Pitch Plane Simulation of Aircraft Landing Gears using ADAMS

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INTRODUCTION

Landing gears with four or more wheels and brakes are common in modern commercial aircraft. Such landing gears are subject to heavy loads and dynamic forces. Much research has been done on single axle (T-gear) systems (Figure 1a). Both analytical and numerical/analog simulations of such systems are available in literature (1-7). However there are several research issues pertaining to Bogie-type landing gears with tandem axes (Figure 1b) that have not been suitably addressed by prior investigators. For instance, the force coupling between fore and aft brakes and effect of bogie pitch on the overall gear stability are not well understood. This paper attempts to develop an analytical model and present numerical simulations using ADAMS to help understand these phenomena.

Specific objectives of this paper are as follows: 1) present pitch-plane ADAMS models of aircraft landing gear, 2) present partial correlation with experiments, 3) study effect of energy-sharing and force-coupling between the different vibration modes, 4) study relative stability of different squeal vibration modes, i.e. out-of phase and in-phase vibration of forward and aft brakes and 5) verify fidelity of dynamometer simulations.

LANDING GEARS: PITCH PLANE MODEL

Pitch plane of a landing gear is defined as the vertical plane in the direction of aircraft motion. This plane is parallel to the bogie in a Bogie-Gear system.

The Bogie-gear model presented in this paper (Fig. 1b) consists of only pitch-plane degrees of freedom, viz. low frequency (~10 Hz) gear walk and bogie pitch, medium frequency (~ 30 Hz) chatter and high frequency (~250 Hz) squeal modes. The model also contains airplane vertical and fore-aft degrees of freedom. These degrees of freedom are comprehensively defined in reference(1).

Friction coupling between the rotors and stators is modeled as a non-linear function of rub-velocity as shown below. This function is obtained from sub-scale and full-scale dynamometer tests.

{ EMBED Equation.3 **}** (1,2,3)

Where P: Net Brake pressure (psi)
A: Disk area (in^2)
μ: Friction coefficient
r_μ: Friction radius (in)
V_{rub}: Rub velocity (in/s)
Ω: Angular velocity (rad/s)
N: Number of friction couples

Following approximation has been made in the landing gear model presented in this paper.

{ EMBED Equation.3 **}** (4)

A typical $\mu(V_{rub})$ curve is shown in Figure 3. Tire-runway friction is also modeled as a non-linear function of SLIP ratio between the tire and runway as follows.

{ EMBED Equation.3 **}** (5)

{ EMBED Equation.3 **}** (6)

{ EMBED Equation.3 **}** (7)

Where F_{normal}: Vertical Contact Force (lb)
μ_{tire}: Tire friction coefficient
r_{roll}: Tire Roll radius (in)
Ω_{tire}: Tire Angular velocity (rad/s)
V_{axle}: Axle Fore-aft velocity (in/s)

STABILITY ANALYSIS

The equations of motion for a T-Gear system are described in detail in Reference 1. Stability of the various vibration modes of the landing gear depends on the system damping and the characteristics of the non-linear friction parameters (ref. 6). For example, decoupled equations for the squeal mode provides criteria for stability as shown below.

{ EMBED Equation.3 } (8)

Where J_{sq}: Squeal Inertia (i.e. Non-rotating brake components)
C_{sq}: Squeal damping
K_{sq}: Squeal Stiffness

Expanding μ_{brake} in a Taylor series around an operating point V_{rubo} (see Figure 3) we obtain

{ EMBED Equation.3 } (9)

Substituting μ_{brake} from equation (9) into equation (1) and resulting expression for T_{μ} into equation (8) we obtain equation (10).

{ EMBED Equation.3 } (10)

It is clear from this equation that squeal DOF is stable if

{ EMBED Equation.3 }. (11)

Thus a brake will have unstable squeal mode if equation (11) is violated. This can happen if the friction material has a negative μ-V_{rub} slope (coefficient which decreases with increasing rub-velocity) that is greater than available positive squeal damping in the system.

Similar stability criteria can be developed for the other degrees of freedom of the landing gear.

ADAMS AIRCRAFT MODEL: DESCRIPTION

The T-Gear model consists of a total of 8 rigid bodies coupled by spring-damper and non-linear friction forces. The strut stiffness and effective gear length (L) are obtained from modal analysis of the gear supplied by the OEM (ref. 7). The brake and wheel are modeled using measured rigid body inertia and lumped stiffness parameters obtained from finite element analysis of the components.

Torque, strut deflection (walk), squeal and aircraft speed from a typical simulation of a landing stop are plotted in Figures 4a,b,c and d respectively.

Notice the peaking of torque at the end of the stop as speed decreases. This indicates a negative toque-velocity slope resulting in the gear-walk instability. The initial divergence of the walk deflection corresponds to the net negative walk damping of the system.

In the absence of tire slip, wheel chatter and brake squeal, the rotational velocities of the rotor and stator are given by the following expression.

{ EMBED Equation.3 } (12 a,b)

Substituting Equation 12 in Equation 3, we obtain

{ EMBED Equation.3 } (13)

$V_{aircraft}$ decreases during a stop and { EMBED Equation.3 } increases due to walk divergence. Towards the end of a stop, V_{rub} can become negative during a back swing of the gear when { EMBED Equation.3 } is negative. When this happens, the brake torque as given by Equation (1), reverses direction. This is manifested as sharp spikes in the brake torque plotted in Figure 4a. These torque-reversals limit walk vibration, resulting in the linear convergence seen in Figure 4b. These sharp torque-reversal spikes excite higher frequency squeal vibration that is quickly attenuated by available positive squeal damping as seen in Figure 4c.

