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MULTI-POINT CONTROL METHOD FOR REDUCTION OF THERMAL GRADIENTS IN FOIL BEARINGS BASED ON THE APPLICATION OF SMART MATERIALS

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Summary: *Foil bearings are tempting alternative for supporting high speed rotor shafts, especially due to their oil-free operation and low frictional moment. The current applications includes compressors and small turbine rotors. The specific construction of the bearing causes nearly 80% of produced heat to be removed by the conduction in the shaft. The remaining 20% is dissipated by the edge leakages and transferred to the bushing through the set of shaft supporting foils. A local difference in heat generation rate can be detrimental to the bearing as it leads to thermal gradients in a foil structure developing both axially and circumferentially. Once developed the thermal gradient may lead to thermal instability and further to the damages of the bearing and the whole machinery. At the moment the only method used in practice to remove the thermal gradient from the bearings is by forced air flow either through the hollow shaft or directly through the foil bumps. The flaw of the abovementioned methods are bulkiness and necessity of delivering a compressed air.*

The authors propose the method for reduction the uneven temperature distribution in the foils with the use of current-controlled thermoelectric modules. The modules are both axially and circumferentially distributed in the bushing of the bearing and controlled independently. The electric power delivered to the system is calculated based on the temperatures measured by thermocouples mounted in the bushing structure. The numerical simulations performed with a FE model of the complete structure of a foil bearing allowed to study the relationship between the currents supplied to the thermoelectric modules and the temperature distribution on the bump and top foils. Moreover, the metamodelling technique was applied to search for dependencies between temperatures measured in different localizations to show perspectives for reducing the complexity of the control algorithm. A set of uniformly distributed virtual sensors (spread on the top foil) were used to reproduce a real temperature gradient in the bearing with sufficiently high spatial resolution, and discuss the validity of considered localizations of modeled thermocouples on both bump and top foils in terms of feasibility of effective reduction of thermal instability.

1 INTRODUCTION

The gas foil bearings (GFB) have become widespread covering the applications of micro-turbines, motors, compressors and turbocharges, prevalently of small size (<200kW)[1]. Their construction allows oil-free operation what favors machinery weight reduction and reduces need of maintenance. An important trait of the GFBs is their ability to operate in high temperature conditions with no need of lubricant other than air or machine working fluid, hence there is no need to deal with oil degradation like in rolling bearing systems. However, proper thermal management is still an important consideration. Radil [2] identified three main reasons for GFBs failure i.e. overheating, thermal runaway and developing of excessive thermal gradients, all related to bearing thermal misbehavior. The first mention failure mechanism involves drop of elastic modulus with temperature what eventually increases the bearing's compliance and reduces the load capacity. Thermal runaway is induced by the heat flux distribution in the bearing structure. As most of the heat is absorbed by the shaft it expands faster resulting in increasing bearing preload what increases heat generation rate in the bearing and may lead to thermal seizure [3]. Last mentioned cause of failure is most dangerous as it occurs unexpectedly when speed or bearing load changes even though the bearing exhibits stable operation. Moreover, developing axial thermal gradients is natural for nearly all GFB types [2]. The same author stated that the bearing failure due to excessive thermal gradient may happen at any, not necessarily elevated temperature. To overcome the thermal stability problems of GFBs several cooling methods were introduced, all involving forced air flow. The cooling stream may be directed at the journal surface (direct cooling), may be injected inside the hollow shaft (indirect cooling) or forced to flow through the foil bumps (axial cooling) [4]. A modified cooling strategy (radial cooling) has been proposed by [5]. In this study several nozzles have been positioned so that the air impinges directly on the rotor shaft and allows the control of spatial temperature distribution of a bearing what is unachievable with other methods. Experimental studies provided by the aforementioned authors proofed that the overall temperature of the bearing may be successfully decreased. All methods allow lowering the temperature of the bearing while decreasing the axial thermal gradient at the same time but axial cooling that is most likely to increase the gradient. Only radial cooling method provides means for controllable gradient removal. The tradeoff is that radial cooling is not an efficient tool to lower the bearing temperature. Some other authors [6] noticed the fact that the low cooling flows are not effective, hence a substantial air flows are necessary. That in turn affects the machine's efficiency e.g. compressor's bleed air cooling a bearing reduces the amount of delivered compressed medium [7]. Large cooling flows may also cause a substandard hydrodynamic conditions within an air film or may successfully unable revealing failure syndromes leading to unexpected failure [7]. This and other disadvantages of force air cooling drove the researchers' attention towards alternative cooling methods like passive cooling [7].

