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Experimental Assessment of a 3D-Printed Stainless Steel Gas Foil Bearing

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Abstract

Gas Foil Bearings (GFBs) are a key enabling technology for high-speed turbomachinery. The manufacturing of GFBs relies mainly on sheet metal forming techniques in order to conceive the compliant structure (e.g.: bump foil) and the top foil. Such techniques require the development of a special know-how, and most importantly limits the design creativity to what is manufacturable using sheet metal forming. Additive Manufacturing (AM) is a disruptive technology in prototyping and fabrication. This paper assesses the feasibility of AM in the fabrication of GFBs using Selective Laser Melting (SLM) technology. A stainless steel GFB is 3D-printed in one piece including the sleeve, the bump and top foils. The bearing is assessed geometrically and statically before being tested on a gas bearing test rig, where it supported a $\phi 40$ mm rotor ($m = 2\text{Kg}$). The bearing performed similar to a conventional GFB, showing rotordynamically stable and repeatable operation up to 37.5 krpm. Such result highlights the potentials of AM as a viable alternative for foil bearing manufacturing.

1. Introduction

Gas foil bearings (GFBs) are a potential key technology for high-speed turbomachinery [1,2]. The two main advantages of GFBs are their compliance and low maintenance requirements. The compliance of a GFB plays an essential role in its performance, it allows the rotor to travel in excursions beyond the nominal assembly clearance of the bearing. Moreover, it makes the GFB more tolerant to misalignment and thermal gradient, which are bottlenecks for rigid gas bearings. Agrawal [1] claimed an endurance of 100k hours and 100k

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start/stop for GFBs, thus entitling them as a “maintenance-free” technology, which has drastic implications on the Mean Time Between Failure (MTBF) of high-speed turbomachinery.

One of the hurdles hindering the wide spread of GFBs is the reliance on complex sheet metal forming techniques in their manufacturing procedure [3–5], as well as the high sensitivity of the bearing performance to manufacturing errors [6]. Furthermore, the reliance on sheet metal forming drastically limits the design space and creativity of the compliant structure, the top foil and the fixture method.

Additive Manufacturing (AM) was proposed by Cima et al. [7]. AM adopts a bottom-up philosophy, where layers of material are added on top of each other to finally build a part, which is in contrast to the conventional material removal manufacturing process that adopts a top-down approach. AM is widely used in early design and rapid prototyping, as well the manufacturing of complex geometries, and multi-material parts which are impossible to produce using conventional manufacturing methods. Selective Laser Melting (SLM) is an AM technology used to 3D-print metallic parts. The technique relies on melting specific layers through a bed of metal powder using a laser beam to finally yield a 3D metal part. The concept was introduced by Meiners et al. in 1996 [8].

Projecting the capabilities of AM highlights a potential to disrupt different sectors. An example is the transportation industry, where one could foresee a paradigm shift in design philosophy that would favor systems with a lower Mean Time Between Failure (MTBF), but with recyclable 3D-printable components. The space industry is another sector that will benefit from developments in AM. In-space manufacturing allows the 3D-printing of components in space (microgravity), which will be vital for long term manned space exploration and planetary settlements [9,10]. Specifically, if different parts are manufactured out of the same material, no specific spare parts will be required to be sent via frequent expensive re-supply missions. The raw material (e.g.: powder) will be sent for in-space 3D-printing. Such approach will increase the space mission confidence, as well as ensure the communality of the spare parts since they are sent in the form of a non-fabricated raw material [11].

2. Motivation, Aim and Objectives

The main motivation behind the assessment of the 3D-printed GFB is the opening of new doors to designers, which would allow them to attempt complex designs, without being restricted to designs manufactured using sheet metal forming. Moreover, 3D-printing will facilitate the diffusion of the GFB technology without significant reliance on proprietary or secret know-how related to the manufacturing of GFBs.

This paper aims at assessing selective laser melting as an additive manufacturing technique to fabricate a GFB.

The specific objectives of the paper are the evaluation of:

- I. The SLM manufacturing process in terms of time and cost.
- II. The quality of the manufactured GFB in terms of geometry and surface roughness.
- III. The performance of the GFB in machine-like conditions.

3. Gas Bearing Design

The GFB chosen for this endeavor is the bump type sinusoidal design proposed by Shalash and Schiffmann [5]. Such design showed superior manufacturing traits compared to the standard bump design with flat segments between bumps [12]. The foil thickness was increased from the standard 100 μm to 150 μm to ensure 5 layers of metal through the foil thickness. The nominal inner diameter of the bearing is equal to its length of 40 mm. The bump foil contains 29 bumps, each has a nominal height of 0.657mm.

It is emphasized that the sleeve, bump, and top foils are all printed together as a single part. Similar to a conventional GFB, the foils are printed to be fixed from one circumferential side and free from the other. The bump foils are not welded to the top foil nor the sleeve elsewhere in the bearing. A metal 3D-printer is used for the selective laser melting of the bearing using 1.4404 stainless steel powder. The machine has a laser beam diameter of 30 μm , and a layer thickness of 10-50 μm .

