MiTi® Developments

Mohawk Innovative Technology, Inc.

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Mesoscopic Turbojet Simulator Tested at Speeds Above 700,000 rpm on Air Foil Bearings!

Mohawk Innovative Technology, Inc. (MiTi®), in a company funded effort, recently conducted the first successful test of a mesoscopic scale turbojet engine simulator using specially designed miniature air foil journal and thrust bearings. This operation of the simulator rotor and foil bearing system will pave the way for turbine powered micro and miniature aerial vehicles (MAV). The need for MAV and mesoscopic power generating (MPG) sources has recently been identified due to the wide spectrum of situations that the 21st Century warfighter will likely experience and the increasingly power hungry electronic equipment needed to sustain the warfighter in the field. The shift toward a more diverse array of military operations, often involving small teams of individual soldiers operating in non-traditional environments, has already been seen and will likely increase. As such, MAVs and MPGs are envisioned for use at the platoon level or below. To support the single fuel forward concept, ensure high reliability and long term storability of these machines, MiTi® has been developing the critical supporting oil-free bearing technologies needed to make these mesoscopic turbojet machines reality. Significant commercial applications are also expected in support of miniature fuel cells, diesel engines and other propulsion and generating machinery.

For this demonstration, a 56 gram simulator (including the 9 gram rotor) was designed, built and operated at speeds in excess of 700,000 rpm to demonstrate the technology readiness of MiTi® foil bearings for application to mesoscopic sized turbojet engines and generators. This technology demonstration test also showed that MiTi®'s newly developed radially split journal and thrust bearings perform as designed and will permit single piece ceramic rotor designs in the future. Figures 1 and 2 show the simulator including the split housing, single piece rotor, split thrust foil bearings and the split journal foil bearings.

Compliant foil air bearings were selected for this demonstration because of their ability to operate at almost unrestricted speeds and temperatures above 1100°F for extended durations. Additionally, MiTi®'s Korolon series of high temperature coatings are designed to permit thousands of bearing start/stop cycles without degradation. Since the very high operating speeds and temperatures of the mesoscopic turbojet will exceed the capabilities of any available rolling element bearings (including hybrid ceramic ball bearings) and conventional lubrication approaches, oil-free compliant foil air bearings were chosen. While this initial demonstration achieved 700,000 rpm, future designs are targeted at one million rpm. Even at the 700,000 rpm demonstrator test

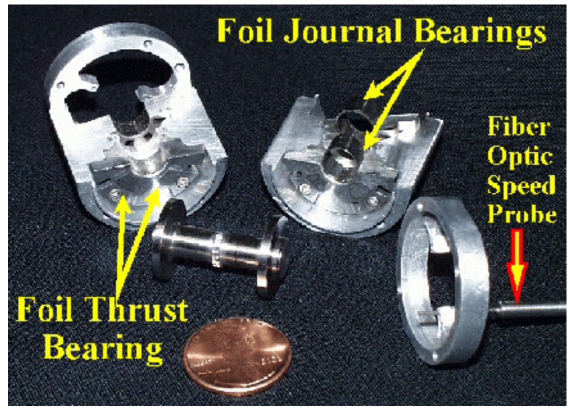

Fig. 1. Mesoscopic turbojet simulator rotor, split housing and MiTi® split air foil bearings.

speeds, the bearing DN value of 4.2 Million exceeds ceramic rolling element bearing capabilities by two times. Bearing DN, where D is bearing diameter in mm and N is speed in rpm, provides an indication of the severity of the operating conditions and bearing life. Rolling element bearing DN values above 2 Million DN are rarely seen, except in the most demanding applications where routine maintenance is mandatory. When the bearing environmental temperatures, which are expected to exceed 1000°F are also accounted for, oil-free or gas bearings are the only solution. Oil-free bearings are necessary because at temperatures above 600-700°F oil, especially in the small quantities to be used in mesoscopic turbojets will likely coke and rolling element bearing failure will quickly occur.