ADAMS MODEL VALIDATION

L1011 landing gear was used for validation of the model. ADAMS simulation is done for a complete landing stop. Brake torque and walk degree-of-freedom are plotted in Figure 5a and b. A half-scale L1011 landing gear was also tested on a dynamometer. Torque and strut deflection (walk) obtained during one of the stops is plotted in Figure 5c and d. Compare these to ones obtained from ADAMS simulation. It is clear that dynamic response of the brake is very well predicted by the ADAMS simulation.

VIBRATION MODE COUPLING

Due to the negative μ-V_{rub} characteristics of the friction material, a certain amount of "negative damping" exists in the system. In Figure 4, this shows up as instability of walk mode. However, if by some means, one were to increase the positive damping of this mode, one of the other modes becomes unstable. This is illustrated clearly in Figures 6 a,b and c. Walk, Squeal and Chatter modes are plotted for three different damping conditions in these figures.

Figure 6a corresponds to a case where walk is most unstable resulting in this mode of vibration. As explained in the previous section, walk couples with squeal and chatter modes by providing higher frequency excitations in the form of torque-reversals.

In the second case, shown in Figure 6b, walk damping was increased to make this mode stable. However, this merely shifted the instability to the higher frequency squeal mode. Now the torque-reversals due to squeal vibration couples this mode with walk and chatter, exciting them to some extent.

In the third case, shown in Figure 6c, squeal damping was increased to stabilize this mode. Now the chatter mode becomes unstable. Again, torque-reversals due to chatter excites walk and squeal, confirming the force coupling present between the different vibration modes.

Dynamometer tests, using a fixture to represent the walk mode, were conducted on a large commercial aircraft brake with varying walk damping. Torque, pressure and aircraft speed obtained from these tests are plotted in Figures 7a and b. The oscillations in torque and pressure are proportional to walk and squeal vibration respectively. Walk vibration is more unstable with a damping of 2.8%. As expected, walk vibration stabilizes when the walk damping was increased to 5.2%. However, this results in an increase in squeal vibration as seen in Figure 5b. This confirms the predictions of the ADAMS simulation discussed above.

RELATIVE STABILITY OF SQUEAL MODES

Two pitch plane squeal modes exist for a Bogie-type landing gear. In the first mode, the fore and aft brakes have an in-phase torsional oscillation. In the second mode, the fore and aft brakes vibrate out-of-phase. ADAMS prediction of fore and aft brake squeal vibration in a Bogie-gear are plotted in Figure 8. Initial squeal vibration is due to the inherent squeal instability and is not initiated by any particular disturbance. As seen in the figure, this vibration is out-of-phase at 210 Hz. However, later squeal vibration pulses are initiated by torque-reversals that occur simultaneously in both the fore and aft brakes. This results in an in-phase vibration mode at a lower frequency of 137 Hz.

A conclusive assessment of the relative stability of the two squeal modes can be made from Figure 9 which shows fore and aft brake vibration for a typical stop with squeal instability. In this simulation, both brakes had identical μ-V_{rub} function and the amount of positive viscous damping in the in-phase and out-of-phase modes were made equal. The vibration is initiated by a runway bump which is applied to the two brakes simultaneously. As expected, vibration starts out as in-phase, but quickly changes to out-of phase. This indicates that for this gear configuration, out-of-phase squeal mode is less stable than in-phase mode, possibly due to bogie pitch and other system dynamics.

PITCH PLANE DYNAMOMETER SIMULATION

Extensive dynamometer tests of aircraft brakes are conducted before qualification on aircraft. Dynamics related tests require that the brake be attached to mechanical simulators that have impedance characteristics similar to aircraft landing gear. Design and mathematical analysis of such simulators are presented in detail in Reference (1).

An ADAMS model of a bogie-gear simulator was built to study the fidelity of dynamometer tests. This model is shown in Figure 10. The fore-aft motion of aircraft walk degree-of-freedom is simulated as torsional motion of the simulator walk beam. Simulator walk inertia, stiffness and damping are adjusted to match those of aircraft. Torque, walk and squeal motion for a typical stop with walk vibration on the dynamometer are shown in Figure 10a. Corresponding plots for the aircraft simulation with identical operating conditions are shown in Figure 10b. Note that amplitude of walk is greater on the simulator than on the aircraft. This is a result of small angle approximations made while calculating the simulator parameters. Thus dynamometer simulations are actually conservative, i.e. dynamometer tests would certainly identify potential aircraft brake instabilities.

CONCLUSION

In summary, this paper presents results of ADAMS modeling and analysis done at BFGoodrich, Aerospace over the past few years. Basic ADAMS simulation models have been built for T-gears, Bogie-type gears and Dynamometer Simulators. Four specific conclusions can be made from the study presented in this paper. First, the ADAMS models have been correlated with experimental data. Second, the different modes of vibration are coupled and stability of the landing gear is truly a system parameter. Adding damping to a particular unstable mode merely results in destabilizing or reducing the stability margin of some other mode. Third, aft brake in out-of-phase mode is the least stable brake for the bogie-gear configuration studied in this paper. Fourth, ADAMS simulation have successfully verified fidelity of dynamometer tests. In fact, it has been found that the pitch-plane simulators are conservative. The basic ADAMS models presented in this paper have been fully parameterized and will be used as framework to perform extensive design studies in the future.

