# Enhancement of dynamic properties for a gas foil bearing using structural components made of shape memory alloys – experimental study

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**ABSTRACT**

Bearings are commonly employed in various types of rotating machineries. Their properties indisputably influence the overall performance and time of maintenance-free operation of the mechanical systems in which they are used to support the shafts. Consequently, much effort is considered to provide reliable bearings' solution and develop new methods and technical tools for measurement and possibly modification of the operational characteristics of the above-mentioned parts. In reference, the concept of a smart bearing is developed as providing the means for real-time passive and active control of the bearings' behavior as well as different types of smart materials are used to enhance their characteristics. The current study deals with an application of structural components made of shape memory alloys to gas foil bearings (GFB). The paper presents and discusses the results of experimental tests conducted for the bearing's prototype to characterize the efficiency of thermally-induced modifications of geometric properties of one of the crucial parts of the investigated GFB.

## 1. INTRODUCTION

Gas foil bearings (GFB) stand for a type of slide bearings in which a gaseous medium is used to lubricate them and fill in the clearance between the shaft's journal and bearing's bushing [1,2,3]. Particularly, the GFBs support lightly-loaded rotors and shafts in small-size and high-speed machineries, i.e., at the rotational speeds as high as several hundred thousand rpm [4,5]. A transversal cross-section of a radial GFB is presented in Figure 1.

In a GFB, the suspension layer present between the shaft's journal and the bushing composes of the two counterparts:

- structural part – it is made of a set of thin (e.g., 0.1mm-thin) foils: top and bump foils that are made of an superalloy, e.g., Inconel 625; the structural part assures the elasto-damping properties desired to keep stable shaft's trajectory;
- fluidic part – it is a several-micrometer-thin gaseous (air) film that develops during the hydrodynamic action which is initiated when the rotational speed is sufficiently high; after the generated fluidic film is fully formed the elevated shaft starts contactless high-speed rotation;

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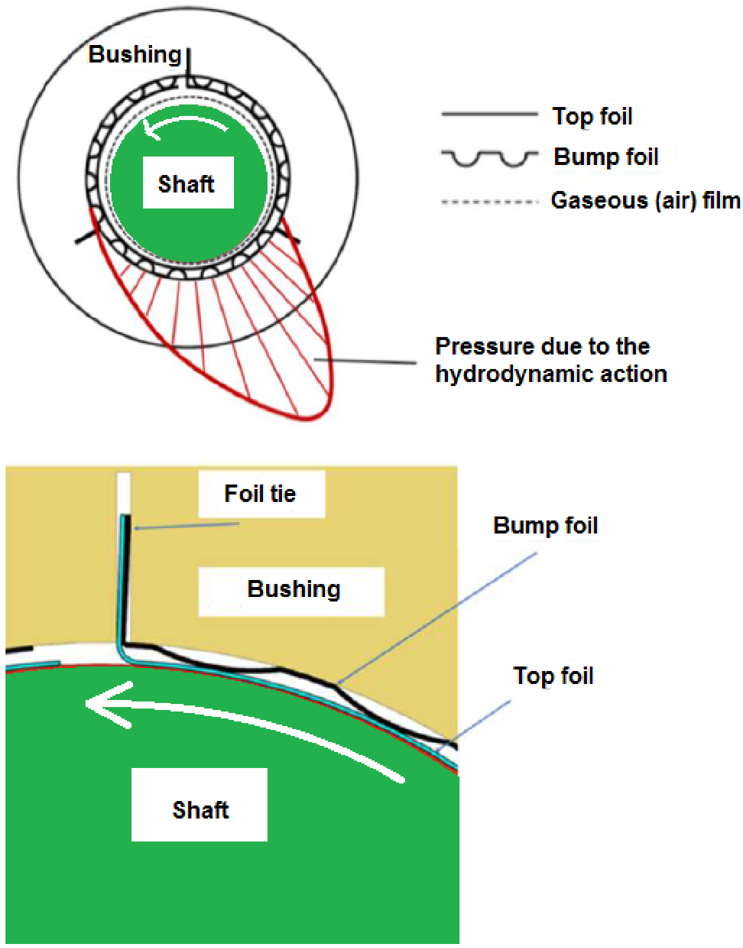


Figure 1: Transversal cross-section of a typical radial GFB [6].

