Journal of Machine
Construction
and Maintenance
PROBLEMY EKSPLOATACJI
QUARTERLY
ISSN 1232-9312 2/2017 (105)
p. 7–17

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NONLINEAR PHENOMENA IN MICROTURBINE DYNAMICS

Key words: dynamics of rotors and slide bearings, ORC microturbines, hydrodynamic instability, distributed power engineering.

Abstract: This paper presents the results of the analysis of the dynamic performance of a rotor that is a component of the ORC turbine set with the net electrical output of 100 kW and the nominal speed of 9000 rpm. This device is dedicated for municipal Local Energy Centres (LEC).
The research was conducted using tools capable of performing the necessary simulation of the system operating under highly unstable conditions, i.e. in a strongly nonlinear regime. In this regard, the author of the paper followed the subsequent phases of whirl/whip formation manifested in the fluid film. Three constructional solutions within the scope of the bearing were examined with conventional and non-conventional lubricating mediums (mineral oils and low boiling mediums). An approach using rolling bearings was also considered. On the basis of those scientific studies, the decision to build a working prototype of the machine was taken. Such a prototype has already been manufactured, having regard to the outcome of the conducted analyses.

Nieliniowe zjawiska w dynamice mikroturbin

Słowa kluczowe: dynamika wirników i łożysk ślizgowych, mikroturbiny ORC, niestabilność hydrodynamiczna, generacja rozproszona.

Streszczenie: Praca przedstawia wyniki badań dynamiki mikroturbin ORC o mocy elektrycznej 100 KW i prędkości nominalnej 9000 obr./min. Urządzenie to jest dedykowane dla lokalnych klastrów energii (LEC). Badania przeprowadzone zostały za pomocą narzędzi badawczych umożliwiających ocenę stanu maszyny w warunkach jej niestabilnej pracy, a więc w zakresie silnej nieliniowości.
Autor pracy prześledził rozwój wirów i bicia olejowego powstających w filmie olejowym po przekroczeniu granicy stabilności. Przebadane zostały trzy warianty konstrukcyjne łożysk ze smarowaniem konwencjonalnym oraz niekonwencjonalnym (olej mineralny i czynniki niskowrzące).
Rozważony został również przypadek łożysk tocznych. Na podstawie uzyskanych wyników wybrana została wersja łożyskowania zastosowana przy budowie prototypu maszyny.

1. Preliminary remarks

Distributed power engineering based on low power devices, commonly called 'prosumer' or, more broadly speaking, 'civic' power engineering is an attractive and forward-looking direction for the growth of the energy sector. Distributed power generation is an outstanding addition to a traditional large-scale power generation, and a vision in which a citizen is not only the consumer but also the prosumer on the electricity market is a vision for the future.

Communities and municipalities that use local renewable energy resources, no matter how small, all have an important role to play. What we are referring to here are Municipal Energy Centres, Autonomous Energy Regions, or municipal Local Energy Clusters (LEC).

The concept of the LEC is not only an opportunity to enhance the national energy security policy, but also to support the development of rural areas and environmental protection.

It goes without saying that new technologies dedicated to specific needs are necessary for the development of local energy clusters (LEC). One such technology is a low power turbine set which is economically viable and simple to operate. An ORC (Organic Rankine Cycle) turbine operating with a low boiling medium continues to be an attractive solution. It can operate with low-temperature heat sources (such as waste heat or biomass boilers), and diagnostics of its operation is relatively straightforward.

In spite of numerous advantages of ORC turbines, their operation can give rise to a number of problems associated with a stable operation of the turbine rotor and the low boiling medium itself, especially if it plays a role as a lubricating fluid for the bearings. Furthermore, if an ORC turbine is to be used for the purposes of municipal energy clusters, its output power should be within the range of 0.1 MW to 1.5 MW, and very often even 50–250 kW. The turbine sets falling within this power range that are reliable, simple to operate, and driven by low-temperature heat sources are hardly commercially available. This fact inspired us to undertake our own research and develop production technologies for low power ORC turbine sets.

The author of this publication was the leader of the research team, acting as Project Manager in several EU funded research projects (FP7, BSR) and national projects (e.g., the strategic programme called New Energy Technologies). These works were co-financed by the national energy sector (including ENERGA SA as the main contributor to our projects). The majority of the experimental research was carried out at the Institute of Fluid-Flow Machinery Polish Academy of Sciences (IMP PAN) in Gdańsk, using state-of-the-art research infrastructure, the most modern in Poland.

2. Formulation of the problem

Designing and developing of low power ORC microturbines requires advanced analyses to be carried out, such as analyses covering all aspects of working medium selection, 3D flows of this medium (thus determination of aerodynamic interactions), gravity loads analyses, and analyses concerning mechanical vibrations of the whole system.

The analyses concerning the dynamic performance of the turbine set are particularly important, since the rotors mounted in machines of this type are characterised in general by high rotational speeds while being subjected to low static forces. This means that difficulties in maintaining stable system operation may be encountered, particularly if the rotor is supported by slide bearings. The final outcome includes the hydrodynamic instability during which a lubricating medium in the slide bearings quickly passes from whirl to whip which results in very dangerous mechanical vibrations of the entire system. The processes of this type can also be found in traditional high power turbine sets, but they are not as rapid or as common as in low power units.

In ORC turbines, if a low boiling fluid is to be used as a working medium in the turbine, there is always a temptation to use the same fluid as a lubricant for the slide bearings. This solution not only greatly simplifies the construction, it also makes it possible for the turbine – bearings system to form a whole and be mounted in a hermetic enclosure. It is a very attractive idea. Unfortunately, the low boiling agents used in ORC systems have extremely poor lubricating properties, and furthermore, a two-phase flow occurs relatively often in the lubricating film of the bearing, which adversely affects its operation.