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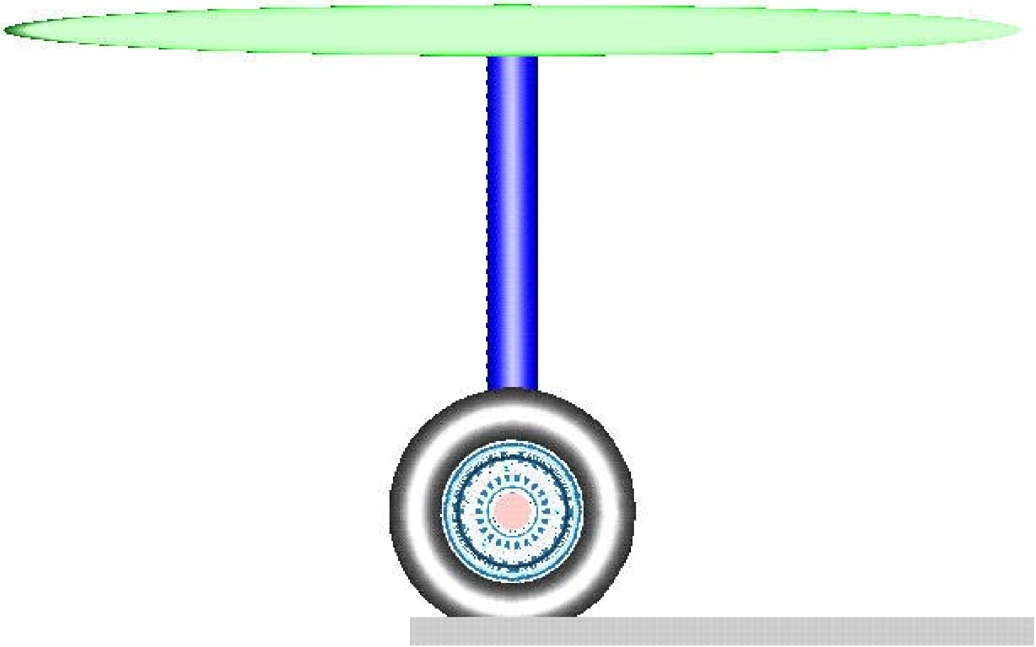
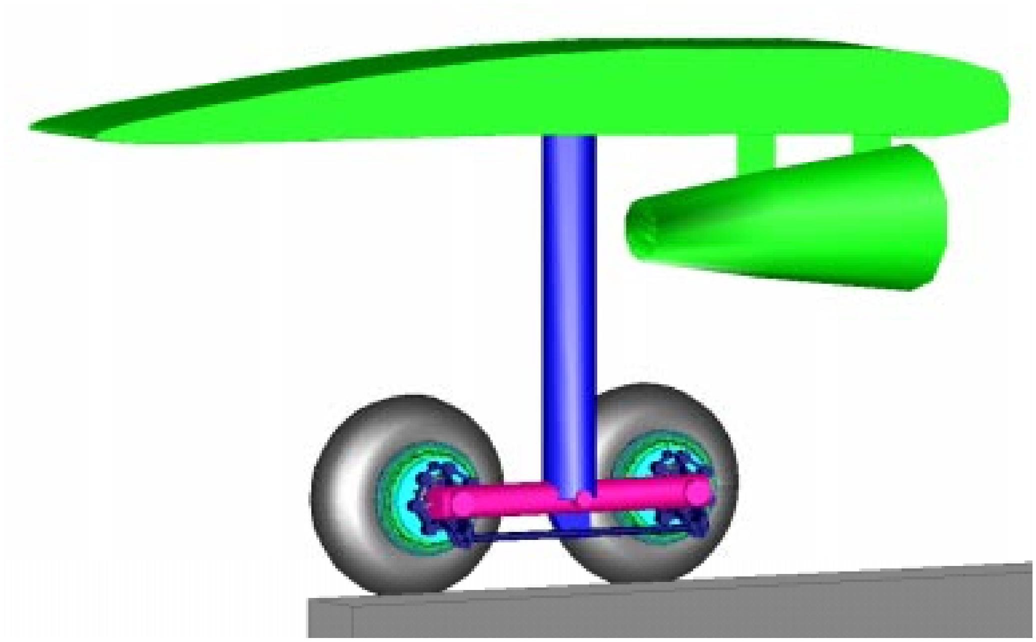


