sciendo
DOI: 10.1515/agriceng-2019-0035

ISSN 2083-1587; e-ISSN 2449-5999
2019,Vol. 23,No.4, pp.41-51
Agricultural Engineering
www.wir.ptir.org

METHODS OF RESEARCH OF FOIL BEARINGS IN START-STOP CYCLE IN THE PRESENCE OF WORKING MEDIUM

Bartosz Moczulak[a*], Wojciech Miąskowski[b]

[a] Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, Poland, bartosz.moczulak@uwm.edu.pl, ORCID 0000-0002-4110-0273

[b] Faculty of Technical Sciences, University of Warmia and Mazury in Olsztyn, Poland wojmek@uwm.edu.pl, ORCID 0000-0001-6080-7357

Corresponding author: e-mail: bartosz.moczulak@uwm.edu.pl

ARTICLE INFO

Article history:
Received: October 2019
Received in the revised form: November 2019
Accepted: December 2019

Key words:
bearing
foil bearing
START-STOP tests

ABSTRACT

A method for testing sliding bearings with an elastic bearing liner was presented in the paper with a focus on the issue of selection of particular time intervals of the START-STOP test cycle. Then, results of the tests carried out according to the selected material combinations were presented. The working cycle of foil bearings tested on the test stand was performed in an automatic mode at the set number of sequences start-work-rundown-stop. Due to the highest use of sliding bearings during start and rundown of a machine, this type of tests is essential for selection of relevant sets of material for bearing elements. The article also presents the use of a thermo-visual camera for identification of additional thermal loads and manners of temperature stabilization in the test chamber.

Introduction

Fast-rotating power machines have a complex work cycle. It is mainly an extended period of operation in set conditions and short time of runup and rundown. Bearings with an elastic bearing liner, such as foil bearings, operate as aerodynamic or hydrodynamic sliding bearings using viscosity of the surrounding medium for production of the load-bearing wedge (DellaCorte, 1998; Howard and San Andres, 2011).

Within the range of loads that do not exceed the bearing capacity, there is no direct contact between a shaft neck and an elastic liner of a bearing. The most important for wear and tear of the bearing system elements is runup and rundown of a machine. At the beginning of the runup, a sliding foil is pressed onto the shaft neck, thus an intensive friction phenomenon occurs here which causes wear and tear of the bearing unit. A foil bearing (fig. 1), except for typical elements from which foil bearings are built of, is equipped with an elastic liner comprising a sliding foils unit (top foil) and supporting foil unit (bump foil) (Daejong and Soongook, 2009; Miąskowski et al., 2017).

The use of elastic liner foil units causes that rotors of machines placed in those bearings show a higher resource of stability since the shape of the oil gap in a bearing during its operation regularly adjusts to present conditions. On the other hand, worse suppressing properties of the oil film are at the same time compensated with suppression of the bump foil (Kiciński and Żywica, 2010; Kiciński et al., 2010; Miąskowski et al., 2009b; Miąskowski et al., 2017).

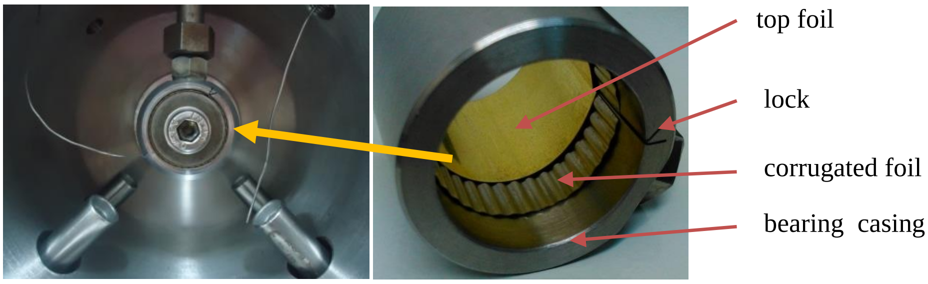

Figure 1. View of the exemplary bearing set prepared for tests

Tests of foil bearings dedicated for work in the working medium environment used in devices in which foil bearings were applied, require special procedures and test devices to be applied.

