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Determination of the Lift-Off Speed in Foil Bearings Using Various Measurement Methods

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One of the most important parameters describing the operation of foil bearings is the speed at which—under certain load conditions—a lubricating film is created. Knowing the value of this parameter, one can determine the nature of the operation of a rotor that is supported by these bearings. The lift-off speed is usually determined during the run-up and coast down of the rotor using the measured moment of friction as a function of the rotational speed. In this article, this method has been compared with other measurement methods proposed by the authors. The first method consisted in recording the temperature of the bearing's top foil during its operation, while the second method was based on measuring the current-voltage characteristics of the electro-spindle used in the drive system. As a result of the conducted research, a simple method that allows determining the lift-off speed in foil bearings was proposed. This method can be applied to various types of high-speed machines, such as turbocompressors or microturbines.

Keywords: foil bearings, measurement methods, lubricant wedge, lift-off speed.

1. Introduction

Gas foil bearings are increasingly used to support rotors in high-speed rotating machines with a power of 1-100 kW. In comparison with conventional solutions, such bearings don't need oil lubrication, sealing or a lubricant cooling system, which makes the whole system cheaper, less complicated and environmentally friendly [1].

A key operational parameter, which describes the possibility of using gas foil bearings in systems such as microturbines, is the lift-off speed. This parameter tells the designers of rotating systems about the rotational speed range, in which the bearing has a load capacity, and that while operating in this speed range for an extended period of time does not involve wearing the surface of the top foil [2]. The major benefit for the dynamics and the exploitation of the designed rotating system is so that the lift-off speed occurs at the lowest rotational speed [3]. This phenomenon is interpreted by researchers in different ways. The most common statement is, however, that the lift-off speed is the moment when, during the run-up and run-down, dry friction changes into fluid friction. One of the methods for determining the rotational speed at which this situation occurs is measuring the frictional moment on a test stand with one bearing [4], [5]. Then, during the acceleration of the rotor, the moment of friction increases (surfaces of the journal and top foil rub against one another), and after reaching the speed at which the lubricating film is formed, it drops rapidly to minimal values [6], [7]. In literature, one can also find such an approach that the lift-off speed occurs when the amplitude of absolute vibrations during increasing rotational speed decreases its value by approaching the value of the amplitude of relative vibrations [8]. Such determination of this important parameter is used in systems equipped with two foil bearings, where direct friction torque measurement cannot be used. However, the reduction of the vibration amplitude is caused by the increasing load capacity of the foil bearing, which increases as the rotational speed and thickness of the lubricating film rise [9], [10]. The lift-off speed determined on one bearing by measuring the frictional moment does not necessarily have to be the same as in the rotor - two foil bearings system. To check this, an alternative method is needed to determine this parameter, which can be used in high-speed machines built at the Institute of Fluid-Flow Machinery Polish academy of Sciences. In the research described in this article, several methods have been used, which all give a chance to determine this important parameter. The article discusses the results of experimental investigations conducted in various configurations.

2. Test stand

In order to experimentally determine the lift-off speed of the tested foil bearing, a new test stand was built. The layout of the stand is shown in the Fig. 1. The measurement of the moment of friction as a function of rotational speed was essential for estimating the lift-off speed. Based on the recorded measurement data during the run-up / coast-down, it was possible to observe the formation of a gas film, which was manifested by a significant reduction in the friction torque value.

To measure the rotational speed, an optical reflection sensor was used, which was placed perpendicularly to the rotation axis. The torque was determined by the force sensor (measurement range is 0–444 N) placed on the test rig frame. It was connected to the bearing sleeve by a wire and arm with a length of 47 mm (C in Fig. 1). The aim of the research was also to check the possibility of using alternative methods of determining the lift-off speed, which could be used in high-speed machines equipped with foil bearings. One of these methods was to measure the temperature of the lubricating film. Previous experience has shown that there is a correlation between the change in temperature and the value of the frictional moment (appearance of the lubricating film) [11]. Thermocouples were mounted in the same way as it had been described in publication [11].