a) T-Gear System



b) Bogie-Gear System
Figure 1.ADAMS Simulation Models

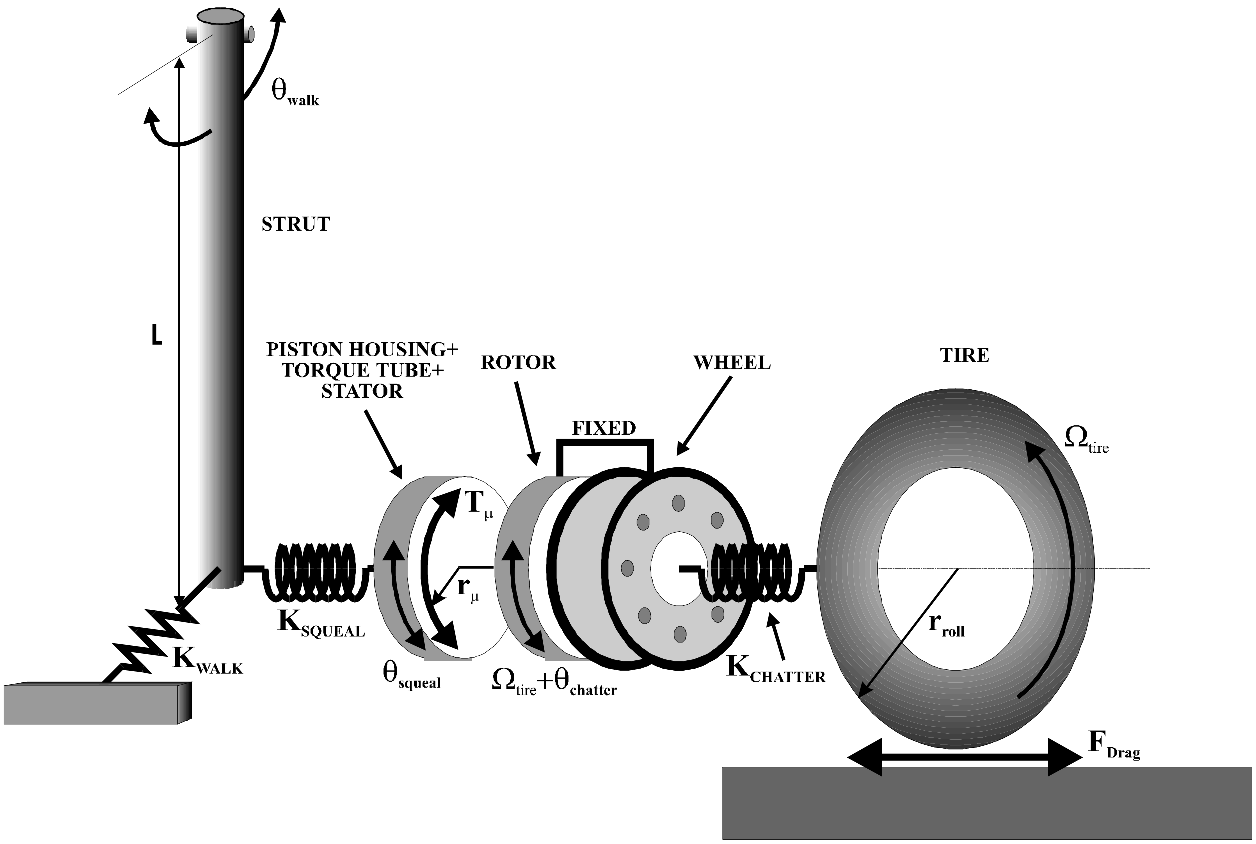


FIGURE 2. SCHEMATIC OF A LANDING GEAR SYSTEM

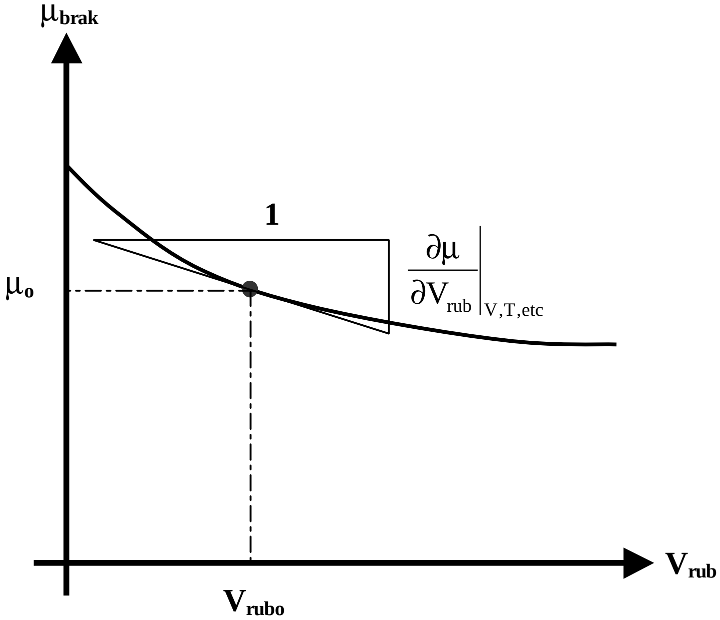


