

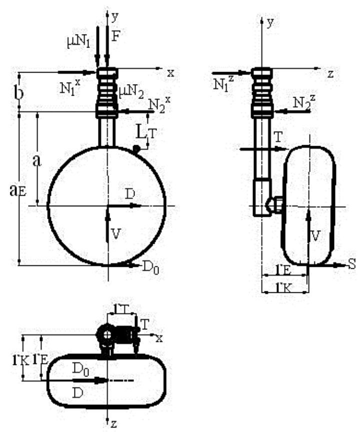

Fig. 2. Forces on wheel and inner strut

In Figure 2: μ is the friction coefficient of bearings, a is the displacement between wheel axle and lower bearing, b is the displacement between lower bearing and upper bearing, L_t is the displacement between pivot point of torque arm and lower bearing, r_K is the displacement between the center of wheel axle and shock strut axis, r_T is the displacement between the line of torque arm action force and shock strut axis, F_{xl} and F_{yl} is the longitudinal and vertical ground reaction force respectively, N_1^x and N_1^z is the upper bearing reaction force in Oxy plane and Oyz plane respectively, N_2^x and N_2^z is the lower bearing reaction force in Oxy plane and Oyz plane respectively, P_{xl} and P_{yl} is the longitudinal and vertical wheel axle force respectively, T is the torque arm action force.

3. Drop dynamic model

The basic equations of motions are those used for a two-degree-of freedom system as shown in Figure 3. Figure 4 shows the schematic representation of the land gear's oleo-pneumatic shock strut.

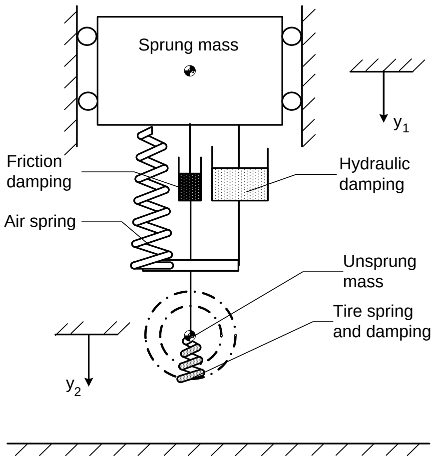

Fig. 3. System with two degrees of freedom

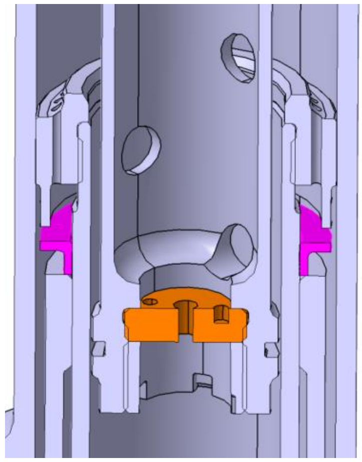

Fig. 4. Schematic representation of shock strut

Equations of motion, tire forces and shock strut forces are modeled according to Nie's research [1].

Equation of motions can be expressed by:

$$m_1\ddot{y}_1 = m_1 g - F_a - F_h - F_f, \quad (1)$$

$$m_2\ddot{y}_2 = -F_V + m_2 g + F_a + F_h + F_f, \quad (2)$$

where m_1 and m_2 is the sprung and unsprung mass respectively, F_a is pneumatic force, F_h is hydraulic force, F_f is friction force.

Equations of motion, tire forces and shock strut forces are the same as Nie's research, except that shock strut friction force is modeled as follow.

Friction in this gear comes mainly from two sources, friction due to tightness of the seal and friction due to the forces on tire(moment), and can be expressed by:

$$F_f = F_{f1} + F_{f2}, \quad (3)$$

where F_f is shock strut friction force, F_{f1} is seal friction force and F_{f2} is friction force due to the forces on tire.

The seal friction is assumed to be a function of internal air pressure and can be expressed by:

$$F_{f1} = \mu_{se} F_a, \quad (4)$$

where μ_{se} is the friction coefficient of seal cup, F_a is the shock strut air spring force.

The friction due to the forces on tire is the result of the moment produced by the nonaxially loaded piston within the cylinder. Considering flexibility of the shock strut, Figure 5 shows the forces in Oyz plane, then:

$$N_1^z - N_2^z + S + T = 0, \quad (5)$$

$$M_1^z + M_2^z + N_1^z b - V r_K - S a_E - T L_T = 0, \quad (6)$$

where a_E is the displicement between ground and lower bearing, d is the displacement between upper bearing and the end of outer cylinder, S is the side ground reaction force, M_1^z and M_2^z is the bending moment due to shock strut flexibility at upper and lower bearing in Oyz plane respectively.

