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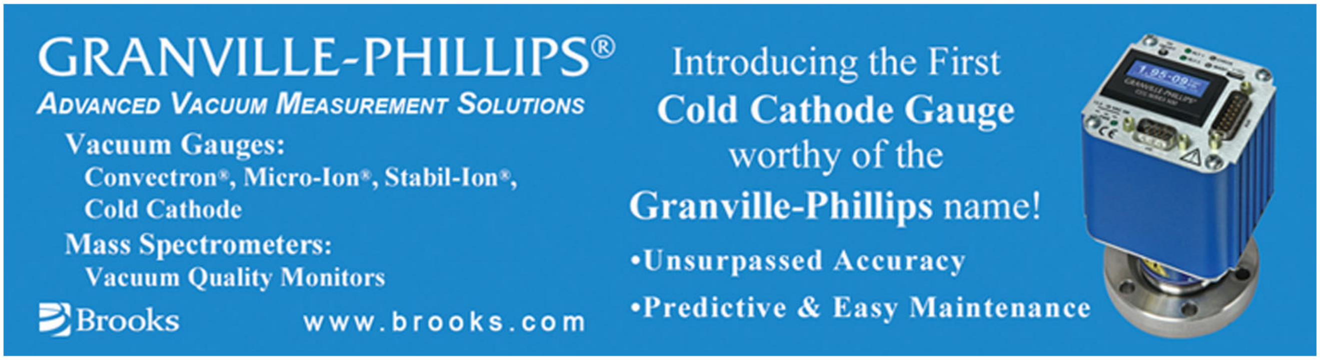

REVIEW OF SCIENTIFIC INSTRUMENTS **84**, 106102 (2013)

Note: Radial-thrust combo metal mesh foil bearing for microturbomachinery

Cheol Hoon Park,[1,2,a)] Sang Kyu Choi,[1] Doo Euy Hong,[1] Tae Gwang Yoon,[1] and Sung Hwi Lee[1]

[1]*Advanced Manufacturing Systems Research Division, KIMM, Daejeon 305-343, South Korea*
[2]*Department of Mechanical Engineering, KAIST, Daejeon 305-348, South Korea*

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This Note proposes a novel radial-thrust combo metal mesh foil bearing (MMFB). Although MMFBs have advantages such as higher stiffness and damping over conventional air foil bearings, studies related to MMFBs have been limited to radial MMFBs. The novel combo MMFB is composed of a radial top foil, thrust top foils, and a ring-shaped metal mesh damper—fabricated by compressing a copper wire mesh—with metal mesh thrust pads for the thrust bearing at both side faces. In this study, the combo MMFB was fabricated in half-split type to support the rotor for a micro gas turbine generator. The manufacture and assembly process for the half-split-type combo MMFB is presented. In addition, to verify the proposed combo MMFB, motoring test results up to 250 000 rpm and axial displacements as a function of rotational speed are presented. © *2013 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4825037]

Recently, microturbomachinery such as micro gas turbine generators (MTGs) and micro compressors are being actively developed because their power density increases with rotational speed, despite their small sizes.[1] Air foil bearings (AFBs) have been extensively used in microturbomachinery because of their advantages such as oil-free operation, low power loss, and ability to operate over a wide temperature range. Conventional radial and thrust AFBs are shown in Figures 1(a) and 1(b), respectively. Despite their many advantages, radial AFBs are known to have a drawback in that they are susceptible to a self-excited whirl instability at high speed owing to relatively low damping.[2,3] Radial metal mesh foil bearings (MMFBs), which as an example is shown in Figure 1(c), have been studied as a measure to overcome the instability problem by increasing damping.[4,5] Radial MMFBs are composed of a top foil, a ring-shaped metal mesh, and a bearing housing. By using the structural stiffness and hysteresis damping of a metal mesh, MMFBs can attain higher stiffness and damping than conventional AFBs. Because radial MMFBs are inexpensive and simple to construct, they are good candidates for replacing conventional AFBs in microturbomachinery. However, research related to MMFBs has been limited to radial MMFBs despite existing demands for the higher stiffness of the axial load. In the case where turbomachinery is under a large axial load, the axial stiffness of conventional thrust AFBs may be insufficient to support the axial load within the clearance between the impeller and the shroud. To utilize the advantages of metal mesh dampers for thrust bearings, a novel radial-thrust combo MMFB for MTGs is presented in this study. The combo MMFB comprises a radial top foil, thrust top foils, and a ring-shaped metal mesh damper—fabricated by compressing a copper wire mesh—with metal mesh thrust pads for the thrust bearing at both side faces. Motoring test results up to 250 000 rpm and the dependence of the axial displacements on the rotational speed are also investigated to verify the performance of the proposed combo MMFB.