The paper presents the research concerning the possibility of applying the low boiling fluids for lubricating the slide bearings being part of a hermetically sealed low power ORC turbine. The rapid passes of the working medium to a 'whip' state mean the system operates under conditions of developed hydrodynamic instability. A theoretical analysis of the system operation under such conditions can only be conducted with tools based on nonlinear (and even strongly nonlinear) vibration theory. The identification of phenomena occurring under such conditions was the main objective of the research presented herein. In this context, the fundamental question arises: Can non-conventional lubricating mediums be used in slide bearings to provide stable operation of a hermetically sealed low power ORC turbine?

The answer to this question was an essential objective for the author of this paper and was also a utilitarian aspect of the study. In order to respond in the most efficient manner possible, an analysis must be made consisting of the examination of the performance of slide bearings operating with conventional lubricating mediums (mineral oil) and the examination of the operation of the system equipped with rolling bearings. This approach will allow the author to evaluate the advantages and disadvantages of each solution and to take a final decision on selecting turbine design.

Figure 1 shows typical circulations of the working and lubricating mediums used in ORC turbines. In order to attain the above-mentioned objective of the study, the research shall be carried out for the following configurations of the circulations of the working and lubricating mediums:

- The working medium of the turbine and lubricating medium of the bearings are the same fluid;
- A low boiling fluid is used as a working medium for the turbine and the bearings are lubricated with a typical mineral oil; and

– The turbine rotor is supported by rolling bearings, and a low boiling medium is used only to set turbine blades in motion.

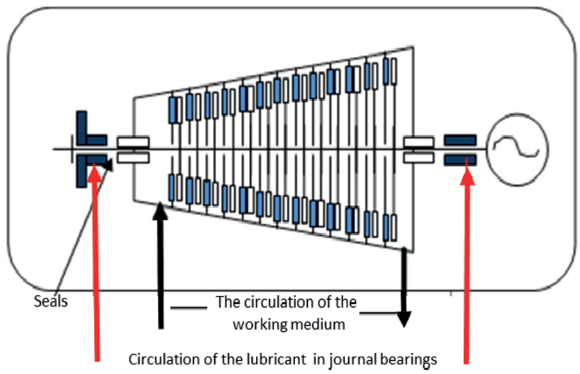

Fig. 1. Circulation of the working medium and the bearing lubricant in the ORC turbine

The following chapters present the results of the dynamic performance of the system for all three configurations of circulations of the working and lubricating mediums.

The issues related to the non-linear description of the rotors dynamics are the subject of research in many centres in the world [1–16]. An important part of these studies are microturbines in the context of distributed energy and renewable energy sources RES [15–18].

Published in recent years, EU legislation (Energy Road Map 2050, SET Plan, Horizon 2020) clearly determine the path for energy system development based on RES, in particular, small-scale and distributed [16].

3. The object of study and research tools

The object of the study was a multi-stage axial ORC turbine offering the power capacity of 100 kW at rated speed (9000 rpm). The working medium is a low boiling fluid from the group of silicone oils. The turbine is to be used in the Local Energy Cluster situated in the municipality of Żychlin. The municipality has about 12 000 inhabitants. Its energy needs have so far been secured by an outdated coal-fired boiler house. Within the framework of the national strategic project entitled *New Energy Technologies*, the ENERGA SA power concern and the IMP PAN in cooperation with other scientific entities decided to build a modern CHP (Combined Heat and Power) plant in place of the old boiler house. It will be equipped with highly advanced equipment, including, among other things, an ORC module operating all year round.

The municipality of Żychlin – as the first in Poland – can be proud of the Local Energy Cluster (LEC). The turbine set operating with a low boiling medium is the heart of the ORC module. The basic operational parameters of the turbine (i.e. 100 kW and 9000 rpm) result from the feasibility study of the project and the modernization concept of the municipal heating station. Detailed technical and economic analyses go beyond the scope of this paper.

The modern laboratory infrastructure located at the IMP PAN in Gdańsk was applied for research purposes, including, among other things, the ORC installation operating with low boiling fluids and the slide bearings installation (see Fig. 2). These are the most modern installations of this type in Poland.

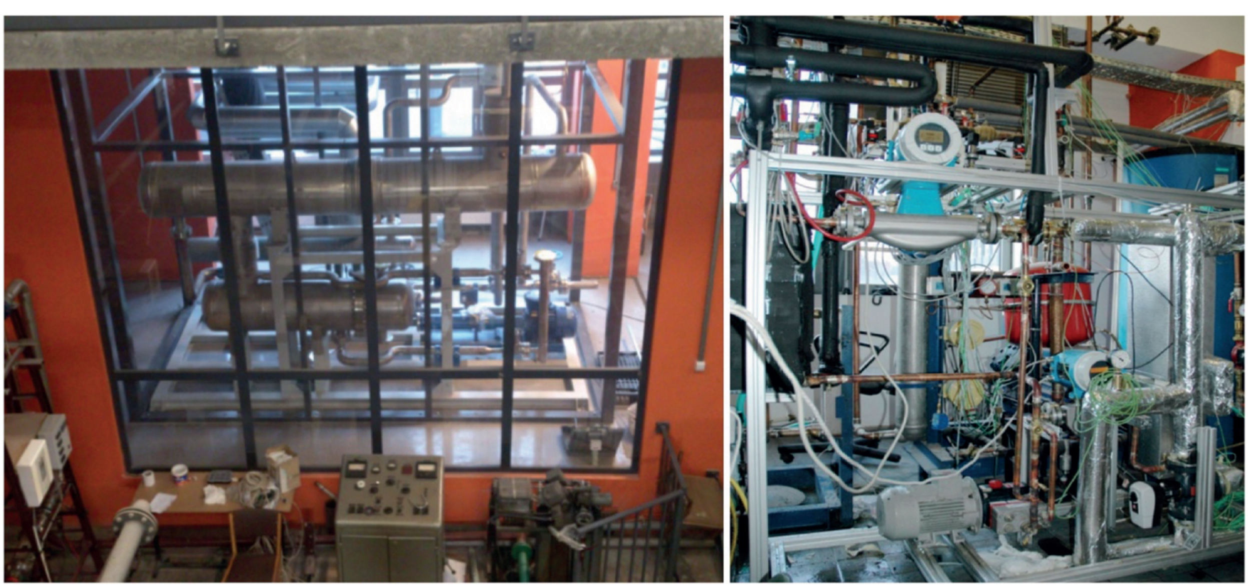

Fig. 2. Micro Power Plant Laboratory situated at the IMP PAN in Gdańsk – ORC installation (on the left) and slide bearings installation (on the right). These installations were used for research on a 100 kW ORC turbine

The thermal and flow computations were carried out by means of popular commercial software (Fig. 3). The software made it possible, on the one hand, to determine the profiles of the blades and the whole aerodynamic system, and on the other hand, to identify the distribution of the axial aerodynamic forces acting on the rotor. The static loads acting on the rotor were established on the basis of the rotor geometry and the distribution of masses.

