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.

In Figure 2: $\mu$ 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, $L_c$ 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, $N_{1x}$ and $N_{1z}$ is the upper bearing reaction force in $Oxy$ plane and $Oyz$ plane respectively, $N_{2x}$ and $N_{2z}$ 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.

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

Equation of motions can be expressed by:

\[ m_1 \ddot{y}_1 = m_1 g - F_a - F_h - F_f, \]  \hfill (1)
\[ m_2 \ddot{y}_2 = -F_V + m_2 g + F_a + F_h + F_f, \]  \hfill (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:

\[ F_f = F_{f1} + F_{f2}, \]  \hfill (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:

\[ F_{f1} = \mu_{se} F_a, \]  \hfill (4)

where \( \mu_{se} \) 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:

\[ N_1^z - N_2^z + S + T = 0, \]  \hfill (5)
\[ M_1^z + M_2^z + N_1^z b - Vr_K - S\alpha_E - TL_T = 0, \]  \hfill (6)
where $a_E$ is the displacement 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.

\[ \theta_{A0} = \theta - \theta_{Ai}, \]
\[ \theta_{Bo} = \theta_{Bi} + \theta, \]
where \( \theta_A \) and \( \theta_B \) is the deformation angle of outer cylinder at upper and lower bearing respectively, \( \theta_i \) and \( \theta_I \) is the deformation angle of inner cylinder at upper and lower bearing respectively, \( \theta \) 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.

\begin{align*}
\theta_A &= \theta - \theta_i - \Delta \theta_A, \quad (11) \\
\theta_B &= \theta_I + \theta - \Delta \theta_B, \quad (12)
\end{align*}

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 \( K_\theta = 0 \sim 1 \) to describe actual deformation. The value of \( K_\theta \) can be obtained from special test.

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

\begin{align*}
M_1 &= \sqrt{(M_1^x)^2 + (M_1^z)^2}, \quad (13) \\
M_2 &= \sqrt{(M_2^x)^2 + (M_2^z)^2}, \quad (14) \\
N_1 &= \sqrt{(N_1^x)^2 + (N_1^z)^2}, \quad (15) \\
N_2 &= \sqrt{(N_2^x)^2 + (N_2^z)^2}, \quad (16)
\end{align*}

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.

\begin{align*}
N_A^1 - N_A^2 &= N_1, \quad (17) \\
(N_A^1 + N_A^2) \cdot \frac{d_A}{2} &= M_1, \quad (18)
\end{align*}
\[ N_B^2 - N_B^1 = N_2, \]  
\[ (N_B^1 + N_B^2) \cdot \frac{d_B}{2} = M_2, \]  
\[ \text{where } d_A \text{ and } d_B \text{ is the width of upper and lower bearing respectively. } N_A^1 \text{ and } N_A^2 \text{ is the equivalent reaction force at upper bearing, } N_B^1 \text{ and } N_B^2 \text{ is the equivalent reaction force at lower bearing.} \]

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

\[ N = |N_A^1| + |N_A^2| + |N_B^1| + |N_B^2|, \]  

where \( N \) is the total reaction force of bearings.

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

\[ F_{f2} = \mu N. \]  

Friction model can be expressed [24] by:

\[ F_f = \begin{cases} (F_f(\dot{s})), & \dot{s} \neq 0, \\ F_e, & \dot{s} = 0 \text{ and } |F_e| < F_{fS}, \\ F_{fS} \text{sng}(F_e), & \text{other}, \end{cases} \]  

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

![Fig. 10. Schematic diagram of friction model](image)

4. Numerical calculation and analysis

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Nm_1 ) / kg</td>
<td>692.5</td>
<td>( a_0 ) / m</td>
<td>0.352</td>
<td>( a_{f0} ) / m</td>
<td>0.542</td>
<td>( \mu_{se} )</td>
<td>0.06</td>
</tr>
<tr>
<td>( Nm_2 ) / kg</td>
<td>15</td>
<td>( b_0 ) / m</td>
<td>0.134</td>
<td>( r_{T0} ) / m</td>
<td>0.126</td>
<td>( \mu_x )</td>
<td>0.3</td>
</tr>
<tr>
<td>( V_{sink} ) / (m/s)</td>
<td>2.34</td>
<td>( d_0 ) / m</td>
<td>0.266</td>
<td>( \mu )</td>
<td>0.025</td>
<td>( R_0 ) / m</td>
<td>0.19</td>
</tr>
<tr>
<td>( V_x ) / (m/s)</td>
<td>36.7</td>
<td>( r_K ) / m</td>
<td>0.165</td>
<td>( L_{T0} ) / m</td>
<td>0.127</td>
<td>( k_\theta )</td>
<td>0.2</td>
</tr>
</tbody>
</table>

In Table 1, \( V_{sink} \) is the sink speed of the landing gear, \( V_x \) is the longitudinal speed of the landing gear, \( \mu_x \) 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](image1)

![Fig. 12. Time history of friction force](image2)

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

<table>
<thead>
<tr>
<th></th>
<th>$F_{s_{\text{max}}}$ / N</th>
<th>$V_{\text{max}}$ / N</th>
<th>$D_{\text{max}}$ / N</th>
<th>$F_{f_{\text{max}}}$ / N</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Test results</strong></td>
<td>/</td>
<td>22400</td>
<td>6630</td>
<td>/</td>
<td>3.30</td>
</tr>
<tr>
<td><strong>Rigid strut model</strong></td>
<td>Calculated results</td>
<td>21643</td>
<td>22038</td>
<td>6611</td>
<td>3.29</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>/</td>
<td>$-1.6%$</td>
<td>$-0.2%$</td>
<td>/</td>
</tr>
<tr>
<td><strong>Flexibility strut model</strong></td>
<td>Calculated results</td>
<td>21855</td>
<td>22245</td>
<td>6674</td>
<td>4764</td>
</tr>
<tr>
<td></td>
<td>Relative error</td>
<td>/</td>
<td>$-0.6%$</td>
<td>$0.5%$</td>
<td>/</td>
</tr>
</tbody>
</table>

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

According to Figure 11 and Table 2, good correlation has been established between drop test data and the simulation predicted 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](image3)
According to Figure 13 and Table 3, shock strut friction 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 friction 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.

<table>
<thead>
<tr>
<th>$k_\theta$</th>
<th>0.2</th>
<th>0.1</th>
<th>0.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative variation</td>
<td>/</td>
<td>-50 %</td>
<td>50 %</td>
</tr>
<tr>
<td>Max friction force</td>
<td>4764</td>
<td>2777</td>
<td>7529</td>
</tr>
<tr>
<td>Relative variation</td>
<td>/</td>
<td>-41.7 %</td>
<td>58.0 %</td>
</tr>
</tbody>
</table>

### Table 4. Comparison of shock strut flexibility

<table>
<thead>
<tr>
<th></th>
<th>Flexibility of outer cylinder</th>
<th>Flexibility of inner cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative variation</td>
<td>/</td>
<td>-30 %</td>
</tr>
<tr>
<td>Max friction force</td>
<td>4764</td>
<td>30 %</td>
</tr>
<tr>
<td>Relative variation</td>
<td>/</td>
<td>-8.9 %</td>
</tr>
<tr>
<td></td>
<td>4339</td>
<td>30 %</td>
</tr>
<tr>
<td></td>
<td>5170</td>
<td>-30 %</td>
</tr>
<tr>
<td></td>
<td>5284</td>
<td>30 %</td>
</tr>
<tr>
<td></td>
<td>4671</td>
<td>-2.0 %</td>
</tr>
</tbody>
</table>

### 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 friction 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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References