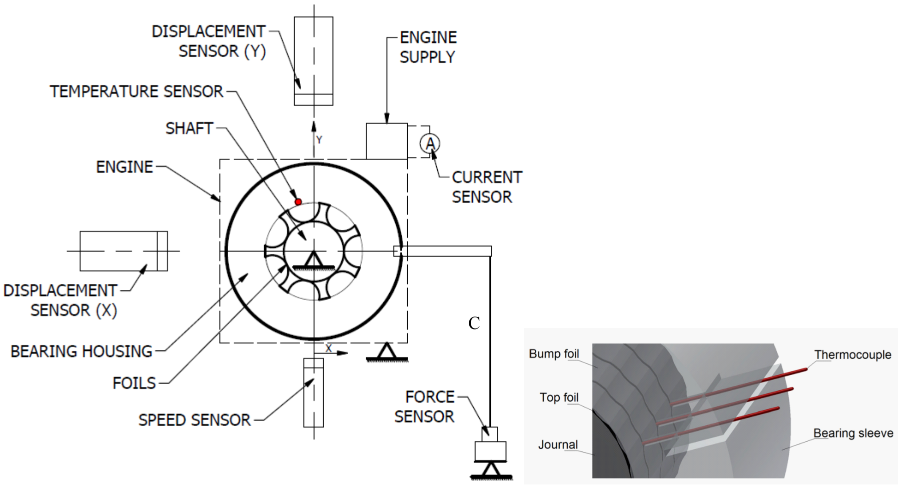

Figure 1 On the left: Test stand for experimental determination of the lift-off speed of foil bearings. On the right: Arrangement of thermocouples [11]

One of the thermocouples was in contact with the outer surface of the top foil at the point in which a high pressure could have occurred (Fig. 1). The other registered characteristics are displacements of the sleeves in the X and Y directions, which were obtained using optical displacement sensors. The electric current consumed by the electro-spindle was also measured, thanks to which the correlations with friction torque values could be determined.

On the molybdenum coated journal, the foil bearing sleeve (weighing 792 g) was loosely mounted. The frame of the test stand was constructed with rigidly connected aluminum profiles. The maximum engine speed was 24,000 rpm. The power pack and signal conditioners have been mounted on a DIN rail. The data acquisition module was the SCADAS Mobile analyzer. The sampling frequency has been set to a very high value (6,400 Hz, with a resolution of 1 Hz) in order not to omit important changes in the course of the measured parameters. The time of acceleration of the journal to the maximum speed was 120 s. The test stand is shown in Fig. 2, together with the foil bearing.

While preparing the test stand, the engine's power consumption (without the bearing characteristics) was measured at different run-up and run-down tests. Then, identical curves were determined for the tested bearing, and on this basis, the current of the electro-spindle with the mounted test object was obtained. The test rig has been constructed in such a way, that it can be used to examine other foil bearings.

3. Test results

The tests were performed for two bearing configurations. The first one made it possible to test the foil bearing at two different initial temperatures. The purpose of this research was a comparison of the temperature of the top foil with other methods that allow determining the lift-off speed. In the second configuration, the bearing was loaded with an additional weight of 106 g. The results of the tests carried out during the lift-off are shown below. Each test was preceded by numerous start-stop cycles to wear in the bearing and cause the foil to settle in the sleeve. When repeatable results of the measured values were obtained, the proper measurement was performed (described below).

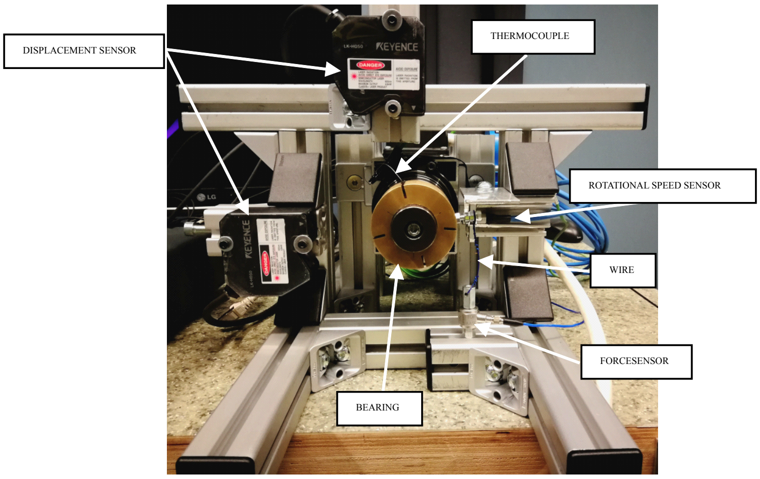

Figure 2 Photo of the test stand for experimental determination of the lift-off speed of foil bearings