It is also important to determine external excitation forces affecting the rotor during its operation. I have in mind here the residual unbalance of the rotor. Since it was accurately balanced, the residual unbalance of 140 g·mm was adopted, complying with standard ISO 1940/2 for class G2.5.

Figure 4 shows the rotor deformations resulting from longitudinal and gravitational forces and the position of the residual unbalance force vector. These deformations and forces were the input data during dynamical analysis that allowed the selection of a suitable bearing system. In addition, an assumption was made that the bearing supports are rigid, which is justified by a very rigid construction of the turbine casing.

Figure 5 shows the finite element mesh which was used during the dynamic analysis of the turbine rotor.

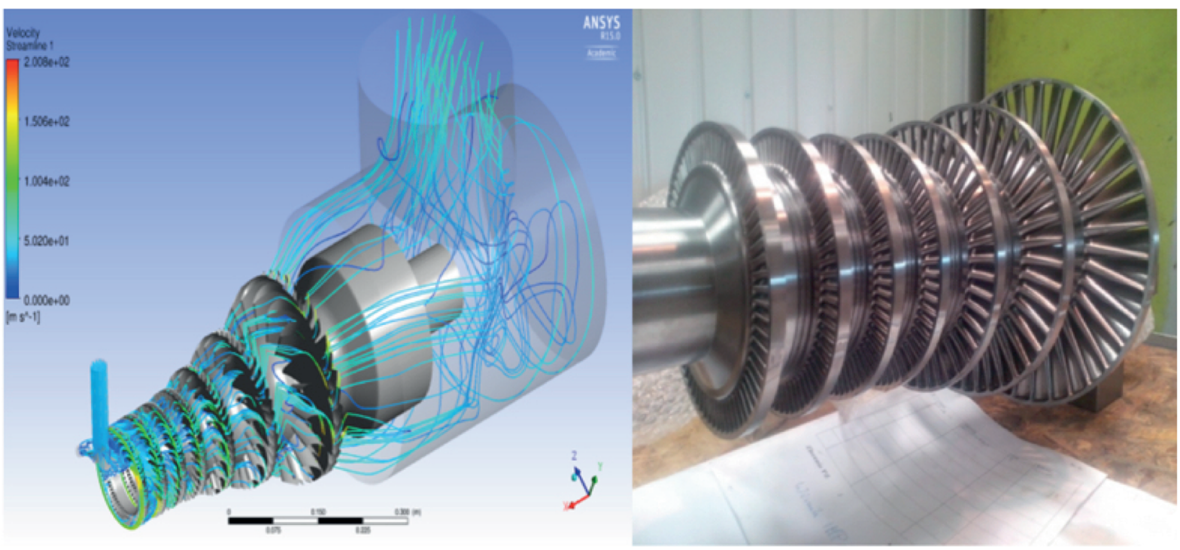

Fig. 3. Heat transfer and fluid flow analysis of a 100 kW ORC turbine carried out using ANSYS software (on the left) and the resulting test version of the rotor (on the right)

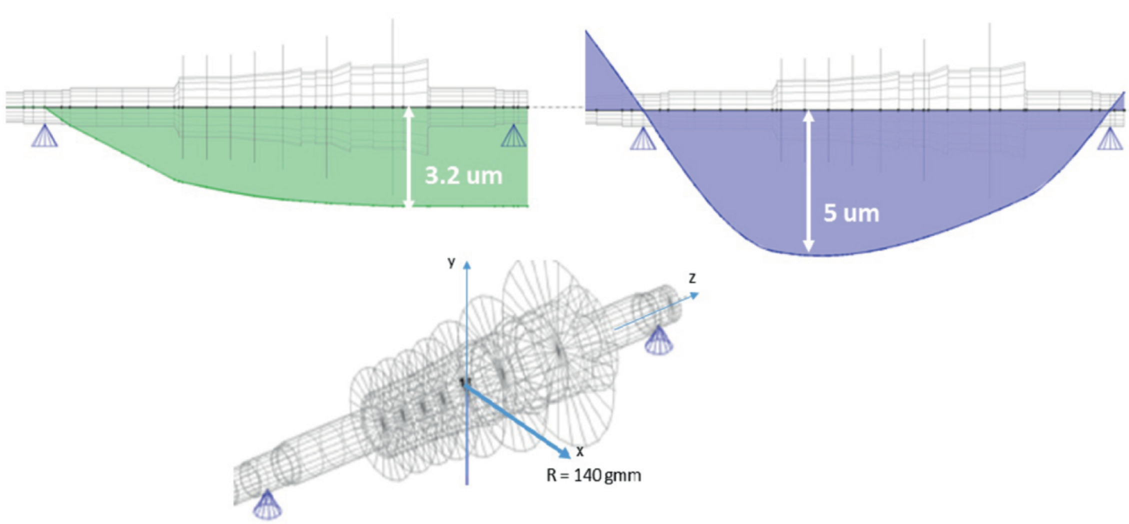

Fig. 4. Baseline data used for the calculations concerning system dynamics and the selection of a bearing technology. Rotor deformations resulting from longitudinal aerodynamic forces (the left top corner) and gravitational forces (the right top corner), and the position of the residual unbalance force vector (bottom half of the figure)