The aim of the stage of work presented in this article, is determination of the START-STOP method of testing, which will be used for foil bearing elements developed by a team consisting of authors of this article. The procedure also includes the process of selection of time intervals of the measurement cycle, that influence the stabilization of the temperature of the factor in the test chamber.

A test rig in START-STOP cycle

The presented test stand enables the START-STOP test in the presence of a medium, which may be a working medium which supplies power micro-turbines simultaneously used for smearing bearings at the strictly defined working conditions. Tests of foil bearings in the START-STOP cycle discussed in this article, very well determine the life span of working elements of foil bearings, in particular of top and bump foils (Miąskowski et al., 2009a; Michalak et al., 2014; Miąskowski et al., 2017). The described stand was developed as a part of the project POIG.01.03.01-00-027/08-00 realized at the Faculty of Technical Sciences of the University of Warmia and Mazury in Olsztyn as a part of the Operational Program Innovative Economy 2007-2010 co-financed by the European Union.

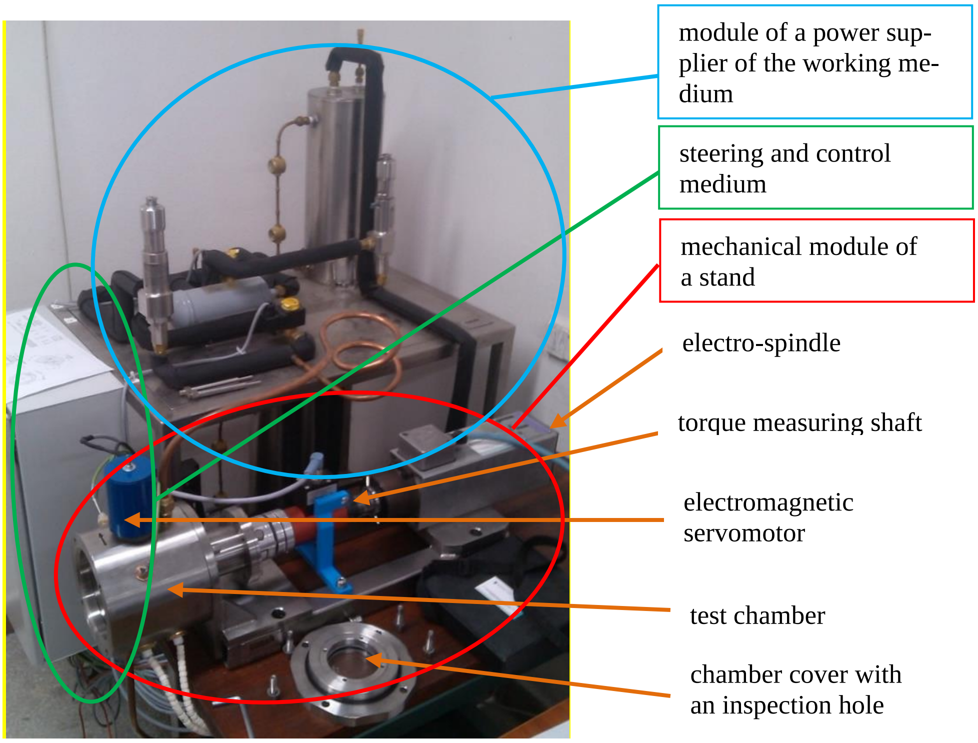

Figure 2. Test rig in START-STOP cycle in the presence of a medium

The main task of the test rig in the START-STOP cycle is to ensure testing conditions for foil bearings, similar to the conditions that are present in the device, for which they were designed. Taking into consideration a considerable scope of variability of working conditions and physical states of the working medium, it is necessary to control the temperature and pressure in the chamber and to ensure tightness of the chamber in the presence of the low-boiling medium under high pressure and in the raised temperature. The next especially important task of the stand is automatic control