MiTi Developments

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COMPLIANT FOIL PROVIDES EXCEPTIONAL DAMPING FOR OIL-FREE, HIGH TEMPERATURE APPLICATIONS

SYNOPSIS

A metallic, self-contained, high temperature, compliant foil damper has been developed by Mohawk Innovative Technology (MiTi®) for use in harsh environments where oil-free operation is highly desirable. Extensive testing in a rotor system test rig (Free-Orbit Test Rig) simulating the hot section of a gas turbine engine, with temperatures up to 1000°F, produced results exceeding required damping for this type of system. This testing demonstrated effective stabilization of an imbalance rate equivalent to 15 times MIL-SPEC G.2.5 requirements for gas turbine engines having a 15 lb. rotor operating at 50,000 rpm. Life, durability, and stable performance characteristics were also exceptional.

Immediate applications include use in advanced, expendable gas turbine engines for unmanned aircraft and propulsion systems requiring very-long "shelf life". The compliant foil damper may be combined with vapor-phase lubricated (VPL) rolling element bearings, allowing higher bearing chamber operating temperatures. Potential applications also include use with man-rated high temperature backup bearings for active magnetic bearing (AMB) and MiTi®'s hybrid foil/AMB bearing-supported rotors. Future applications of this enabling technology may well provide the means to completely eliminate oil lubricating systems in high power density rotating machinery.

High-Temperature, Dry Dampers Needed

With the advent of ever more severe operating requirements, more and more rotating machinery and structural systems require high capacity dampers to achieve their performance and life goals. At the same time, environmental concerns are leading the drive to eliminate oil in many machines. This push toward oil-free machinery has dictated that an entirely new class of vibration dampers be developed to replace the conventional squeeze-film oil dampers currently in use. Under U.S. Air Force sponsorship and company internal funding, MiTi® has developed and tested a dry, high-temperature damper for use in high-speed rotating machinery. The technology may also be used in many structural applications.

The Concept

The damper is comprised of compliant, corrugated structural members made of a high-temperature, spring-like alloy, as shown in Figure 1. It is suitable for use with either dry or with vapor-phase lubricated (VPL) applications being developed by the U.S. Air Force. Its unique design provides both stiffness and damping. The damping, or energy dissipation, is the result of the micro stick-slip friction that occurs between the compliant corrugated members and the surrounding materials.

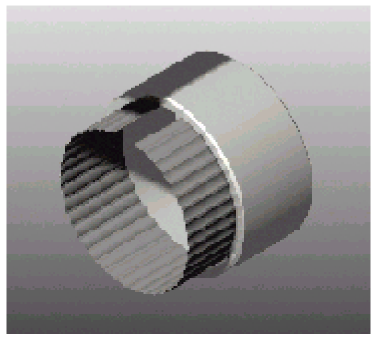

Figure 1. Corrugated Damper Insert

For example, in a rotor-bearing application, when the shaft vibrates, the corrugations are squeezed. This action causes micro-movement of each individual corrugation relative to its surrounding material as the static friction forces are overcome. It is the cumulative friction losses of each corrugation that dissipates the vibrational energy. Using this concept, the designer specifies the number and orientation of each corrugation to achieve specific damping levels for each application. In a like manner, the thickness and strength of the corrugation material determines the overall stiffness of the damper.

Dynamic Characterization

A damper characterization test rig was designed and built to duplicate the range of motions and forces the damper would be required to control in typical gas turbine applications. This rig was used for the experimental characterization of candidate damper designs. This included shaker excitation of a series of pre-loaded bump foil designs to induce vibratory motion having amplitudes in the range of 0.0001 to 0.0006 inches over a frequency range of 0 to 2000 Hz. This rig is depicted in Figure 2.

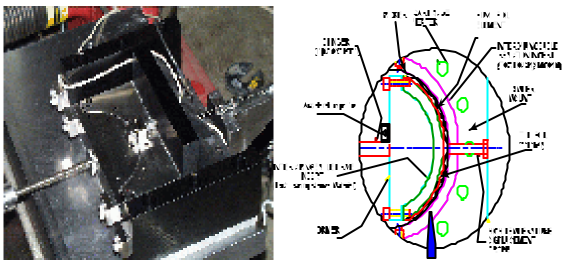

Figure 2. Foil Damper Dynamic Characterization Test Rig

Frictional damping characteristics of the contact micro-motion phenomena were documented using bump foils of different materials and different coatings. Temperature effects were obtained by testing while the bump foil contacts were held at 1000°F using cartridge heaters installed in the test section. The high temperature tests also included the effect of VPL at the contact surfaces. The results of this experimental testing produced a better understanding of frequency of motion, amplitude of motion, materials, temperature, and load on the dynamic stiffness and damping properties of the bump foils. Typical stiffness and damping vs frequency are shown in Figure 3.