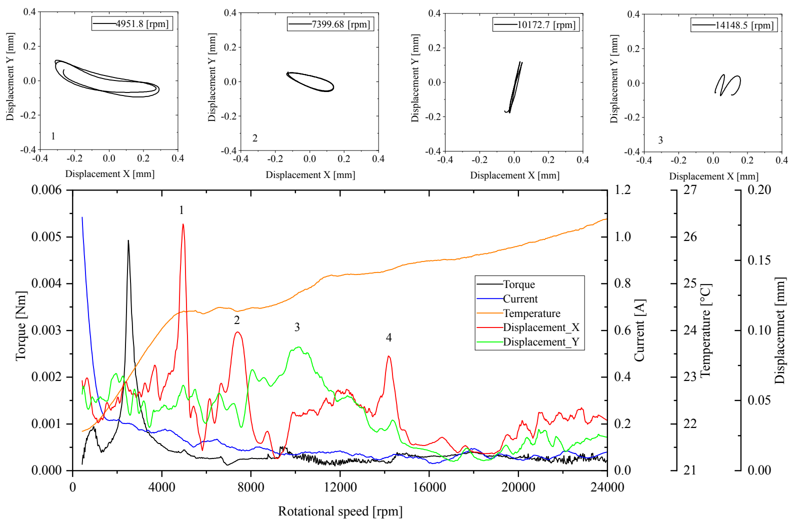

Figure 3 Photo of the test stand for experimental determination of the lift-off speed of foil bearings

3.1. *Foil bearing without load*

In the first case (Fig. 3), the top foil temperature at the beginning of the run-up test was approx. 22°C. At the initial run-up phase (up to 5,000 rpm) there were two maxima of the friction torque value (black). The first of them was caused by the initiation of the movement between the journal and the top foil. At this point, the static friction in the bearing changed to kinetic (dynamic) friction, although the journal and the top foil were in direct contact all the time. This increased friction torque was 0.00094 Nm and occurred at a speed of 950 rpm. The second maximum was created due to the increase of the rotational speed (and the linear speed between the journal and the top foil) at 2,500 rpm. The friction moment reached 0.0049 Nm, which was the highest value in the entire tested rotational speed range. Next, a sudden decrease of the frictional moment was observed, which can be explained by the emergence of the air layer between the mating surfaces and the gradual transition from dry friction into fluid friction. This phenomenon is very often identified with the appearance of a gas lubricating film [12-15]. After exceeding a rotational speed of 4,975 rpm, the moment of friction torque dropped to low values (0.0002 Nm). At the same time, the vibration amplitude of the sleeve in the Y direction reached the maximum value (0.17 mm - red). In addition, at this time the temperature of the bearing's top foil (orange) stopped increasing, stabilizing at a constant level, which may mean that the vibrations of the journal contributed to the formation of a fully formed gaseous lubricating film. The increase of friction torque was not visible during analyzing the characteristic of the electric current consumed by the motor.