GFBs exhibit important advantages, particularly, capability of operation at wide ranges of temperature and speed, however, they are sensitive to the temperature gradients. In fact, the thermal control is required to keep the desired load carrying capability and avoid exceedance of the allowed thermal expansion for the GFB's structural components that would finally lead to shaft clamping and damage of the bearing [7,8,9].

Nowadays, to address the above-stated issues, various approaches are extensively investigated by the researchers for GFBs [10]:

- passive and active methods for improving the elasto-damping characteristics of the bearing's structural components, including [11-31]:
  - installation of ceramic and elastic composite piezoelectric transducers (actuators) in the GFB's foils and bushing,
  - use of metallic springs made of shape memory alloys (SMA) instead of the bump foils or installed on a top foil,

  - non-smart material based approaches, e.g., the concept of progressive stiffness of the supporting layer, modification of the bump foils' shape, installation of additional structural components between the GFB's bushing and bump foils, installation of metal meshes and dampers and texturing the top foil;

- passive and active methods for thermal management including [32-35]:
  - modification of bushing and foils geometry to enhance both the heat and air flow,
  - modification of materials used to enhance the heat transfer,
  - application of air cooling,
  - installation of thermoelectric modules (Peltier modules) in bushing to actively manage the heat transfer within the entire structure of a GFB;

The above-listed approaches to GFB's modifications enable various advantageous changes of the bearing's properties, including precise and fast control of the shape and thickness of the air film (the bearing's clearance) as well as control of the mechanical preload and thermal energy transfer. It is worth noticing that, in a broader view, SMA are willingly used to modify the properties of the host structures [36]. On the other hand, the involved complex fluid flow and fluid-structure interaction related phenomena need the researchers' particular attention to be correctly and efficiently addressed to enable the enhancement of the dynamic properties for various types of structural components [37-40].

Following the overview on the current approaches to smart GFBs, i.e., the GFBs that are equipped with various types of smart materials, the authors of the present work designed and created a prototype installation of the GFB with the components made of SMA (Nitinol). As shown below, the considered structural modification allowed to enhance the dynamic properties for the tested bearing. In the paper, a novel top foil is presented that is capable of performing both sensing and actuating tasks. Specifically, the temperature and strain readings are conducted to conclude about the effectiveness of the thermally-induced mechanical response of the top foil being activated to modify the shape of the air film.

There are 4 sections in the paper. Introductory Section 1 is followed by the description of the developed test stand that is presented in Section 2. Next, in Section 3, the authors provide the results of the experiments complemented with an adequate discussion. Final Section 4 summarizes the work and draws general conclusions.

## 2. PROTOTYPE OF A GAS FOIL BEARING EQUIPPED WITH SHAPE MEMORY ALLOYS

A prototype of a GFB was constructed to test the usability of SMA for changing the geometry of the top foil. Figure 2 presents the main structural parts of the bearing before installation sensing and actuating components. Radial guidance of wires for the temperature and strain sensors is managed with 12 openings in the bushing tierces. A novel multifunctional sensing-actuating top foil is shown in Figure 3. Its design refers to the concept presented in the authors' previous study [41]. Figure 4 describes a thermomechanical treatment carried out for the wires made of SMA to make them remember the desired geometric shape. A prototype installation of the investigated smart GFB is shown in Figure 5, in turn.

