euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Integrated capacitive gap height sensing with aerostatic bearings and non-conductive guides

Petteri Haverinen[1], Mikael Miettinen[1], Raine Viitala[1]

[1]*Aalto University*

petteri.haverinen@aalto.fi

Abstract

Aerostatic bearings are frictionless components conventionally used in high-precision linear guides, such as those found in coordinate-measuring machines. In high precision applications, some parameters must be known, such as the supply pressure, which affect the fly-height of the bearing. Direct measurement of gap height is therefore useful in many applications. The air gap is typically measured with either external sensors, such as capacitive sensors or eddy current sensors. However, the gap height can be also directly measured with an aerostatic bearing with conductive restrictor. The conductive restrictor acts as an electrode of a capacitive displacement sensor. The geometry of the aerostatic bearing can be modified to add a guard ring when measuring against a conductive guide surface.

Previous work on using an aerostatic bearing as a capacitive sensor to measure the thickness of its air gap has focused on conductive guide surfaces. The present work expands on the previous further by utilizing the same concept with insulating guideway materials, such as natural stone, also known as granite. In this study, a porous graphite-restrictor aerostatic bearing was designed, manufactured and investigated. The design of the bearing consists of a split-restrictor that acts as two plates of a capacitive sensor. The gap height measurement was investigated with granite surface using the developed bearing and measurement electronics. The fly height was varied by loading the bearing using a static test bench. The results show corroborative evidence on the feasibility of the proposed method.

Keywords: Measurement, sensors, gas lubrication, capacitive sensing, externally pressurized gas bearing, capacitive displacement sensor

1. Introduction

Aerostatic bearings are externally pressurized bearings, which utilize the flow of gas, such as air, to levitate. The gas flows through a restrictor between the bearing and a guide surface creating a thin film. This film is known as air gap. The air gap allows for minimal friction between the bearing and the guide surface. The air gap thickness, fly height, is related to the properties of the bearing, such as the stiffness [1]. If the bearing has a constant load and the supply pressure is varied, the fly height varies. The global maximum stiffness is present at some fly height, depending on the parameters of the bearing such as the size and permeability of the restrictor [1]. Therefore, measuring the fly height provides advantages in active control and condition monitoring.

Various methods exist for measuring the fly height. Such methods include, for example, pressure-based methods [2] where the pressure in the air gap is measured and the fly height is determined by comparing the air gap pressure to the bearing's characteristics, using external capacitive- or eddy current sensors [3, 4], and interferometry.

However, combining the sensing function to the bearing function by using the restrictor of the aerostatic bearing as the electrode for a capacitive sensor has not been widely investigated. Previous studies have used nozzle-type aerostatic bearing and a conductive steel surface to determine the fly height with capacitance measurement [5], and porous type aerostatic bearing to measure against conductive surfaces similarly [6]. The present work proposes a novel aerostatic bearing with porous split restrictor that acts as capacitive sensor and measures its fly height against non-conductive surfaces, such as natural stone. Natural stone is referred to as granite in this paper.

A novel type of bearing was designed and manufactured. The variance of capacitance against granite was analyzed using finite element simulation in COMSOL. Interface electronics were designed and manufactured based on the simulation results to tune the circuit to a capacitance range corresponding to the operational fly height range of the developed bearing. The bearing performance and the integrated sensor were validated with a static test bench developed in previous studies [3, 7]. The results showed that the method of using the aerostatic bearing as a capacitive sensor for measuring its fly height against an insulating granite guideway is viable.

2. Methods

2.1. Measurement principle

An electric field between two electrodes will have fringe fields on the edges of the electrodes. When a dielectric object is brought into the field close to the electrodes, the electric field will cause charge distribution, polarization, inside of the dielectric. The polarization creates opposing electric fields inside of the dielectric, therefore increasing the number of charges in the electrodes. The increased charges increase capacitance between the electrodes.

The capacitance between the electrodes increases, as the distance between the dielectric and the electrodes decrease. The change can be measured with a capacitance-to-voltage converter and the corresponding separation distance solved by either creating a model corresponding to the used dielectric and electrode geometry and circuit response, or by determining the change experimentally and fitting a curve. In the present work, the latter method was used.

2.2. Investigated bearing

The investigated aerostatic bearing was constructed from anodized aluminium body with a split graphite restrictor as presented in Figure 1. The split restrictor consisted of a disk and an annular restrictor with a 1 mm epoxy insulation area. The epoxy in the groove was relieved by 0.5 mm to not protrude past the graphite and affect the grinding or lapping of the bearing surface. The investigated bearing is presented in Figure 2.