Figure 3. Typical μ-V_{rub} Plot

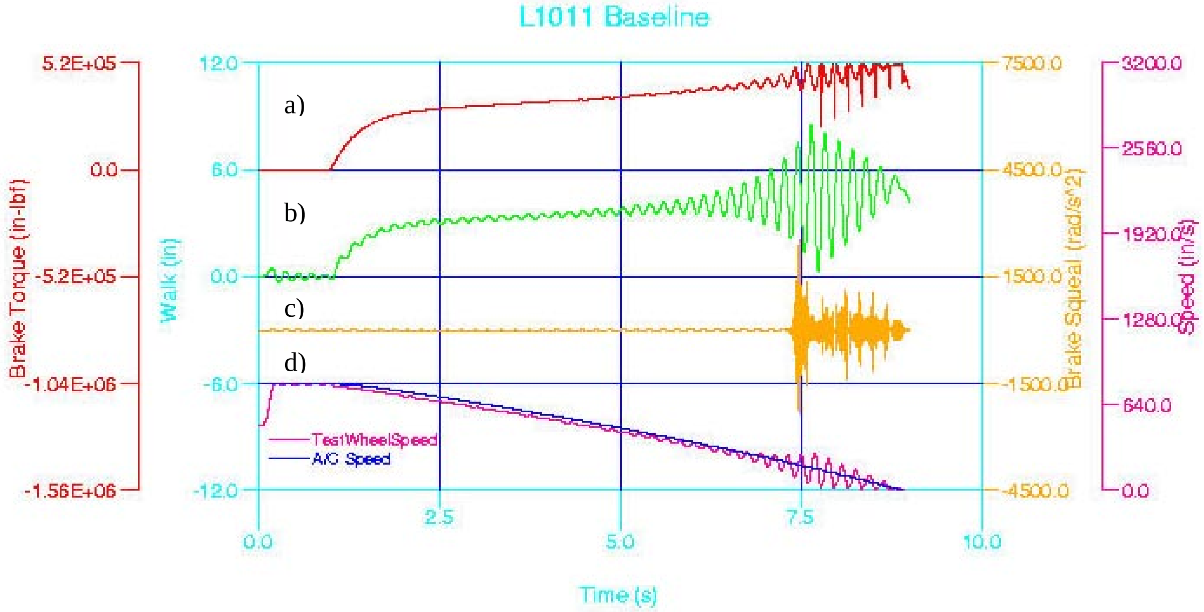
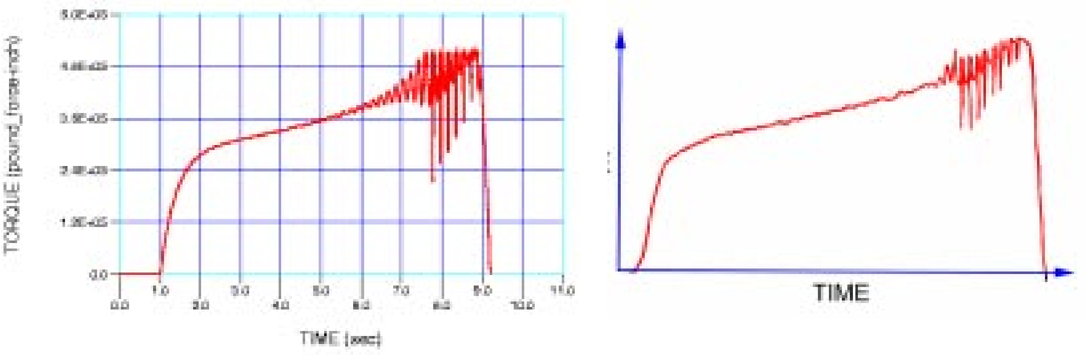
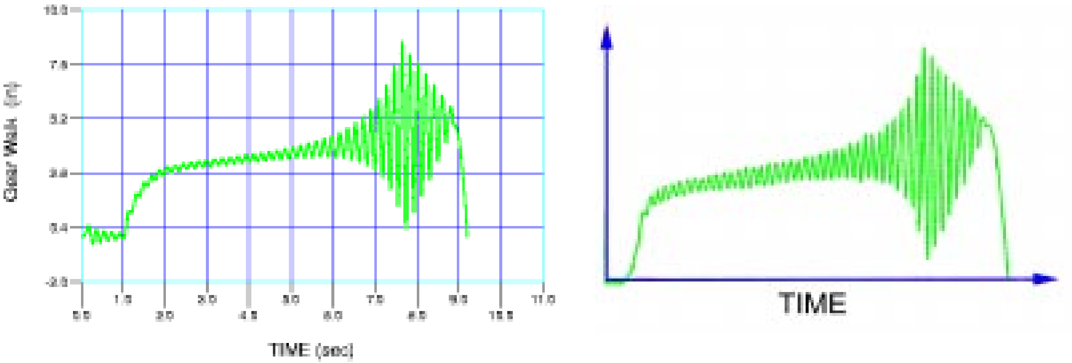


Figure 4. Torque, Walk, Squeal, A/C Speed and Wheel Speed for a typical stop.