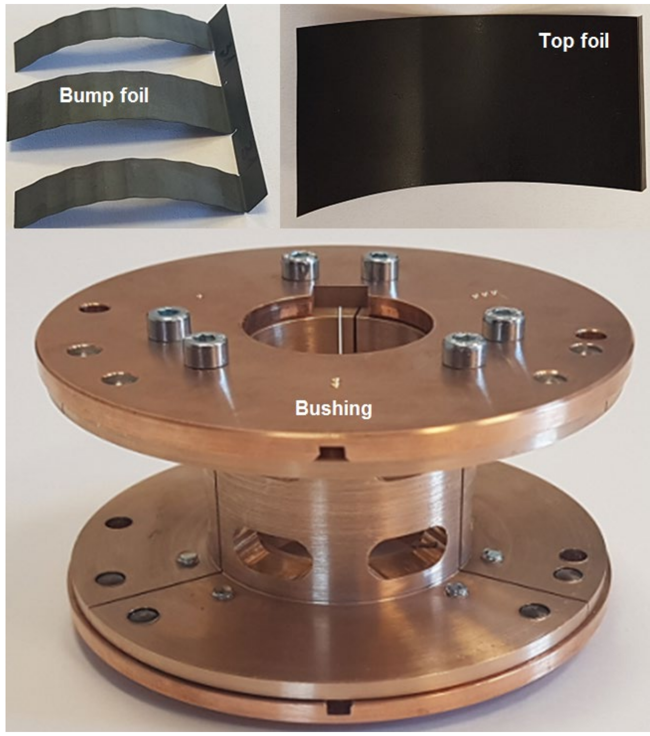


Figure 2: Main structural components of the GFB before their assembly.

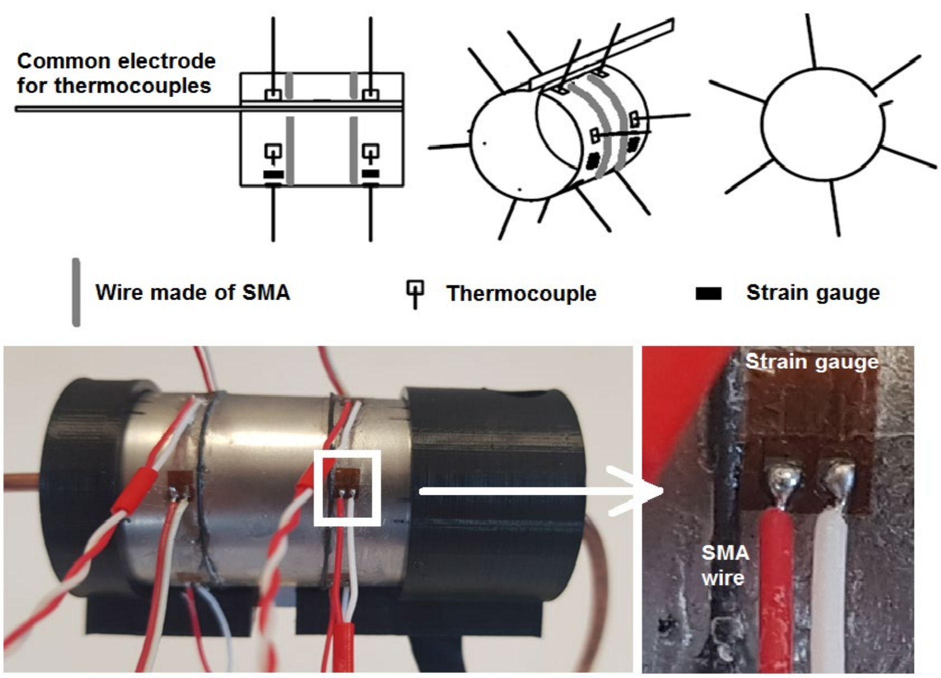


Figure 3: Multifunctional top foil – visualization and prototype.

