MiTi® Developments

Mohawk Innovative Technology, Inc.

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4 Million DN & 1000 °F Operation: From 6 mm to a 150mm Diameter Foil Bearing

Mohawk Innovative Technology, Inc. (MiTi®) has successfully operated its largest compliant foil bearing (CFB) so far at speed close to 27,000 rpm. This achievement resulted in a break through of 4million DN (DN=d[mm]*N[rpm]) on a 150mm diameter foil bearing. The length of the bearing was 100mm. The CFB was tested successfully for hours at housing temperature of 1400°F and at close to 1100°F of bearing surface temperature. This bearing design only requires a minimum rotor speed of 650 rpm (about 5 m/s surface speed) for non-contact operation.

This break trough development was accomplished through contribution of MiTi® expertise in design and development of high speed CFB's as well as support of NASA GRC and US Air force. Figure 1 shows a close-up of the CFB with rotor partially installed. In the previous MiTi® Developments (Vol. 17), successful operation of a 6 mm compliant foil bearing tested at speeds above 700,000 rpm (equivalent of 4.2 million DN) in a mesoscopic turbojet simulator was reported. Pervious successful operation of MiTi® bearing at various size between 6 to 150 mm have been also reported.

The successful operation at various sizes indicates the well behavior scalability, which has been adopted in design of these CFB's. Figure 2 shows the scaling path from 6mm to 150mm foil bearing. The challenges associated with scaling are such as tolerances included in design process for thermal growth, minimum lift off speed, structural stiffness and damping, and other manufacturing tolerances.

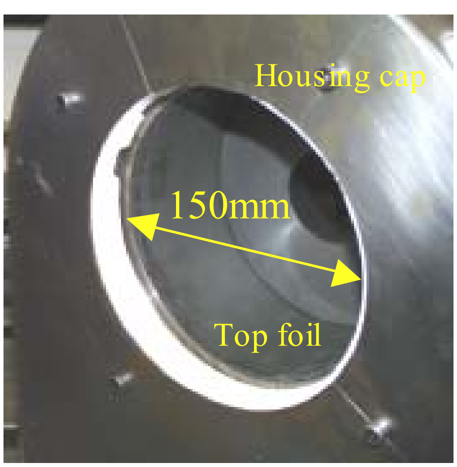

Figure 1 150 mm CFB with rotor partially installed

Figure 2 Scaling of CFB, from 6 mm to 150 mm

This 150mm foil bearing is sized to meet a wide range of potential applications such as gas turbine engines for high-performance commercial and general aviation aircraft systems as well as larger industrial compressors. The surface of both bearings was protected via a super lubricious coating, Korolon 800, developed by MiTi®. This coating, reduces remarkably the rub and wear of rotor and bearing surfaces during start-up and shutdown where hydrodynamic film is not fully developed. Transient tests, simulating the failure of magnetic bearing in a hybrid foil-magnetic bearing were also conducted.

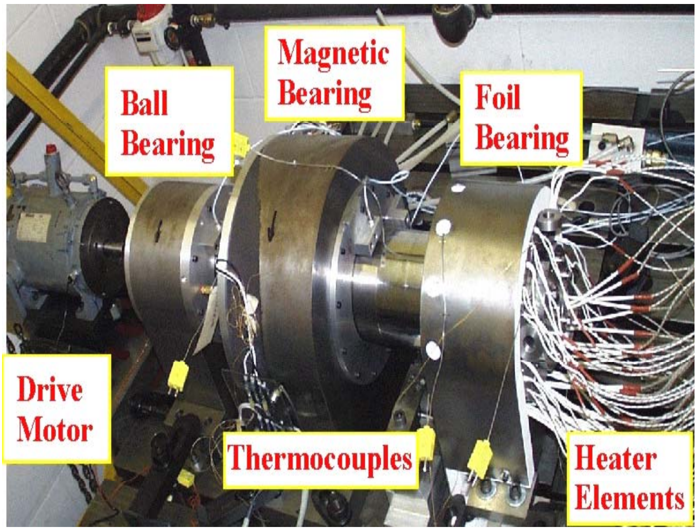

Figure 3 Hybrid foil-magnetic bearing test setup

EXPERIMENTAL TEST SETUP

The set up included a ball bearing (REB), a magnetic bearing (AMB) and a compliant foil bearing (CFB). The REB and CFB were located at the opposite end of the rotor. The CFB was tested in combination with a magnetic bearing made it a hybrid system of support. This hybrid system allowed taking advantage of the magnetic bearing at low speeds and benefit from the advantages of foil bearing at high speeds The magnetic bearings are suitable for small loads and low speeds/shocks while CFB could provide high load with high shock tolerance at maximum speeds. The AMB in this test rig was used to provide the following tasks:

a. Levitate rotor at zero and low speed during run-up and coast-down course in order to avoid contact, rub and wear between rotor and bearing

b. Combine with CFB to support rotor in a hybrid mode

c. Orbit control while the rotor is running

d. Apply a load to the rotor while the rotor is running on the REB and CFB

The test rig employed for testing the CFB is shown in figure 3. To simulate an engine installation, an approximately 65 kg, 0.85 m long rotor was used. The rotor is driven by an electrical motor connected via an axially soft and radially stiff coupling. The drive motor was a three-phase motor with about 44.7 kW of power and a maximum rotational speed 30,000 rpm. An optical speed pick-up was used to obtain rotor speed and as a phase reference. Displacement probes were installed in vertical and horizontal directions close to AMB, CFB and REB for monitoring the rotor orbits. Thermocouples were installed on each bearing. Pressure transducers were also provided to record cooling air pressures. Cooling air flow was recorded with mass air flow sensors. Loading on the CFB with the AMB loader was calibrated to determine actual applied load and monitored by AMB bias currents.

High speed data reduction system included a digital high signal recorder and an on-line analog signal analyzers. These signals included the displacement of the rotor at various locations in vicinity of all bearings. MatLab was used for post processing of the data. All the temperature and pressure signals as well as the speed were recorded and process via LabView.

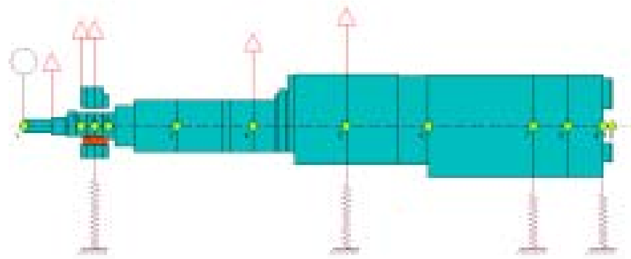

Figure 5 Rotordynamic model of hybrid system

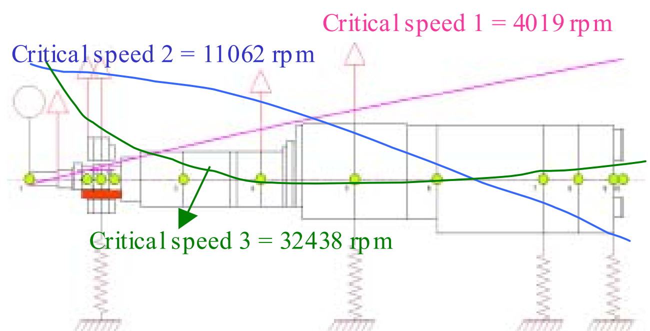

Figure 4 Mode shapes

OPERATIONAL MODES and ROTOR MODEL

One of the objectives of this study was to address the feasibility of CFB operation when in hybrid mode. The operations focused on the following different modes by switching AMB from off mode to on mode and reversely:

(1). AMB mode at low speed;
(2). CFB mode at high speed;
(3). Hybrid mode when AMB is treated as a bearing;
(4). Hybrid mode when AMB is treated as a loader.

Figure 4 and 5 present the rotor model and the mode shapes predicted by the rotor system analysis program, DyRoBeS. As shown the first, second rigid modes and the bending mode tool place at rotor speeds of 4,019, 11,062 and 32,438 rpm, respectively. It is of importance to note that at the 2nd rigid mode challenge arose from small damping in the system due to small motion of rotor at the foil bearing station. For foil bearing in order to provide necessary damping, small amount of motion is necessary. However, the system successfully passed this mode.

EXPERIMENTAL TESTS ANS RESULTS

Each test started with levitation of the rotor and spinning the rotor by the magnetic bearing up to a speed above the minimum speed for CFB. Then magnetic bearing was turned of and the rotor was supported by REB and CFB. At a selected speed, the magnetic bearing was then turned on. The run-up/coast-down of rotor is shown in Fig.6. As shown there, the full operation process consisted of two hybrid modes and a CFB single mode. The rotor was levitated by AMB at zero speed and was spun to 7,600 rpm. The AMB was then turned off to let CFB work alone and the rotor speed was gradually increased to reach the top speed of 26,923 rpm. During the acceleration period, some load was applied with AMB as a loader. The FFT recording was not taken due to an emergency; however, the coast-

