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Integrated capacitive measurement of air gap height in aerostatic bearings

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Abstract

Measurement of air gap height in aerostatic bearings is often necessary, for example, in closed-loop position control of precision stages. The air gap height can be measured directly with distance sensors, or indirectly from pressure in the bearing gap when the performance is well known.

The present study investigated an air gap height measurement method for aerostatic bearings using an integrated capacitive sensor. The method was investigated experimentally with a thrust bearing. The structure of the bearing was made from conductive material which was used for one of the electrodes for the capacitive sensor. The second electrode, in this case, was the steel guide surface of the bearing. Thus, a plate capacitor was formed between the steel guide surface and the graphite restrictor, where the air gap is the dielectric medium. The distance between the two plates in a plate capacitor is inversely proportional to its capacitance. Therefore, measurement of the air gap between the bearing and the guide surface is possible.

The integrated capacitive sensor consisted of a modified aerostatic bearing and a measuring circuit. The circuit consisted of a Wien bridge oscillator and an LC-tank in which the aerostatic bearing acted as the capacitor. Current through the LC-tank was measured using a resistor and an amplifier. The measurement results of the proposed method were compared to measurements obtained using an external gap-height sensor in a static test bench. The results show corroborative evidence on the feasibility of the proposed method.

Capacitive displacement sensor, porous aerostatic bearings, integrated sensors

1. Introduction

Capacitive sensing is a widely researched topic with over 2,000 publications in 2018 alone [1]. Capacitive sensing is a noncontact, low cost, and low-power sensing technique which uses the change in capacitance across two electrodes to measure the distance between them. The resolution of this technique is limited primarily by achievable signal to noise ratio [2].

Measurement of the height of the air gap in aerostatic bearings is interesting, for example, in academical research and in precision applications. Because the performance of these types of bearings heavily relies on the thickness of the air gap between the restrictor and the guide surface, the accurate measurement can be useful in a multitude of applications. Typically, the air gap height is measured with external capacitive sensors [3, 4, 5]. These sensors are often mounted on the outside of the bearing or in the air gap region. The air gap height of aerostatic bearings is typically between 2 to 20 µm, which is well within the measurement range and resolution of even simple capacitive sensing methods.

Using an integrated approach to air gap measurement, instead, could reduce measurement uncertainty by reducing effects of external factors on the measurement loop and permit in-situ measurement in applications of the bearings.

Furthermore, the integrated gap sensing could be used in actively controlled aerostatic bearings or in condition monitoring of aerostatic seals. Because it is critical that aerostatic bearings do not collide with or draw too near to their guide surfaces during operation, the live monitoring of a bearing's air gap may be a useful tool in certain applications.

The present study investigated a proof-of-concept method for the direct measurement of air gap height of a porous-restrictor- type aerostatic bearing using capacitive sensing methods. The proposed gap-sensing concept was investigated experimentally and compared to the current state-of-the-art externally mounted capacitive sensors.

2. Measurement principle

A plate capacitor is formed between the graphite restrictor of the aerostatic bearing and the steel guide surface (Figure 1) since both surfaces are conductors separated by insulator. The air gap between the restrictor and steel surface of the bearing is a variable-thickness insulator with a relative permittivity of approximately 1. The capacitance of a plate capacitor is given by the well-known equation:

$$C = \varepsilon_0 \varepsilon_r \left(\frac{A}{d}\right) \qquad (1)$$

where ε_0 is the permittivity of free space, ε_r is the relative permittivity (dielectric constant), A is the surface area of the electrode, i.e., the bearing, and d is the height of the air gap. From the equation, it is evident that the capacitance is directly proportional to the distance between the electrodes, i.e., the air gap height: $C \propto d$.

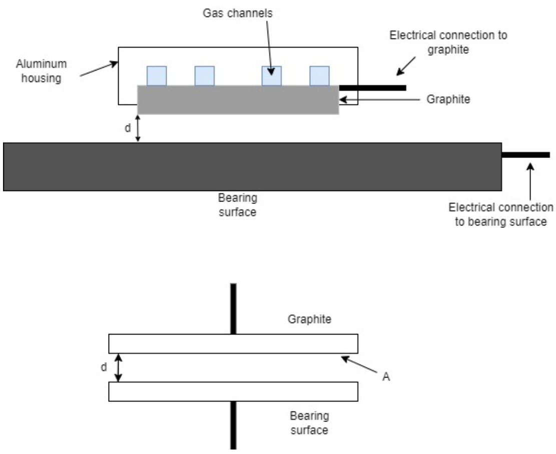

Figure 1. An axis-symmetric porous aerostatic bearing as a capacitor with conducting bearing surface.