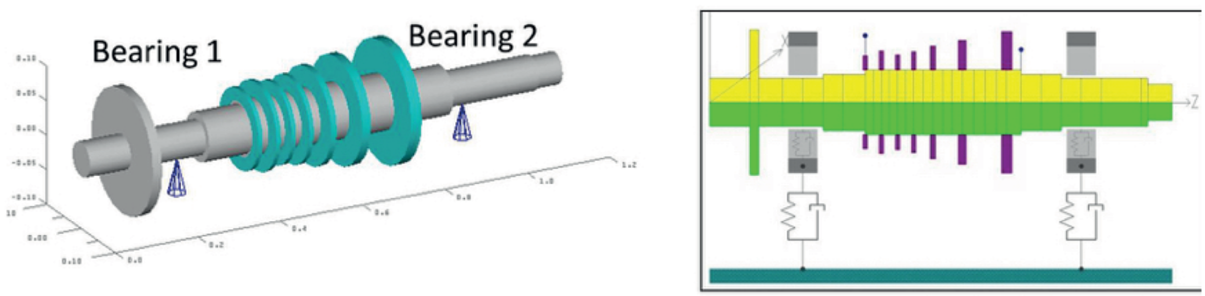

Fig. 5. FEM model of a 100 kW ORC turbine's rotor

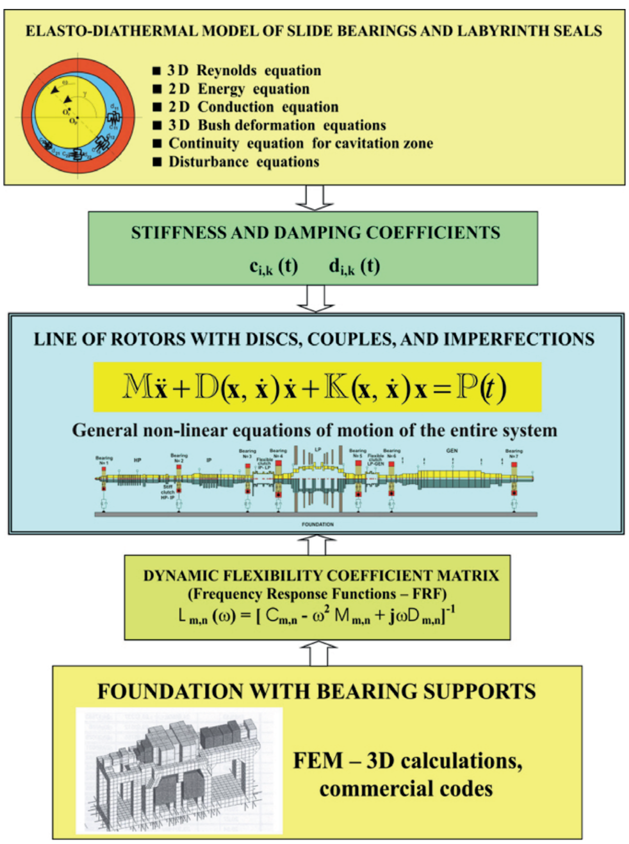

Fig. 6. The general scheme of the MESWIR system that was used to study the dynamics of a 100 kW ORC turbine

As already mentioned above, it is very difficult to model phenomena taking place in the bearings' lubricating films, especially sudden whirl/whip events related to hydrodynamic instability. Relations between excitation forces and displacements are strongly nonlinear. This fact requires the application of research tools capable of coping with nonlinear rotor dynamics.

The dynamical analysis of the machine was conducted using our unique in-house developed applications, which form part of the system known as MESWIR. This software was developed at the IMP PAN and is dedicated to deal with mechanical systems that are inherently nonlinear in nature. The MESWIR system was already described in the paper [10], the content of which need not be repeated here.

The application that was used for the purposes of this research is based on the so-called elasto-diathermal three-dimensional bearing model, which takes into account the heat exchange between the lubricating film and the bush, and also the possibility of a break of the continuity of the film due to cavitation. Equations of motion for the system are a set of several hundred differential equations that are strongly nonlinear and mutually conjugated. Nonlinearity stems from the fact that the main damping and stiffness matrixes belonging to the equations of motion are modified at each time step according to bearing properties, and so they are dependent on the displacements and velocities of bearing journals. As a result, we receive non-elliptical vibration trajectories and vibration spectra that can be even more useful. This sort of results makes it possible to follow up on phenomena related to hydrodynamic instability. Figure 6 presents the scheme of the MESWIR system [10].

4. Analysis of the dynamic performance of the system equipped with bearings designed to operate with non-conventional lubricants

In this section, we will go over the first configuration of the circulations of the working and lubricating mediums referred to in Section 2, namely, the case in which the working medium of the turbine and the lubricating medium of the bearings is the same. In this specific case, the medium chosen was a low boiling fluid belonging to the group of silicone oils, the characteristic of which is given in Fig. 7. It clearly follows from this characteristic that the ambient pressure for the operating bearing must be increased in order to maintain the working medium in the liquid phase at the journal temperature exceeding 80°C. Failure to do so could result in the gaseous phase of the medium or in a mixed two-phase flow having properties that are difficult to define and model.

During our analysis, we will assume that the low boiling medium remains in the liquid phase at all times, and thus the ambient pressure for the bearing has been carefully selected. The ambient pressure value was set at 0.6 MPa in order to ensure that the bearing operates with the lubricant in the liquid phase across virtually the whole temperature range. At atmospheric pressure (i.e. when p = 0.0 MPa), we are facing the gaseous phase of the medium across practically the entire range of journal temperatures. It is therefore necessary to increase ambient pressure in the slide bearings' chambers. The results obtained from the analysis conducted by means of the MESWIR system are presented in Figs. 8–10.

Figure 8 shows that increasing the ambient pressure in the bearings' chambers to 0.6 MPa results in a sharp increase of the vibration amplitudes for both bearings. Although the bearings operated with the lubricant in the liquid phase, it turned out that the hydrodynamic instability had already been strongly developed. Figure 9 demonstrates it in detail. The vibration spectrum for p = 0.6 MPa (first from the right) has a dominant subharmonic component and the displacement trajectory of the bearing has the typical shape of a developed lubricant whip. Such operating condition of the turbine is very dangerous and therefore unacceptable.