of the process of data acquisition. This is predominant due to a great time consumption of the tests. A driving system of the test stand in the START-STOP cycle (Fig. 2) is equipped with electro-spindle with the power of 2.2 kW and the rotational speed of 24000 rpm. It cooperates with an inverter that serves for regulation of the rotational speed of the electro-spindle and the automatic control system which ensures the START-STOP cycle test and the measurement of parameters of the work of the system. The drive is provided from the electro- spindle to the measurement chamber through a torque measuring shaft which provides information on the value of the rotational moment and the rotational speed.

A test chamber (Fig. 3) of the stand serves for the START-STOP cycle tests with a working medium. A unit of working foils of a bearing is placed in the housing connected with an electromagnetic servomotor for induction of a transverse load of the investigated bearing. Inside the chamber, a working medium is maintained in the set physical state (liquid, moist or dry steam). A working medium is supplied to the test chamber from the supply system with a connection pipe placed in the upper part of the chamber and removed in the bottom part.

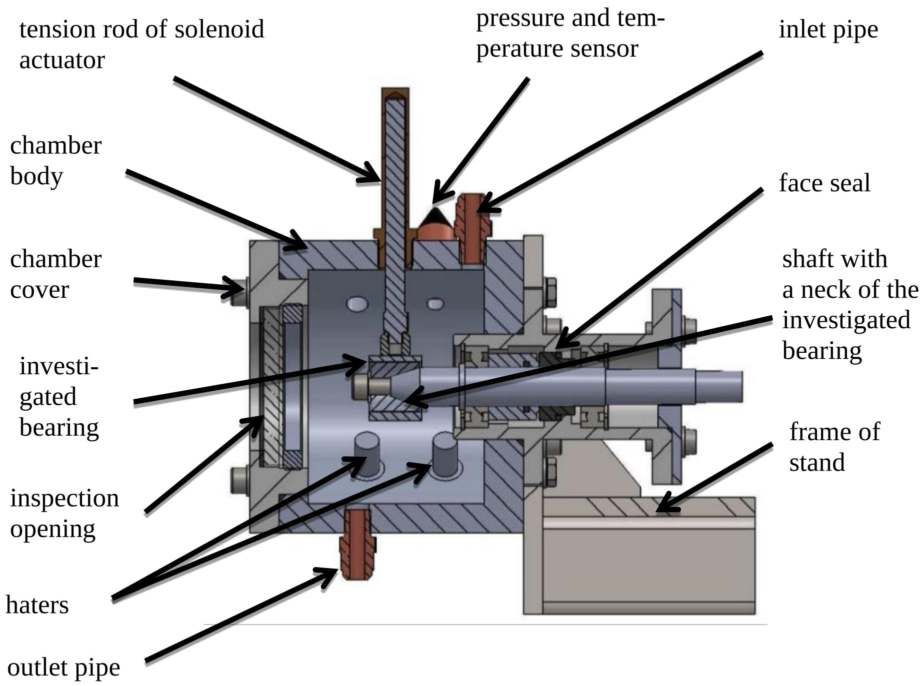

Figure 3. Test chamber of the stand (Nalepa et al., 2013)

Inside the chamber, a working medium is maintained in the set physical state (liquid, moist or dry steam). Heating elements which heat the working medium in the chamber, combined with the supply module of a working medium enable obtaining the required conditions of temperature and pressure of the working medium. A working medium is supplied to the test chamber from the supply system with a connection pipe placed in the upper part of the chamber and removed in the bottom part. A detailed description of the test stand was placed in (Nalepa et al., 2013).