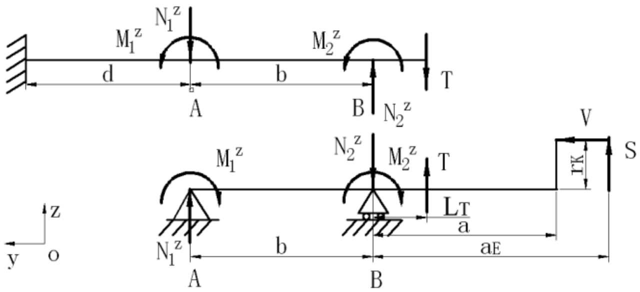

Fig. 5. Forces in Oyz plane

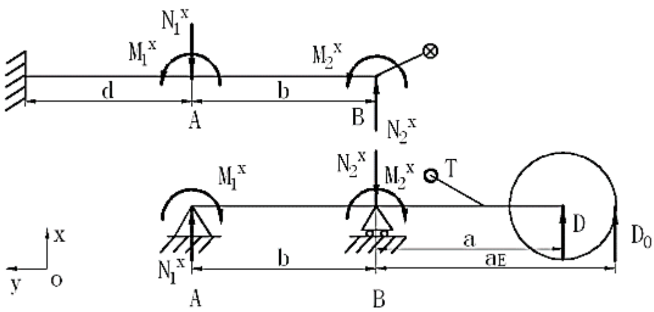

Fig. 6. Forces in Oxy plane

Figure 6 shows the forces in the Oxy plane, then:

$$N_1^x - N_2^x + D = 0, \tag{7}$$
$$M_1^x + M_2^x + N_1^x b - Da = 0, \tag{8}$$

where M_1^x and M_2^x is the bending moment due to shock strut flexibility at upper and lower bearing in Oxy plane respectively.

Assuming that the deformation of outer cylinder and inner cylinder at upper and lower bearings is compatible, ideal situation is shown in Figure 7.

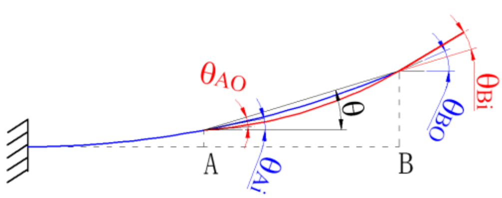

Fig. 7. Ideal deformation compatibility

Then, the equation of deformation compatibility can be derived as:

$$\theta_{Ao} = \theta - \theta_{Ai}, \tag{9}$$
$$\theta_{Bo} = \theta_{Bi} + \theta, \tag{10}$$

where θ_{A0} and θ_{Bo} is the deformation angle of outer cylinder at upper and lower bearing respectively, θ_{Ai} and θ_{Bi} is the deformation angle of inner cylinder at upper and lower bearing respectively, θ is the angle between the line connecting A and B before and after the deformation.

In fact, there is a slight deflection angle due to bearing deflection or fit clearance as shown in Figure 8.

Fig. 8. Actual deformation compatibility

Then Eq. (9) and (10) can be revised as:

$$\theta_{Ao} = \theta - \theta_{Ai} - \Delta\theta_A, \tag{11}$$
$$\theta_{Bo} = \theta_{Bi} + \theta - \Delta\theta_B, \tag{12}$$

where $\Delta\theta_A$ and $\Delta\theta_B$ is the slight deflection angle due to bearing deflection or fit clearance at upper and lower bearing respectively.

$\Delta\theta_A$ and $\Delta\theta_B$ are affected by many factors. This paper presents a comprehensive deformation compatibility factor $K_\theta = 0\sim1$ to describe actual deformation. The value of K_θ can be obtained from special test.

Then the total bending moment and reaction force at upper and lower bearing can be expressed as:

$$M_1 = \sqrt{(M_1^z)^2 + (M_1^x)^2}, \tag{13}$$
$$M_2 = \sqrt{(M_2^z)^2 + (M_2^x)^2}, \tag{14}$$
$$N_1 = \sqrt{(N_1^z)^2 + (N_1^x)^2}, \tag{15}$$
$$N_2 = \sqrt{(N_2^z)^2 + (N_2^x)^2}, \tag{16}$$

where M_1 and M_2 is the total bending moment at upper and lower bearing respectively, N_1 and N_2 is the total reaction force at upper and lower bearing respectively.

In order to calculate the equivalent reaction force, the forces at upper and lower bearing can be model as Figure 9.

