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Measurement of gas pressure distribution in aerostatic thrust bearings using pressure-sensitive film

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ABSTRACT

Pressure distribution in aerostatic thrust bearing clearance has received a lot of attention for its fundamental influence on bearing lubrication characteristics. Study of pressure distribution in the bearing clearance has commonly been conducted by numerical calculation and experimental measurement is very limited. In this paper, a new method is proposed to experimentally measure pressure distribution in the aerostatic thrust bearing clearance. In this method, the Fuji prescale pressure-sensitive film is used to record pressure distribution in the gas film, and calibration is performed before the digital image of the pressure-sensitive film is post-processed and transformed into pressure values. Applications of the proposed measurement method in circular aerostatic thrust bearings with recesses of different shapes demonstrate its feasibility and accuracy.

1. Introduction

Aerostatic bearings have been a key components in high precision system, and nanometer scale moving and positioning accuracy has been achieved due to near-zero friction and low heat generation of gas lubrication [1,2]. The pressure distribution in the bearing clearance has attracted continuous attention for its influence on lubrication characteristics of the bearing, such as load capacity, stiffness, and mass flow rate. Mori et al. [3] firstly found the existence of pressure depression near the orifice outlet. Kassab et al. [4] further studied this pressure depression and believed that it is related to the decrease of load capacity and mass flow rate of the bearing. Yoshimoto et al. [5] numerically investigated pressure distribution in circular aerostatic bearings and compared their numerical results with experimental data. Belforte et al. [6] experimentally measured pressure distribution in aerostatic thrust bearings with orifice-type restrictors and studied supply hole discharge coefficients of the bearings with different orifice and pocket sizes.

With the increasing requirement of higher precision manufacturing devices, inherent nano-vibration of aerostatic thrust bearings was observed by Chen et al. [7], which severely degrades the positioning accuracy and moving stability of the bearing. Chen et al. [8,9] numerically analyze the air flow field in bearing clearance and discovered the existence of an air vortex near the orifice outlet, and the vortex center coincides with the local pressure minimum. Aoyama et al. [10] also observed air vortex in the bearing clearance and proposed geometrical arrangements of the orifice to suppress this vortex flow and nano-vibration of aerostatic thrust bearings. Almost at the same time, the transient air flow behaviors in the aerostatic thrust bearing are numerically investigated using large eddy simulation (LES) by Zhu et al. [11] and Li et al. [12]. They claimed that small vibration of the bearing is caused by air vortex shedding and pressure fluctuation near the orifice outlet. Later Chen et al. [13] proposed a novel arrayed micromole restrictor to suppress the pressure fluctuation in the vortex flow and reduce nano-vibration of aerostatic bearings.

Despite the above research interests in pressure distribution and lubrication characteristics of aerostatic thrust bearings, most of these works are numerical, and experimental measurement of pressure distribution in the bearing clearance has been very limited. This is mainly due to the extreme small size of the air gap height, which is usually on the order of 10 μm. To the best of our knowledge, the only method so far is to drill a small hole on the supporting face and measure the pressure with a pressure sensor connect to the drilled hole [5,6]. However, this measurement method has intrinsic limitations. Firstly, a finite size of the drilled hole (on the order of 0.1 mm) obviously results in non-negligible disturbance to the air flow in the thin gap, and considerable measurement errors will occur. In addition, this measurement method is zero-dimensional in the sense that only a single pressure value can be obtained each time, and the bearing has to be moved with precise

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Nomenclature

R,θ	polar coordinate
ΔR	annulus window width
R_0	orifice radius
R_1	bearing radius
R_3	cylindrical recess radius
H	recess depth
P_0	air supply pressure
h	gas film thickness
L	rectangular recess side length
W	rectangular recess side width
μ	dynamic viscosity of air
k	turbulent kinetic energy
ε	turbulent kinetic energy dissipation rate

displacement to obtain pressure values at other locations.

In this paper, a new experimental measurement method is proposed which measures 2D pressure distribution in the bearing clearance using pressure-sensitive films. With calibration data obtained through a novel approach, digital images of the pressure-sensitive film are transformed into pressure values after several image processing procedures. In addition to being 2D, the proposed experimental measurement method has the merits of easy operation, low cost, high spatial resolution and high accuracy. The applications to the bearings with different recesses shapes demonstrates the effectiveness of the proposed method.