As not all foil bearings work in temperatures measured in several hundred degrees and therefore require air cooling to mitigate the threats of overheating or thermal seizure they are still under risk of failure stems from thermal gradients. In this article the concept of active system for control of temperature distribution on the foil surface is presented.

The first chapter introduces the enhanced construction of the bearing's bushing that embodies Peltier modules further used for gradient removal, what is presented in the consecutive chapters. Next the metamodeling process is described. As a result the control currents values are determined showing ultimately the effectiveness of the introduced cooling technique.

2 ENCHANCED BUSHING/CARTRIDGE CONSTRUCTION OF FOIL BEARING

The principle of operation of air bearings is based on hydrodynamic action, which is generated by the rotating shaft. Two surfaces in relative motion generate pressure in fluid, which for gas bearings is usually air. Generated pressure creates force, which pushes away rotating shaft and makes the bearing contactless. There are several foil bearings generations, but only three of them are widely used in industry [8]. Differences between particular generations are related to stiffness varying along the axial, radial or both directions at the same time. Number of bump and top foils may also differ, but the general principle of operation stays the same. In this article a bearing that falls between first and second generation is considered.

The 34mm diameter air bearing has been considered in this paper. Figure 1 shows foil bearing which consist of: bronze bushing with 40mm width and 65mm outer diameter (left), top and bump foils made of Inconel 618 (right). Foils are attached to bushing in three slots. Thanks to press fitting between bearing and journal, no soldering or gluing is required. Top and bump foils thickness is only 0.1mm which makes whole structure very sensitive to damages.

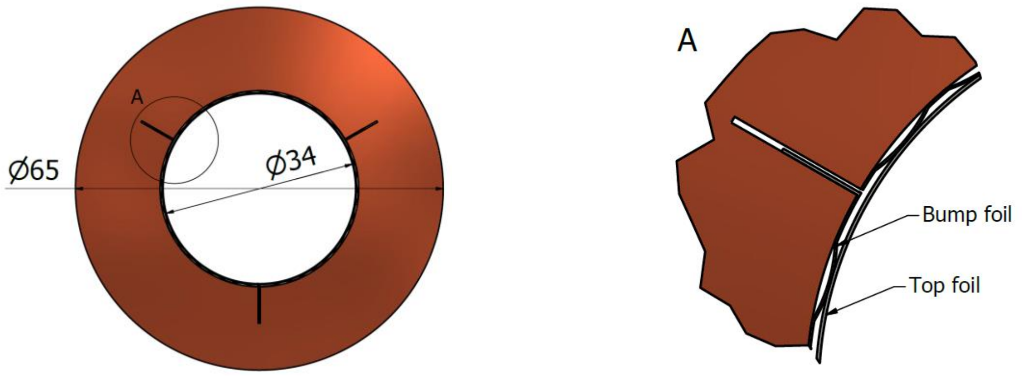

Fig. 1. Foil bearing. Bushing has 65mm outer diameter and 40mm width. Detail A shows top and bump foils attached to bushing by special slot.

Creating operating foil bearing model involves taking into account the phenomena related to fluid mechanics, structural mechanics and heat transfer. Top and bump foil numerical models were presented by the authors [9]. Simulations of film pressure were shown by [10]. Issues related to thermal management of foil bearings were widely described in following papers [11-14].