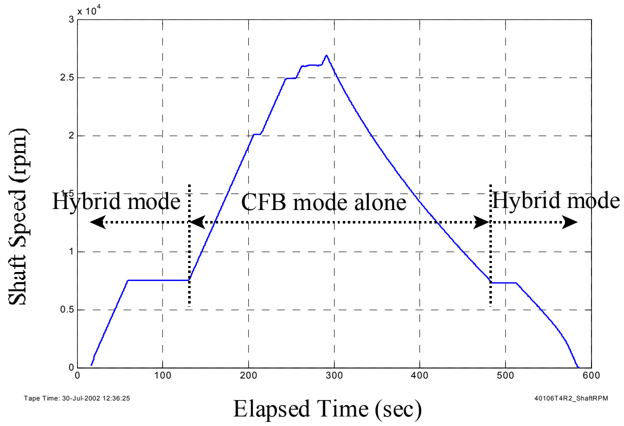

Figure 6 Rotor speed with time

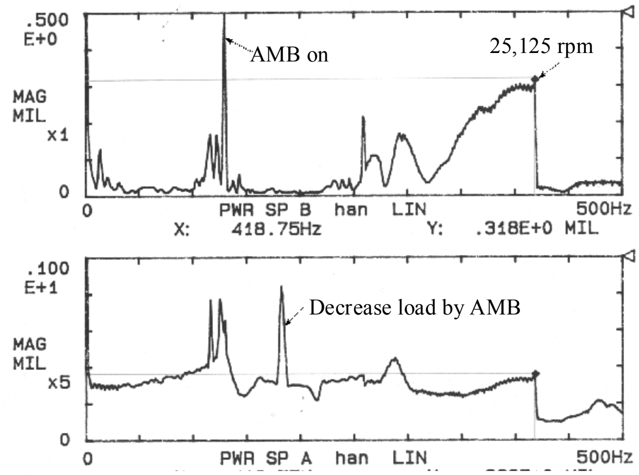

Figure 7 FFT response of CFB for vertical (top chart) and horizontal directions (bottom chart)

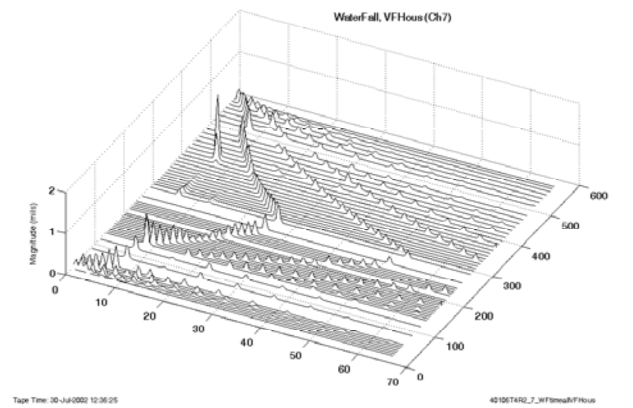

Figure 8 Waterfall of vertical response of CFB

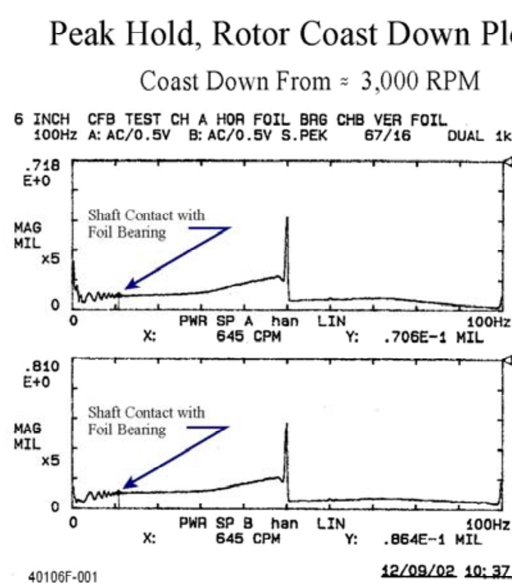

Figure 9 FFT response of CFB at low-speed

down FFT response curve taken at 25,125 rpm was recorded and shown in Fig.7. It was noted that the magnitude of the displacement at 25,125 rpm is only 8 mm. A peak signal was caused by switching on the AMB. The typical synchronous response of the vertical displacement of CFB for speeds up to 26,923 rpm showed a magnitude of 11.4µm for displacement at the vicinity of the CFB. During run-up and coast-down between 0 rpm and 26,923 rpm (i.e. 4 MDN), maximum amplitudes of rotor vibration did not exceed 20µm even passing through the two rigid modes. Fig.8 shows the corresponding waterfall plot for this test run. The results show the stable operation over a range of operating speeds.