Test methods in the START-STOP cycle

The aim of the tests in the START-STOP cycle is to assess cooperation of working foils which constitute an elastic part of a bearing liner through a measurement of the torque in the start-work-rundown- stop cycle, as well as measurement of the loss of mass in case of some foils. The START-STOP tests referred to foil bearings are crucial since the basic reason for the use of foil bearings is friction between working elements of a bearing, mainly of a sliding foil and a shaft neck which takes place during runup and rundown of a machine and momentary overloads of a rotor. Tests in the form of a many times repeated cycle enables determination of the endurance of foil bearings. It also enables determination of the basic exploitation parameters such as bearing capacity and the resisting torque during start and rundown which may decide on the usefulness of some structural solutions of foil bearings and suggested material combinations on working elements of the built bearings. Pairing material combinations for sets of working foils and a shaft neck takes place based on the previously obtained information from the tests on the wear and tear of friction couples prepared from materials that were selected for working elements of foil bearings. This type of tests is performed in a combination of foil-roll on the test rig that was prepared for this purpose as a part of the project POIG.01.03.01-00-027/08-00. Results of works were placed as an example in (Komar, 2015). These tests constitute one of the first stages of works on selection of materials for particular elements of foil bearings. Another stage of the works are START-STOP tests, methods of which are described in this paper.

Preparation of the bearing to the research

Before the tests are initiated elements of the foil bearing should be precisely cleaned (degreased and washed in the ultrasound washer) and then mass must be measured according to the test procedure. After cleansing and weighting of elements of a bearing they must be assembled (Fig. 1) and then the prepared sample must be mounted in the test chamber (Fig. 3). During installation of working foils (top and bump foil) in the casing of the bearing one should pay attention to setting of corrugated foil and smooth foil towards each other and towards the direction of the shaft neck rotations. Top foil is based on the corrugated foil and cooperates directly with the shaft neck. The system of deformable elements is based on the stiff sleeve of a casing of the bearing. After the bearing is placed in the test chamber (Fig.3) a relevantly selected setting of a sample should be entered to the program. They will result directly from real conditions of the bearing work (type of a medium, physical state, temperature range etc.) as well as the process of its testing on the test stand.

Selection of time intervals of the test cycle

One of the most important set parameters are particular time settings of the cycle. Their values will depend on both the operational parameters of the bearing, its geometry, and the physical state of the medium and the range of temperature variability. The working cycle of a foil bearing tested on the test stand is performed in an automatic mode at the set number of sequences start-work-rundown-stop. Figure 4 presents the course of changes of the speed with time intervals of the test cycle.

During the runup and rundown, a considerably increased resisting torque of motions in foil bearings occurs which results from forming of the load-bearing film (runup) and its fading (rundown) during a relatively low rotational velocities of a rotor and the initial grip of the sliding foil on the shaft neck. During the first and the last phase of the cycle, the size of the resisting torque of the motion results from the friction force which depends on the friction coefficient between the surfaces of the foil and shaft neck set and the grip force of the working foil on the shaft. Moreover, the temperature increase is influenced by the heat release by a ball bearing which supports the main shaft directly at the working chamber.

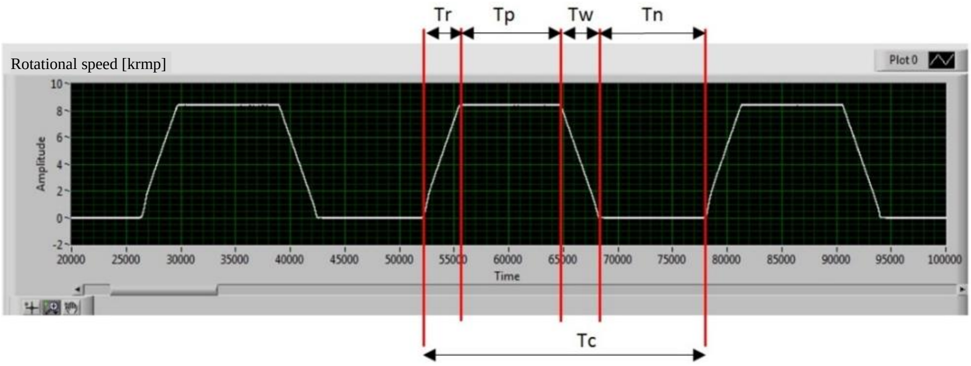

Figure 4. Course of rotational speed of changes during a test cycle: Tc – duration of cycle, Tr – runup time, Tp – working time, Tw – rundown time, Tn – stop time