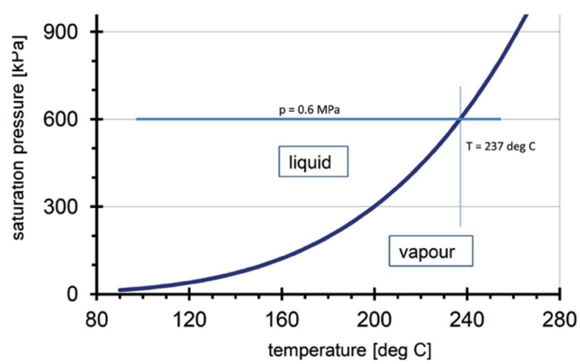

Fig. 7. Characteristics of a low boiling silicone oil used as a working medium: saturation pressure as a function of the temperature

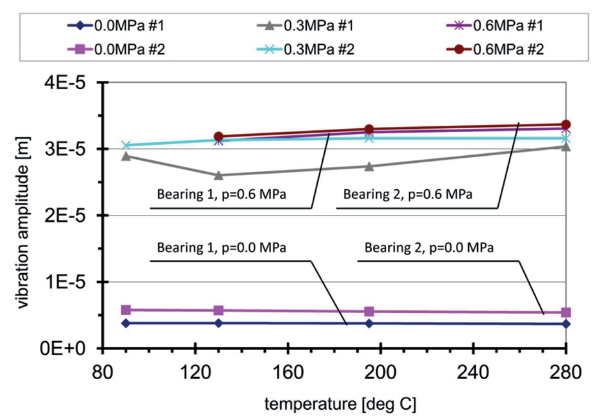

Fig. 8. Graph showing vibration amplitudes for Bearings Nos. 1 and 2 being the components of a 100 kW ORC turbine. The amplitude values are presented as a function of the journal temperature for different ambient pressures in the bearing chambers

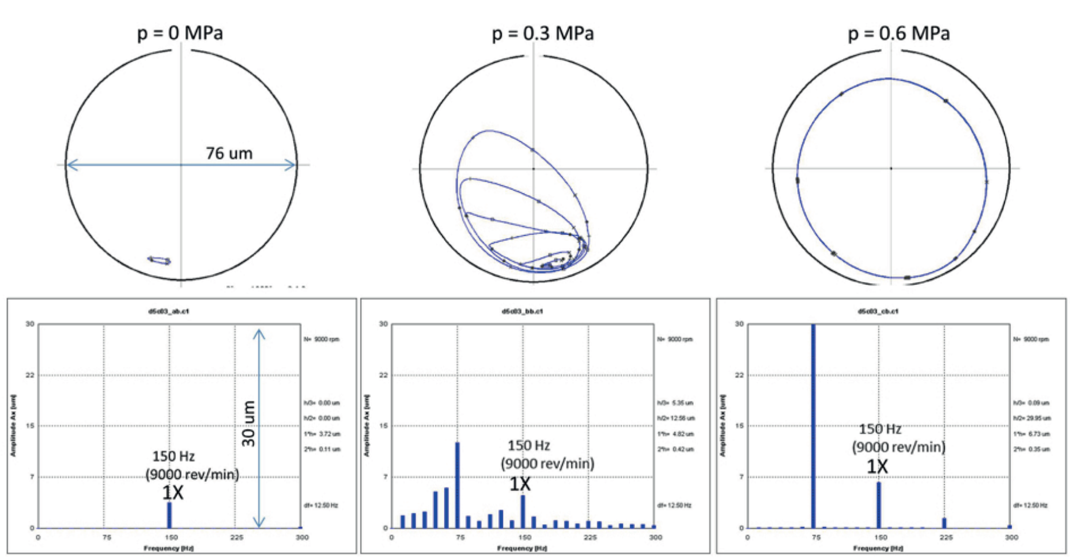

Fig. 9. Vibration trajectories and spectra calculated for Bearing No. 1, presented for different ambient pressures in the bearing chamber (denoted as "p"). Research object: a 100 kW ORC turbine (nominal speed – 9000 rpm)

Figure 10 explains why such an operational state occurred. While ensuring operation with a liquid medium, a high ambient pressure also totally changes pressure distribution in the bearing clearance. For p = 0.6 MPa, the pressure distribution takes on the shape similar to a Sommerfeld pressure distribution, which has a negative impact on the stability of the whole system.

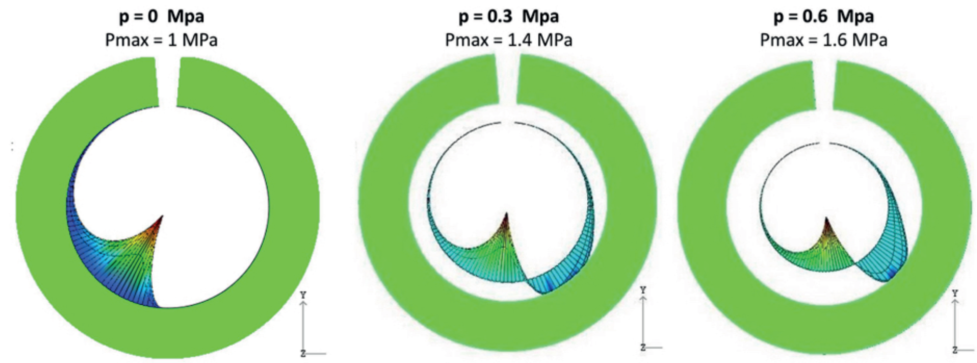

Fig. 10. Calculated pressure distributions in Bearing No. 1 for different ambient pressures in the bearing chamber (denoted as "p"). Research object: a 100 kW ORC turbine with a nominal speed 9000 rpm

Similar results were obtained for other configurations of bearing clearances and ambient pressures which are not described herein. In all of these cases, there has been no stable operation of the system.