Beyond just considering the bulk temperature, small

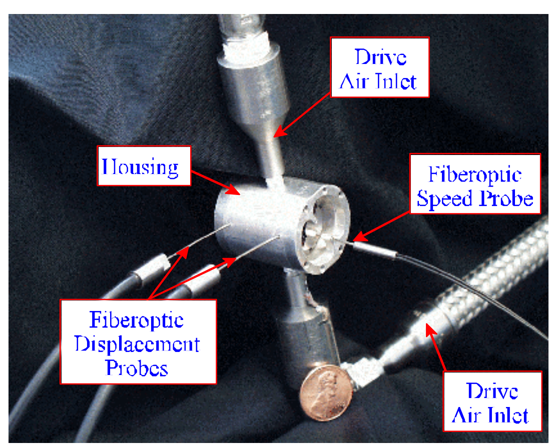

Fig. 2. Assembled and instrumented mesoscopic simulator.

mesoscopic sized system rotor and bearing designs must address system thermal management. For these small systems, heat removal becomes very challenging due to the limited pathways and available heat sink. Thus when selecting the bearing design, both the ability to operate at elevated temperatures and remove heat from the bearing must be considered. In contrast to conventional rigid gas bearings, MiTi®'s foil bearing designs inherently accommodate high temperature environments and differential thermal growths through the designed in compliance and cooling passages which are the result of the corrugated bump foil support design.

Machine Description

Figures 3 and 4 present schematic cross sections of a potential mesoscopic turbojet engine concept and the test simulator used to demonstrate the high speed operation and capability of the foil bearing system. As seen in these figures, the mesoscopic turbojet engine concept and simulator are very simple in construction. While the mesoscopic engine uses a double acting thrust bearing located behind the compressor and is shown with an axial flow turbine, concepts considering a radial inflow turbine and all ceramic construction are also desirable and are being pursued. As such, the simulator was designed as a single piece rotor. The single piece rotor design required that split bearing designs and housing be developed. As seen in Figure 1 this objective was met.

Since these first tests were intended to demonstrate the rotordynamic stability of a mesoscopic sized rotor and foil bearing system, the compressor and turbine impellers were simulated in mass properties only and a central impulse turbine was used to spin the rotor up to speed.

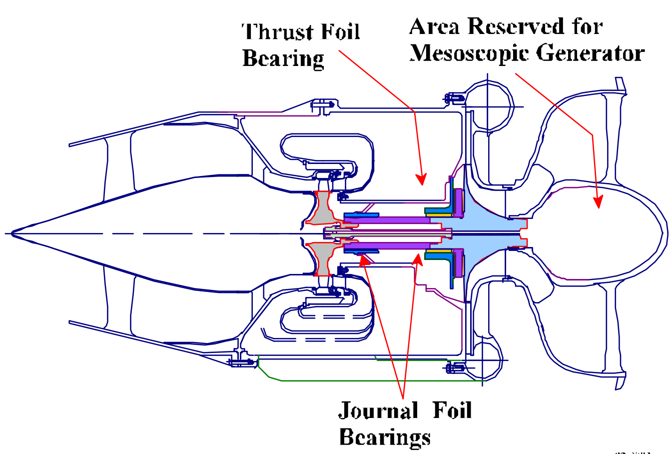

Fig. 3. Conceptual cross section diagram of oil-free mesoscopic turbojet engine.

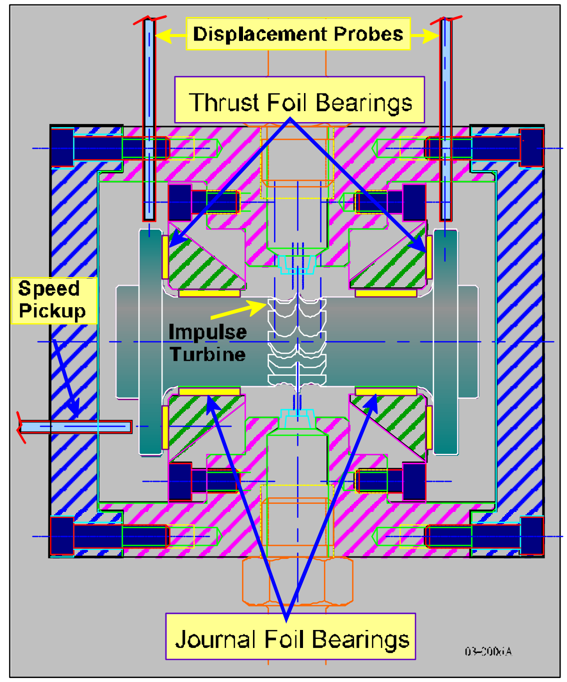

Fig. 4. Cross section of dynamic simulator.