In this study, MMFBs are developed to support the rotor for the MTG shown in Figure 2(a). The specification of the output power for the MTG is 500 W at the rated speed of 400, 000 rpm, and its volume is less than 1000 cm^3. The rotor should be as short as possible to increase the first bending mode critical speed and ensure rotordynamic stability at 400 000 rpm; it should also have the structural strength to withstand the centrifugal force caused by ultra-high speed rotation. To meet these requirements, the integral rotor was designed to have back-to-back turbine and compressor impellers directly machined on the rotor, the back faces of which would be used as thrust plates. A NdFeB magnet for the motor and generator is assembled in the middle of the rotor; the material for the rest of the rotor is Inconel 718. Journal areas for the radial bearings are located at the left rotor end and between the turbine and compressor impellers. The rotor diameter in the journal areas is 11.6 mm, and the rotor length is 79 mm. The fabricated rotor is shown in Figure 2(b). The radial MMFB, which is of the same bearing type as that shown in Figure 1(c), could be used as the left journal bearing. However, a number of problems should be resolved beforehand to mount the radial and thrust bearings in the space between the turbine and compressor impellers. Because the space is too small to mount separate radial and thrust bearings, a radial-thrust combo bearing needs to be developed. In addition, because the impellers cannot be disassembled from the rotor, the combo bearing should be able to split into two pieces. To deal with the abovementioned problems, a half-split-type radial-thrust combo MMFB was developed, as shown in Figure 3. The manufacture process of the half-split-type radial-thrust combo MMFB is as follows. First, a metal mesh of copper (Figure 3(a)) is compressed into a combo metal mesh damper with thrust pads (Figure 3(b)), after which it is split in half by a wire-cut electrical discharge machine (EDM;

[a)] Author to whom correspondence should be addressed. Electronic mail: parkch@kimm.re.kr

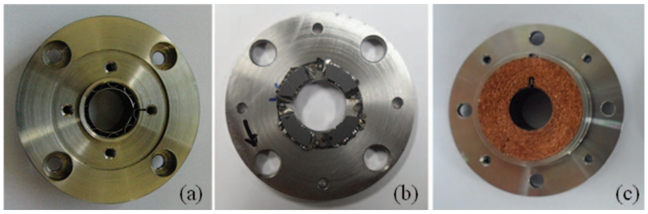

FIG. 1. (a) Radial air foil bearing. (b) Thrust air foil bearing. (c) Radial metal mesh foil bearing.

Figure 3(c)). The metal mesh thrust pads correspond to the bump foils of the conventional thrust AFBs. The density and geometric parameters of the compressed damper are selected by referring to related studies.[5,6] Table I lists the specifications of the fabricated combo MMFB. Next, each half-split combo metal mesh damper is covered with stainless steel plates (Figure 3(d)). Because welding the thrust top foil made of Inconel 718 onto a metal mesh damper made of copper is difficult, extra welding surfaces for thrust top foils should be provided by using stainless steel plates.

The assembly process of the combo bearing and a rotor is shown in Figure 4. First, the radial top foil is wrapped around the journal area between the turbine and compressor impellers. Second, the radial top foil is held in place by the half-split combo metal mesh dampers that are combined around it. Lastly, the bearing housing is assembled to fix the half-split combo MMFB with the fitting tolerance of 20 μm. The eccentricity of the bearing caused by the fitting tolerance could be compensated by the radial flexibility of the metal mesh damper. To evaluate the fabricated combo MMFB, a motoring test rig was prepared (Figure 5). The combo MMFB has almost the same configuration as the MTG layout given in Figure 2(a), except that it has neither a combustor nor recuperator-related parts. Both the radial MMFB in Figure 1(c) and the combo MMFB in Figure 3 support the rotor, which is rotated by a motor with 1.5 kW power. Two eddy-current-type displacement sensors are installed right behind the neck of the rotor to measure the vibration in the radial direction, and another sensor is installed to measure the axial vibration. The motoring tests were performed from a standstill to 250 000 rpm; the latter was chosen as the upper limit because it was the maximum speed with which the motor could rotate the rotor by itself to overcome the aerodynamic force due to impellers. The liftoff speed of the MMFBs was about 45 000 rpm; Figure 6 shows the radial and axial vibrations for rotational speeds ranging from 48 000 to 250 000 rpm at intervals of 12 000 rpm. The zero-to-peak magnitudes of synchronous components in the radial and axial vibration were less than 7 and 1 μm, respectively, across the entire range of rotation speeds. These results suggest that the combo MMFB