The analysis carried out demonstrates that the idea consisting in lubricating the bearings using the turbine's working medium in its liquid phase (i.e. the idea of using a hermetically sealed turbine) may not always be used in practice. In turn, neither lubricating with a medium in the gaseous phase nor permitting two-phase flows provides sufficient load capacity of the bearing.

Based on the analysis performed, the idea in which bearings are lubricated with non-conventional lubricants has become a thing of the past. During further development of a 100 kW ORC turbine dedicated for the use in the Local Energy Clusters, other ideas urgently needed to be dealt with.

Let us now investigate the operational behaviour of the turbine's bearing system lubricated with a conventional medium such as the mineral oil.

5. Analysis of the dynamic performance of the system equipped with bearings operating with conventional lubricants

Let us now tackle the second configuration of circulations listed in Section 2 of this paper. For the sake of this analysis, let us suppose that, in our turbine, the slide bearings are lubricated with classical machine oil (Z-26), and the silicone oil acts as a working medium in the turbine. Obviously, in this case, there is no need to increase ambient pressure in the bearing chambers. Both the external excitation and all geometrical parameters of the ORC turbine are the same as in the case described in the previous sections. The results of the dynamic analysis of the system obtained using the MESWIR software are shown in Figs. 11–14.

Figure 11 illustrates a disturbing state of the machine, namely, the situation in which both bearings show clear signs of hydrodynamic instability when the turbine operates at nominal speed (9000 rpm). The subharmonic components on the vibration spectrum became dominant and the trajectories are large – far from a stable operation. The vibration amplitude was approximately 36 μm. Under such conditions, there is a real risk of seizure and damage to the bearing, because it has the radial clearance of 55 μm.

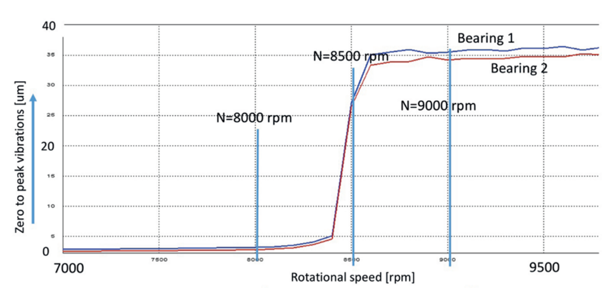

Fig. 11. Vibration amplitudes of the bearings (Nos. 1 and 2) being the key components of a 100 kW ORC turbine (nominal speed – 9000 rpm)

In order to thoroughly examine the transition from stable to unstable phases of operation, the calculations were also carried out for two rotational speeds of the rotor that are just below the rated speed, namely, 8000 rpm and 8500 rpm. These results give us the opportunity to compare to one another the three machine states: stable operation (8000 rpm), a transitional phase (8500 rpm), and operation with fully developed instability (9000 rpm). The analysis of the results presented in Figs. 13 and 14 is very interesting. These figures show the pressure distributions registered for two revolutions of the rotor, namely, for angles ranging from 0° to 720°. All these pressure distributions were obtained at constant static and dynamic loads (Q and R, respectively) and for the same geometry of the entire system. The rotational speed of the rotor was the only value changed for this comparison. It should be noted that Figs. 13 and 14 were prepared originally with the same scale to facilitate analysis.

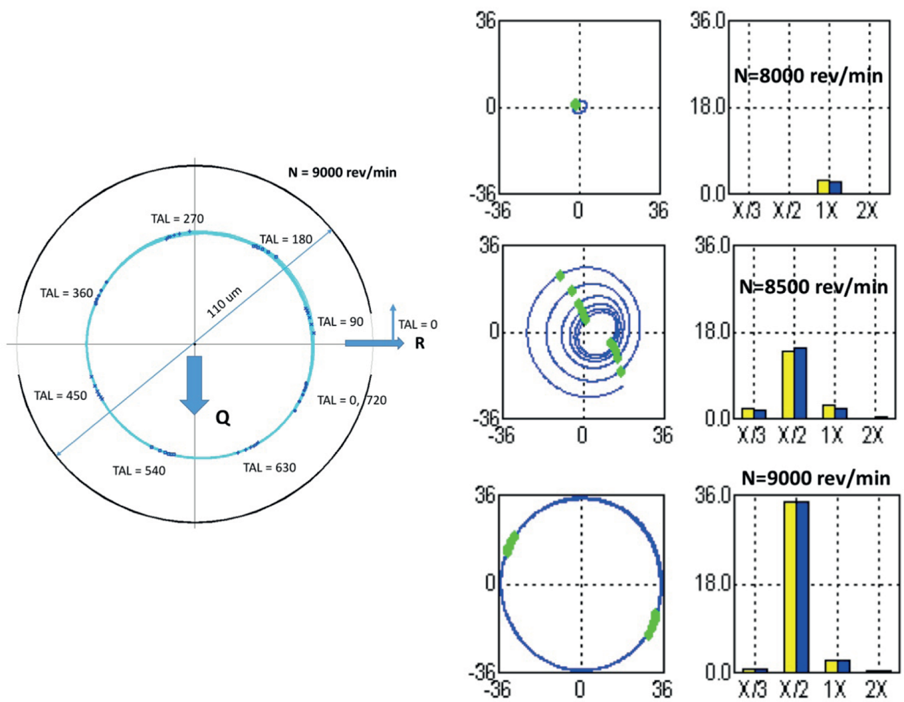

Fig. 12. The positioning of the residual unbalance force vector (R) as a function of TAL angle (on the left) and vibration trajectories and spectra of a 100 kW ORC turbine calculated for the three different rotational speeds of the rotor (on the right)