The capacitance, and, thus, the air gap height, can be measured using multiple methods such as frequency counting or by measuring the current running through the capacitor and its adjacent circuit [2, 6]. In the present study, an RLC-circuit was used to allow for the tuning of the resonant frequency of the circuit to match a specific gap height range to be measured. The basic circuit, presented in Figure 2, possesses a resonant frequency, f_0. At this frequency, the reactance of the inductor and capacitor are at a minimum therefore allowing the greatest amount of current to flow through the circuit. The resonant frequency can be calculated using the formula:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

where L is the inductance and C is capacitance of the capacitor. The reactance of the inductor and capacitor are defined as:

$$X_L = 2\pi f L \text{ and } X_C = \frac{1}{2\pi f C}$$

where L is the inductance of the inductor, C is the capacitance between the aerostatic bearing and its counter surface, and f is the frequency of the supply voltage which is set to be f_0. The current through the RLC-circuit can be found using:

$$I = \frac{U_{supply}}{\sqrt{R^2 + (X_L - X_C)^2}} \tag{2}$$

where U_{supply} is the oscillator output voltage, R is the current sense resistor, X_L is the inductors reactance and X_C is reactance of the capacitor formed between the aerostatic bearing and the bearing surface. The denominator of the equation 2 is the impedance Z_{RLC} of the RLC circuit.

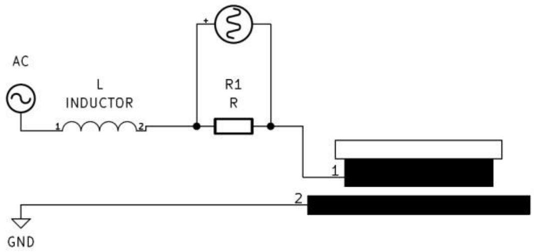

Figure 2. Simplified circuit diagram used in the experiments.

2.1. Measurement circuit

The capacitive sensing circuit consisted of an oscillator, an embedded sensor (capacitor formed between the bearing surface and aerostatic bearing), a rectifier and an output amplifier. The circuit design is presented in Figure 3. A Wien-bridge oscillator consisting of a TL031 amplifier and adjacent RC-tanks was used for the AC voltage source. The frequency of the oscillator was set at 27 kHz and the circuit was tuned for corresponding measurement range of 5 to 20 µm. The voltage-drop over the current-sensing resistor (Fig. 3, R5) was rectified with a 1n4148 diode, and amplified with TL031 as the output amplifier. A virtual ground regulator TLE2426 was used for the amplifiers power supply.

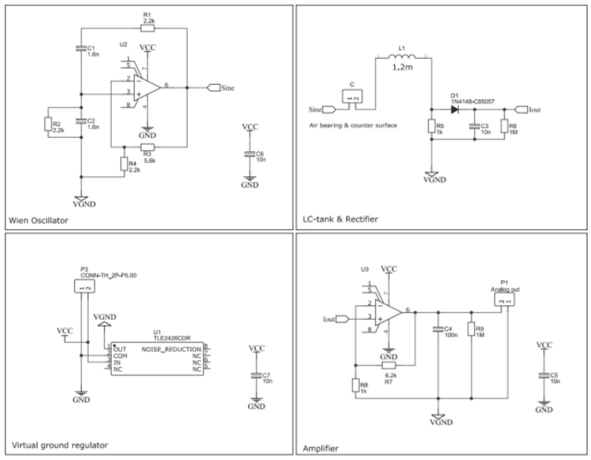

Figure 3. Capacitive sensing circuit. The circuit consisted of a Wien bridge oscillator and an LC Tank.

2.2. Capacitance-Distance relationship

The sensor output was not linear due to the nature of the RLC circuit. Thus, the voltage output signal was converted to displacement using equation 5. The voltage-drop over the current sensing resistor *R5* (Figure 3.) is proportional to the change in the capacitance of the circuit. The current through the resistor is given by Equation 2.

The sensor output is the voltage drop over the resistor multiplied by the gain of the amplifier. This relates the current through the sensing resistor and output voltage as:

$$I_R = \frac{U_{out}}{GR} \tag{3}$$

where U_{out} is the sensor output and G is the gain of the output amplifier (Figure 3. U3).