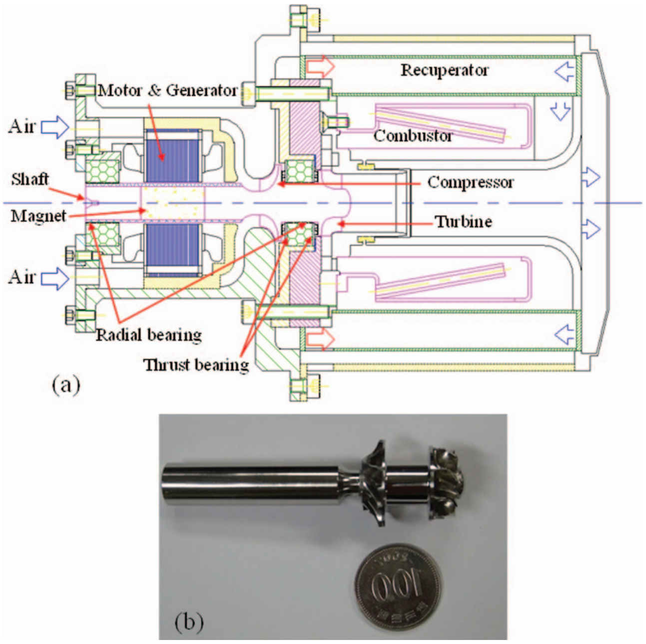

FIG. 2. (a) Layout of MTG. (b) Fabricated rotor for MTG.

FIG. 3. Manufacture process of half-split-type radial-thrust combo MMFB. (a) Copper metal mesh. (b) Top and side views of compressed combo metal mesh damper. (c) Half-split combo metal mesh damper and stainless steel plates. (d) Combo metal mesh damper covered by stainless steel plates and thrust top foils. (e) Combo metal mesh damper with welded thrust top foils and radial top foil. (f) Side view of combo MMFB.

TABLE I. Specifications of fabricated combo MMFB.

Parameter name	Value
Diameter of copper metal mesh wire	0.2 mm
Density of metal mesh damper	60%
Outer diameter of metal mesh damper	25.6 mm
Inner diameter of metal mesh damper	12 mm
Axial length of radial top foil	7.6 mm
Thickness of radial top foil	0.15 mm
Outer diameter of metal mesh thrust pads	19.4 mm
Inner diameter of metal mesh thrust pads	13 mm
Thickness of metal mesh thrust pads	1.4 mm
Thickness of thrust top foil	0.15 mm
Clearance between top foil and shaft	20 μm

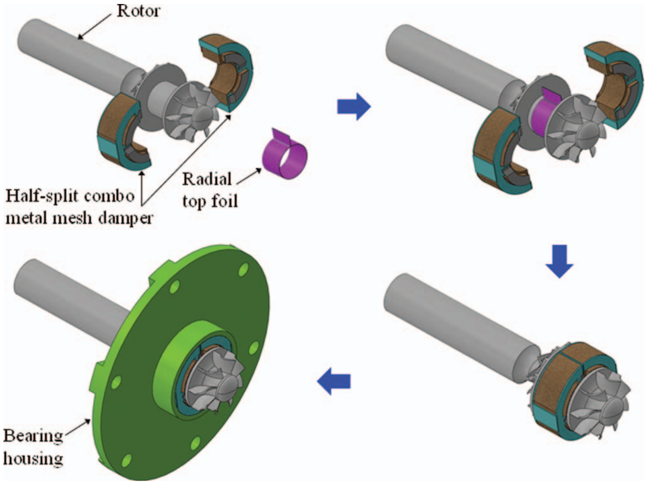

FIG. 4. Assembly process of half-split-type radial-thrust combo MMFB and rotor.

