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High Precision Manufacturing for Air Foil Bearings

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Abstract

Air bearings have seen to be more popular in recent years owing to the increasing demands of ultra high-speed rotating machineries, such as turbo motor/alternators, turbo compressor, micro gas turbines and turbo blowers. Such machines can see speeds of up to 200,000 rpm or equivalent of 200 m/s. Reason for such high speed is because the increasing trend of having compact size and higher efficiencies. The most critical parameter for the air bearing is the clearance as this has great influence in the load carrying capacity, frictional losses and above all the reliability. Air foil bearings are a good examples of a compliant air bearing that offers additional damping and adaptable shaft growth, making it considerable more tolerable to the rigid air bearings. This paper illustrates the manufacturing processes of the components that makes up a typical air foil bearing. It covers the importance of the tolerance stack up from the thickness of the foils, to the precision of the press tools, to the thickness of the coating and also the precision of the bearing sleeves and shaft diameter.

Keywords: Air bearings; compliant air foil bearings; manufacturing, sleeves, bump foils, top foils, coating

1. Introduction

Bearings are clearly defined as the most critical components in turbomachinery and they are needed to enable the smooth relative motions between components. Most bearings still use oil as a lubricant, but their energy losses can be considerable for applications of high speeds of above 50 m/s. A cooling system is therefore necessary in turbomachinery to ensure the bearings do not overheat. Considering the viscosity and the thin film thickness of oil, the amount of viscous shear in the fluid films can be up to 0.5 kW at full speed.

Air bearings on the other hand use a thin pressurised gas film to keep the bearing surfaces separated whilst running at high velocity. The pressurised air or gas need to be sufficient to carry both static loads like weight of shaft and imbalance of dynamic loads. Dynamic loads are a combination of shaft imbalanced mass and the critical modes. To some extent the dynamic loads can be predicted using rotodynamic analysis and further reduced by proper balancing procedures and adjusting the stiffness and damping characteristics of the bearings.

Recent years showed in increasing demands in turbomachinery with shaft speeds exceeding 100 m/s. This is a result of creating more compact machines but ones that run faster to achieve a high-power output. Examples of high power density machines include the likes of turbo motor/alternator, turbo blowers, turbo compressors, air cycle machines and micro gas turbines [1]. The trend for these type of machines is to adopt air bearings in favour of the conventional oil and ball bearings, for three very important advantages; a significant reduction of power consumption, longer bearing life and the absence of a complex cooling system. Other mentioned advantages may include less noise, zero maintenance, lower vibrations and lower operating costs.

The major disadvantages of air bearings are the high cost of manufacture due the tight tolerances, the lower load carrying capacity and the catastrophic damages in event of a bearing failure. It is this very reason that air bearings for turbo machineries are higher engineered products and still remains to be so [2].

Compliant air bearings such as air foil bearings have seen growing trends towards turbomachinery, particularly where high temperatures are involved. Air foil bearings incorporates flexibly features to allow for addition damping to improve on the rotodynamic stability and more importantly to adapt to changes in the shaft growth whilst maintaining a consistent air film gap [3-5]. It is these attractive reasons why air foil bearings are more tolerable and the precision in the manufacturing of such bearings are regarded as more relaxed in comparison to the rigid bearings. This paper details the manufacturing procedures for a typical Generation 2, bump type air foil bearing and the associated precisions in the components that makes up the bearing.

2. Bearing Size, Load Capacity and Power Loss

An aerodynamic or hydrodynamic bearing is termed as a bearing that self generates pressure with relative surface speed by dragging in the fluid through a converging thin gap. This load capacity is best described as the Bearing Number as shown in Equation 1, for a radial or journal bearing [2]. It can be seen whilst the fluid properties and the speed affects the load capacity, the size and the clearance remains the dominating factor. Whilst increasing the bearing size has its advantages, it should also be noted that the surface speed of air bearing is limited to 200 m/s, while most generally targets between 100 m/s to 150 m/s, providing this satisfies the rotordynamics stability.

$$\Lambda = \frac{6\mu\omega}{p_a}\left(\frac{R}{C}\right)^2 \qquad (1)$$

Where

Λ	is the bearing number
μ	is the fluid viscosity
ω	is the angular rotational speed
p_a	is the ambient pressure
R	is the shaft radius
C	is the mean bearing clearance

The other important factor to take into account when sizing the bearing is the power loss, as excessive temperature rises will inevitably result in bearing seizure, leading to a catastrophic failure. The power loss of air bearings is a direct result of viscous shear of the air gap, which is shown in Equation 3, derived from Equation 2. Equation 3 shows that the power loss is most sensitive to the speed and the radius. It is obvious from Equations 1 and 3 that the best balance of good load capacity and low losses would be to control the fluid film clearance. This however, is the most difficult parameter to control during manufacturing as it involves the stack-up of two or more components.