4. Manufacturing Assessment

The manufacturing procedure and the quality of the printed part are assessed through the evaluation of the printed foils geometry, the surface roughness of the top foil, as well as the printing time and the weight of the printed GFB as a measure of cost. It should be highlighted that the 3D-printed GFB under investigation is the result of the first printing trial, hence emphasizing the high potentials of SLM in printing GFBs - Figure 1.

4.1. Geometrical Assessment

The bump foil geometry is an important factor in the assessment of the printed GFB [5]. Recent literature [6,13] suggests that manufacturing errors in bump foils can have significant effects on the structural stiffness and circularity of the GFB, which as a consequence affects the overall performance of the rotordynamic system.

After the printing of the GFB, it is scanned from both sides, yielding a high-resolution image of for the bump foils, which is consequently fed to a numerical code that performs a non-intrusive measurement of the bump radii. Further details on the measurement technique can be found in [5].

It was found that the average error in bump radii is 1.2%. This level of accuracy is similar to the levels produced through the standard sheet metal forming techniques [5]. Hence, it can be concluded that AM is qualified in terms of the accuracy of the manufactured GFB.

4.2. Surface Roughness

The surface roughness of the printed GFB is assessed using the roughness gauge TESA RUGOSURF 90G. The critical point of assessment is the surface roughness of the top foil as it plays a pivotal role in defining the startup torque, and the rotor lift-off speed. The probe of the roughness gauge passed along the length of the bearing from side to side at different circumferential angles.

The resulting Arithmetical mean deviation of the assessed profile (R_a) is equal to 6 μm and a Maximum Height of Profile (R_z) that is equal to 32 μm (minimum foil thickness 150 μm), yielding an ISO grade close to N9 – Figure 2. Such high roughness values will definitely hinder the performance of the bearing, as it scales with the

gas film thickness. Therefore, it was decided to shim the printed bearing with a conventional Teflon coated top foil (100 μm thick) on top of the high surface roughness printed top foil - Figure 3. Such, approach allowed the continuation of the experimental assessment of the printed GFB without jeopardizing the rotor.

4.3. Time and Mass

The complete manufacturing process took less than 7 hours to yield the finished GFB, which measured 0.299 kg. Such values can be used to get an estimate of the cost per unit. Depending on the size of the powder bed 3D-printers can print several parts simultaneously, and therefore drastically reduce the time of manufacturing per unit.

5. Performance Assessment

Following the dimensional manufacturing assessment, the printed GFB was assembled within the gas bearing test rig for a rotordynamic performance assessment.

5.1. Test Rig Description

The test rig used for this assessment consists of a 2 kg test rotor supported on two radial gas foil bearings ($L/D = 1$), and driven via electric motor and through a flexible bellow coupling – Figure 4. The drive end bearing near the coupling is a conventional GFB, which was successfully used and characterized in a previous paper by the authors [14]. The free end bearing far from the coupling is the 3D-printed GFB under investigation. The test rotor has an outer diameter of $\varnothing 40$ mm, and is coated with a Diamond Like Carbon (DLC) that serves as a dry lubricant during boundary lubrication regimes occurring at startup and coast down.

The test rig is equipped with 2 orthogonal capacitive proximity probes on each test bearing for the rotor orbit and vibration measurements (uncertainty $\pm 1.3\%$). An optical probe is used as a trigger for phase and rotational speed measurements. Each test bearing is equipped with a J-Type $\varnothing 0.25$ mm thermocouple for temperature monitoring, which is placed between the bump and top foil.

An auxiliary setup is used to measure the load-displacement curve for the tested bearings – Figure 5. This is the standard static identification of foil bearings that yields an insight into the assembly clearance, the structural stiffness, and the hysteresis damping. Details on the load-displacement setup can be found in a previous publication by the authors [14].

5.2. Quasi-Static Load-Displacement Testing

The results of the load-displacement testing of the bearing suggest a radial assembly clearance of approximately 125 μm – Figure 6. The assembly clearance is defined as a rotor displacement at negligible load. The large clearance is measured prior to the insertion of the additional Teflon coated top foil, which would reduce the clearance to 25-30 μm . The uncertainty of the used load cells is $\pm 1\%$.

The measurements also confirmed a typical nonlinear stiffness resulting from the sequential engagement of the individual bumps as the rotor is displaced. Finally, a hysteresis loop was observed during the push-pull excursion of the rotor. The measured data describes a behavior that is considered similar to conventionally manufactured foil bearings [6,12,15].

5.3. Rotordynamic Testing

The bearing was tested up to 37.5 krpm while being subjected to the load representing the mass of the rotor (6.4 kPa per bearing).

The dynamic response of the rotor was measured during coast down from maximum speed. Figure 7a shows the peak-peak synchronous response measured from the drive end and the free end bearings – The former is the one closer to the flexible coupling, the latter is the 3D printed bearing. The critical speed of the system is detected at 10 krpm through the presence of an amplitude amplification and a phase shift – Figure 7b. The same test rotor was tested on conventional gas foil bearings in a prior work by the authors [14], the rotordynamic response showed similar behavior, with a lower amplitude at the free end bearing due to a lower assembly clearance and higher preload.