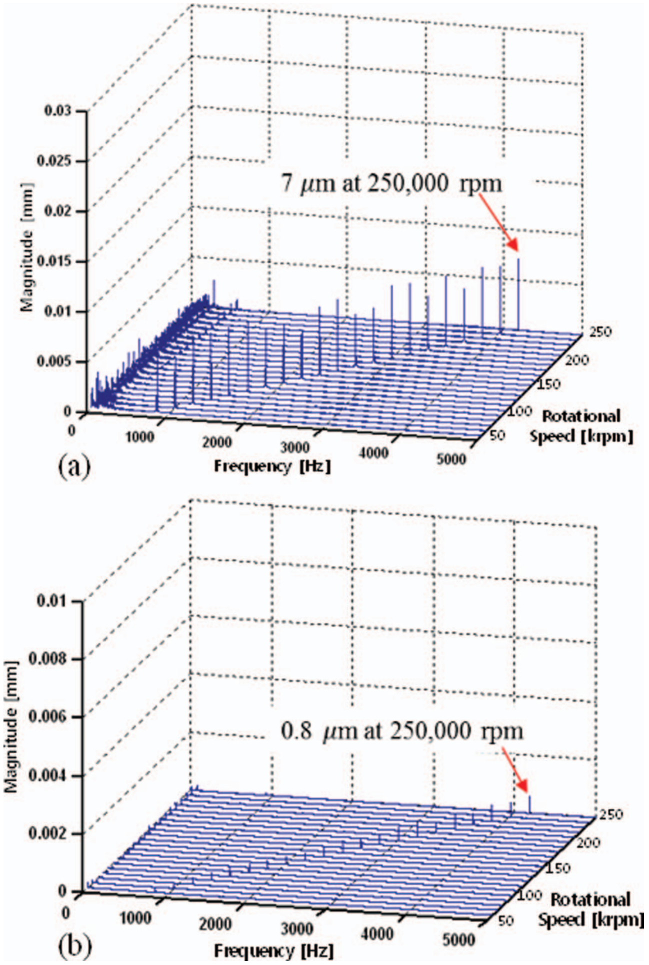

FIG. 6. Cascade plots from 48 000 to 250 000 rpm at intervals of 12 000 rpm. (a) Radial vibration in vertical direction. (b) Axial vibration.

can stably support the rotor in both the radial and the axial directions.

The axial displacement caused by the thrust force was measured as a function of the rotational speed. This measurement revealed that the axial displacement is proportional to the rotational speed, and its direction is from the turbine side to the compressor side. The measured axial displacement at 250 000 rpm was about 0.07 mm, suggesting that the axial displacement at 400 000 rpm would be about 0.1 mm. Computational flow analysis predicted that the thrust force by the turbine impeller would be about 20 N at 250 000 rpm in the turbine-to-compressor direction. Therefore, the axial stiffness of the combo MMFB is predicted to be about 285 714 N/m.

On the basis of the experiments, we confirmed the feasibility of a half-split-type radial-thrust combo MMFB. This novel combo MMFB is especially suitable for ultra-high-speed rotors because its length should be as small as possible and the space for the bearings should be minimized. Because the combo MMFB presented in this study is of the half-split type, it has the additional merit that it can be assembled on a rotor, the impellers of which need not be disassembled. Furthermore, its manufacture and assembly process is simple. In this study, the performance of the MMFB was verified through motoring tests up to 250 000 rpm only because of the lack of motoring power. However, a rotor under aerodynamic load at 250 000 rpm was stably supported by the novel combo MMFB. When the combustor is integrated with the test rig in the near future and the turbine torque is able to increase the rotor speed, further investigation of the novel combo MMFB will be continued. The novel combo MMFB has considerable potential for use in microturbomachinery, which requires ultra-high-speed rotors.

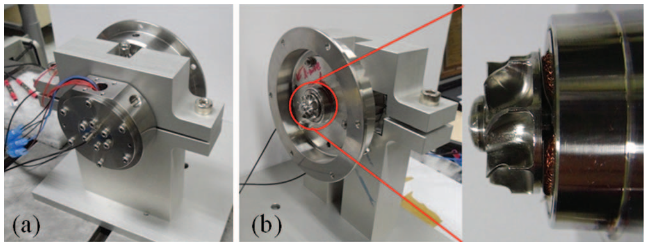

FIG. 5. Fabricated motoring test rig. (a) Top perspective view of the rear. (b) Side perspective view of the front, and zoomed view of turbine impeller and combo MMFB.

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