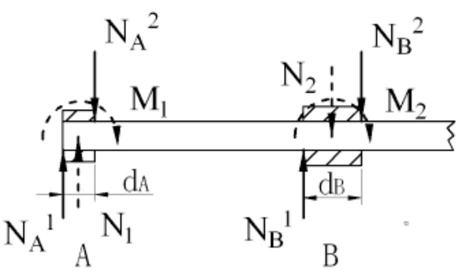

Fig. 9. Equivalent forces

According to Figure 9, then:

$$N_A^1 - N_A^2 = N_1, \tag{17}$$
$$(N_A^1 + N_A^2) \cdot \frac{d_A}{2} = M_1, \tag{18}$$

$$N_B^2 - N_B^1 = N_2, \tag{19}$$

$$(N_B^1 + N_B^2) \cdot \frac{d_B}{2} = M_2, \tag{20}$$

where d_A and d_B is the width of upper and lower bearing respectively, N_A^1 and N_A^2 is the equivalent reaction force at upper bearing, N_B^1 and N_B^2 is the equivalent reaction force at lower bearing.

Then, the total reaction force of bearings when taking shock strut flexibility into account can be expressed by:

$$N = |N_A^1| + |N_A^2| + |N_B^1| + |N_B^2|, \tag{21}$$

where N is the total reaction force of bearings.

Then, the total friction force due to the forces on tire can be expressed by:

$$F_{f2} = \mu N. \tag{22}$$

Friction model can be expressed [24] by:

$$F_f = \begin{cases} F_f(\dot{s}), & \dot{s} \neq 0, \\ F_e, & \dot{s} = 0 \text{ and } |F_e| < F_{fS}, \\ F_{fS}\mathrm{sgn}(F_e), & \text{other}, \end{cases} \tag{23}$$

where F_e is the sum of outer forces, F_{fS} is shown as Figure 10.

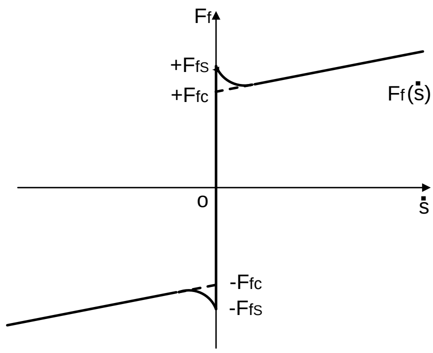

Fig. 10. Schematic diagram of friction model

4. Numerical calculation and analysis

Parameters of the landing gear used in the analysis are list in Table 1.

Table 1. Parameters of the landing gear

Parameters	Value	Parameters	Value	Parameters	Value	Parameters	Value
Nm_1 / kg	692.5	a_0 / m	0.352	a_{E0} / m	0.542	μ_{se}	0.06
Nm_2 / kg	15	b_0 / m	0.134	r_{T0} / m	0.126	μ_x	0.3
V_{sink} / (m/s)	2.34	d_0 / m	0.266	μ	0.025	R_0 / m	0.19
V_x / (m/s)	36.7	r_K / m	0.165	L_{T0} / m	0.127	k_θ	0.2

In Table 1, V_{sink} is the sink speed of the landing gear, V_x is the longitudinal speed of the landing gear, μ_x is the friction coefficient between tire and ground, R is the tire radius, subscript 0 stands for the value at initial time.

According to the drop dynamic model constructed above, an analysis program based C++ was developed to calculate the dynamical response of the landing gear during drop process. The results are shown as Figure 11, Figure 12 and Table 2.

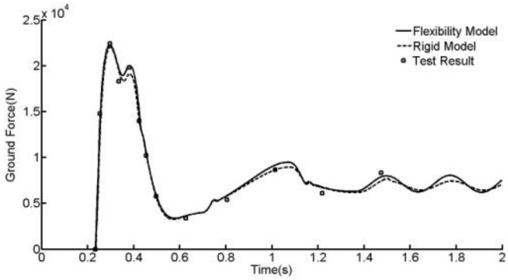

Fig. 11. Time history of shock strut axis force

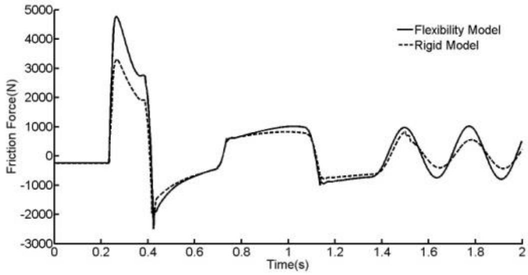

Fig. 12. Time history of friction force

Drop dynamic performances came from rigid strut model were presented in Figure 11, Figure 12 and Table 2 in addition.

Table 2. Comparison of numerical calculated and test results

		F_{Smax} / N	V_{max} / N	D_{max} / N	F_{fmax} / N	n
Test results		/	22400	6630	/	3.30
Rigid strut model	Calculated results	21643	22038	6611	3296	3.25
	Relative error	/	–1.6 %	–0.2 %	/	–1.6 %
Flexibility strut model	Calculated results	21855	22245	6674	4764	3.28
	Relative error	/	–0.6 %	0.5 %	/	–0.6 %

In Table 2, F_s is the total axis force of the shock strut, subscript max stands for the maximum value.