Bearing System Design and Integration

During this effort, MiTi® completed extensive rotordynamic and bearing analyses to ensure scalability of the technology. The journal bearings have a 6 mm bore and are designed to provide the stiffness characteristics shown in Figure 5. The thrust bearings have an outside diameter of 15 mm and a inside diameter of 8 mm. The rotor used for these preliminary feasibility tests was made of stainless steel and weighed only 9 grams. Figure 5 shows the predicted stiffness characteristics as a function of speed for the journal bearings. The results of the rotordynamic analysis are presented in Figures 6 and 7. Figure 6 shows both the predicted and measured rigid body natural

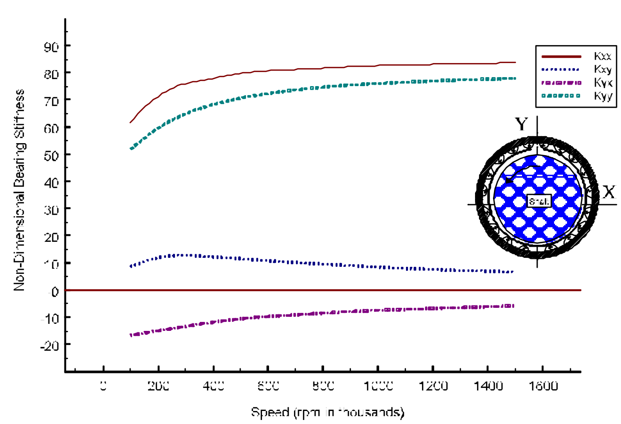

Fig. 5. Stiffness coefficients as a function of rotor speed for 6 mm diameter foil bearing .

frequencies when operating at speeds up to 550,000 rpm. Figure 7 shows that rotor system stability is expected over the entire operating speed range as noted by the positive logarithmic decrements for all speeds.

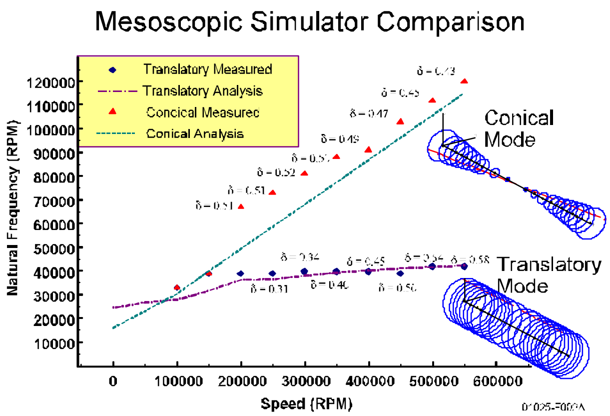

Fig 6. Whirl speed map and mode shapes for the mesoscopic rotor-bearing simulator system.

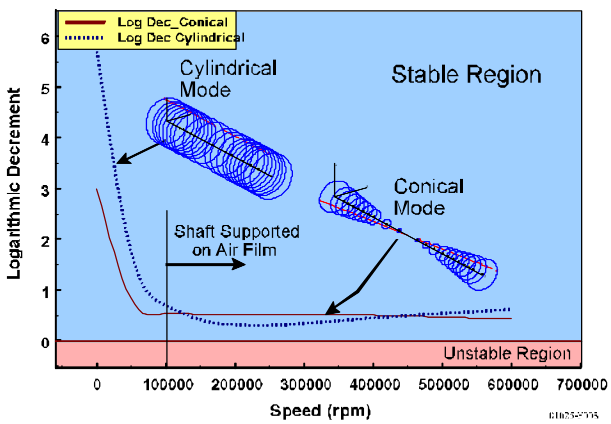

Fig 7. Stability map showing logarithmic decrement versus rotor speed for the rigid body natural frequencies

