BRAKE DYNAMICS

FOREWORD

Changes in the revision are format/editorial only.

1. SCOPE:

The landing gear is a complex multi-degree of freedom dynamic system and may encounter vibration problems induced by braking action. The vibratory modes can be induced by several frictional characteristics and brake design features. These should be assessed during the design concept and verified during the development of the hardware.

This SAE Aerospace Information Report (AIR) has been prepared by a panel of the A-5A Subcommittee to present an overview of the landing gear system problems associated with aircraft brake dynamics and the approaches to the solution of these problems. In addition, facilities available for test and evaluation are presented and discussed.[1]

2. APPLICABLE DOCUMENTS:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

[1] The terminology used is consistent with AIR1489, Aerospace Landing Gear Systems Terminology.

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2.1 SAE Publications:

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AIR1489 Aerospace Landing Gear Systems Terminology
SAE Paper 851937 Laboratory Simulation of Landing Gear Pitch-Plane Dynamics

3. PROBLEM DEFINITION:

3.1 Brake design characteristics are sources for several dynamic landing gear vibration problems. There are many categories of excitation of brake-landing gear vibration:

3.1.1 Self-Excitation of the Natural Modes of the Landing Gear Caused by the Frictional Characteristics of the Brake: These problems generally are more pronounced with steel heat sink brakes with lining material containing mixtures of ceramic and metallic particles or plain metal particle lining materials. They exhibit variation of coefficient of friction with instantaneous slip velocity with a resultant of "negative damping." However, carbon on carbon friction surfaces can also develop destructive self-excitation due to negative damping arising from the variation of the coefficient of friction with instantaneous slip velocity.

3.1.2 Forced Oscillation Arising from Irregularities or Mechanical Interruptions in the Friction Surfaces: These vibrations may be controlled by proper detail design of the brake guided by suitable analysis and test.

3.1.3 Self-Excited Vibration of a Whirl Nature: This is a large motion instability that requires an initial excitation and eccentricity between the rotating and nonrotating parts of the brake. The order of magnitude of the whirl natural frequency is in the same range as the squeal frequency. The whirl motion is a function of brake structural and design characteristics, the frictional characteristics of the lining, the frictional characteristics of the rotor-wheel interfaces, the system or assembly damping, including hydraulic fluid circulation losses, axle cross sections and elastic properties, and the dynamic characteristics of the wheel/brake/axle back-up structure.

3.1.4 Parametric Self-Excitation: This can contribute to some cases of squeal instability and is brought about by large periodic variations in the stiffness of brake components.

3.1.5 Self-Excitation from Poorly Phased Feedback from Anti-Skid System: This type of feedback can cause instability and limit cycle motion of the low frequency chatter mode (gear walk) of the complete landing gear. It is not dependent on adverse brake frictional properties but is a function of the anti-skid characteristics and the fore and aft natural frequency of the landing gear.

3.1.6 Tire Lockup: Might occur at low speed after the anti-skid control has dropped out, can cause instability and limit cycle motion of the gear walk mode. The instability is not dependent on adverse brake frictional properties. It is the result of the negative slope of the tire-runway friction characteristics beyond that level of slip, which corresponds to maximum drag. The instability is increased if the landing gear has a forward cant angle.

3.1.7 Self-Excitation from the Anti-Skid Software: The software of modern anti-skid systems can couple with the mechanical characteristics of the landing gear and brake hardware to produce self-excited vibrations. Thus, an accurate dynamic simulation of the complete system should be exercised in the design stages of the system.

3.2 Of the above basic problems, the self-excitation problem causes the most concern in the landing gear system development. Landing gear vibrations may be categorized in three primary response modes. The first is the gear "walk" (chatter) mode when frequencies are in the 5 to 25 Hz range. The second, or brake "squeal" mode, produces higher frequencies primarily from vibration of the stationary parts of the brake winding up against the elasticity of the torque carrying linkage between the brake and shock strut. In addition to chatter and squeal, there is whirl, which involves three dimensional motion of the brake and landing gear structure, anti-skid modes that involve three dimensional motion, torsional modes during both turning and straight ahead motion, and coupling of chatter and squeal with axial and roll plane motions. A variety of squeal modes can be excited.

Squeal modes can couple with both the axial motion of the brake discs and the bending of the torque tube/piston housing and axle in both the fore and aft, and vertical direction. Beside these, a strut torsional mode of vibration can be excited during a pivoting turn. It may be induced or aggravated by a combination of brake torque and tire slippage, according to some investigators.

3.2.1 Gear walk (chatter) can impose high loads on the strut and airframe structure, while modes in the squeal frequency range can create problems in equalizer rods, brake attachment bolts, hydraulic lines, axle mounted anti-skid components, wheel heat shields, and internal brake components. These cyclic loads must be considered in the design of the landing gear system.

4. PROBLEM SOLUTION:

4.1 Some gear configurations are more responsive to brake vibrations than others. A friction pair suitable for one gear is not necessarily satisfactory for a different design. Probability of compatibility is increased by testing and analysis during the development program. The objective of such efforts will be to match gear and brake characteristics to minimize adverse vibration throughout the anticipated operating range and to uncover any adverse wheel and brake features that promote or aggravate vibrational motion.