In order to further analyze the rotordynamic data, a waterfall plot was created for further insights into the system – Figure 8. The spectrum measured from the drive end bearing (closer to coupling) was mainly synchronous and clear of any noticeable subsynchronous vibrations. The free end bearing (3D printed bearing) adopted a similar synchronous behavior, however some minor subsynchronous vibrations were observed at a locked frequency of 75 Hz that appears to be independent of the synchronous frequency.

The measured rotor orbits at the maximum speed of 37.5 krpm are presented in Figure 9. The x-y signal is used to deduce the rotor orbit, after being subjected to a low pass filter with a cut-off frequency equal to five times the synchronous frequency (rotational speed). The figure shows 20 overlaid orbits. The maximum observed orbit is at the free end bearing (3D-printed) and is equal to 20 μm . It is observed that the two orbits are highly circular, hence suggesting an isotropy in the bearing stiffness.

5.4. Lift-off Speed Estimation

In order to measure the lift-off speed of the rotor, and since the test rig is not equipped with direct torque measurement capabilities, a coast down test was executed in order to produce a Stribeck curve for the system. Such technique is not as accurate as direct torque measurements in terms of absolute values, however, it is sufficiently accurate to identify the minima of the torque vs. rotational speed, which is an indication of the rotor lift-off speed.

The equation of motion of the rotating shaft can be expressed as follows:

$$(J_{rot} + J_{mot} + J_{coup})\dot{\omega} = T_{FB} + T_{REB} + T_{windage} \quad (1)$$

where J_{rot} , J_{mot} , and J_{coup} are the inertias of the test rotor, the electric motor, and the coupling respectively, the rotor acceleration $\dot{\omega}$, and T_{FB} , T_{REB} , and $T_{windage}$ representing the friction torque from the test foil bearings, the rolling element bearings in the motor, and the windage losses respectively.

Measuring the rotational speed of the rotor during a free coast down allows the deduction of the deceleration. Given the prior knowledge of the inertias ($J_{rot} + J_{mot} + J_{coup} = 12.5 \times 10^{-4} \text{ kg m}^2$) and motor losses ($T_{REB} + T_{windage}$) - measured to be between 50 and 120 N.mm depending on speed, the friction torque of the foil bearings (T_{FB}) is calculated and plotted versus the rotational speed in Figure 10.

The curve starts with a mixed lubrication regime up to a rotational speed of 15 krpm, which is the point of minimum friction torque indicating the inception of the fluid film lubrication regime and the lift-off speed of system. Further details on the coast down test methodology can be found in a previous publication by the authors [14].

6. Conclusions and Implications

In terms of manufacturing accuracy, the 3D-printed GFB is considered similar to a modified design proposed by the authors [5] that reduced springback errors in conventional manufacturing. The average error in bump radii is 1.2% with a relative standard deviation of 1.5%. The quasi-static evaluation through a load-displacement test highlighted the fitness of the 3D-printed GFB in terms of nonlinear stiffness and hysteresis damping, which is equivalent to conventional GFBs. Finally, in terms of performance as a fluid film journal bearing, the 3D-printed GFB operated very similar to a conventional GFB up to 37.5 krpm. The resulting performance was repeatable throughout different tests during the course of the campaign.

The main issue observed with the 3D-printed gas foil bearing was the high surface roughness of the printed top foil. The issue was resolved by shimming the bearing with a conventional Teflon coated top foil. However, it is worth mentioning that the surface quality of 3D-printed parts using SLM is the current subject of several researchers in the field of AM [16–21]. In the scenario that current research efforts fail to improve the surface roughness of the printed top foil, a potential solution is coating the surface with a Teflon and allowing the rotor and bearing to grind the excess Teflon peaks. This would eventually fill all the surface valleys, and hence would make the GFB ready for standard operation.

An important point that remains open for further evaluation is the expected MTBF for the 3D-printed GFBs. The porosity of the 3D-printed part using SLM might have an influence on fatigue limits. Such evaluation would require long endurance tests for tens of thousands of hours.

Evaluating the different assessment factors tested in this experimental campaign, it can be concluded that the 3D-printed GFB generally exhibits similar traits compared to conventionally manufactured GFBs.

The conclusions of this work will have several disruptive implications on a variety of topics:

- SLM 3D-printing of GFBs can be used to fabricate complex compliant structures which are impossible to achieve using standard sheet metal forming or simple cutting/etching.
- Prototyping of stainless steel or Inconel GFBs will become much easier and faster, since no manufacturing learning curve will be required.
- The 3D-printing of GFBs will play a role in the diffusion of the technology, particularly after addressing the high surface roughness of the printed top foils.
- SLM 3D-printing has the potentials to reduce the low volume (less than 10 bearings) cost of manufacturing of GFBs when compared to the standard sheet metal fabrication techniques.

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