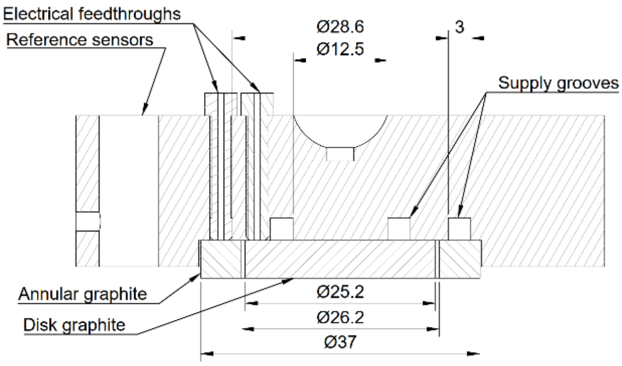

Figure 1. Main dimensions of the investigated bearing. The electrical feedthroughs were insulated from the aluminium by nylon screws with a 0.8 mm throughhole to allow for an electrical feedthrough.

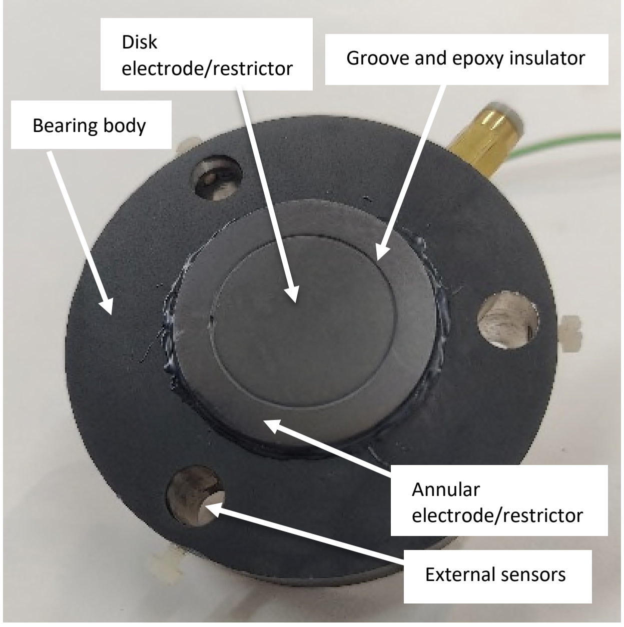

Figure 2. Investigated bearing. The body was anodized aluminium, with three bored holes for mounting external reference capacitive displacement sensors. The restrictor was constructed from two pieces separated by insulating gap with a 0.5 mm groove to prevent the epoxy from creating a high spot in the surface of the bearing.

2.3. Interface electronics

The interface electronics for measuring the air gap as a function of capacitance were designed for capacitance variance given by COMSOL simulation. The simulation was an axisymmetric 2D electrostatic simulation, with the disk electrode as a supply terminal and the annular electrode as ground. The simulated guide surface was set as a high permittivity boundary with permittivity of 5 according to granites permittivity from literature [8]. The simulation was a stationary simulation with a parametric sweep. The controlled parameter was the air gap thickness from 1 µm to 15 µm with 1 µm step size. The simulation provided capacitance variation between 15.85 pF to 21.75 pF (15 µm to 1 µm).