Setting Equation 2 equal to Equation 3 yields:

$$\frac{U_S}{Z_{RLC}} = \frac{U_{out}R}{G} \tag{4}$$

which allows the displacement to be calculated as a function of the output voltage:

$$d(U_{out}) = 2A\,\varepsilon_0\,\varepsilon_r\,f_0\,\pi\,\frac{(R\sqrt{-(U_{out} + G\,U_s)(U_{out} - G\,U_s)} + 2\,\pi\,L\,U_{out}\,f_0)}{U_{out}} \tag{5}$$

2.3. Parasitic capacitance

The aluminum body of the bearing was anodized with a layer of epoxy between the anodization and the graphite. This effectively insulated the graphite from the aluminum body. The wires used to connect the bearing surface and the graphite to the sensing circuit introduced some parasitic capacitance and inductance. The floating bearing body has some parasitic capacitance between itself and the bearing surface. However, this parasitic capacitance is minimal since the aluminum was recessed 2 mm from the graphite surface. The parasitic capacitance due to the bearing body was analyzed with equivalent circuit presented in Figure 4.

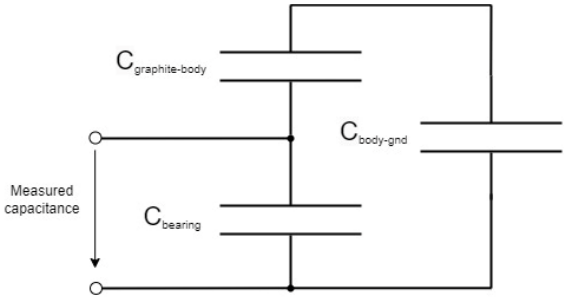

Figure 4. Equivalent circuit of parasitic capacitance due to the bearing body. $C_{bearing}$ is the capacitance formed between the bearing surface and the graphite, $C_{graphite-body}$ is the capacitance between the graphite and the bearing body and $C_{body-gnd}$ is the capacitance between the body and the bearing surface.

The total parallel parasitic capacitance over the measured $C_{bearing}$ is formed from series connected $C_{graphite-body}$ and $C_{body-gnd}$. The total parasitic capacitance can be calculated with:

$$C_{parasitic} = \frac{C_{graphite-body}C_{body-gnd}}{C_{graphite-body} + C_{body-gnd}} \quad (6)$$

The total parasitic capacitance due to the bearing body was below 1 pF, which was insignificant compared to the capacitance of the $C_{bearing}$.

3. Experiment

A test setup, presented in Figure 5, was used for investigating the feasibility of the proposed capacitive sensing concept. A flat, 40mm diameter aerostatic thrust bearing sourced from New Way Air Bearings was selected for use in the study. The investigated bearing was loaded against the guide surface with loads ranging from 50 N to 600 N, corresponding to gap heights of approximately 20 µm to 1 µm. The supply pressure of the bearing was kept constant at 0.6 MPa during the experiments. The bearing was loaded incrementally to maximum load force and unloaded to minimum load force. This cycle was repeated twice. In each measurement trial, 24 points were measured and averaged from the force and displacement sensors.

The measurements were conducted in two parts. The investigated integrated sensor and the external reference sensors could not be used simultaneously due to the interference from the electric field applied to the bearing surface. First, a reference measurement was made using external reference sensors. The reference sensors were Micro-Epsilon CSH-05 capacitive displacement sensors with range of 0-500 µm and accuracy of ±0.3% FS. In the second measurement, the integrated capacitive sensor was used instead of the external capacitive sensors. Both parts were conducted in succession using the same investigated bearing together with the same experiment parameters.

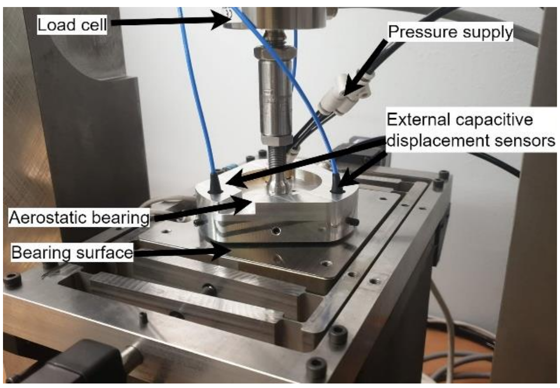

Figure 5. Experiment setup.