Testing

Testing was completed at speeds to 705,000 rpm with the rotor spin axis positioned at various orientations. Figures 8 through 12 show the frequency spectrums obtained from the two fiberoptic displacement sensors for each of the rotor test orientations. Figures 8 and 9 show the high speed operation with the rotor in the preferred horizontal orientation at two different speeds. Figures 10 and 11 show rotor spectrum with the rotor remaining horizontal, but the housing rolled or rotated 90° and 180° from its preferred orientation. Figure 12 shows the vibration spectrum when the rotor spin axis is vertical. The increase in rotor orbits when operating with the spin axis vertical is expected due to the reduced bearing stiffness experienced during unloaded operation. These tests verified the high-speed all attitude operation of the mesoscopic turbine rotor simulator. Of most importance is the lack of any real subsynchronous natural frequency vibration content in the measured spectrum. These clean spectra are indicative of a well damped rotor bearing system. Further, the lack of observed subsynchronous vibrations throughout the test speeds indicates that operation to speeds of one-million rpm are possible. Based on previous high temperature testing of MiTi foil bearings up to 1200°F, operation of mesoscopic turbojets appears highly feasible. For this initial test series, over 30 start stop cycles and more than 1 hour of run time were accumulated. The maximum operating speeds attained during testing represent the first ever demonstration test of its kind.

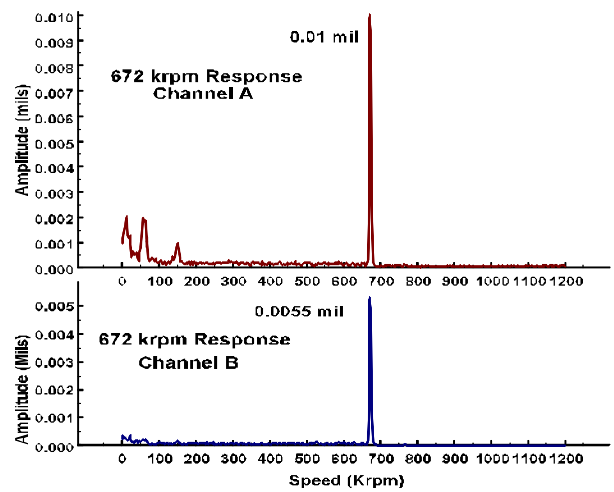

Fig 8. Spectrum for rotor at 672,000 rpm

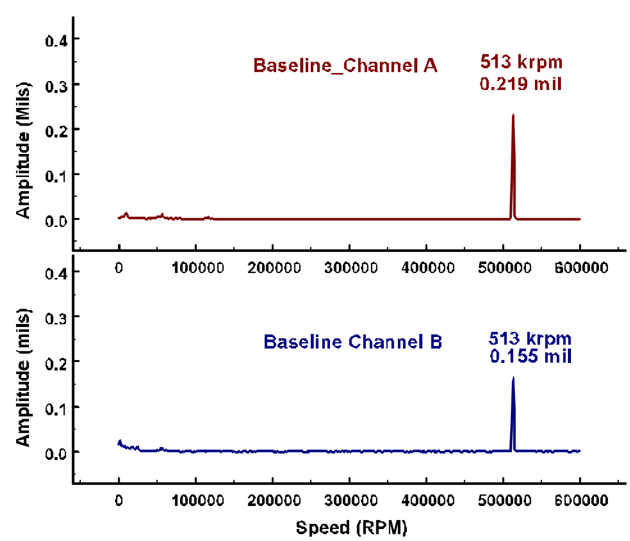

Fig. 9. Rotor vibration at 513,000 rpm for horizontal orientation.

