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BRAKE DYNAMICS

1. INTRODUCTION

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 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 solution of these problems. In addition, facilities available for test and evaluation are presented and discussed.

While brake dynamic problems are well known to a segment of the aerospace industry, formal definitions of the problems and their possible solutions are not readily available in current literature.

2. PROBLEM DEFINITION

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

- a. 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 "negative damping." However, carbon on carbon friction surfaces can also develop destructive self-excitation.
- b. 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.
- c. 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 rather than the frictional characteristics of the lining.
- d. 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.
- e. 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 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.

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2.2 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 two response modes. The first is the "chatter" mode, when frequencies are in the 5 to 25 Hz range. The second, or "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. 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 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.

2.2.1 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, anti-skid components and internal brake components. These cyclic loads must be considered in the design of the landing gear system.

3. PROBLEM SOLUTION

3.1 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.

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

- a. Fore and aft spring rate of the landing gear or flexibility matrix for 5D motions of the truck or axle center point (multiple wheel gears) or wheel center (single wheel gears)
- b. Angular spring rate associated with squeal motion of the landing gear system
- c. Damping coefficient associated with the fore and aft chatter motion of the landing gear system or loss factor for the spring matrix mentioned in a, above.
- d. Angular damping coefficient associated with the squeal motion of the landing gear system.
- e. Strut mass and distribution of weight
- f. Chatter frequencies of landing gear system
- g. Axle geometry, stiffness and damping characteristics, configuration, and mounting flange details
- h. Other parameters based on analysis of specific gear geometry
- i. Various tire characteristics

3.3 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 at which 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.

4. DATA CLASSIFICATION

4.1 In spite of the scatter in results of identical stops, which 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 the brake manufacturers and cooperation with the users on vibration problems is essential.

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

a. Coefficient of Friction:

- (1) Static - cold, hot, and dynamic breakaway (termination of skid)
- (2) Dynamic - initial, average, and maximum
- (3) Transition - dynamic to static (entering skid)
- (4) Carbon brakes - wet, dry, and transition wet to dry

b. Dynamic Coefficient of Friction Variation with:

- (1) Kinetic energy absorption rate
- (2) Temperature
- (3) Amount of absorbed kinetic energy
- (4) Velocity
- (5) Unit pressure
- (6) Number of prior landings and/or applications
- (7) Amount of water applied (carbon brakes)

c. Wear-Variation with:

- (1) Level of kinetic energy absorption/mass loading/temperature
- (2) Rate of kinetic energy absorption/power loading/velocity
- (3) History of past usage
- (4) Unit pressure
- (5) Wet or dry condition on carbon brakes

d. Torque vs Pressure Characteristics:

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

e. Landing Gear Dynamic Characteristics:

- (1) Chatter natural frequency
- (2) Squeal natural frequencies (first through third)
- (3) Positive damping associated with chatter and squeal

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

5. BRAKE DYNAMIC CHARACTERISTICS EVALUATION

5.1 Following is a discussion of techniques, equipment and/or facilities that can be used for brake dynamic evaluation:

5.1.1 Shaft Dynamometer:

5.1.1.1 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 "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. Temperatures 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

5.1.1.2 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.

5.1.1.3 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.

5.1.2 Conventional Brake Test Dynamometer:

5.1.2.1 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 an 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.

5.1.2.2 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)

5.1.2.3 Disadvantages and/or limitations of the use of this type of test equipment are as follows:

- a. Limits test to single wheel-brake installation mounted on cantilever axle
- b. Cannot duplicate total gear, particularly trucks
- c. Lacks fore and aft freedom for "chatter" assessment, as installed
- d. Frequently lacks sufficient drive power to permit assessment of taxi environment

5.1.3 Landing Gear Simulation:

5.1.3.1 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 trunion 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 wing beam. 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.

5.1.3.2 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

5.1.3.3 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 truck type or very wide twin gears. It is necessary to install special spacers. The curvature of the flywheel prohibits use of truck gears due to operation on the curved surface.
- b. For correct testing, the equipment should be positioned above the dynamometer. Some facilities do not have this capability.
- c. 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.

5.1.4 Computer Simulation Alternative to Test: Computer analysis can be a valuable assistance in assessing the effects of assignable variables on brake dynamic characteristics. Utility of the information from this tool is dependent upon an accurate assessment of both strut and brake design parameters.

5.1.5 Track Facilities: There are facilities available which permit mounting of an actual gear or major component which is then propelled down a track to test velocity and loaded in a manner similar to that experienced on the aircraft. The two known facilities which have this or similar capabilities are NASA at the Langley Loads Track at Langley AFB, Virginia, and the U.S. Navy at the Naval Air Engineering Center, Lakehurst, New Jersey. They differ in propulsion method and method of applying vertical load. However, the NASA Langley facility is more experienced with many more tests being conducted in this technical area. Therefore, the facility is more advanced in sophistication of test techniques.