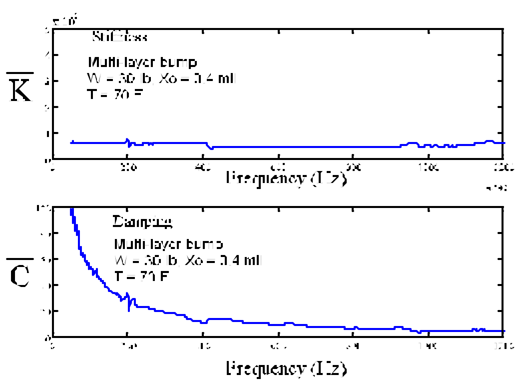

Figure 3. Typical Stiffness & Damping vs Frequency

Application Testing

A dynamic, Free-Orbit Test Rig (FOTR) was utilized to fully evaluate the damping capabilities while the test rotor was subjected to imbalances of varying magnitudes in a simulated gas turbine engine environment. MiTi modified an existing foil seal test rig (Fall 200 Newsletter, Vol. 10) to perform this testing. The FOTR, as shown in Figure 4A (Schematic) and Figure 4B (Hardware), was a hybrid dynamic simulator that featured a compliant foil bearing for testing of the damping effects on one end (hot section), and an oil mist lubricated angular contact ball bearing in the other end (cold section) that also carried the thrust load. This rig provided a completely isolated (dynamically) hot end. For convenience, the existing foil bearing assembly design was used in place of a ball bearing/foil damper combination, as their damping effects are identical.

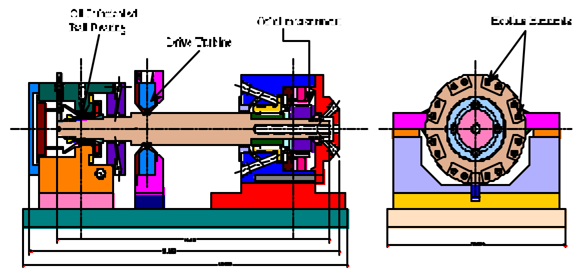

Figure 4A. Free-Orbit Test Rig (Schematic)

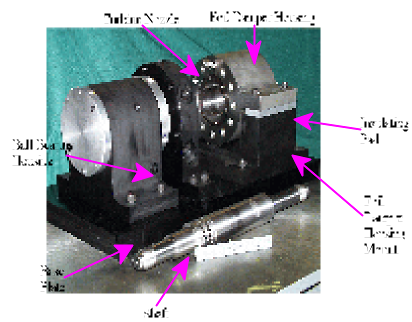

Figure 4B Free Orbit Test Rig Hardware

The rotor was 18.45 inches long, weighed 14 lb., was driven by an air turbine, had the capability of running at speeds up to 60,000 rpm (approximately 3 million DN), and provided the means of imposing dynamic loads up to 10 times the steady-state loads. Actual testing was done at speeds up to 50,000 rpm. The hot end had a fully instrumented, pressurized, and heated test chamber.

In this study, both structural and hydrodynamic effects were included. Progressively higher imbalances from 0.150 up to 1.8 gram-inch and 75°F to 1000°F temperatures were introduced with 5 basic candidate damper designs and their perturbations. All configurations provided stable operation over the entire imbalance and temperature ranges.

The designs utilizing a multi-layer bump foil with a predetermined initial clearance provided higher damping over a wider range of operating speeds. This was attributed to the progressive load sharing of the layers as the loads increased and additional friction generating surfaces engaged. Results for the best performing damper are shown in Figure 5. These`tests were run as a base case, at 1.8 gram-inch imbalance at room temperature and again at a 1000°F damper temperature. The higher response magnitude of the high temperature test when traversing down through the critical speed is due to the changes in material properties of the housing as well as the bump foils.

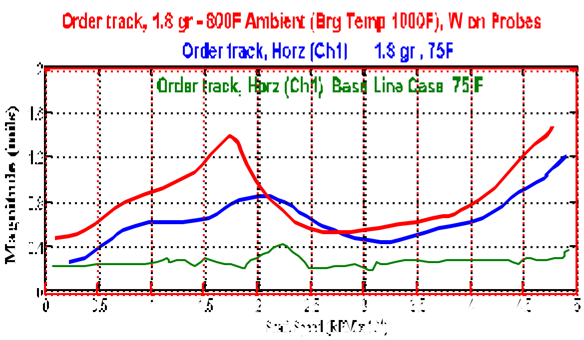

Figure 5. Order Tracking Plots, Baseline and Two Tests

Figure 6 is a plot of the ratio of the change in orbit over the change in imbalance against increasing imbalance that serves to characterize the sensitivity of the orbit size to imbalance. The three areas progressively represent high changes in sensitivity until all bumps are activated, to reduced changes in sensitivity during the design range of the damper as higher loads are imposed, to a return of higher sensitivity as the design range is exceeded.
This places the burden of proper damper operation squarely on the designer to select the proper configuration for each specific operating window. Current state of the art places high emphasis on the need for simulator testing for design verification before release to build.