Based on aforementioned references, Nummerical (FEM) model of foil bearing enhanced by thermoelectric coolers was created in ANSYS environment. Figure 2. Shows general view of air bearing with integrated thermoelectric coolers. Compared to original foil bearing, aluminum spool and Peltier modules were added. Complex structure of bump foil is shown on Figure 3.

Mesh convergence test was performed in order optimize computation time. Boundary conditions includes: heat generation rate in air film which represents heat dissipation in operating bearing and convection attached to outer bearing surfaces.

Peltier modules are extremely sensitive to mechanical strain. Therefore aluminum spool was placed between thermoelectric modules and bump foils. This solution prevents Peltier modules from being damaged by torsional forces. Bushing was cut into three pieces to allow parts assemble. Analytical model of thermoelectric modules has been implemented after [15]. Data provided from commercial Peltier modules manufactures were used. Thermal resistance, Seebek coeficient and electrical resistance were provided and implemented into the model.

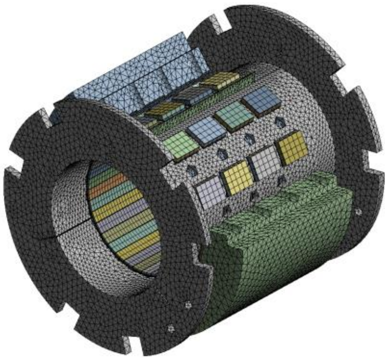

Fig. 2. Foil bearing enchenced by thermoelectric coolers

Figure 3. Bump foils assemble

The idea is to use Peltier modules to locally induce higher heat transfer rates from top and bump foils to bushing. Modules, in total number of 36, were arranged in four rowes on the bearing circumference. Each of them can be controlled independently. Heat can be transferred from areas of increased temperature to bushing which will results in local cooling and therefore will directly lead to thermal gradient reduction. This method only requires to transfer a small amount of heat to take the effect.

During the first step of numerical study the case with no current flow through the thermoelectric modules was considered. Figure 4 presents the temperatures measured along the circumference of the top foil, at the central transverse cross-section. The angular resolution for the measurement equals 10deg. Similarly, the temperature distribution along the longitudinal direction is shown in Figure 5. For the latter plot the cross-section which exhibits the greatest temperature for the whole bearing is taken into account. The shape of the curve referring to the longitudinal temperature distribution seems quite irregular - due to geometric longitudinal discontinuities, but still remains symmetric with respect to the center of bearing. The absolute scatter is only 3.4degC and is much less than the respective range of variation determined for circumferential distribution, which is 15.58degC, for the central cross-section. Taking into account the similarities regarding temperatures determined for longitudinal distribution, the authors decided to group every 4 thermoelectric modules localized at the same circumferential position for more convenient control of the currents.

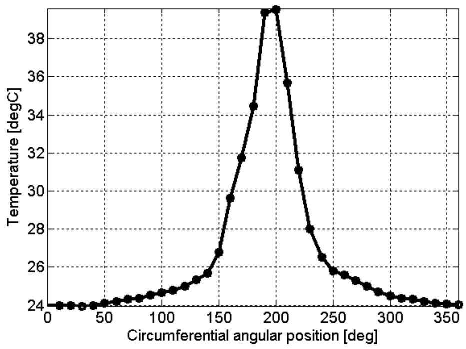

Figure 4. Circumferential temperature variation for the central transverse cross-section of the bearing.

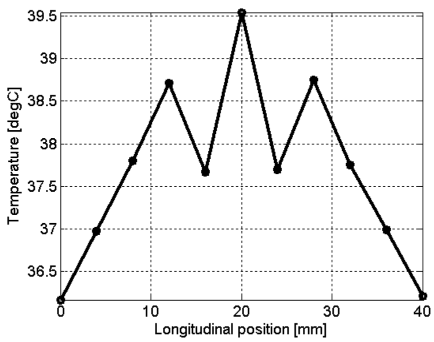

Figure 5. Temperature variation for the longitudinal cross-section exhibiting the highest temperature measured for the bearing.