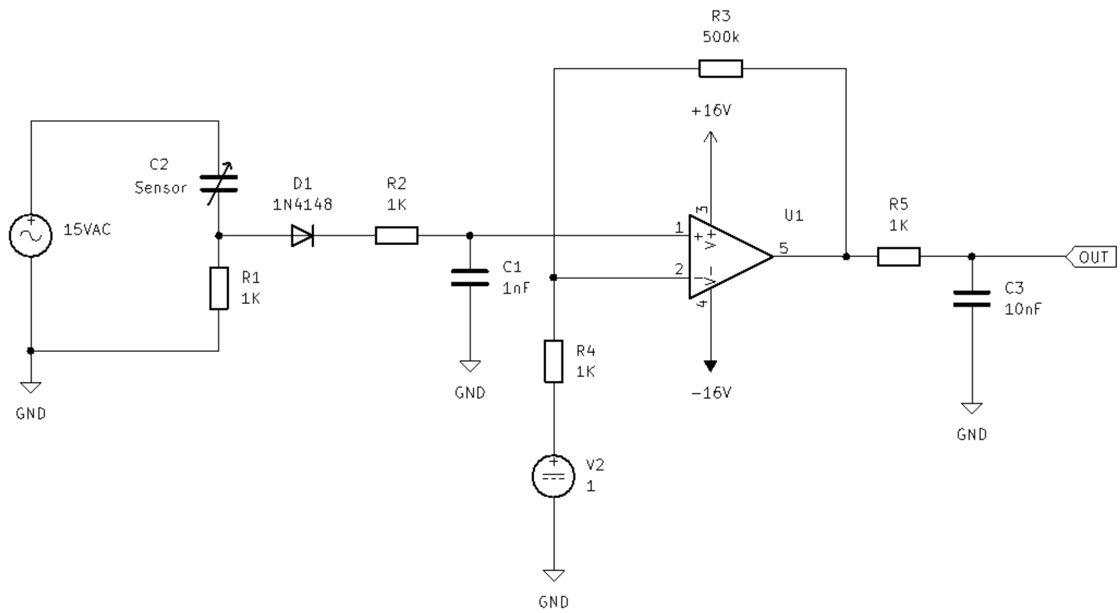

Figure 3. Schematic of the measurement circuit. The supply voltage was ±16V with a centre tap ground. The biasing voltage V2 was produced with a regulator and a 100 turn 10kΩ trimmer potentiometer.

To convert the capacitance to voltage, a circuit presented in Figure 3. was developed. The circuit used a sine wave and an RC circuit to determine the capacitance. As the capacitance increased, the current through the capacitor increased, providing larger voltage drop over the resistor. The sine wave was generated by a signal generator with a signal amplitude of ±15 V and frequency of 200 kHz. A sine wave was used, as there was worry about charge build up on the granite causing hysteresis as could be the case with a square wave. The sine wave was fed through the bearing. As the capacitance increased, the current through R1 increased, giving a larger voltage drop. The voltage across R1 was converted to DC using a 1n4148 diode and a low-pass filter tuned to 159 kHz -30 db cut-off frequency. The output was amplified with a biased operational amplifier with a gain of 500. The amplifier output was measured though a low-pass filter, set at 159 Hz cut-off frequency. The voltage output was converted to distance using a curve fit.

2.4. Experiments

The investigated bearing was verified experimentally. The concluded experiments were divided into two sets. In the first set of experiments, the pressure distribution of the investigated bearing was measured using a static test bench presented in Figure 4. The integrated sensor was not active in the pressure distribution measurement as the guide surface was steel. The bearing was loaded from 0 N to 600 N to 0 N with 15 steps of increasing and 15 steps of decreasing load. The loading/unloading cycle was performed to determine the significance of hysteresis in the setup. The supply pressure of the bearing was kept constant. The pressure of the air gap and the fly height were measured at each point. The guide surface was moved after every measurement loop by 1 mm radially over the bearing to create the pressure distribution and to analyze the stiffness and load carry capacity of the bearing. The results were compared against analytical model of the aerostatic bearing.

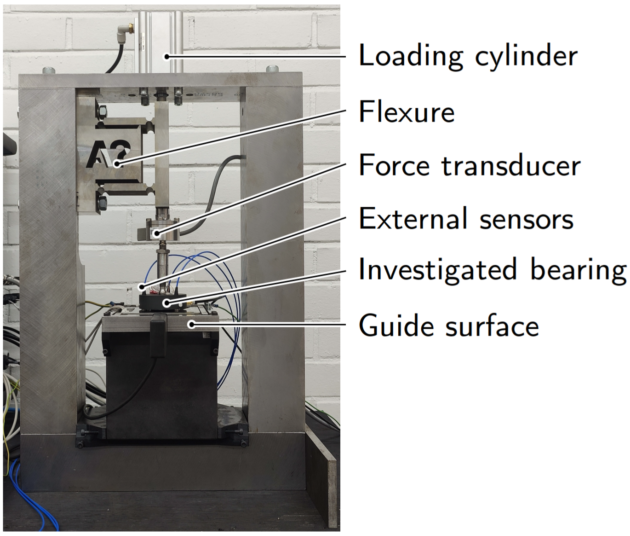

Figure 4. Static test bench. The loading cylinder was used to vary the force. The fly height was measured using the external capacitive sensors.

The second set of experiments utilized granite as the guide surface. The steel guide surface was removed. The bearing was loaded from 0 to 600N and the fly height was measured using external capacitive sensors. The external capacitive sensors were mounted on a cradle above the investigated bearing. The body of the bearing was connected to ground to act as a reference and to shield the sensing electrodes of the investigated bearing from the reference sensors. The output of the interface electronics was measured at each measurement point after the bearing had settled. The maximum voltage was set by loading the bearing without supply pressure to the guide surface and adjusting the trimmer potentiometer until output of around 4.8 V was reached. The setup is presented in Figure 6.