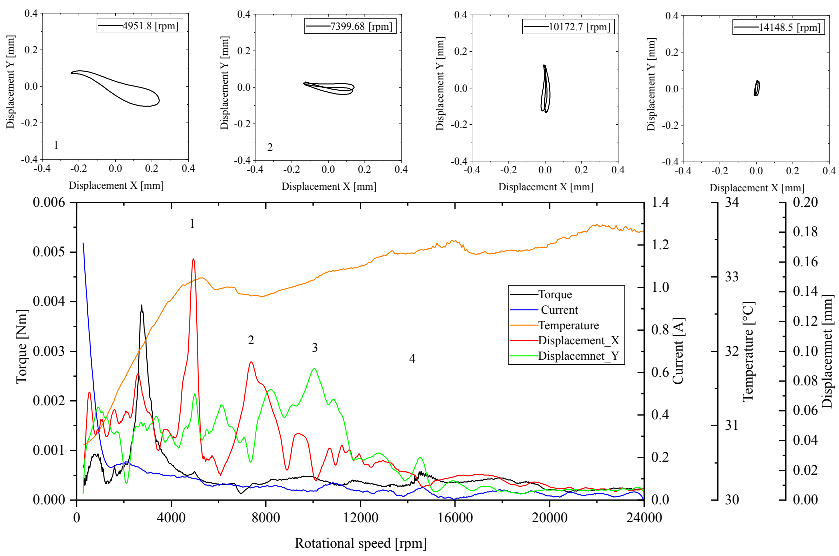

Figure 4 The characteristics of torque, electric current, temperature and displacement as a function of rotational speed recorded during run-up No. 1

The increasing rotational speed of the journal did not cause a significant increase in friction torque, but the course was not constant - there was a fluctuation of its value. This was caused by the movement of the foil set and the sleeve itself, which was recorded by the position sensors. For rotational speed, at which there is an increase in the vibration amplitude of the sleeve marked with numbers from 1 to 4, the trajectories of the sleeve movement were plotted. The first two vibration trajectories of the sleeve (4,951 rpm and 7,399 rpm) are flattened and somewhat similar in shape. In the further stage of the research, irregularly shaped vibration trajectories were observed in the sleeve. This was accompanied by an increase of temperature in the bearing. The vibration amplitudes decreased as rotational speed increased. The course of the electric current consumed by the motor did not fully correspond to the course of the moment of friction, because the electro-spindle starts working with a high torque that asymptotically approaches the minimum value. This is a typical characteristic of an electric motor. The rotational speed at which this occurred coincided with the speed at which the trajectories became irregularly shaped and the temperature in the bearing increased (around 9,300 rpm).

To check all assumptions, similar tests were performed at a higher initial temperature of 30 °C (Fig. 4). The value of the moment of static friction at the start of the run-up did not change. It was noticed, however, that the moment of dynamic friction decreased, which was related to the positioning of the foil set during previous attempts. At higher speeds of the rotating journal, the friction torque value decreased and the force sensor reacted only to the increasing vibration amplitude of the sleeve.

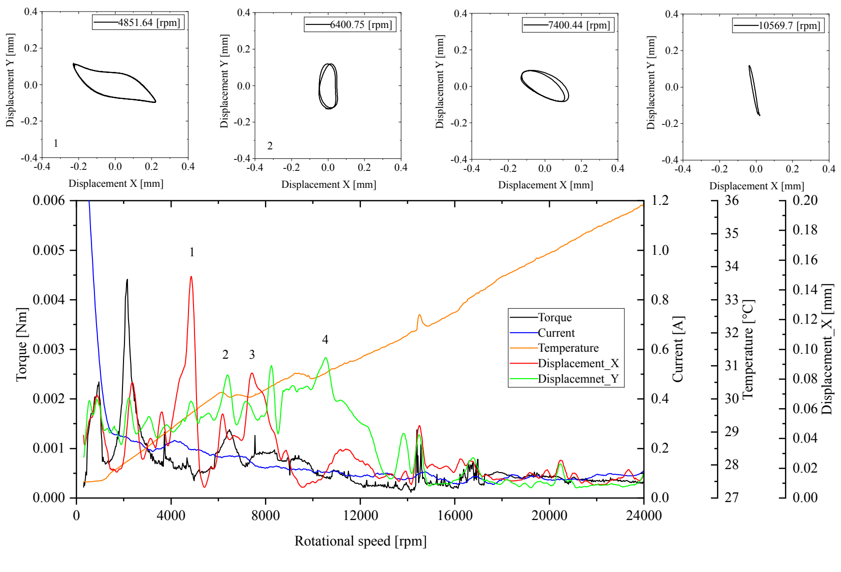

Figure 5 Torque, electric current, temperature and displacement characteristics as a function of rotational speed recorded during run-up No. 2

After the journal reached a speed of about 5,200 rpm, the temperature dropped (like in the previous case) and started to grow only after the increase of the amplitude in the X direction indicated in Fig. 4 as No. 2. It is assumed that the gaseous lubricating film, which formed itself, slightly cooled the surface of the top foil. The rotational speed, at which the first small value of electric current consumption can be seen, once again matches the rotational speed at which the trajectories are non-elliptical and irregular in shape. Trajectory No. 3 (Fig. 4) was registered just before the occurrence of this phenomenon.