$$P = T\omega \qquad (2)$$

$$P = \mu R^3 \omega^2 \frac{2\pi L}{C} \qquad (3)$$

Where P is power loss
T is torque
ω is the angular rotational speed
μ is the fluid viscosity
R is the shaft radius
L is the bearing length
C is the mean bearing clearance

3. Compliant Air Foil Bearings

Air foil bearings are great examples of a compliant bearing. A compliant bearing includes a flexible structure to allow the bearing to comply with shaft movements and shaft growth. Figure 1 shows a typical bump type air foil bearing, with a two lobe configuration. It consists of a rigid bearing sleeve and two layers of foils, being a corrugated bump foil and a smooth top foil. The top foils act as the bearing surface and hence should have a smooth and low friction finish. Whilst the bearing sleeve is often made out of stainless steel as this is the same material as the housing, the foils are typically Inconel offering high strength and high temperature capability. The compliance feature of the bearing is the bump foils as this acts as a structural spring and damper device.

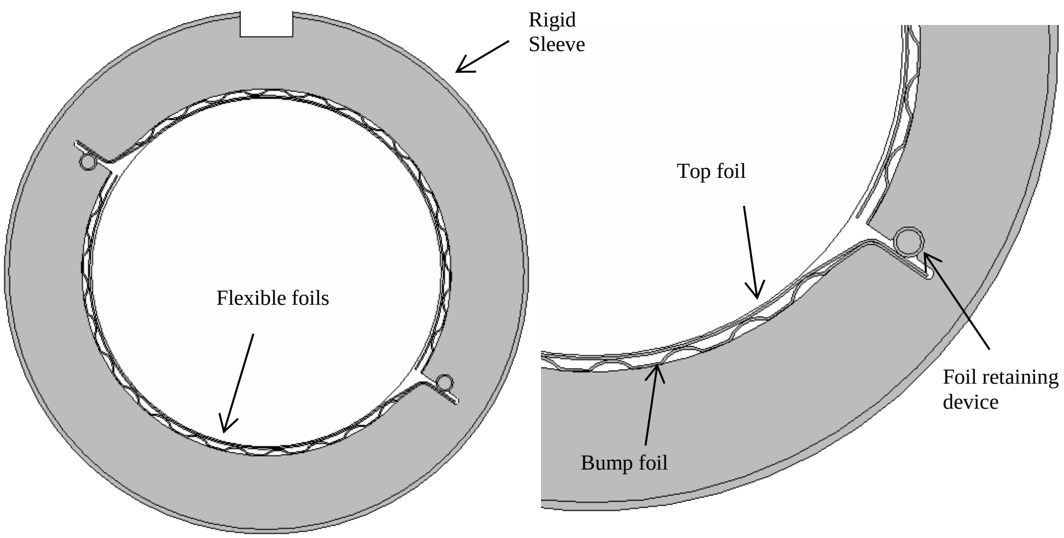


Fig. 1. Components of a radial air foil bearing

4. Sleeves and Bore Profile

The sleeve may be a simple or a complicated piece of metal work. The bore profile is what defines the profile of the air film gap and therefore requires to be of high precision, similarly to the rigid fluid film bearings. To generate good hydrodynamic pressure, the film needs to flow through a converging gap with a taper that is similar to the film thickness, therefore one would use a taper of 20 to 50 µm. Wire Electrical Discharge Manchining (EDM) is often used to profile the bore of the sleeve as this method offers high precision within 5 µm accuracy and the capability to create fine details like narrow slots and radii. Other possible methods of producing similar outcome is by CNC mill, but this is of lower accuracy of 10 µm at best. In the past there have also been examples of adopting a standard circular bore but using shims to create the tapered air gap or using bump foils of varying heights.

5. Bump Foils

The bump foil is the most important feature of the of the air foil bearing as this defines the stiffness and damping characteristics of the bearing [3, 5]. The bump foil is compressible and hence can tolerate shaft growth during high temperature operation. The geometry of the bump is particularly important as this not only defines the stiffness but also the bearing clearance. Fig. 2 shows a typical geometry a bump foil with the key parameters. The bump height is typically 0.3 mm to 0.5 mm. Equation 4 shows a typical model of the stiffness of the bump foil [3]. It can be seen that stiffness is most sensitive to the bump length (or bump radius) and the foil thickness and therefore these are the most important parameters to control. Typical bump foil stiffness ranges from 0.5 N/µm to 5 N/µm. The stiffness is often preferred to be nonlinear, having a low stiffness when the bump foils begins to compress and up to 5 times stiffer when it is compressed to the extreme.

It should also be noted that although there is some flexibility in the pitch of the bumps (s), is it recommended not to exceed beyond a few millimeters as this often shows signs of the top foil sagging.

