Dynamics of a Reduced Scale Landing Gear System Considering the Effect of the Viscoelastic Interaction of the Brake Pads and Rotors

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ABSTRACT

Gear walk is a dynamic instability condition that can pose serious harm to an aircraft and its passengers. The instability is believed to be borne as a result of braking, in which vibration of the landing gear can be induced generating motion reminiscent of a walking movement. This paper focuses on the theoretical account of a Reduced Scale Landing Gear (RSLG) apparatus and studies gear walk phenomenon. The mathematical approach involves lumped–parameter model representation of the RSLG that accounts for the landing gear’s struts, the wheels and the caliper-disc brake dynamics. The theoretical treatment of the RSLG apparatus entails consideration of the structure of the device that includes the account of dynamic response of the assembly consisting of a fuselage, two struts and two wheels. Various physical and geometrical parameters are determined and included in the mathematical model of the apparatus.

It is demonstrated that the occurrence of gear walk vibration is greatly influenced by the structural stiffness of the system. Both synchronous and 180° out of phase motion of the struts are generated in a parametric study in which structural stiffness is varied.

The Landing Gear

The RSLG apparatus, shown in Figure 1, consists of a fuselage supported by two arms with spring-damper attachments to provide a reduced scale representation of an aircraft and its landing gear system. Each arm is supported by a bicycle wheel that maintains rolling contact with the drum. The drum is brought to a desired speed and hydraulically actuated pad-rotor caliper-disc brakes are used to impart braking of the system. The braking force is achieved by brake pad and rotor contact. The caliper is attached to each arm (strut) and by means of hydraulic pressure, pads are pressed against a rotor keyed to the shaft of the bicycle wheel. The design of the setup also allows adjustment of the structural stiffness. This is accomplished by either replacing the linear springs with softer or harder ones, or relocating the springs in order to obtain a lower or higher equivalent torsional spring rate for each strut.

The RSLG apparatus has eight degrees of freedom, which are represented by eight generalized coordinates. They are given below.

\[ \Theta \] - Rotation of the Drum
\[ \phi \] - Rotation of the Fuselage
\[ \theta_{ij} \] - Strut rotation of side j of the apparatus
\[ h_{ij} \] - Mean plane separation between brake pad j and rotor of side i

The Governing Equations: Generalized Forces

The generalized forces constitute the constant applied force \( F \) and the elastic and rate dependent forces due to the contact of the brake pads and rotors. To obtain the generalized forces, we consider the virtual work done by the generalized forces, through virtual displacements of points of application of these forces. The virtual work done by the applied force \( F \), through a virtual displacement of \( h_{ij} \), is given by

\[
\partial W_1 = -F \cdot \delta h_{ij} - F \cdot \delta h_{12} - F \cdot \delta h_{21} - F \cdot \delta h_{22} \quad (1)
\]

The virtual work done by the elastic and rate dependent contact torques \( T_{11}, T_{12}, T_{21} \) and \( T_{22} \) on the strut is positive whereas the virtual work done by the same torques on the wheel is negative. So the virtual work done by the elastic and rate dependent contact torques through a virtual displacement of \( \delta \theta_{11} \) is given by

\[
\partial W_2 = T_{11}(\delta \theta_{u1} - \delta \theta_{j1}) - T_{12}(\delta \theta_{u1} - \delta \theta_{j1}) - T_{21}(\delta \theta_{u2} - \delta \theta_{j2}) - T_{22}(\delta \theta_{u2} - \delta \theta_{j2}) \quad (2)
\]

where, \( \theta_{ij} \) is the relative angular displacements wheel and the strut.

\[
\theta_{ij} = \theta_{u1} - \theta_{j1}, \quad \delta \theta_{ji} = \delta \theta_{u1} - \delta \theta_{j1} \quad (3)
\]

where,

\[
\partial W_3 = \left(1 + \frac{r_w}{r_d}ight) \delta \psi_1 - \frac{r_w}{r_d} \delta \psi_2 \quad (4)
\]