3.2. *Foil bearing with load*

The above-described dependences may have been influenced by certain phenomena of random nature and in order to verify this, tests were carried out with an additional mass (106 g) attached to the foil bearing sleeve. The weight dangled from a thin steel wire, which had been attached to the bearing sleeve. From a practical point of view, this action was aimed at decreasing the rotation speed at which there are elevated vibration amplitudes and an increase in speed at which the gaseous lubricating film appears. The results are shown in Fig. 5.

The loaded bearing did not have such a regular course of friction torque as before. As expected, the static torque value increased, while at higher speeds the friction torque decreased. The first increase in the vibration amplitude (**??**) of the sleeve occurred at a lower rotational speed, which did not involve a local temperature drop. Trajectory No. 1 indicates the lack of a gaseous film because it has sharp edges, which may suggest that the journal was supported directly by the foil set. A local temperature reduction occurred only at a speed of 6,200 rpm (which is about 1,000 rpm higher than in the case when the bearing operated without an additional load). But at the same time, another increase in the vibration amplitude of the sleeve was observed, due to the increase of friction torque, which remained at an elevated level until the rise of amplitude No. 4 (Fig. 5). After passing through this resonant speed, the temperature increased, while the friction torque and electric current consumption decreased slightly.

The temperature curves, obtained in each test, could be approximated or certain rotational speed ranges on the graphs could be determined. As far as the first two tests without load are concerned (Fig. 3 and Fig. 4), the first speed range starts when the temperature increases abruptly and ends when the first high displacement value in the X direction occurs (1). The second speed range denotes the stabilization of temperature. Within the third speed range, the temperature also increases but not as rapidly as in the first speed range. For the test with the increased radial load, similar rises in the temperature can be observed within the first and second speed range (Fig. 5). However, the speed range in which the temperature stabilizes itself is not so wide as in the test carried out without the additional load.

4. Summary

The tests confirmed that in the examined foil bearing the moment of friction drops rapidly as the gaseous supporting layer forms itself. Measurement of friction torque is the most popular method for estimating the lift-off speed. As proven, the drop in the moment of friction does not necessarily mean the formation of a fully formed gaseous lubricating film, but it can be caused by the formation of a very thin and very rigid but non-continuous gas layer. For the foil bearing in the basic configuration (without additional load and at room temperature), the friction torque was low at speed above 2,500 rpm and decreased even more at a speed of approx. 5,000 rpm. Changes in the bearing's working temperature and load caused a change in the lift-off speed, which could also be observed on the basis of friction torque.

On the basis of the conducted tests, it can be concluded that the temperature measurement can also be used to assess the lift-off speed in a foil bearing. The temperature change depends not only on the presence of a lubricating film but also on the shape of the vibration trajectory. Therefore, the temperature should be measured at two points (or at several points around the circumference) to obtain values independent from the temporary position of the journal. It was also found that this type of testing should be repeated for a better-chosen friction pair. The bearing should be loaded with a sleeve that will load it evenly. Rotational speed control should allow for a longer operation at the speed at which the temperature starts to drop.

Measurement of the electric current at the electro-spindle power supply proved to be ineffective. This parameter did not respond quickly enough to the dynamics of the bearing node, which in some respects may be its advantage. The measurement of this type shows the current power consumption and the estimation of the friction torque on its basis would be very difficult. Measurement of the electric current in the power supply of the electro-spindle for assessing the lift-off speed in foil bearings seems possible but requires further research.

The comparison of the values of vibration amplitude and moment of friction proved that the decrease in vibration level is not directly related to the appearance of a lubricating film. High vibrations of the journal at a low rotational speed help to build a thin gaseous film, which can be used to reduce the moment of friction in the foil bearings during the run-up of the rotor. It was also noticed that at low rotational speed when there is no lubricating film yet, the vibration trajectories resemble the ones obtained in the study of the dynamic stiffness of the structural part of the foil bearing [16-19]. This is due to the fact that the systems studied in these two cases differed only in the way of vibration excitation.

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