a) L1011 ADAMS: Torque

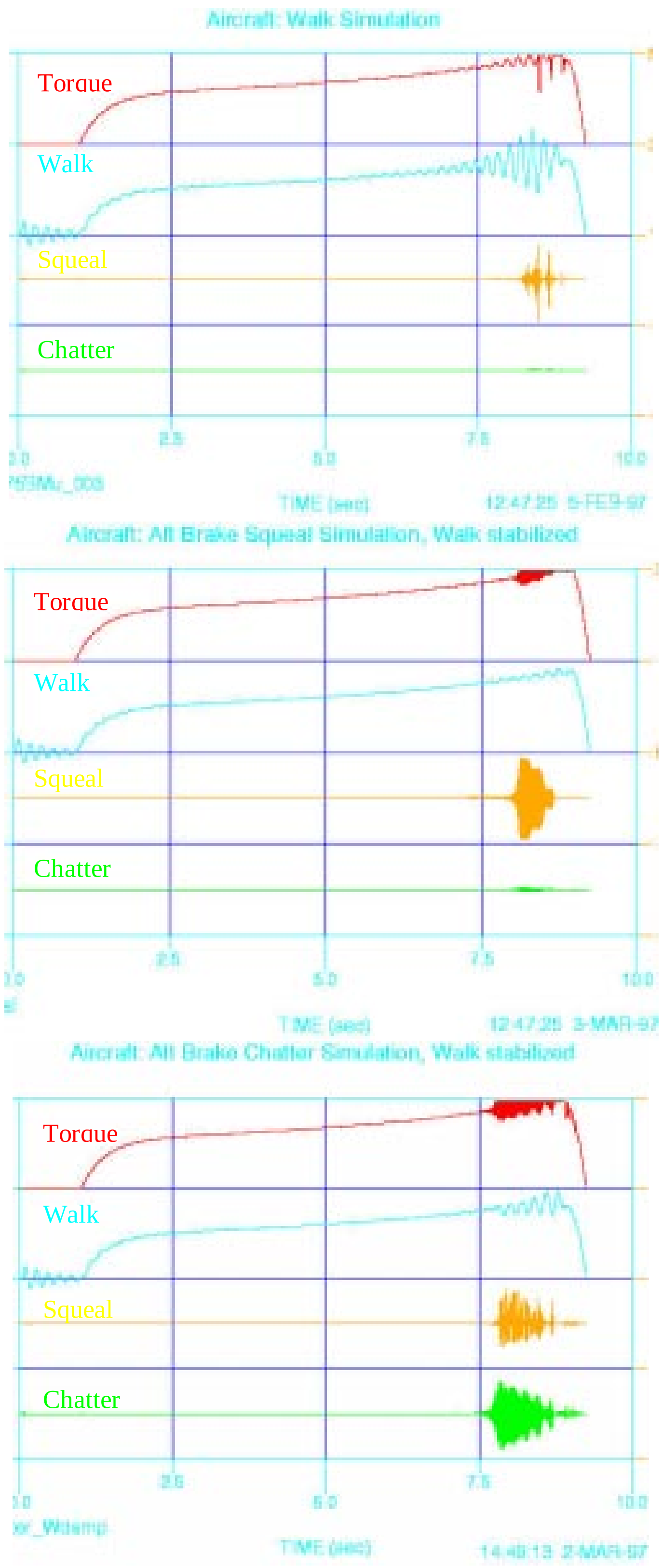
c) L1011 Dynamometer: Torque



b) L1011 ADAMS: Walk

d) L1011 Dynamometer: Walk

FIGURE 5. COMPARISON OF ADAMS PREDICTION TO DYNAMOMETER TESTS

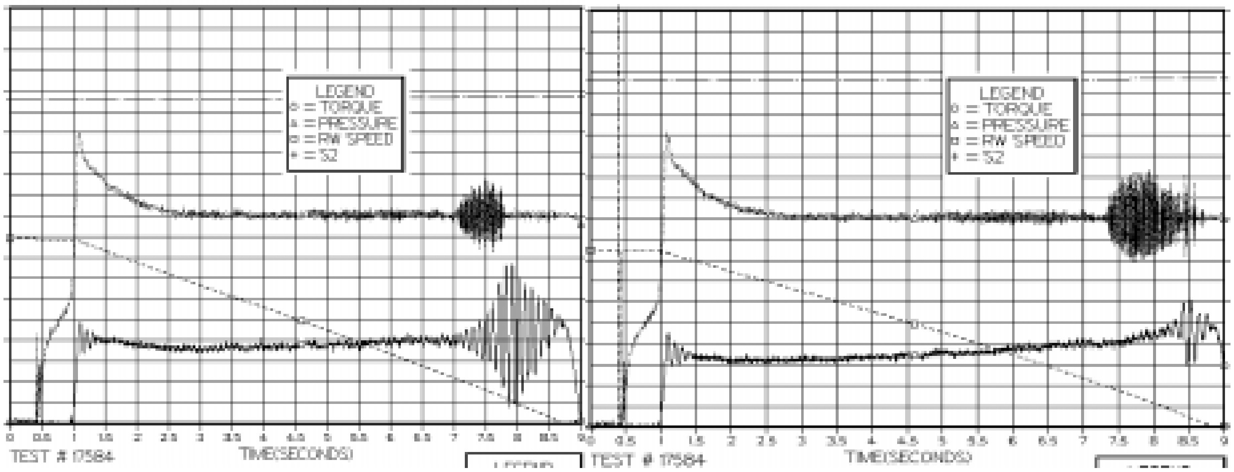


a) Walk Instability

b) Squeal Instability

c) Chatter Instability

Figure 6. Energy sharing between different modes of vibration



a) Aircraft walk damping = 2.8%