As a consequence of the above described phenomena, considerable amounts of heat are released (Fig. 5) which cause the increase of the medium temperature inside the test chamber. Due to the limited possibilities of the medium exchange during the test, two methods of stabilization of the temperature increase are suggested. The first one, is an increase of the heat reception speed by cooling of the chamber casing. The second one, is selection of relevant time intervals of the cycle in order to reduce the heat increase (reduction of the runup and rundown time) or extension of the time between the periods of the increased heat release (optimization of the working time and the stop time).

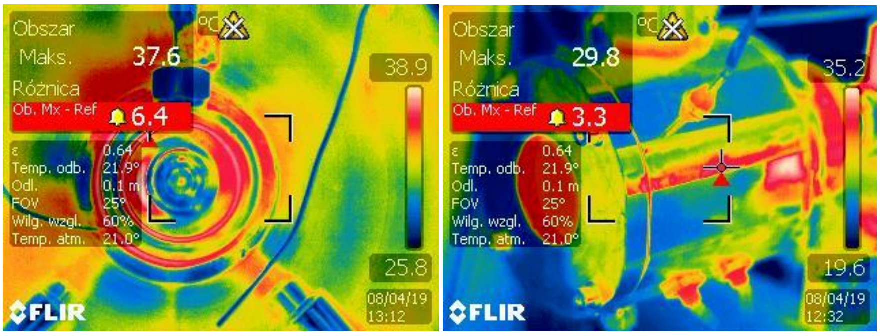

Figure 5. Image from thermo-visual camera

Exemplary discussions on the selection of time intervals of the test cycle through analysis of the impact of particular time intervals on the increase of the temperature of the factor in the test chamber was presented below. Figure 6 presents the set of exemplary characteristics which picture the temperature increase for four selected cases:
Variant 1 - time settings: Tr = 3 (s), Tp = 3 (s), Tw = 3 (s), Tn = 3 (s),
Variant 2 - time settings: Tr = 3 (s), Tp = 2 (s), Tw = 3 (s), Tn = 3 (s),
Variant 3 - time settings: Tr = 3 (s), Tp = 2 (s), Tw = 3 (s), Tn = 10 (s).

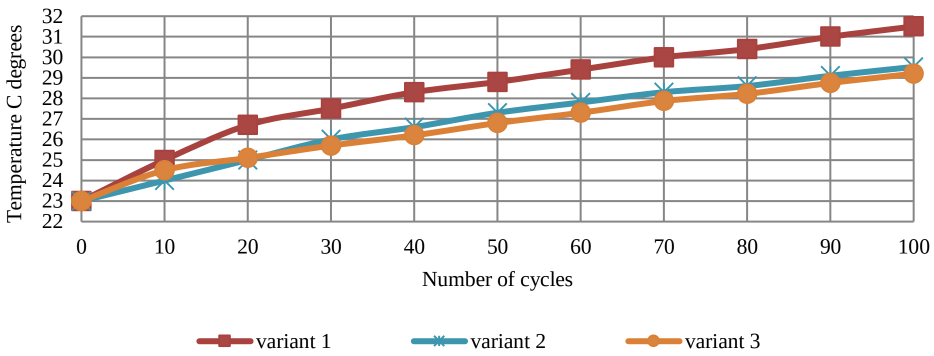

Figure 6. Exemplary data from time selection tests of START-STOP cycle

The cycle time should be selected each time when conditions of operation of a bearing change, e.g. medium change, change of friction force (friction coefficient - materials, grip force). In the presented case, analysis was carried out for the low boiling working factor HFE7100, foils made of copper 2.0321 (top foil) and bronze CuA17 (corrugated foil). A gripping force of foil on the shaft neck was the same for all the presented ones.