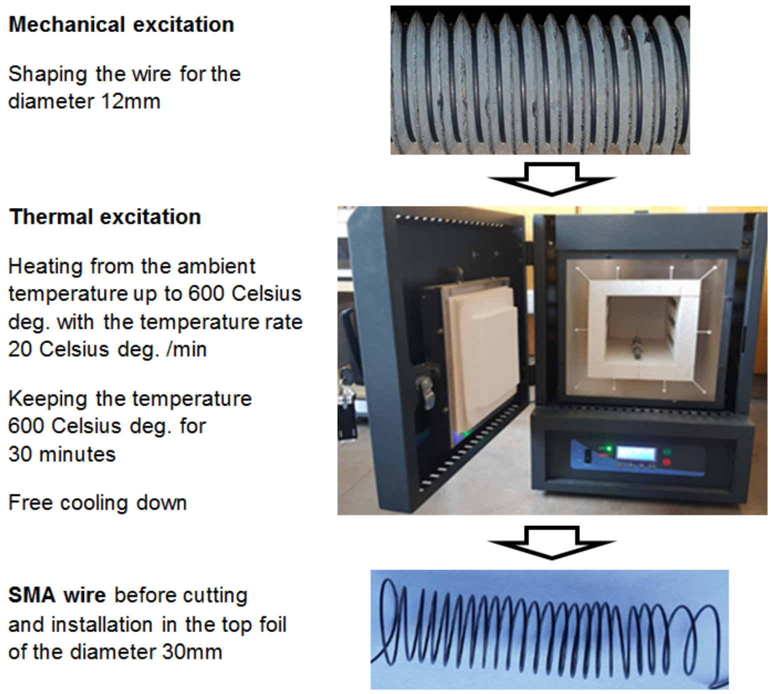


Figure 4: Thermomechanical treatment carried out for the SMA wires glued to the top foil.

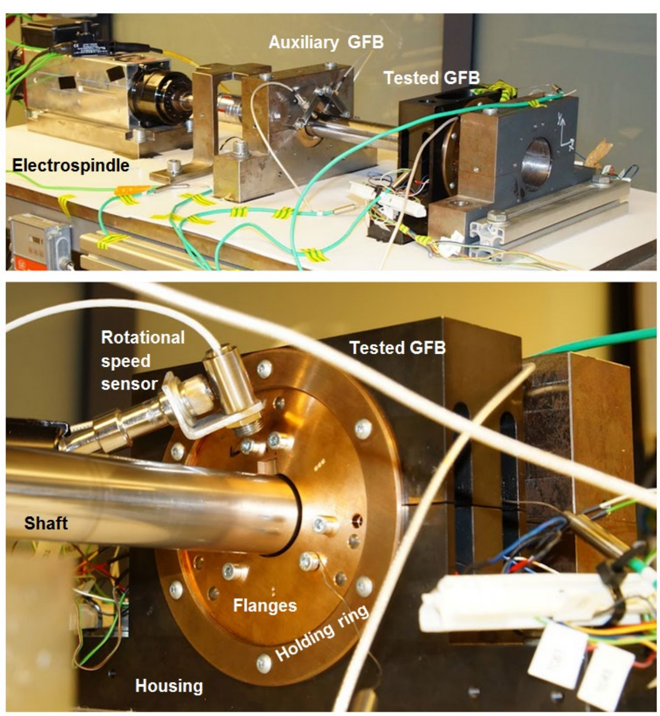


Figure 5: Prototype of the tested smart GFB.

As seen in Figure 5, the two-node support configuration was considered during experiments. It assumes an application of the tested SMA-based smart GFB and an auxiliary bearing. The newly-developed multifunctional top foil was employed to perform measuring and actuating tasks. On one hand, the built-in thermocouples and glued strain gauges allowed thermomechanical characterization of the bearing via temperature and strain measurements. On the other hand, an SMA actuation was assumed to provide the means for controlling the shape of the top foil. Making use of the developed test stand, the authors conducted the investigation on the perspective of the GFB's operational properties enhancement via introduction of thermally-induced air film adaptation, as described thereafter.

## 3. EXPERIMENTAL RESULTS AND DISCUSSION ON THE CAPABILITY OF DYNAMIC PROPERTIES ENHANCEMENT

In the following, there are presented and discussed measurement results obtained for the bearing's complete operation cycles. Both the temperature and strain readings are provided to study the temporal courses of the GFB's characteristics and to conclude about the bearing's behavior during development and losing the air film. The summarized properties of the test stand and characteristics of the experiments are presented in Table 1. Figure 6 visualizes the temporal courses for the GFB's operational parameters.