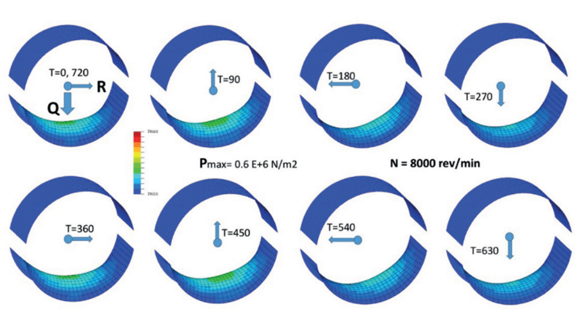

Fig. 13. Pressure distributions in the bearing clearance (Bearing No. 1) at different positions of the residual unbalance force vector (R) registered during the last two rotor revolutions (T = 0°, 90°,…, 720°) in conditions where the bearing operated at gravity loads of constant magnitudes and fixed positions (Q). The calculations were made using MESWIR software, and the rotational speed of the rotor was 8000 rpm. Stable operation of the system was noted at that speed

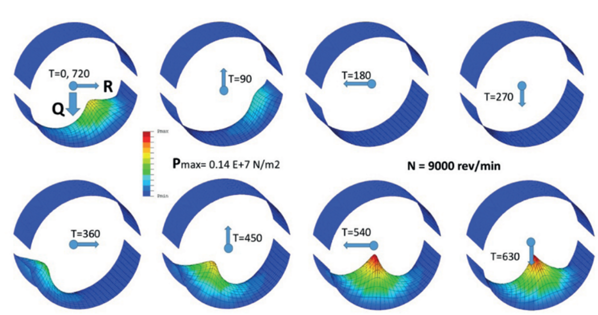

Fig. 14. Pressure distributions in the bearing clearance (Bearing No. 1) for different positions of the residual unbalance force vector (R) registered during the last two rotor revolutions (T = 0°, 90°,…, 720°) in conditions where the bearing operated at gravity loads of constant magnitudes and fixed positions (Q). The calculations were made using MESWIR software, and the rotational speed of the rotor was 9000 rpm. The highly unstable operation of the system was observed at that speed

Analysing the figures, several conclusions can be formulated. In the case of stable operation of the system (Fig. 13), the direction of the residual unbalance force vector (denoted as R in the figure) only very slightly influences the pressure distribution, and it does this on a repetitive basis throughout the two successive revolutions of the rotor shaft. In other words, the pressure distributions for the corresponding angle positions of the shaft (T = 0°–360° and T = 360°– 720°) are the same for two successive revolutions. These results are in accordance with the author's expectations. The situation is different in Fig. 14. We notice that the direction of the residual unbalance force vector (R) has a very large impact on the pressure distribution, and that is the case for both revolutions. The case in which the vector R is directed downwards, that is for the angular positions T = 270° (the first revolution) and T = 630° (the second revolution), gives us an indication of how much impact it can have. Intuitively, one could have expected that the vector R, which was directed vertically downwards (regardless of which rotor revolution is actually being registered), would have enhanced the static reaction Q acting in the same direction and the system would have shown a natural reaction in the form of maximum pressure values being concentrated in the lower part of the bush. One could also have expected that pressure distributions registered for both revolutions (i.e. T = 0°–360° and T = 360°–720°) would have been identical, because the configuration of external loads was repeated every full revolution of the rotor.

What happened in reality was more complex. Let us take a look at T = 270° — there is hardly any hydrodynamic pressure in the bearing clearance! In contrast, at the second revolution (see T = 630°), the maximum pressure is more than double that observed in the case of stable operation of the system (Fig. 13).

The results of this study are very surprising and, in terms of conventional science, only hardly explainable. They can be explained by the existence of a complex interaction between the inertial forces of the rotor and the inertial forces of the oil being pumped in a circumferential direction inside the bearing clearance, and this interaction takes place under the conditions of a strong hydrodynamic instability. This interaction is especially apparent in the case of large journal displacements. As in the case with non-conventional lubricants, the research was conducted for different bearing geometries and several mineral oils. The results were similar – the system was unstable or close to the stability threshold. Therefore, I can unfortunately only conclude that the ORC turbine being tested cannot function properly if it is equipped with slide bearings lubricated with conventional lubricants. The only thing we are left to do is to conduct research on rolling bearings.

6. Analysis of the dynamic performance of the rotor supported by rolling bearings

The turbine rotor (see Fig. 3) is supported by plain ball bearings (Mfr. Part No. 6316 C3) with a journal diameter of 80 mm. Radial and axial stiffness of the bearings were determined using catalogue cards and were 16x107 N/m and 13x107 N/m, respectively. As in previous cases, it was assumed that they are rigidly mounted into the bearing housings. The dynamic performance of the turbine rotor was analysed using commercial software called MADYN 2000. The results are presented in Figs. 15 and 16.

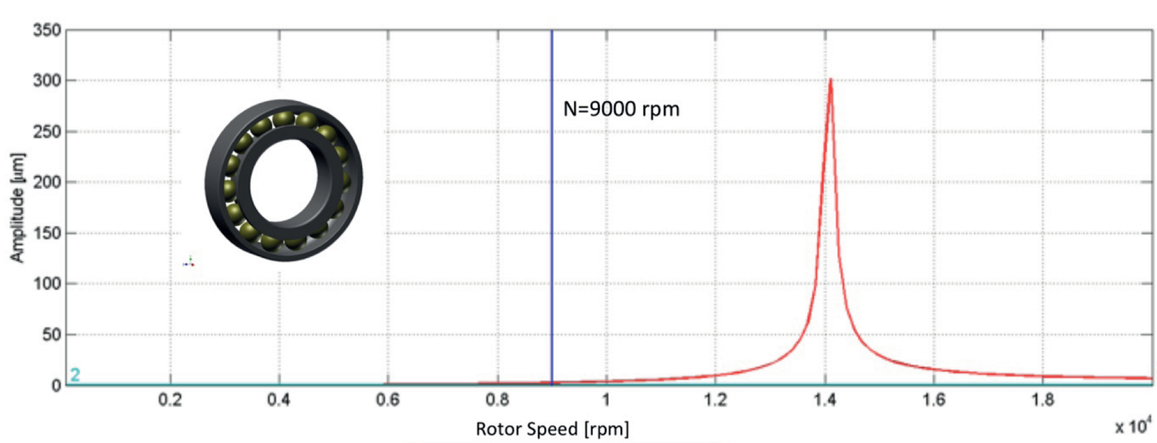

Fig. 15. The amplitude of the forced vibrations as a function of the rotational speed of the rotor supported by rolling bearings, being a significant component of a 100 kW ORC turbine