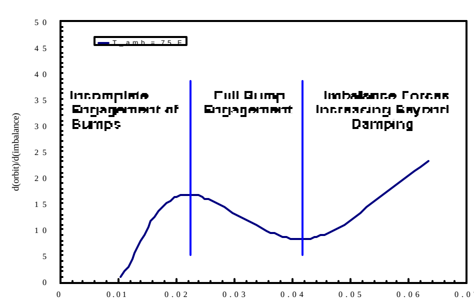

Figure 6. Orbit Sensitivity with Imbalance and Range

Figure 7 is a log of the durability testing performed on the selected damper configuration. A complete inspection was performed after the tests to verify component and assembly integrity. No signs of wear or abnormalities were found. The results support predictions of long, maintenance-free life for this application.

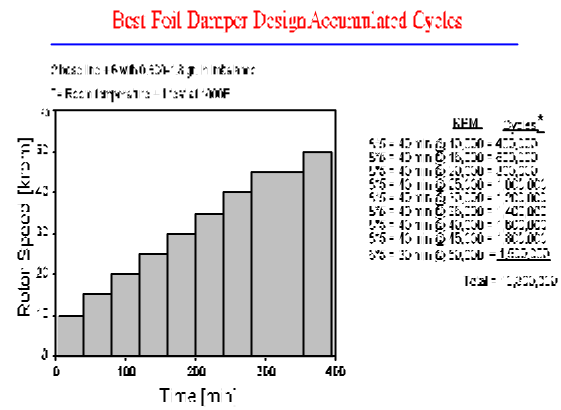

Figure 7. Accumulated Cycle Testing on the FOTR

Application of the Technology
An existing Air Force ceramic bearing/VPL testing device was redesigned to accommodate foil dampers. A complete finite element model (FEM) analysis was conducted on the design, and it predicted a remarkable reduction of amplitude of motion in the ball bearing holder and loader assembly. Dampers were then manufactured, and the device was revamped by MiTi. The assembly was

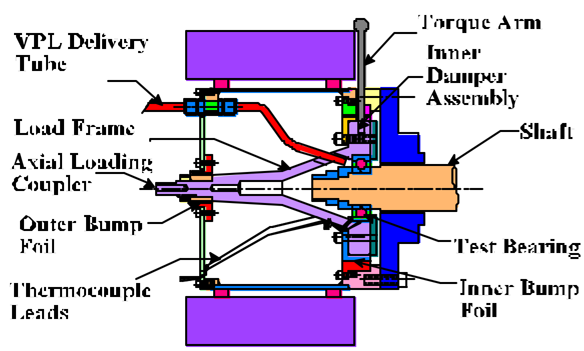

Figure 8. Ceramic Bearing/VPL Testing Device

validated by determining the natural frequencies (via impact test) before returning the device to the Air Force.

Test rig components are identified in Figure 8. The Outer

Damper Assembly controls the radial vibratory motions of the outer end of the Load Frame. The Inner Damper Assembly, controls the radial vibratory motions of the load frame supporting the Test Bearing. Both ends utilize foil dampers. The Torque Arm is used to measure the rotational force generated by the frictional drag of the bearing. The Load Frame is free to rotate only to the extent that torques can be measured. Axial loads (simulated thrust) can be imposed through the outer end of the Load Frame. VPL is introduced through the Delivery Tube. Thermocouples are used to measure temperatures at the bearing. Radial loads and rotation are provided by the Shaft.

About MiTi®

Mohawk Innovative Technology, Inc. (MiTi®) is one of the world's leading developers and suppliers of high efficiency, oil-free compliant foil, magnetic, hybrid and auxiliary bearings for high temperature, high speed and load applications. MiTi® is committed to providing innovative, cost-effective, and timely rotor bearing system solutions for challenges in high-speed rotating machinery.

Besides foil bearings and seals, MiTi has developed unique auxiliary, or backup bearings for use with magnetic bearings. Examples of this product are shown in Figure 9. The Zero Clearance Auxiliary Bearing (ZCAB) has small planetary ball bearings that are cam mounted to automatically close down and engage a rotor during

Figure 9 50 & 140 mm diameter Zero Clearance Auxiliary Bearings

magnetic bearing failures or overloads. Suitable for oil-free and vacuum applications, ZCAB can be applied to flywheels, compressors, or other high DN applications.

Facilities

MiTi® has a 13,000-square-foot, stand-alone facility that includes engineering design offices, manufacturing facilities, and laboratory space for research and development, testing and quality control, and a well- equipped precision machine shop. Welding, forming, material heat treating, and lubricant coating facilities accommodate the manufacture of compliant foil gas bearings and seals, magnetic bearings, and auxiliary bearings.

For high-speed machinery development, MiTi has both component and system dynamic balancing machines as well as a wide array of networked digital and analog data acquisition systems

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