Table 1: Summary of the most significant characteristics of the considered case study.

| Characteristics | Descriptions and remarks |
|---|---|
| Support configuration | Two-node (two-bearing) support configuration equipped with the tested SMA-based GFB and auxiliary GFB |
| Stages of the GFB's operation and rotational speed profile | Two-cycle course of the GFB's operation.<br>The stages of the first cycle:<br>• run-up with a linear growth of speed up to 24000rpm – lasting for 30s,<br>• stable operation at 24000rpm – for the period of 2560s, considering two heating activities,<br>• run-out with a linear decrease of speed down to 0rpm – lasting for 30s,<br>• 30s-long break;<br>The stages of the second cycle carried out for the preheated GFB:<br>• run-up with a linear growth of speed up to 24000rpm – lasting for 30s,<br>• stable operation at 24000rpm – for the period of 30s,<br>• run-out with a linear decrease of speed down to 0rpm – lasting for 30s,<br>• break – final cooling down; |

Table 1 is continued on the next page.

| Characteristics | Descriptions and remarks |
|---|---|
| Parameters of the wires made of SMA | Diameter: 0.5mm<br>Transformation temperature: 70 Celsius deg. – averaged value for the four temperatures characterizing initiation and completing of both martensite-to-austenite and austenite-to-martensite transformations |
| Thermal excitation | Heating up with a heat gun up to approximately 90 Celsius deg. for the two periods lasting for 700s and 500s – during the first cycle, respectively initialed 900s and 2050s after the phase of stable operation begins |
| Measured quantities and types of sensors | 1) Temperature - measured with thermocouples,<br>2) Strain - measured with strain gauges,<br>3) Rotational speed – measured with optical sensor,<br>4) Shaft's journal trajectories – measured with laser sensors; |
| Controlled quantity | Actuation performed via thermally-activated SMA wires used to control the curvature of the top foil |

During the experiments the tested GFB behaved correctly which is confirmed by the course of the temperature. Before an external thermal excitation with a heat gun started, there was found the expected decrease of the top foil's temperature initially raised during the run-up stage of the bearing's operation due to a dry friction. Effectively, the shaft must have been elevated over the top foil and continued contactless rotation. Otherwise, a new source of heat energy followed by a sudden temperature increase and possibly damage of the bearing would occur in case when no air film developed.

As far as the measured strains are considered, a repeatable response of the bearing's top foil is found to follow both types of the thermally-induced geometric changes: (a) a standard thermal expansion observed for metallic parts and (b) solid state phase transformations-based deformations introduced by the SMA wires. First of all, during the initial stage of heating, there are visible two different slopes characterizing the temperature rates. They are swapping approximately at the time moment 1340 seconds after initiation of the measurements. This case corresponds to the maximum temperature registered equal to 63 Celsius deg. which notices begin of martensitic transformation in the SMA wires. As mentioned in Section 2 (Figure 4), after thermal excitation, the wires should evoke their remembered shapes characterizing the diameter significantly smaller than the diameter of the bearing's shaft.

Consequently, the clamping of the top foil around the shaft's journal is observed which is confirmed by the positive values of the strains measured at the outer surfaces of the above-mentioned foil, at almost all sensing localizations. Then, while further heating, the standard thermal expansion reveals itself again and reduced the resultant strains. The situation reverses during free cooling, with the difference that the martensitic transformation does not invert, possibly due to the insufficient mechanical response of the deflected top foil. This phenomenon seems to become irreversible for the investigated case study. This GFB's behavior is seen within the 450s-long time period (i.e., from 1667 up to 2117 second after the measurements begin). The second cycle of the thermal excitation leads to the decrease of the strains due to the dominant effect of the thermal expansion phenomenon. Finally, during the second complete run of all stages of the GFB's operation, the bearing operates in a predictable manner, primarily exhibiting thermal expansion and thermomechanical consequences of the consecutive processes of developing and loss of the air film during the run-up and run-out stages. At the end of the measurement session, there are found non-zero strains of the top foil confirming irreversible deflections originated from both the martensitic transformation and geometric adjustment of the shaft that continuously cooperates with two bearing nodes.