2. Description of the measurement method

2.1. Working principle of the Fuji prescale pressure-sensitive film

Fuji pressure-sensitive film has been widely used in the biomechanics community, e.g., for assessing contact area and pressure within articulating joints [14,15], which produces a visible response (in the form of a stain or imprint) on its surface with the application of pressure. There have been a number of custom-made films [15,16]; however, the most popular medium is Fuji prescale pressure-sensitive film (Fuji Photo Film Co., Ltd., Tokyo, Japan), due to its commercial availability, ease of use and wide range of pressure that can be detected. Fuji prescale pressure-sensitive film comprises two sheets, the A-film and the C-film, as depicted in Fig. 1. The A-film is made up of a micro-encapsulated color-forming layer adhering on a polyester base, and the C-film consists of a color-developing layer sticking to a polyester base. A colorless liquid is encapsulated within the microscopic bubbles (2–26 μm diameter) in the color-forming layer. A number of these bubbles will burst depending on the magnitude of applied pressure, and react with the color-developing layer, producing a pink stain. With increasing pressure, more bubbles will burst and a deeper stain will occur. This property of Fuji pressure-sensitive film lends itself to optical measurement of stain intensity and 2D pressure distribution.

In practical tests, the type of pressure-sensitive film should be selected according to external pressure imposed on it, and each type has an effective working range of pressure. A pressure exceeding the permissible working range of a pressure-sensitive film could still produce pink stains but the resultant stain intensity and measured pressure value will be inaccurate and used for reference purposes only. Currently, Fuji prescale pressure-sensitive film is supplied in eight grades (4LW, LLLW, LLW, LW, MW, MS, HS, HHS), which together provide pressure range from 0.05 MPa to 300 MPa. In this paper, an ultra super low (LLLW) pressure-sensitive film is chosen to measure gas pressure distribution in bearing clearance, and the working range of this LLLW prescale pressure-sensitive film is 0.2MPa–0.6 MPa.

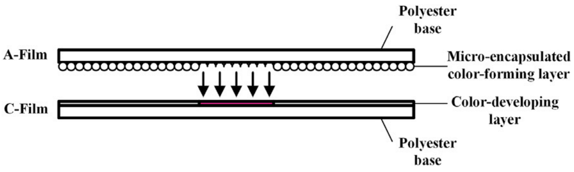

Fig. 1. Schematic of the Fuji prescale pressure-sensitive film.

2.2. Experimental setup

In our experimental tests, a large enough Fuji prescale pressure-sensitive film is fixed, e.g., with adhesive tapes at its four vertices, on a marble base, and a circular aerostatic thrust bearing is placed on top of it, as showed in Fig. 2. It is noted that the upper surface of the A-film is smooth enough (surface roughness less than 1 μm) such that its roughness effects can be neglected.

The external load is imposed on the aerostatic bearing by a pneumatic cylinder and a linear guide is used to eliminate horizontal load components. Both the external load and air supply pressure of the bearing can be adjusted with a precision proportional throttle valve and measured with a pressure sensor (FESTO SDE1) with 0.01bar sensitivity and measurement range of 0–10bar. Three laser displacement sensors (LK-G500) with 20 nm sensitivity and measurement range of ±3 mm are placed on the bearing to measure its vertical position. The data acquisition device is a LMSR SCADAS III, and its accompanying software LMSR Test Lab is used for data analysis.

Before the external load and air supply pressure are applied, it is noted that no visible stain is produced on the pressure-sensitive film because pressure on the film produced by the weight of the bearing is negligibly small. The external load and air supply pressure of the bearing are then increased gradually. By monitoring the displacement sensors on the bearing, it is found that the bearing altitude firstly decreases with fluctuations, indicating the air between the pressure-sensitive film and the marble base is squeezed out, and then remains a constant. At this stage, the pressure-sensitive film is in close contact with the marble base, and this initial bearing altitude is recorded. After the prescribed static load is applied for long enough (at least 2min as mentioned in the user's manual of Fuji prescale pressure-sensitive film), the bearing altitude becomes steady again and the air film thickness of the bearing is calculated as the difference between the final and the initial altitude of the bearing. It should be noted that since the prescale pressure-sensitive film

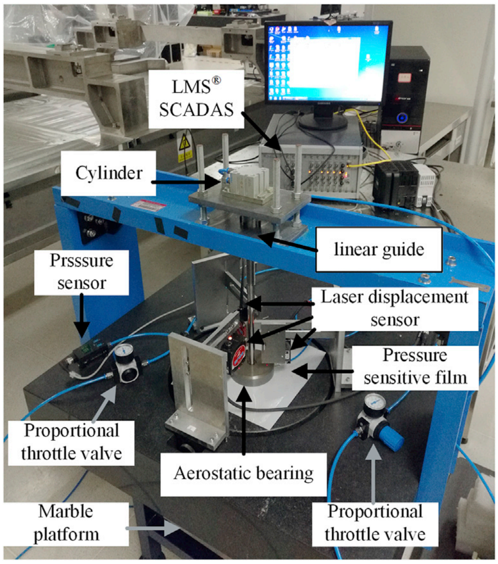

Fig. 2. Photograph of the test rig.