According to Figure 11 and Table 2, good correlation has been established between drop test data and the simulation predicated results. Compared with the rigid model, the total axis force added merely 1 % when taking shock strut flexibility into account. Though shock strut flexibility has a tiny influence on shock strut axis force, the friction force added enormously according to Figure 12 and Table 2. The friction force added almost 45 % when taking shock strut flexibility into account. Shock strut friction force is the main factor that leads to shock strut binding problem.

Comprehensive deformation compatibility factor have a great influence on shock strut friction force according to Eq. (11) and Eq. (12). In order to learn how will this comprehensive deformation compatibility factor affects shock strut friction force, comparisons were presented in Figure 13 and Table 3.

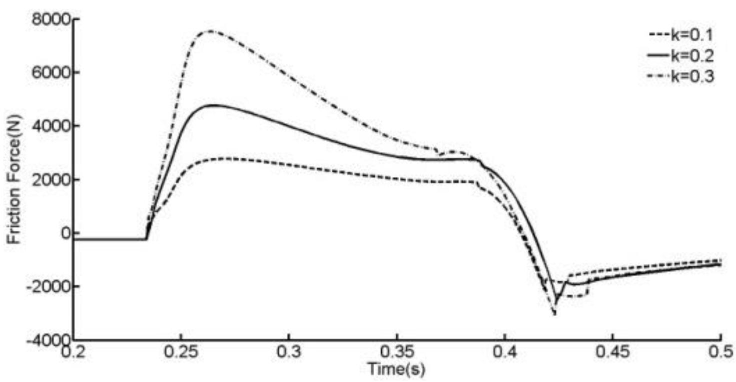

Fig. 13. Effect of deformation compatibility factor

Table 3. Comparison of deformation compatibility factor

k_θ	0.2	0.1	0.3
Relative variation	/	–50 %	50 %
Max friction force	4764	2777	7529
Relative variation	/	–41.7 %	58.0 %

According to Figure 13 and Table 3, shock strut fricton force will decrease 41.7 % when deformation compatibility factor equals 0.1, and will increase 58.0 % when deformation compatibility factor equals 0.3. Shock strut fricton force vary almost linearly with comprehensive deformation compatibility factor.

In order to learn how will shock strut flexibility affects shock strut friction force, comparisons were presented in Figure 14, Figure 15 and Table 4.

According to Figure 14, Figure 15 and Table 4, shock strut friction force will be increased with the increasing of the flexibility of outer cylinder or decreasing the flexibility of inner cylinder. 30 % decreasing of the flexibility of inner cylinder leads to 15.1 % increasing of shock strut friction force.

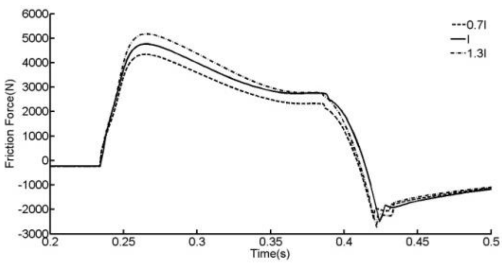

Fig. 14. Effect of the flexibility of outer cylinder

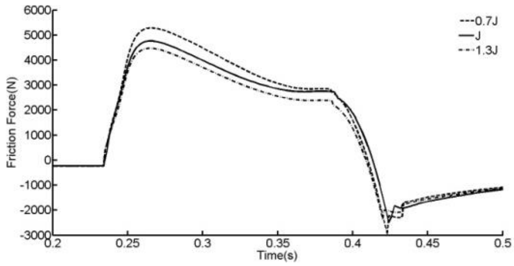

Fig. 15. Effect of the flexibility of inner cylinder

Table 4. Comparison of shock strut flexibility

		Flexibility of outer cylinder		Flexibility of inner cylinder	
Relative variation	/	–30 %	30 %	–30 %	30 %
Max friction force	4764	4339	5170	5284	4671
Relative variation	/	–8.9 %	8.5 %	15.1 %	–2.0 %

5. Conclusions

(1) Shock strut flexibility has a tiny influence on the total shock strut axis force during drop process. However, it has a enormous influence on shock strut friction force. Though the total axis force added merely 1 % when taking shock strut flexibility into account, the friction force added almost 45 %.

(2) Comprehensive deformation compatibility factor has a great influence on shock strut friction force. Shock strut fricton force vary almost linearly with Comprehensive deformation compatibility factor.

(3) Increasing the flexibility of outer cylinder or decreasing the flexibility of inner cylinder will increase the shock strut friction force. In order to eliminate the binding problem of this landing gear, the relative flexibility of outer cylinder and inner cylinder should be decreased suitably.

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