Figure 7 visualizes the changes of the shaft's trajectory orbit induced by the thermal activation of the SMA-based components in the tested GFB.

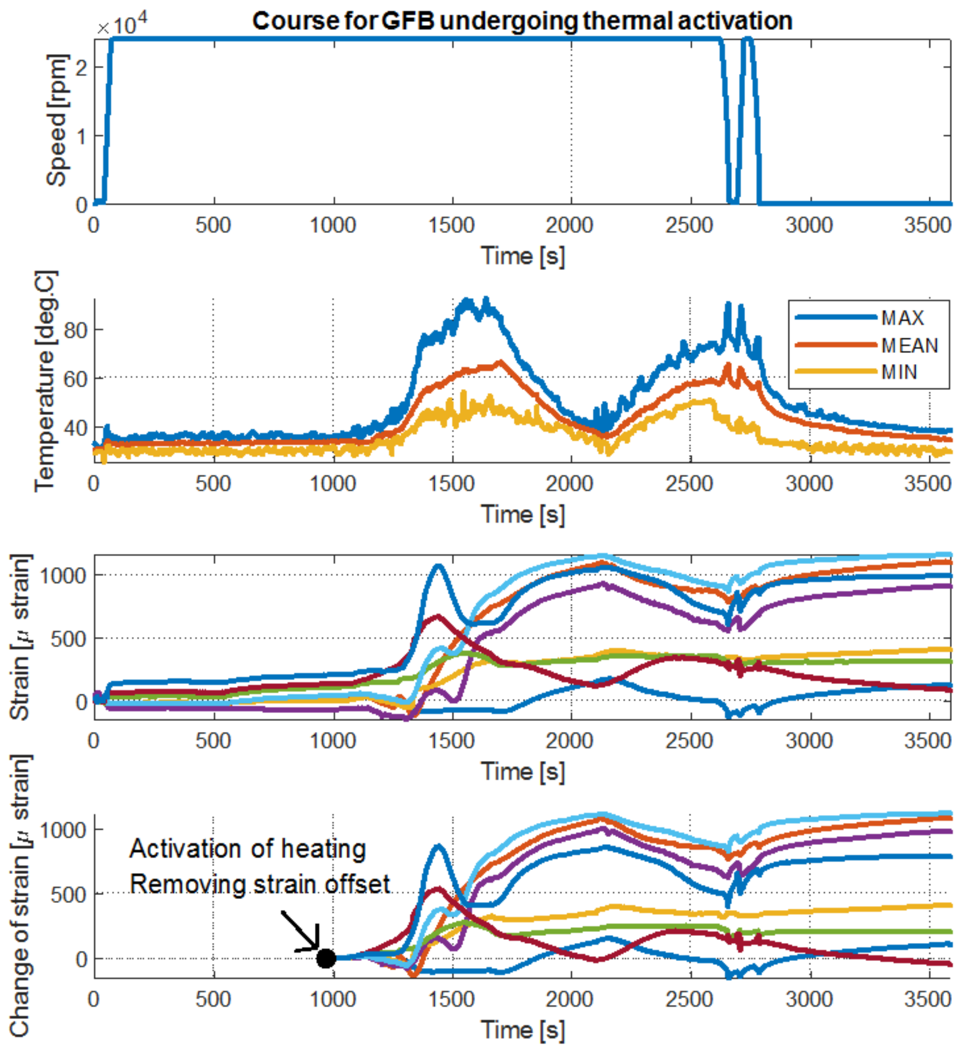


Figure 6: Temporal plots for the GFB's operational parameters. From top to bottom: rotational speed, temperature and strain readings, and strain changes (after excluding the offset values) registered considering thermally activated modification of the top foil's shape.