4. Results

The sensor output voltage as a function of the air gap height is presented in Figure 6. The useable range of the investigated integrated sensor, limited by the nonlinearity of the RLC circuit and saturation of the output amplifier, was 4 to 12 µm. A comparison between the reference sensors and the integrated sensor is presented in Figure 7.

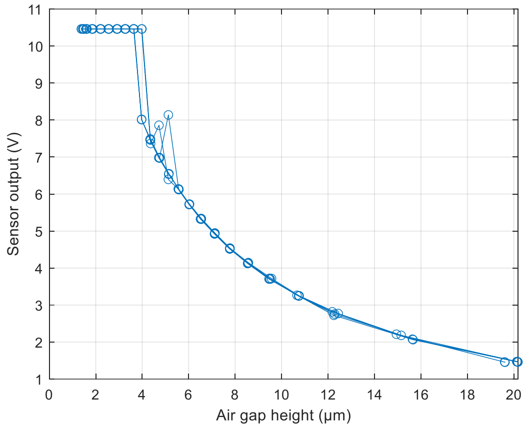

Figure 6. Raw sensor output voltage vs air gap height measured with external sensors. The output saturates at approximately 4 µm gap height.

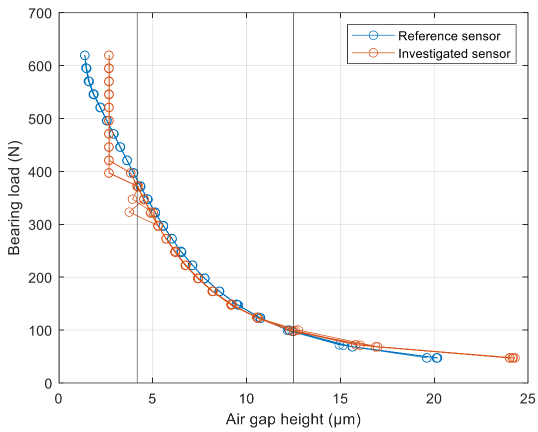

Figure 7. Air gap height measured with the investigated integrated capacitive sensor (orange) and the external reference sensor (blue). Usable range of the investigated sensor, limited by the circuit, is shown with grey vertical lines.

5. Discussion

The results of the present study show that the proposed gap height measurement method is feasible. Figure 7 shows acceptable correlation between the investigated method and the reference method in the usable range of the measurement circuit (4 µm to 12 µm) of the investigated proof-of-concept sensor. The limitation in the measurement range is due to the tuning of the signal conditioning circuit.

The output frequency of the signal conditioning circuit is proportional to $1/\sqrt{LC}$ [2], as an LC oscillator was used. Thus, the output signal increases exponentially as the air gap decreases. Further studies include hysteresis analysis on the loading and unloading test cycles and improvements in circuit design, such as implementation of a synchronous demodulator circuit instead of an LC oscillator to aid in the linearization of the output voltage [2].

One goal of further studies using an integrated sensor is to attain successful, accurate gap height measurements through the full gap height range of the bearing. The performance of the integrated sensor should be able to match the performance of the external sensors to become a viable replacement for external capacitive sensing methods.

Another possibility for future work includes the air gap measurement of radial aerostatic bushings using integrated capacitive sensing methods. Live measurement of air gap height for radial aerostatic bearings could be useful in high-load, high-speed, and varying-load applications.

6. Conclusions

The present research investigated a proof-of-concept method for the measurement of air gap height of aerostatic bearings using capacitive sensing. The performance of the developed sensor was investigated experimentally with a comparison to external sensors. The results show that the integrated sensor performs effectively and can accurately measure the air gap in the specified usable range of 4 to 12 µm. Outside the range, the performance of the investigated sensor decreases rapidly before becoming unusable below 4 µm. The usable measurement range could be improved significantly by improving the design of the circuit.

Overall, the results demonstrated the feasibility of the concept of integrated capacitive sensing in aerostatic bearings. The developed sensor is a low-cost solution, which could be implemented in applications where other methods are not suitable due to space or cost limitations. However, the method is limited for use only when conductive guide surfaces are present due to its reliance on forming a plate capacitor between the bearing and the guide surface. In further work, possible improvements in the measurement range, accuracy and hysteresis of the sensor will be further investigated.

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