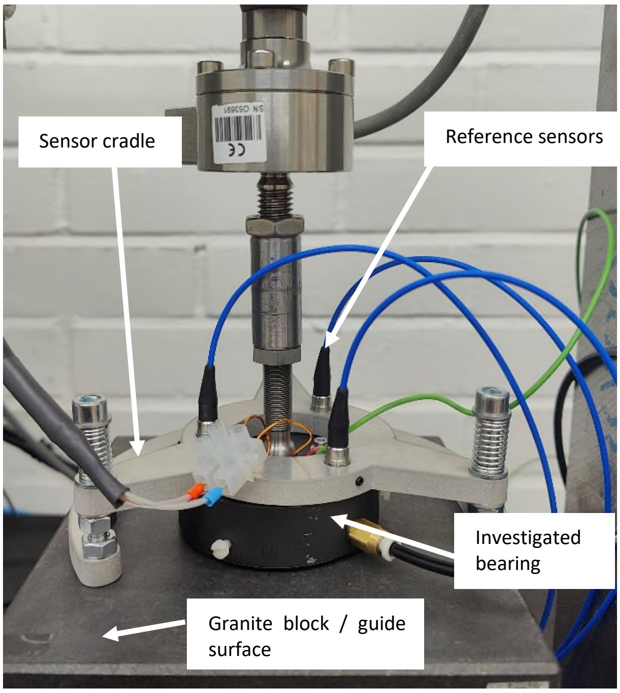

Figure 5. Static test bench with the steel guide surface removed and sensor cradle installed.

4. Results and discussion

The load carry capacity and stiffness of the investigated bearing are presented in Figure 6. The bearing performed acceptable in comparison to the analytical result. The impact of the non-permeable epoxy gap was therefore negligible.

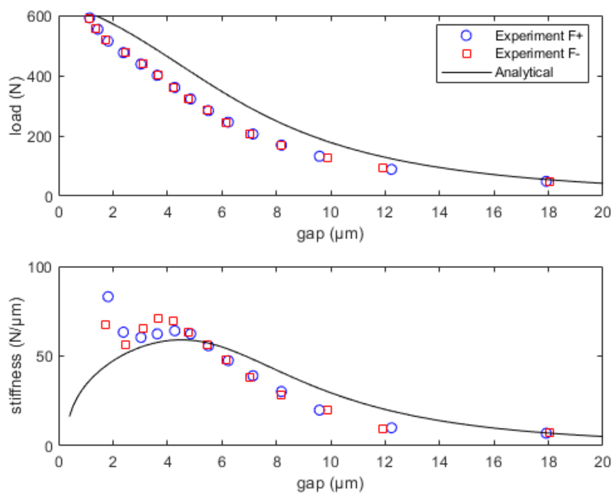

Figure 6. Measured load carry capacity and stiffness. The black line presents excpected values from analytical model, F+ presents the measurement points when loading the bearing and F- presents the results when unloading the bearing.

The output of the interface electronics followed a linear relationship with the fly height. The sensor output vs the air gap is presented in Figure 7. From the figure, noise in the measurement is apparent. The source of the noise was not identified; however, it is likely due to the unshielded interface electronics and charge build up on the granite. Furthermore, the hysteresis of the sensor was not determined in the experiments. The output might have hysteresis due to surface charge buildup.

The noise may be mitigated by mounting the measuring electronics in a grounded enclosure. Furthermore, an additional annular electrode in the bearing acting as a driven shield may improve measuring accuracy.

Properties of the insulator will affect the measurement. The used material for the guide surface was granite and therefore has many metallic inclusions and discontinuities in the structure. Therefore, using the sensor in some applications which require linear motion, the sensor should be calibrated throughout the linear motion range. Surface charge buildup may be possible to overcome by utilizing accurate sinusoidal excitation voltage.

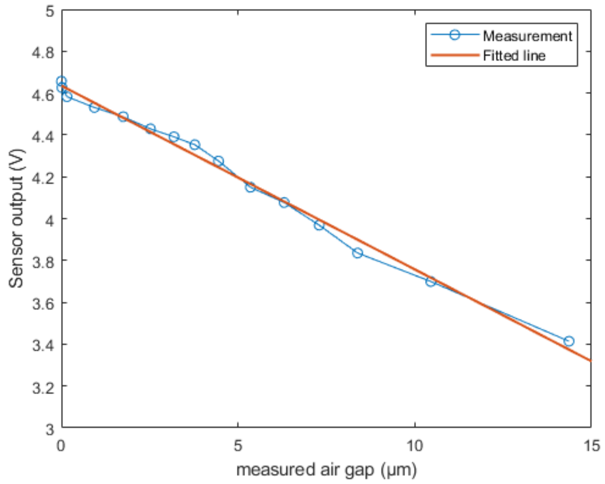

Figure 7. Output of the interface electronics as a function of fly height.