While the non-contact operation of a CFB is always accompanied by a transition through a lower range of speed, it is very essential to address the performance of a CFB at this range. A preliminary low range speed capability of the CFB was conducted via determining the minimum rotation of the rotor when the CFB is in a single mode. To determine the minimum shaft operating speed (i.e. touchdown speed), the rotor was spun to a speed of approximately 3,000 rpm, and the magnetic bearing turned off so that the rotor's free end was supported solely by the CFB. The drive motor was turned off and the rotor was then allowed to decelerate to rest. As noted in the synchronous peak hold spectrum plot, shown in Fig.9, rotor-to-foil contact and touchdown occurs at only approximately 645 rpm. This extremely low spin speed is equivalent to a surface velocity U of less than 5 m/s.

Performance of the CFB's at low speed when operating in hybrifd mode is as important as in high speed. In order to investigate the performance of the CFB in low speed, a drop test was conducted. The result of the process is shown in figure 10.

OPERATION AT ELEVATED TEMPEATURE

Due to non-contact operation of compliant foil bearing, these bearings could be employed in high operating temperature environment where REB usage is not possible. Operation in high temperature is challenging due to the following factors: a. The surface of the bearing and rotor should tolerate the high temperature which exist during the startup and shutdown where no hydrodynamic film is developed; b. a lubricious material should be used to

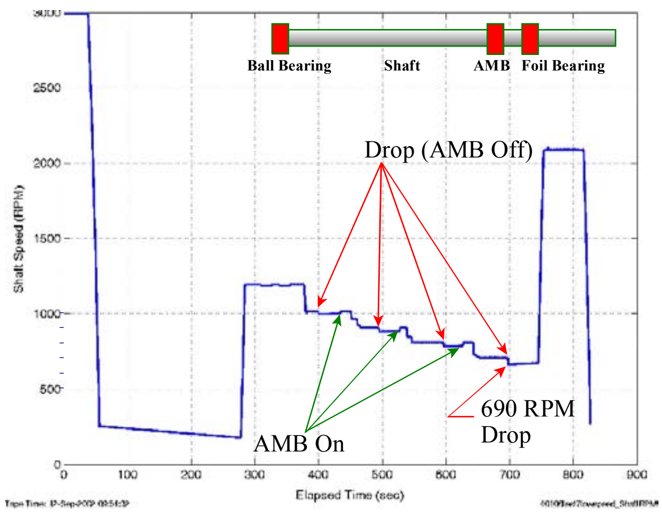

Figure 10 Low speed frequent rotor drop on CFB

prevent any type of adhesion between rotor surface and the bearing surface; c. rotor and bearing surfaces should be protected against corrosion and wear. MiTi® has developed two series of coatings which are capable of operating at temperatures of 800 and 1350 °F. This coating, known as Korolon, posses very small coefficient of friction and has passed hundred thousands of cyclic test at various contact pressure and temperature. Korolon coating was used for testing the performance of the current CFB. A rotor with electrolyzed journal was used against the CFB with Korolon coating. A sample of test result is shown in figure 11. The surface of the CFB was examined via microscope and no indication of sever rub was observed.
In a similar test, a solid journal coated with PS304, a NASA patented coating, was used against Korolon. The operation of this journal at high temperature resulted in disintegration of the PS304 and detachment from the journal.

Road Paved for Further Developments

Based on this successful operation of the 150mm compliant foil bearing at high speed and high temperature, and successful operation of a 6 mm compliant foil bearing in a

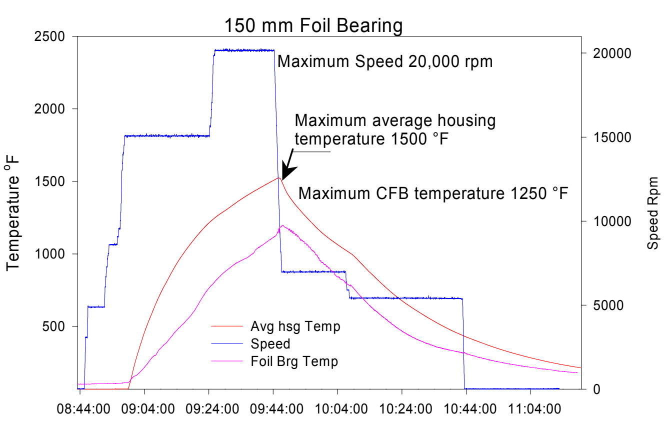

Figure 11 Operation of CFB in high temperature condition

mesoscale turbojet simulator, MiTi® has successfully shown the scalability of its compliant foil bearing in this range.

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