b) Aircraft walk damping = 5.2%

FIGURE 7. DYNAMOMETER TESTING: ENERGY SHARING BETWEEN MODES

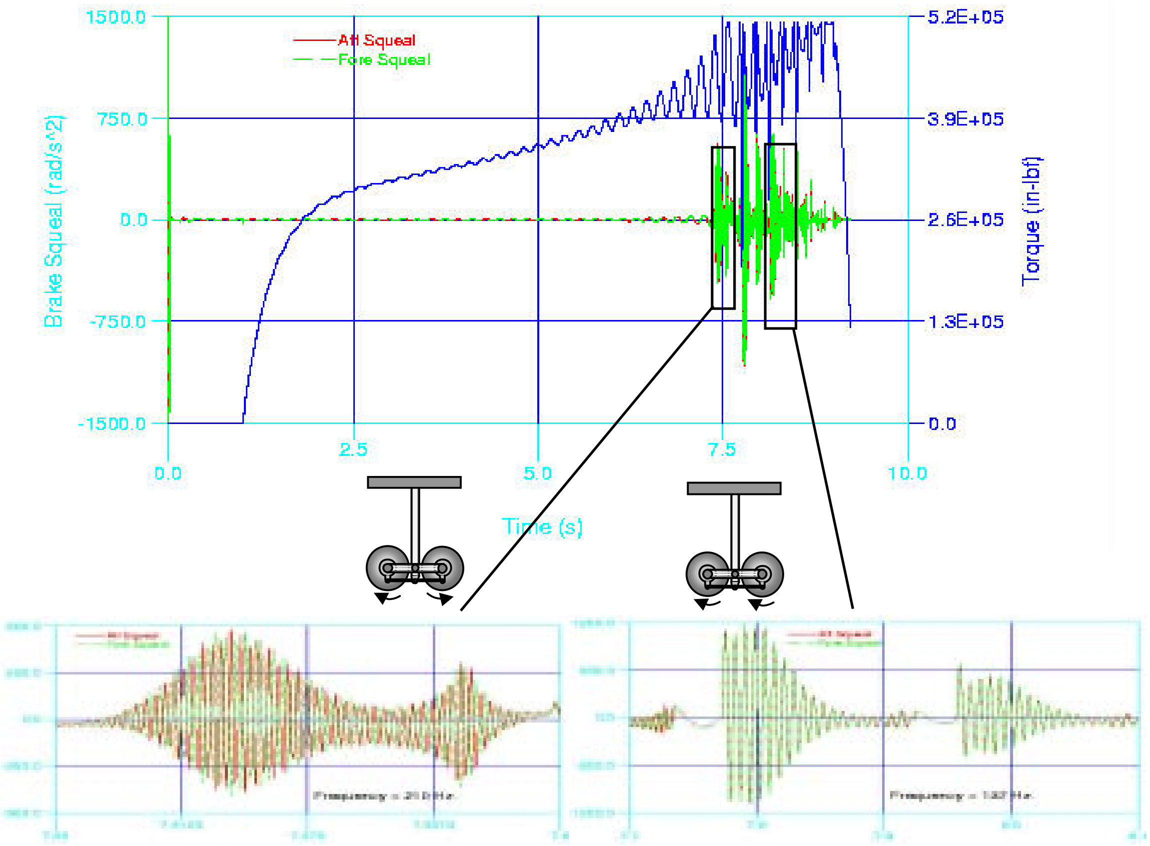


Figure 8. Relative stability of in-phase and out-of-phase squeal modes

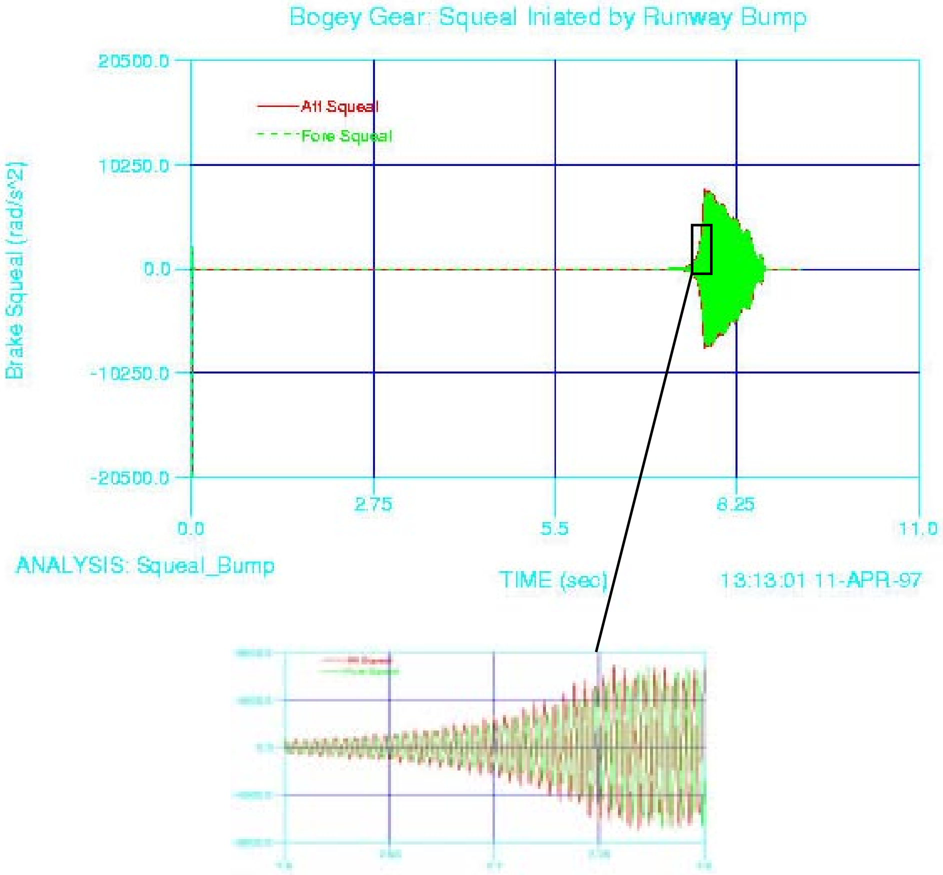


Figure 9. ADAMS T-Gear Simulation: Squeal initiated by runway bump. Indicates: a) out-of phase mode is more unstable than in-phase mode and b) aft-brake is more unstable than fore-brake.