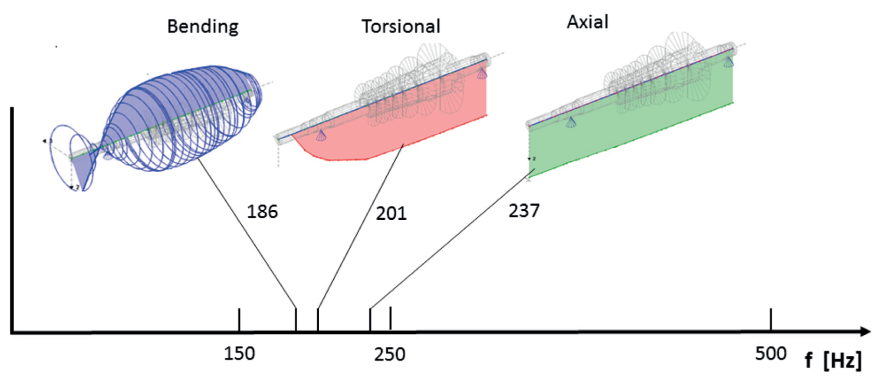

Fig. 16. Modal analysis of the rotor-rolling bearings system. Mode shapes and their frequencies of bending, torsional, and axial vibrations

The analysis of the results showed that the rotating system of the turbine is subcritical, which means that the critical speed of the rotor shaft occurs above the rated speed (i.e. above 9000 rpm). This is confirmed by the results of the modal analysis presented in Fig. 16. The first natural frequencies (i.e. bending, torsional, and axial types) occur above 150 Hz, which is the rated frequency of the system corresponding to the speed of 9000 rpm. There are no disturbing mode shapes in the system up to 500 Hz, which proves its rigid structure and great operational reliability. These features are highly desired, especially when it comes to evaluating dynamic behaviour of the tested system.

As a result of the above analyses, it was decided that the rolling bearings will form part of a 100 kW ORC turbine. The turbine's prototype is already being tested at a laboratory belonging to the IMP PAN in Gdańsk (see Fig. 17).

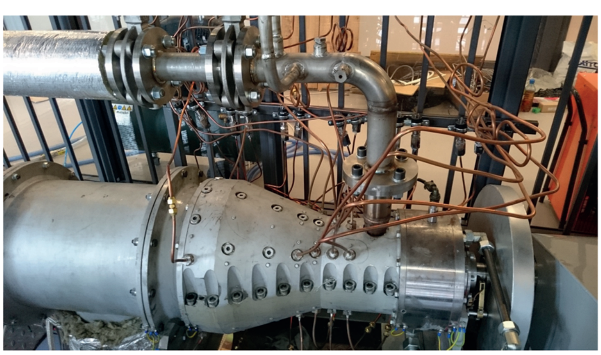

Fig. 17. Photo showing the prototype of a 100 kW ORC turbine set. This device is currently undergoing operation tests at a laboratory belonging to the IMP PAN in Gdańsk

Conclusions

This paper might serve as an example that highly advanced methods of vibration analysis are extremely useful for the design of new machinery, and they may even help to develop a working plan for further steps towards manufacturing the finished product. In the case described here, having at our disposal the research tools in the form of computer programs for nonlinear dynamical analysis (MESWIR software), they revealed the behaviour of the system in various configurations of bearings and lubricants, already at the design stage. In particular, we had the possibility to track the transition between 'whirls' and 'whip' of the lubricating medium after crossing the stability threshold. It turned out that such quick and dangerous phenomena taking place in the bearing clearance can exclude many alternative solutions (e.g., a hermetically sealed turbine, the bearings of which are lubricated with the turbine's working medium). The research produced interesting results, because it clearly showed that, under the conditions of developed hydrodynamic instability, the phenomena occurring in the bearing clearance are not recurrent for each rotor revolution, notwithstanding the fact that the external excitation forces acting on the system are fully repeatable. In fact, we not only have information about these phenomena but also are able to precisely describe them in both quantitative and qualitative terms.

The use of the methods of analysis from the field of nonlinear dynamics has proved to be essential. Even the most advanced commercial software offers displacement trajectories of bearing journals only in elliptical forms or solutions based on a weak nonlinear theory, which in fact makes it impossible to obtain complex vibration spectra; therefore, no proper conclusions can be drawn from them.

As a result of this research, we have developed the prototype of a 100 kW ORC turbine generator dedicated for use in municipal Local Energy Centres. It will be installed in a model power station located in Żychlin – the first municipality in Poland that is going to implement our device.

Acknowledgements

The work has been carried out within the framework of the Strategic Programme of the National Centre for Research and Development entitled *Advanced Technologies for Energy Generation, Research Task No. 4 - Developing integrated technologies of fuel and energy production from biomass, agricultural wastes and other resources* (years of implementation: 2011-2015). I wish to thank my closest co-workers from the IMP PAN research team, especially Grzegorz Żywica, PhD, Eng. and Professor Piotr Lampart and many others, which are hard to be named particularly due to a huge number of them. I also thank Professor Zbigniew Kozanecki from the Lodz University of Technology for the implementation of some turbine subassemblies and for these long years of close and successful cooperation.

My thanks also go to ENERGA SA energy concern, which played the role of an industrial partner. Special thanks should be given to Mr Marek Laskowski, Eng., who is responsible for the implementation process of the product in Local Energy Clusters.

I also thank the workers from the Project's Coordination Office, especially Mrs Ewa Domke, Mrs Katarzyna Trzebiatowska, and Mrs Anna Sawicka for the preparation of the contracts with numerous outside partners and financial clearance of the project.

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