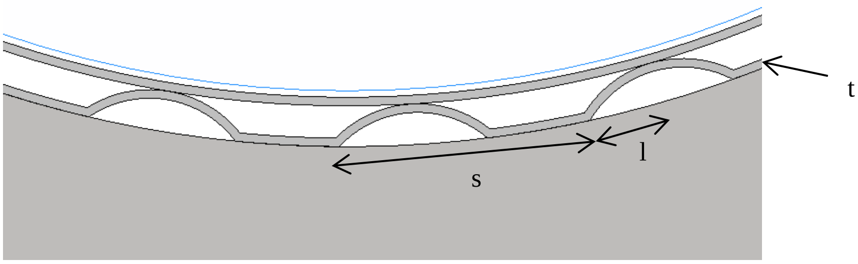
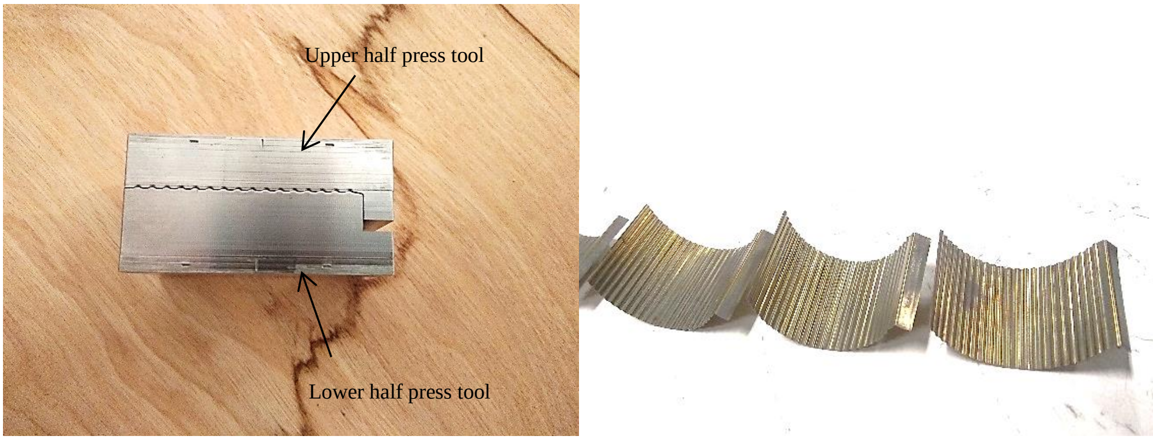


Fig. 2. Key parameters of Bump Foil

$$K_b = \frac{2s}{E}\left(\frac{l}{t}\right)^3 (1 - \upsilon^2) \qquad (4)$$

Where	K_b	Stiffness coefficient of individual bump
	s	is the pitch of the bumps
	E	is modulus of elasticity of the material
	l	is the length of half the bump spacing
	t	is the foil thickness
	υ	is the Poission's ratio of the material

A two-piece press tool is the most practical method of forming the shape of the bump foils. Figure 3 (a) shows a typical die set made out of tooling steel. The profile of the bump is created on the die using EDM or CNC milling methods similarly to the bearing sleeve. Due to the accuracy of the profile required, it is often the case where several set of tools are made in the intention that the bump profiles will show some variations of 10 µm. The most appropriate matched pair of tools will be applied. The outcome of the bump foils is shown in Figure 3 (b), where will next undergo heat treatment and ageing process to strengthen the structure.



(a) (b)

Fig. 3. Bump Foil Tooling and Formed Pieces

6. Top Foils and Coatings

The top foils are often regarded as the easier component to form as they are rolled to a radial that is similar to the shaft without much precision needed. It will conform between the shaft and the bump foil. This illustrates the importance of the precision of the bumps on those bump foils. The top foils are also typical made from similar material and with similar method, its formed and rolled to shape and then heat treated followed by ageing process. The final process is to apply to a tribological coating on the bearing surface of the top foils. Figure 4 shows top foils coated with Teflon coatings, this is a common type of PTFE coating used for foil bearings as it is both affordable and reliable. Other coatings that has been used including molydenum disulphide, tungsten disulphide and even harder coatings such as Diamond Like Carbons. There has been a particular interest in high temperature coatings, particularly for the application of micro gas turbines. The most importance aspect of the coating is that it needs to have some compliance with the flexing of the top foil, therefore the coating generally tends to be the soft type as opposed to hard and brittle.