Next, the temperature measured on the top foil was analyzed for the arbitrary selected 8 thermoelectric modules, located in proximity of the region where the maximum temperature was identified (please refer to the localizations P3 and P4, each involving 4 thermomodules as shown in Figure 5 on left). For the analyzed case the selected modules were commonly supplied with same value of the current, gradually increased up to 3A. The results of this analysis are shown in Figure 6.

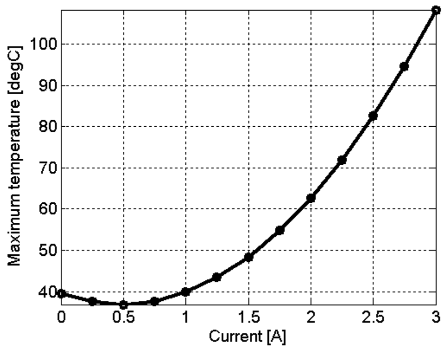

Figure 6. Change of the maximum temperature determined at the top foil and for different values of electric current flowing through selected thermoelectric modules

As noticeable, when the current grows up to 0.5A the overall temperature of the top foil drops, which shows an effective heat transfer towards outer parts of the bearing. However, when the current is continuously increasing this inevitably leads to warming up of the whole structure. A quadratic relationship is visible between the current and the maximum temperature. Based on the above observation regarding the model's behavior, the ranges of allowed variation of the currents applied to the modules were arbitrarily set to 0-1A.

3 REDUCTION OF THERMAL GRADIENT

This section discusses the perspectives of thermal gradient reduction by making use of metamodeling technique application [16]. The main objective of the work is to search for a configuration of the currents supplied to the thermoelectric modules that may lead to effective reduction of the temperature gradient for the top foil. At this point, it should be however noted, that the reduction of the overall temperature of the whole bearing is not considered critical for the present study, as less important for the operation characteristics and performance [2].

The process of the search through the input parameters domain (i.e. a multidimensional space with the currents defined as the studied parameters) was aided by the application of Response Surface Method (RSM) [17]. This technique, if reasonably applied - i.e. with proper design of experiment and orders of used approximating polynomials - may be useful to accurately approximate the relationships between the input (design) parameters and chosen properties of a numerical model. There are known different application areas for effective RSM-based analyses, including variety of types of mechanical structures, also of different geometric scales [18-20]. The approximating formulas may operate on a multidimensional continuous input domain ready to be used for checking potentially infinite number of design configurations, which is the case for the present search of effective thermal gradient reduction.

The preliminary analysis assumed the application of arbitrarily selected 6 groups of thermomodules localized close to the region exhibiting the highest temperatures, as shown in

Figure 7. All considered modules were independently supplied with the currents form the range 0-1A. Moreover, the order of used polynomial approximation was selected based on the physical nature of the simulated phenomena. While metamodel fitting procedure, the three values of the currents were considered: 0, 0.5A and 1A. The temperature scatter - considered as a good approximation of the actual thermal gradients within the top foil - was set to be the output parameter of the metamodel. High quality of the determined metamodel was confirmed with the results of simulation for additional randomly generated current configurations.

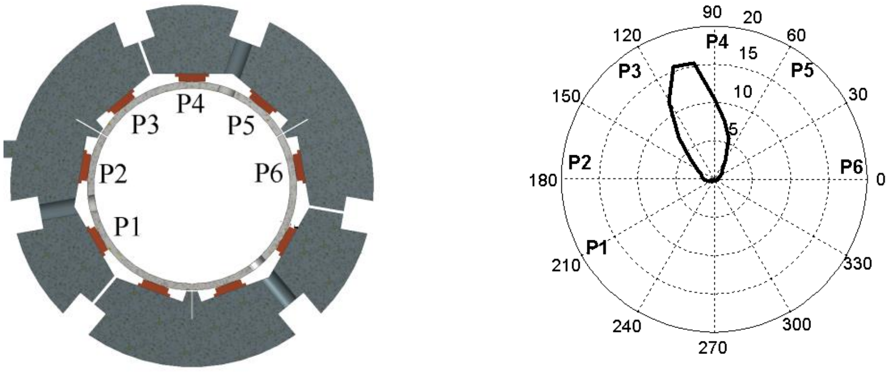

Figure 7. Localization of the selected thermos modules used to reduce thermal gradient (left) and temperature profile in polar coordinate system (right)

The search for an effective current configuration was performed applying uniform and dense coverage of the domain metamodel. Each of six groups of modules could be supplied independently by the current 0-1A with the step of 0.1A.