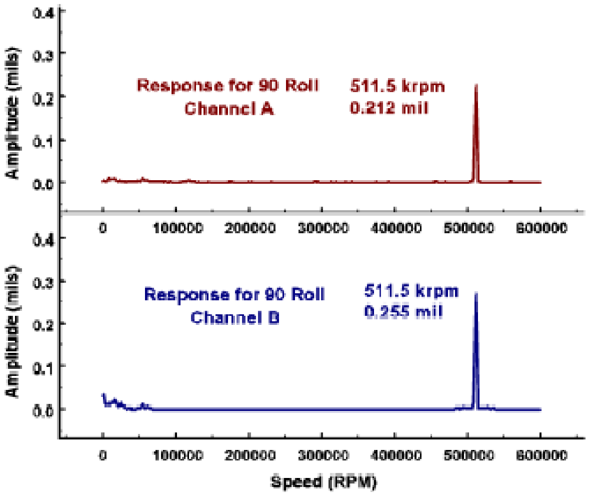

Fig. 10. Spectrum for 90° roll about spin axis.

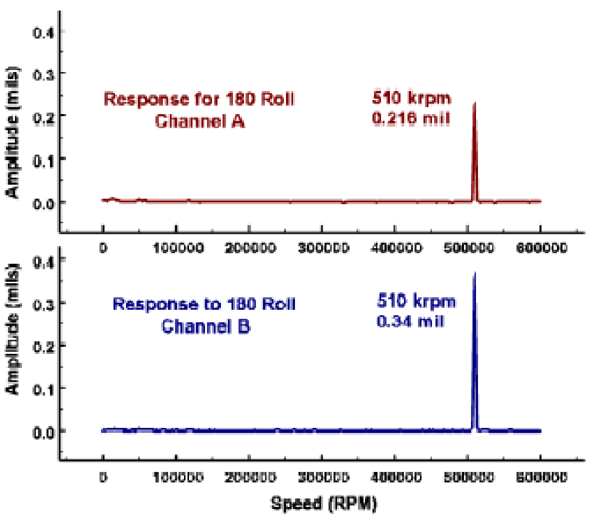

Fig. 11. Spectrum for 180° roll about spin axis

MiTi® has developed foil bearings in sizes from 6 mm to 150 mm

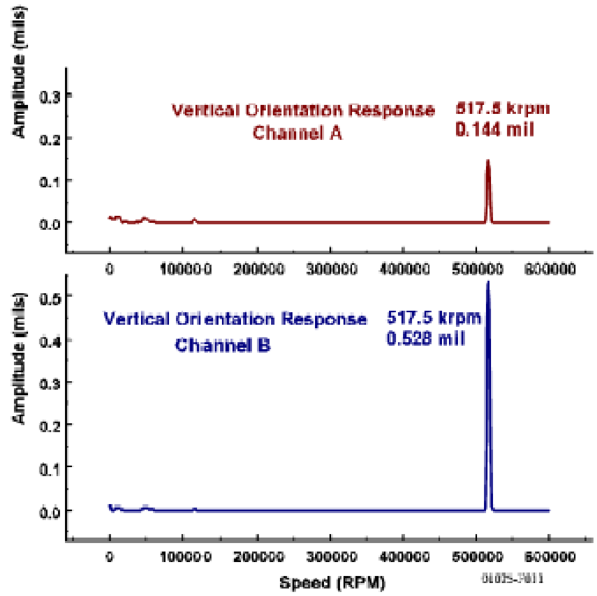

Fig. 12. Spectrum for vertical operation

Road Paved for Further Developments

Based on this very successful demonstration of a mesoscopic sized rotor supported on MiTi® foil bearings, the potential to develop a 1 million rpm lubricant-free mesoscopic turbine rotor system appears highly feasible. Additional testing and developments are planned to further refine and quantify the benefits to be gained with foil bearings in mesoscopic sized applications. These data will then be used to assess the application of foil bearings to numerous other applications for both military and commercial systems. Specific potential applications include turbojets for MAV propulsion and MPG drives. Additional applications include mesoscopic turbochargers for miniature diesel engines, and motor driven compressors for high power density fuel cells.

Mohawk Innovative Technology, Inc.
1037 Watervliet-Shaker Road
Albany, New York 12205-2033, USA
Tel: +1 518-862-4290 Fax: +1 518-862-4293
Email: program_dev@miti.cc
Or visit our web page at: www.miti.cc