Analysis of the course of temperature changes for particular cases shows that it is favourable to accept short times of runup and rundown and the working time. Extension of the break time Tn to 10 s for the investigated case brings smaller effects than the change of the remaining intervals.

Input parameters and measurement data

START-STOP tests consist in a cyclic runup, work in the set conditions and rundown of the tested system and in observation of parameters of work of the bearing to the end of the test consisting of the set number of cycles or to the damage of the tested bearing. Therefore, there is a need to set and acquire determined parameters of work of the investigated bearings (number of set cycles of the test, nominal rotational speed of the bearing work, runup time from stop to the nominal speed, time of operation at the nominal speed, rundown time from the nominal speed to the stop, the stop time between cycles, transverse load of the bearing, moment of resistance of motions in the bearing, parameters at which damage to the bearing occurred, temperature in particular stages of the cycle, etc.) The process of control and acquisition of data on tests in the START-STOP cycle is automatic and the parameters of tests are set through a computer application.

Assessment of wear and tear of the elements of bearings

Observation and analysis of consumption of particular elements of the tested foil bearings may be carried out in a qualitative and quantitative mode. The first stage is assessment of consumption which consists in visual inspection (Fig. 7) of particular elements of a bearing starting with top foils and ending with a stiff liner. Extension of that assessment is possible thanks to microscopes and profilographs which serve for measurement of roughness, corrugated nature, and shape e.g. with an optical method. The use of profilographs enables assessment of the depth of scratches, channels and craters which result from friction of cooperating surfaces (Komar, 2015).

It is necessary to clean the elements subjected to the quantitative analysis before assessment. These elements include units of foil which are an elastic part of the liner, which were cleaned in isopropanol of high cleanness with the use of an ultrasound washer. Directly after cleaning and drying, measurements of their mass with the use of precise scales e.g. electronic weighting and drying machines Radwag MAC 50/1/NH are performed, as in case of tests which were performed by the authors of this article.

Figure 7. Image of exemplary units of working foils before tests and after 500 START-STOP cycles

Analysis of the mass consumption is made by means of the measurement of mass of the cooperating elements before and after the test run, but quality determination of the product consumption is impeded as well as the level of their diffusion between friction elements without a possibility to test the surface of the investigated elements under a microscope.

Exemplary results of tests

The exemplary results of tests presented in this paper were obtained in the tests performed according to the above method for the selected material couples. Due to various material associations, it was assumed that the operation cycle of the foil bearing on the test was carried out in the automatic mode for the sequence start- work- rundown-stop (Tr = 3 (s), Tp = 3 (s), Tw = 3 (s), Tn = 3 (s)). The number of cycles START-STOP for the presented results in figure 10 was 200. All tests were carried out in the surrounding of the low-boiling medium (HFE7100) at the rotational speed of a spindle from 0 to 8500 rot/min for the same structure of the working foil (Fig. 7). The course of speed and the resisting torque of motion of the investigated foil bearings was presented in fig. 8.