The virtual work done by the viscoelastic normal forces \( F_{11}, F_{12}, F_{21} \) and \( F_{22} \) through a virtual displacement of \( h_{ij} \) is given by,

\[
\partial W_4 = F_{11}(\delta h_{11} + \delta h_{12}) + F_{12}(\delta h_{12} + \delta h_{21}) + F_{21}(\delta h_{21} + \delta h_{22}) + F_{22}(\delta h_{22}) \quad (5)
\]

Contact Model

As shown in Figure 2, let us consider a brake pad-rotor model wherein the brake pad rotates with an angular velocity of \( \dot{\theta}_{11} \) in the positive z-direction and is fixed to the strut. The rotor is fixed to the wheel and has an angular velocity \( \dot{\theta}_{u1} \), similar to that of the wheel, in the positive z-direction. The external force \( F' \) is applied normal to the brake pad so the movement of the pad is opposite to the mean plane separation.

The normal viscoelastic contact force \( F_{ne} \) or \( F_{ne} \) constitutes the elastic normal force \( F_{ne} \) and the rate dependent normal force \( F_{ne} \). The term \( F_{ne} \) constitutes the scalar sum of \( F_{ne} \) and \( F_{ne} \), which are the elastic forces at positive and negative asperity interference slopes (Lim, 2003). Likewise \( F_{ne} \) and \( F_{ne} \) are the rate dependent forces at the positive and negative asperity interference slopes (Lim, 2003).

\[
F_{ij} = F_{ne} = F_{+ne} + F_{-ne} + F_{+nv} + F_{-nv} \quad (5)
\]
Results and Discussions

The Simulations have been performed for the two cases of $\eta_v$ as 5e-5 and 1e-5. Figure 3 shows the plots of various degrees of freedom of the RSLG system. First let us examine the case where $\eta_v$ as 1e-5. Figure 3(a) shows the plot of Angular velocity of drum with respect to time. The plot shows that the velocity of the drum decreases from 20 radians/seconds to 2 radians/seconds in a non-linear fashion. The angular displacement of fuselage is shown in Figure 3(b). The angular displacement of the fuselage goes up to 0.3 degrees initially in the positive y-direction and then dampens out to zero degrees. Alike the fuselage displacement, the position vector of the wheel and the angular displacement of the strut have also maximum amplitude of 0.5 and 0.3 degrees respectively. Both these displacements dampen out to their equilibrium state once the angular velocity of the drum decreases. Figure 3(e) shows the angular displacement of the strut with respect to another. The figure shows, for most part of the braking process, both the struts move in-phase with each other. Even though, the positive slope is not exactly 45°, we can presume that the strut vibration experience a part of “Gear Hop” instability.

Figure 4 shows the plots of generalized coordinates for the case where $\eta_v$ is 5e-5. Except for the different $\eta_v$ value the program is simulated for the same physical and geometrical parameters. Like the previous simulation, Figure 4(a) shows the angular displacement of the drum. In this case, the velocity of the drum decreases suddenly from 20 radians/seconds to zero. This behavior is attributed to the transient response of the system. Even though this is a physically impossible case, the results are presented to show how the system responds for a different $\eta_v$ value.

CONCLUDING REMARKS

A lumped-parameter model of a Reduced Scale Landing Gear (RSLG) representation of an aircraft has been presented. The mathematical formulation has employed the Kinematical relationship between the fuselage, struts, wheel and the drum and obtained a set of four nonlinear second-order differential equations. Embedded in the model is the account of frictional forces imparted on the rotors of the RSLG system by the brakes’ caliper-disc assembly.

Parametric studies, through a number of simulations, using the RSLG model, have shown that at low strut stiffness, landing gear instability occurs in form of in-phase synchronous motion of the two struts. At higher stiffness, it is shown that the RSLG system exhibits gear walk vibration in which the strut vibrations are 180 degrees out-of-phase.
Figure 4 (continued) Plots of various generalized coordinates for the case of $\eta$, as 5e-5