4.2 Additional or supplemental review of compatability can be accomplished analytically if proper input data are generated during the development program. The airframe manufacturer must provide basic aircraft parametric data for such analysis or laboratory simulation and testing, or both. These would include:

4.2.1 Fore and aft spring rate of the landing gear or flexibility matrix for 5 deg of freedom motions of the truck or axle center point (multiple wheel gears) or wheel center (single wheel gears).

4.2.2 Angular spring rate associated with squeal motion of the landing gear system.

4.2.3 Damping coefficient associated with the fore and aft chatter motion of the landing gear system or loss factor for the spring matrix mentioned (see 4.2.1).

4.2.4 Angular damping coefficient associated with the squeal motion of the landing gear system.

4.2.5 Strut mass and distribution of weight.

4.2.6 Walk frequencies of landing gear system.

4.2.7 Axle geometry, stiffness and damping characteristics, configuration, and mounting flange details.

4.2.8 Other parameters based on analysis of specific gear geometry.

4.2.9 Various tire characteristics.

4.3 Suitable flight testing should be planned for the development program to verify system compatibility. This compatibility must include demonstration with the full range of skid control operation on wet and dry runway surfaces. Data collection should include information on speeds where vibration occurs, past history of the brake, frequency, and amplitude of vibrations. This will assist in pinpointing problem areas and will also provide insight to problem solution.

5. DATA CLASSIFICATION:

5.1 In spite of the scatter in results of identical stops that prevents pinpointing or predicting a specific event for any one stop, continued effort should be devoted to identifying the dynamic characteristic pattern. Meaningful information can result through use of statistical analysis when a large amount of seemingly inconsistent data is processed. Sustained analysis and testing by brake manufacturers and cooperation with the users on vibration problems is essential.

5.2 A uniform method of classifying brake performance on a statistical basis is desirable. The suggested classification of brake characteristics is as follows:

5.2.1 Coefficient of Friction:

a. Static - cold, hot, and dynamic breakaway (termination of skid)
b. Dynamic - initial, average, and maximum
c. Transition - dynamic to static (entering skid)
d. Carbon brakes - wet, dry, and transition wet to dry

5.2.2 Dynamic Coefficient of Friction Variation With:

a. Kinetic energy absorption rate
b. Temperature
c. Amount of absorbed kinetic energy
d. Velocity
e. Unit Pressure
f. Number of prior landings or applications, or both
g. Amount of water applied (carbon brakes)

5.2.3 Wear-Variation With:

a. Level of kinetic energy absorption/mass loading/temperature
b. Rate of kinetic energy absorption/power loading/velocity
c. History of past usage, including potential vibration induced wear
d. Unit pressure
e. Wet or dry condition on carbon brakes

5.2.4 Torque vs Pressure Characteristics:

a. Response to ramp increases and decreases in pressure at various mean pressures
b. Frequency response characteristics (gain and phase) for pressure variations from 0 to 50 Hz
c. Both of the above as a function of wear and brake operating temperature
d. Brake pressure versus displacement (required fluid volume) as a function of brake wear

5.2.5 Landing Gear Dynamic Characteristics:

a. Gear walk natural frequency and mode shape
b. Squeal natural frequencies (first through third)
c. Positive damping associated with walk (chatter), squeal, and whirl

5.3 The above would classify a brake assembly as a complete unit and as applied to a specific gear.

6. BRAKE DYNAMIC CHARACTERISTICS EVALUATION:

6.1 The following is a discussion of techniques, equipment or facilities, or both, that can be used for brake dynamic evaluation:

6.1.1 Shaft Dynamometer:

6.1.1.1 Direct drive shaft dynamometers have been used to evaluate the brake as an assembly and for evaluation of brake components. Attempts have been made to simulate the flexibility of gear mounting and to operate with a system, which responds to vibration in both the "walk" (chatter) and the "squeal" mode similar to the aircraft. The major advantage of this type of machine is that comparative evaluation of geometry, material, and performance can be achieved at relatively low cost in a timely manner. It is an excellent screening device. Brake design characteristics that can be obtained under controlled conditions are as follows:

a. Wear
b. Temperature of brake elements and relative cooling rates
c. Static and dynamic friction coefficients
d. Variation of friction coefficient under controlled test environments
e. Tendencies toward frictional stability or instability

6.1.1.2 Noted disadvantages of this type of equipment are as follows:

a. The flywheel kinetic energy is transmitted directly to the brake, thus removing the tire, wheel, and brake system effects on brake energy absorption.

b. The influence of tire or strut elasticity on brake dynamic characteristics is not measured. However, the brake dynamic input is characterized.

6.1.1.3 Shaft dynamometers have been used on heat sink segments, single pairs of discs, and complete assemblies with varying degrees of success relative to dynamic estimates.