As the output of the interface electronics followed a linear relationship with the fly height, a linear fit was used to convert the output voltage to distance. The maximum deviation from the reference sensors was 690 nm at 8.3 μm fly height. The average deviation was 300 nm. The measured fly height vs the reference sensors is presented in Figure 9.

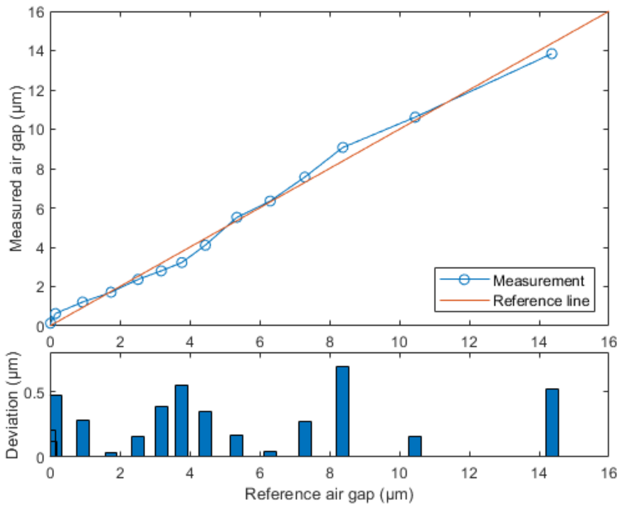

Figure 8. Output of the interface electronics converted to fly height vs reference sensors (above) and the deviation from reference sensors (below). The output was converted from voltage to distance with a fit of $d(U_{out}) = -11.3\ U_{out} + 52.43$.

More homogenous materials for the opposing surface may lead to increased measurement accuracy. However, multiple applications, where air bearings are used, utilize natural stone such as granite as the guide surface. Furthermore, surface roughness of the measured surface may increase the relative permittivity. However, the surface roughness of the guide surface for precision applications is low, therefore mitigating this impact.

5. Conclusions

The present work demonstrated a novel porous aerostatic bearing with integrated capacitive air gap measurement against a non-conductive granite guide surface. The possible applications include infinite-stiffness active control bearings, condition monitoring and tuning of systems utilizing aerostatic bearings. An aerostatic bearing with integrated fly height measurement was designed and manufactured, change in capacitance was simulated and interface electronics were developed. The bearing and the integrated sensor were validated using experiments.

The results showed maximum deviation from the integrated sensor and reference sensor to be 680 nm, with average deviation of 300 nm. The results validated the feasibility of the concept.

References

[1] M. Miettinen, V. Vainio, R. Viitala, 2024 Aerostatic porous annular thrust bearings as seals *Trib. Int.* B **200** 110073

[2] J.-S. Plante, J. Vogan, T. El-Aguizy, A. H. Slocum, 2005 A design model for circular porous air bearings using the 1d generalized flow method *Prec. Eng*. **29** 336–346

[3] M. Miettinen, V. Vainio, R. Theska, R. Viitala 2024 On the static performance of aerostatic elements *Prec. Eng.* **89** 1–10

[4] O. Calonius, P. Kiviluoma, P. Kuosmanen, Calonius, O. Kiviluoma, P. Kuosmanen 2011 *Engineering for a changing world: Proceedings: 56th ISC Ilmenau Scientific Colloquium*

[5] Y. Jing, L. Dongsheng 2012 Capacitive measuring method of the air-film thickness of aerostatic bearing *Int. Journ. of Nanomanufacturing* **8** 173

[6] P. Haverinen, M. Miettinen, L. Harding, V. Vainio, O. Leutonen, R. Theska, R. Viitala 2024 Integrated capacitive measurement of air gap height in aerostatic bearings *Proceedings of the 23rd international conference of the European society for precision engineering and nanotechnology*

[7] V. Vainio, M. Miettinen, J. Majuri, R. Theska, R. Viitala 2023 Manufacturing and static performance of porous aerostatic bearings *Prec. Eng.* **84** 177-190

[8] Matsumoto, T. & Miyamoto, Hideaki & Nishibori, Toshiyuki & Manabe, Takeshi & Ito, Takahiro & Katayama, R. & Haruyama, J. 2014 On the Heterogeneities of Electro-Magnetic Properties of Rocks *45th Lunar and Planetary Science Conference*