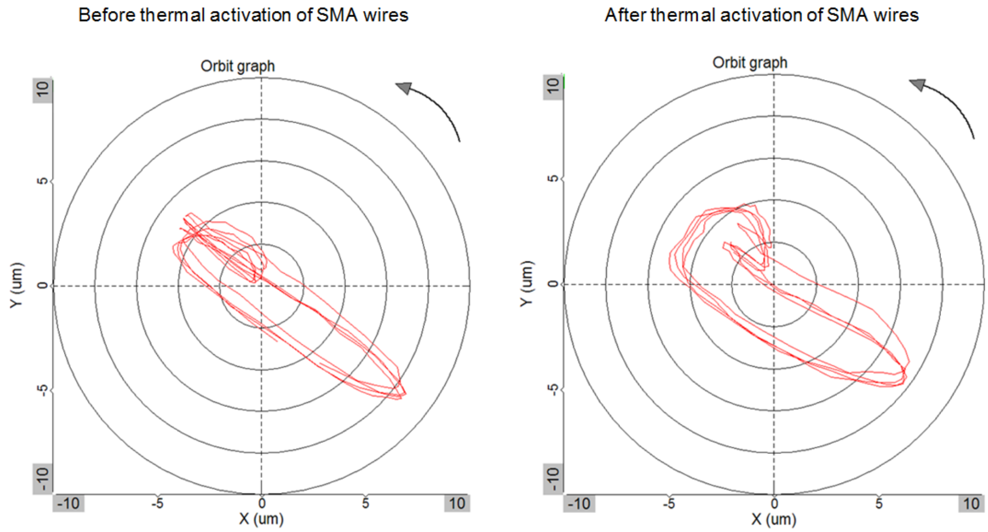


Figure 7: Evolution of the shaft's trajectory orbit due to the thermal activation of the smart GFB – non-filtered data.

Before activation of SMA wires, the shaft's trajectory orbit exhibits a greater degree of flattening that notices higher inhomogeneity regarding the bearing's stiffness or load along the two transversal directions X and Y. Moreover, two loops are visible for the discussed case, most likely resulting from the bearings' axial misalignment. Advantageously, after activation of the SMA parts, the shaft's trajectory orbit gets improved gradually that indicates a change in the GFB's operational characteristics. The loops do not overlap any more. Moreover, they become more rounded, specifically the smaller one. Similarly, the bearings' axial misalignment is reduced with the unchanged vibration amplitude.

## 4. SUMMARY AND FINAL CONCLUSIONS

In the reported study, there were experimentally confirmed the following functionalities of the newly-designed multifunctional top foil installed in the developed GFB's prototype:

- within the sensing activities – characterization of thermomechanical properties of the bearing (GFB's operational parameters) via temperature and strain readings for the outer surface of the top foil performed with installed thermocouples and strain gauges,
- within the actuating activities – modification of the geometric shape of the air film (via modification of the top foil's geometry) with thermal actuation of the SMA wires mounted in the top foil;

The authors present the perspective of a self-operating adaptation of the GFB's behavior (due to the desired change of the top foil's shape) since they successfully examined thermally controlled mechanical response of SMA wires. Activation of smart components led to the enhancement of dynamic properties of the GFB. Consequently, in the paper, there is provided a description on the means, via a relatively simple technical solution, that may be used to influence the bearing's load carrying capacity, efficiently.

However, there should be raised a few practical issues related to the developed prototype installation. The most important ones refer to:

- increase of speed, accuracy and repeatability of mechanical response of the top foil,
- problematic operation of fast cooling down,
- high inertia of the control process due to the specificity of thermal phenomena,
- imprecise data on the course of the transformation process and its characteristics temperatures; Spontaneity of the phase transformation that may cause a non-uniform adaptation of the top foil's shape and lead to an unintentional disturbance of the air film.

In the authors' opinion, the farther study on the applications of SMA to GFB should cover:

- characterization of the influence of external load and speed of rotation on the solution's reliability and performance,
- quantitative and qualitative assessment on the effectiveness of vibration reduction and, possibly, estimation of the achievable level of the demanded mechanical energy loss [42];

## ACKNOWLEDGEMENTS

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