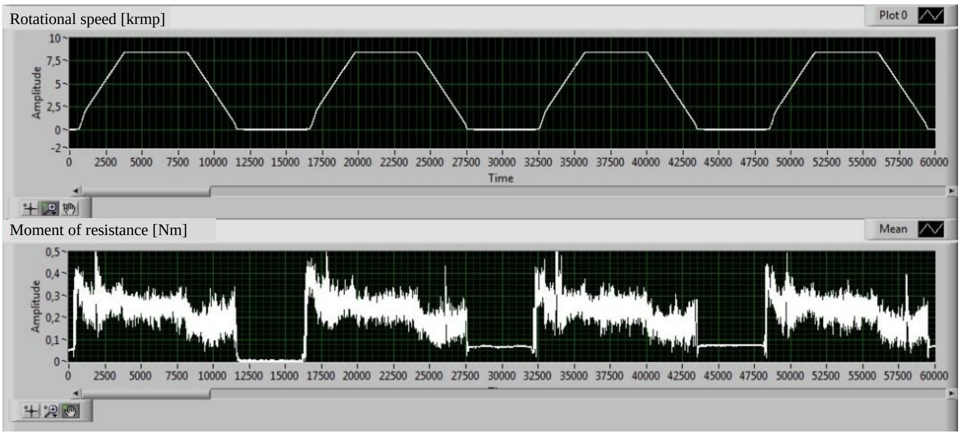

Figure 8. Course of changes of the rotational speed and the moment of resistance of bearing during START-STOP test (197-200 cycles)

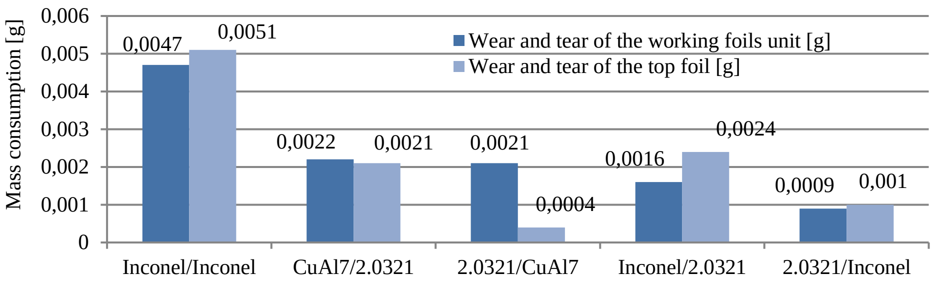

Figure 9. Mass consumption of selected elements of foil bearing (sliding bearing and the unit of working foils)

In the period of the runup of the bearing, the highest resisting torque of the motion can be seen, which is caused by the friction of the shaft neck and foil on the surface before formation of the load-bearing film (top foil gripped on the neck). After the set rotational speed of a spindle was achieved, a decrease of the value of the moment is visible, which is caused by formation of the load-bearing film and its stable course during the bearing operation in the set conditions. During the rundown, at the beginning a decrease and then increase of the resisting torque can be reported, which proves a reduction of the load-bearing nature of the oil film and as a result with a mixed friction and in the final stage almost completely dry air of the neck and top foil of the tested bearing. Based on the measurements of the mass of working foil units (and particular top and bump foil) before and after introduction to the test cycle, a degree of the mass consumption of particular combinations of material couples was determined. The set of results was presented in the form of the column graph in Fig. 9.

All presented courses of speed and the moment of resistance of the bearing motion confirm a correct operation of the foil bearing and a low consumption of material combinations resulting from a small number of test cycles (200 cycles). It proves a proper operation of the investigated bearing in the presence of the low-boiling medium and formation of the stable smearing film.

Conclusion

Observation of the distribution of temperature in the working chamber with the use of the thermo-visual camera may take place only after the chamber cover is removed. Thus, the draft observation of cases of filling the working chamber with the medium in the form of liquid, gas and/or mixed states will not be possible.

Factors that directly and indirectly influence the temperature in the test chamber enforce a need to remove heat from the chamber, in particular at lower temperatures of the working medium. Temperature may be stabilised in the chamber through adding the system of fans to the outside surface of the test chamber or the use of thermo-electrical materials for temperature stabilization e.g. Peltier modules, and selection of the duration of particular time intervals in the measurement cycle.

The cycle time should be selected each time when conditions of operation of a bearing change, e.g. medium change its temperature and physical state), change of friction force (friction coefficient- materials, grip force, transverse load).