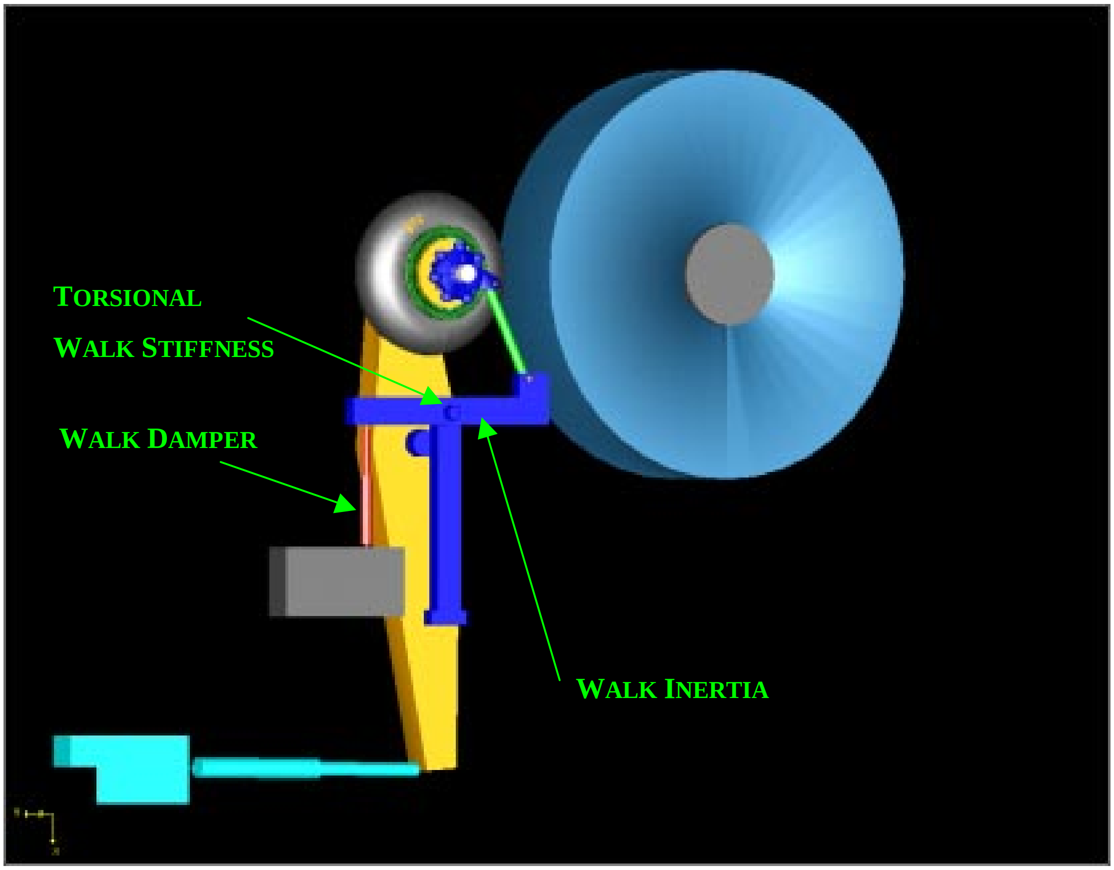
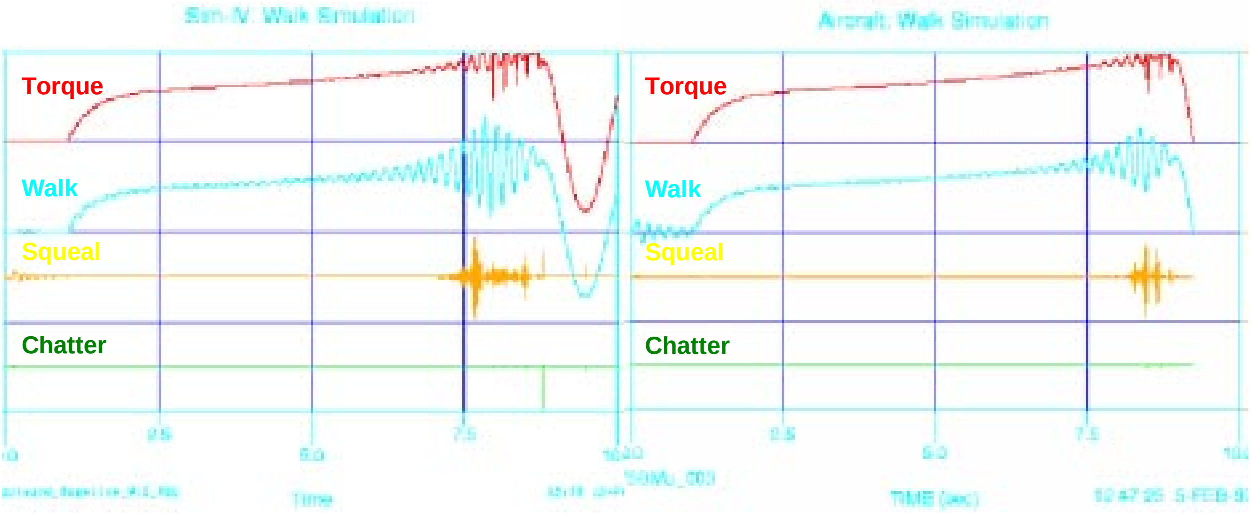


Figure 10. ADAMS model of landing Gear Simulator



a) Dynamometer

b) Aircraft

Figure 11a. ADAMS Simulation

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