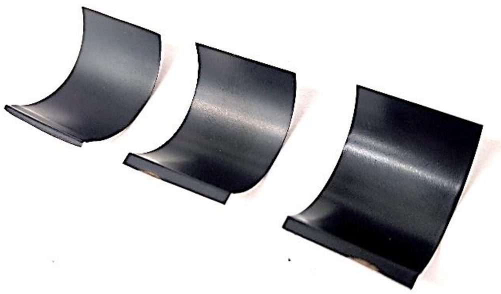


Fig. 4. Formed top foils with Teflon coatings

Figure 5 shows the measured frictional losses of a typical air foil bearing with the standard Teflon coating during a speed coast down test. It can be seen at when the bearing is airborne at full speed, the bearing is running virtually frictional-less. As the speed slows down towards 10 %, the air gap reduces before asperity contact between the shaft and the coated top foil. Before the speed slows to rest, the bearing torque peaks and this is the measure of the friction between the shaft and the coating. From the trend, it can be seen that the start-up stage is most difficult to overcome as this is always the highest power demand for machine to overcome the static friction, furthermore most applications requests the machines to ramp up to full speed within a second which often uses full power during the start-up cycle. Some research was conducted in developing an air foil bearing with aerostatic features to overcome this issue [6]. It is therefore recommended for air bearings to operating close to full speed as for as long duration as possible as this is the most productive and efficient state.

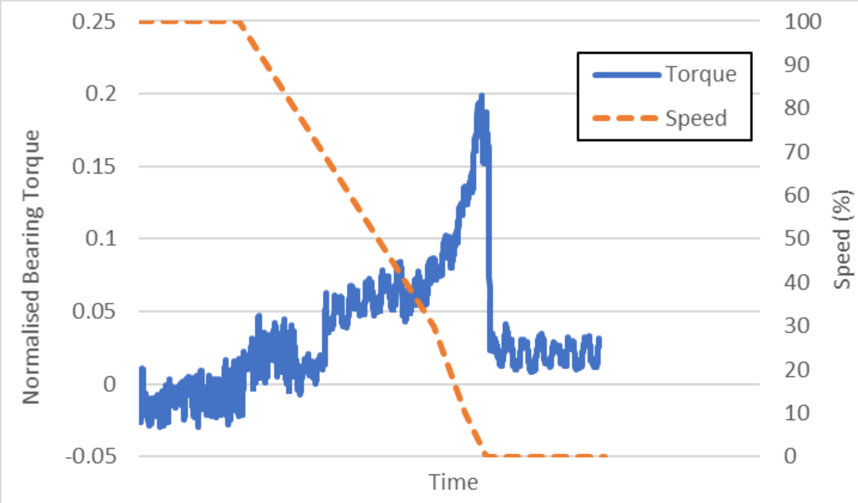


Fig. 5. Friction measurements from a radial air foil bearing during a coast down cycle

7. Components Tolerance Stack-up and Variation in Bearing Clearances

As mentioned in this paper the bearing clearance is critical to the performance but this is often the most difficult parameter to control, particularly with an air foil bearing where more than three components makes up the bearing. Table 1 sumarises the typical manufacturing tolerances that can be achieved for the components that makes up the bearing gap. The metal works being the sleeve and the shaft can generally achieve within 5 µm, that is considered to be exceptional, but this can account for up to 10 µm of diviation just for the two of them. The bump foil height is the most difficult to control as this relies on the precision of the press tools and also the outcome of the formed foils. However, the variation of each bump foil height is not considered to be too critical because of the flexibility of the foils and its compressibility. The top foil and the coating generally shows some consistency in overall thickness and well within 5 µm variation.

Overall, it can be seen the stackup can represent up to 25 µm in variation for the bearing gap, which is considerable for a nominal radial gap of 40 to 50 µm. To overcome too tight or too loose bearing clearances, it is mandatory to measure the static bearing clearance after each build using a purpose built rig. Build acceptance is more closer towards to 5 µm variation in bearing clearance. To achieve this, some use shims to accommodate the variations but it is more common to balance upper limit components with lower limit ones, and vice versa. Either way, it is clear that the build procedure for air foil bearings is time consuming and demands a high level of quality control.

Table 1. Typical Tolerance of Components to Air Foil Bearing

Component	General size	Tolerance	Stackup
Sleeve bore profile	~31 mm	5 µm	5 µm
Bump foil height	0.5 mm	10 µm	15 µm
Top foil	0.1 mm	2.5 µm	17.5 µm
Teflon coating	12 µm	2.5 µm	20 µm
Shaft diameter	~30 mm	5 µm	25 µm

8. Concluding Remarks

This paper describes the individual components of a typical air foil bearing, detailing on the manufatcuring processes and the importance of the tolerances to the overall build of the bearing. In particular, it illsutrates the importance of maintaining a consistence bearing clearance in relation to the load capacity and the energy losses. Whilst the air foil bearing is recoognised for its compliance and tolerance to changing conditions, there are still considerable effort required in building the bearing to achieve the correct bearing clearance. The advantage of the air foil bearing with interchangable components does offer a degree control in the build and the opportunity to repair lightly damaged bearings by replacing the necessary components without scraping the entire assembly.

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