The results placed in figure 9 enable a conclusion that the lowest consumption of the top foil took place for the couple brass 2.0321/CuAl7 and the working foil unit couple bronze CuAl7/Inconel. One should bear in mind, when analysing the results of the START-STOP tests that in case of soft materials mixing of material between working foils may take place.

Another stage of the works will include tests for selected various configurations of materials and structure of elements of the investigated foil bearings at the increased number of cycles which makes the tests very time-consuming.

References

Daejong, K., Soongook, P. (2009). Hydrostatic air foil bearings: Analytical and experimental investigation. *Tribology International, 42,* 413-425.

DellaCorte, C. (1998). A new foil air bearing test rig for use to 700°C and 70,000 rpm. *Tribology Transactions 41(3),* 335-340.

Howard, S.A., San Andres, L. (2011). A new analysis tool assessment for rotordynamic modeling of gas foil bearings. *Journal of Engineering for Gas Turbines and Power, 133(2),* 022505.

Kiciński, J., Żywica, G., Miąskowski. W. (2010). The Dynamic Properties of the Micro-Rotor Supported on Fluid-Film Bearings, *IFToMM International Conference on Rotor Dynamics,* Seoul (South Korea), 681-685

Kiciński, J., Żywica, G. (2010). The numerical analysis of the steam microturbine rotor supported on foil bearing, *Advances in Vibration Engineering, 11(2),* 113-119.

Komar, W. (2015). Analiza zużycia cienkiej folii metalowej. *Mechanik 7,* 417-424.

Miąskowski, W., Nalepa, K., Żywica, G. (2009a). Foil micro-bearing tests. *Technical Sciences, 12,* 249-258

Miąskowski, W., Pietkiewicz, P., Żywica. G. (2009b). Modelling foil bearing. *Technical Sciences, 12,* 241-248.

Miąskowski, W., Moczulak, B., Nalepa, K., Pietkiewicz, P., Komar, W. (2017). START-STOP analysis of high-speed bearings with a flexible bushing. *SGEM2017 Vienna GREEN Conference Proceedings, 17(63)*, 69-76.

Michalak, M., Michalczewski, R., Piekoszewski, W., Szczerek, M., Wulczyński, J. (2014). Urządzenie do badania odporności na zużycie materiałów przeznaczonych na elementy łożysk foliowych. *Tribologia*, 3, 131-142.

Nalepa, K., Miąskowski, W., Pietkiewicz, P., Miazio, Ł. (2013). Stanowisko do badania łożysk foliowych w cyklu START-STOP w obecności czynnika niskowrzącego. *Mechanik, 7,* 519-524.

METODYKA BADAŃ ŁOŻYSK FOLIOWYCH W CYKLU START-STOP W OBECNOŚCI CZYNNIKA ROBOCZEGO

Streszczenie. W artykule przedstawiono metodykę badań łożysk ślizgowych z elastyczną panwią, skupiając się na zagadnieniu doboru poszczególnych przedziałów czasowych cyklu badań typu START-STOP. Następnie zaprezentowano wyniki badań przeprowadzonych według przyjętej metodyki dla wybranych par materiałowych. Cykl pracy testowanych łożysk foliowych na stanowisku badawczym przeprowadzony był w trybie automatycznym przy zadanej liczbie sekwencji *rozruch-praca-wybieg-przerwa*. Ze względu na największe zużycie łożysk ślizgowych podczas rozruchu i wybiegu maszyn, badania tego typu są kluczowe w doborze odpowiednich zestawów materiałów na elementy łożysk. W artykule przedstawiono również wykorzystanie kamery termowizyjnej do identyfikacji źródeł dodatkowych obciążeń termicznych oraz wskazano sposoby stabilizacji temperatury w komorze badawczej.

Słowa kluczowe: łożysko, łożyskowanie, łożysko foliowe, badania START-STOP