A deterministic search (performed with fast enumeration of all configurations) allowed to find the following currents configuration:

- $I = 0.8A$ for the module P3
- $I = 1A$ for the module P4
- No currents for the modules P1, P2, P5 and P6

The comparison between temperature profiles for both the case with no currents flow and the found configuration is presented in Figure 8.

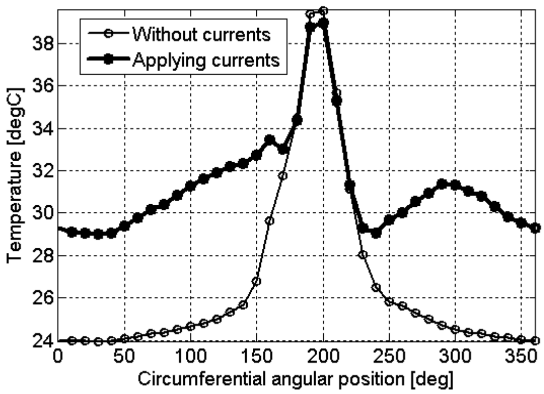

Figure 8. Circumferential temperature scatter for the central transverse cross-section of the bearing for the found currents' configuration.

The temperature scatter decreased from 15.6degC down to 10.5degC which means the reduction of 32.7%. The relative error for the temperature scatter found with the metamodel (10.4degC) and the above mentioned value found with FEA for the selected configuration (10.5degC) is less than 1%. The maximum temperature for the whole bearing was even slightly reduced from 39.5degC down to 38.9degC, which is an additional advantage of the found current configuration.

3 SUMMARY

The proposed concept of local thermal management for the foil bearings proofed to have the capabilities to reduce the radial thermal gradient by one third while the calculated energy expenditure was at the level of 5W. The important flaw of used method is that the absolute temperature of the bearing cannot be significantly reduced due to insufficient heat pumping capabilities of the thermoelectric modules. On the contrary, the available comparatory study [4] shows the forced air flow can reduce the absolute bearing temperature as far as 20%, 13% and 60% for direct, indirect and axial cooling method respectively. The thermal gradient can at the same time be reduced by maximum 44%, 17% for direct and indirect method respectively. However, the axial air flow had an adverse effect on the axial thermal gradient giving maximum rise of 46%. Compared to this study the use of thermoelectric modules has potential to reduce the thermal gradient to at least the same extent as other methods. However, the energy cost of this operation is minimal due to the fact that the proposed approach is based on a local heat flow unification in the thin foil rather than cooling the whole volume of the bearing. What is worth taking note of is that only 8 out of 36 modules were used to get the this significant gradient reduction. The preliminary study also revealed that good effects can be achieved not only with sole cooling but also with thermoelectric modules working in mixed mode i.e. some of them cooling while others heating the foil at the same time. The implementation difficulty is related to the size of the whole bearing assembly (35mm of bearing diameter). This is especially seen, since to implement the control scheme several temperature measurement points are necessary. Due to the small size and large number of modules used the spatial distribution of the thermocouples has to be reduced and the control strategy has to be simplified. Moreover, the control scheme needs to respond in automatic manner providing the control currents by adapting to the machine state of load. Currently the metamodeling technique was used in order to select the control currents to get best results on the assumption that only circumferential gradient is addressed. The future works will cover both axial and circumferential gradient removal as well as elaborating the control law based on the metamodel.

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