6.1.2 Conventional Brake Test Dynamometer:

6.1.2.1 The most common method of brake testing consists of landing a complete wheel, brake, and tire unit against an inertial wheel. The unit to be tested is mounted on a fixture that can embody or simulate the aircraft axle and brake mounting flange. With such as installation, it is possible to vary wheel vertical loading to simulate actual aircraft sequencing. This is accomplished by adjusting tire pressure (at fixed radius) or by controlling the loading of the dynamometer application arm (varying rolling radius). Additional system response information is obtained by duplicating as much of the aircraft hydraulic and skid control system as possible.

6.1.2.2 The major advantages in the use of this type of equipment are as follows:

a. Kinetic energy input rates and mass/heat transfer environments are reproduced fairly accurately.

b. Temperature distributions are simulated accurately.

c. The total kinetic energy inputs are accurate.

d. The mounting system can be made sufficiently close to actual aircraft design to evaluate "squeal" mode of vibration.

e. The lining stability measurement will permit tendency evaluation of "chatter" mode of vibration.

f. Preliminary assessment of anti-skid compatibility is possible. (Transition of dynamic to static characteristics, torque response, and ability to move actuation fluid).

6.1.2.3 Disadvantages or limitations, or both, on the use of this test equipment are as follows:

a. Usually limits test to single wheel-brake installation mounted on cantilever axle

b. Cannot duplicate total gear, particularly with truck configuration

c. Lacks fore and aft freedom for gear walk (chatter) assessment as installed

d. Frequently lacks sufficient drive power to permit assessment of taxi environment

e. Fixture modes of conventional dynamometer sites can be in the same frequency range as critical modes of the mounted brake. Consequently, unrealistic coupling can occur and true dynamic interactions can be masked.

f. Tire-to-flywheel friction becomes erratic during antiskid testing because of the patchy rubber buildup on the flywheel.

6.1.3 Full Gear Simulation:

6.1.3.1 Recognition of the elastic nature and complex interaction of each element of the landing gear system has resulted in the desire to test as much of the actual system as possible. Various degrees of simulation have been achieved with the use of each type of test facility (shaft dynamometer and conventional inertia dynamometer). Under certain conditions, it has been possible to duplicate or simulate very closely the full-scale landing gear dynamics from the trunnion attachment interface to the tire flywheel interface. Several aircraft systems have been investigated in this manner; and in some cases, the simulation has been extended to include the actual aircraft attachment structure. Most successful simulation has been achieved by overhead mounting on a conventional brake test variable inertia dynamometer. This has generally been limited to a two-wheel gear or a two-wheel simulator producing dynamic response of a four-wheel gear on the aircraft. Single wheel simulation has been accomplished on a shaft dynamometer and with fixtures simulating the flexibility of the mounting on a conventional brake test variable inertia dynamometer.

6.1.3.2 The major advantages in the use of this type of equipment are as follows:

a. Dynamic compatibility of brake and structure is verified before aircraft installation.
b. Numerous design discrepancies and compatibilities can be evaluated.

6.1.3.3 Some of the disadvantages or limitations in the use of this type of test equipment are as follows:

a. Physical size of the system. Most present test dynamometers do not have the necessary width to accommodate very wide twin gears. It is necessary to install special spacers. When this is done, the inertia requirements may conflict with the width requirements of the system simulation.

b. The aircraft must be in an advanced state of construction to utilize actual gear components. Simulation requires detail knowledge of actual strut parameters. Cost and size can be a limiting consideration of this testing technique.

c. The planning of tests and the analysis of test results should take into account road wheel curvature, which can affect tire parameters and effective strut fore and aft stiffness.

d. Truck-type gears cannot be tested with this technique.

6.1.4 Pitch-Plane Simulation:

6.1.4.1 The interaction of the braking system with vertical, yaw, roll, and shimmy modes of the landing gear are often of secondary interest compared to the landing gear's walk, squeal, and whirl stability. Accurate simulation of the pitch-plane dynamics of the landing gear can be accomplished by replacing the relatively rigid axle restraint on conventional dynamometers with a flexible one. When the stiffness is properly sized, the resulting low frequency angular degree of freedom is dynamically equivalent to the fore-aft gear walk mode, based on the fact that the equations of pitch-plane motion of both systems are the same when second order effects are eliminated. This technique and the design criteria for dynamic equivalence are discussed in SAE Paper 851937, Laboratory Simulation of Landing Gear Pitch-Plane Dynamics. Some investigators believe that this technique does not properly account for coupling effects on brake squeal due to tire-flex damping.

6.1.4.2 The major advantages of this technique derive from its relative simplicity and the fact that the simulation is accomplished without fore-aft gear motion.

a. Roadwheel curvature effects are eliminated

b. Actual landing gear hardware is unnecessary

c. The brake assembly is isolated from the masking effects of conventional dynamometer fixtures.

d. Damping can be reduced to a small fraction of full-gear damping, thus deliberately destabilized configurations can be tested to verify on-aircraft stability margins and help develop accurate computer models.

e. The equipment and its installation are relatively inexpensive.