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Investigations of Oil–Free Support Systems to Improve the Reliability of ORC Hermetic High–Speed Turbomachinery

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The design of a small turbo–generator to produce electricity in the range from a few kWs requires the use of an aerostatic or aerodynamic gas bearing system. The theoretical analysis and the experimental test at the present stage of the study show that such highly rotating constructions are feasible. The problem consists in the optimal design selection from the viewpoint of the machine reliability and the adjustments are connected to the diminution in static thrust and lateral loads of the bearings by a correct design of the turbine flow structure and a correct selection of the gas bearing type.

Keywords: Oil–free support systems, hermetic high–speed turbomachinery, ORC

1. Introduction

The micropower system is used in a low-power source, with the power output ranging between 0.05 and 20 kW. It is based on the Brayton or Rankine cycle and consists of a turbine and a generator. The system requires high revolutions to generate sufficient power in the small–size turbine (microturbine). The term "microturbine" is often used for turbine systems applied to produce electricity in the range from a few kWs to a few hundreds of kWs at the speed of approximately 10000÷100000 rpm [3].

The existing conventional oil–lubricated bearings reveal performance limits at these revolutions, especially when the stability of a bearing is taken into account. Furthermore, in order to increase the efficiency of small, high–speed turbomachines, we are searching to use hermetic bearings, lubricated with the machine working medium. Especially, in ORC (Organic Rankine Cycle) turbomachinery, propelled by a low–viscosity, organic, working gas or liquid, the application of bearings lubricated by that working medium makes it possible to:

- increase the total efficiency of the machine by decreasing friction losses in the bearings and by eliminating the oil system and seals connected with it,
- simplify the design of the shaft and to reduce its length,
- maintain absolute purity of the working medium,
- build a "hermetic" machine without a rotating shaft end protruding outside the casing, to eliminate the mechanical gear and "working medium atmosphere" seals in an electric generator or a motor integrated with the shaft.

These issues are possible to achieve thanks to more and more common applications of non–conventional materials in the machine design. The materials used in such bearings have to secure:

- conditions for short, non–destructive contact of the rotating bearing journal with the bush during machine start–ups and shut–downs;
- low friction coefficient between the journal and the bush;
- corrosion resistance during the contact with the lubricating medium.

Therefore, while studying possible applications of non–conventional lubricating media, one should analyze thoroughly the dynamics of the "rotor–bearing–casing" system within the whole range of machine operation. The presented here concept of the microturbogenerator is connected to the following assumptions:

- electrical power output 2÷4 kW,
- working medium of the turbine – HFE 7100,
- oil–free technology for the bearing system design,
- a turbine shaft integrated with an electrical generator.

2. Unconventional support system selection

One of the basic problems connected with a practical application of non–conventional bearings or supports to high–speed rotors is the machine operational reliability under various working conditions. We can enumerate several criteria to be taken into account while selecting an unconventional support system, namely:

- load carrying capacity,
- energy consumption,
- stability of the lubricant,

- viscosity of the lubricant (hence friction),
- cleanliness,
- manufacturing.

Theoretical and experimental investigations of oil–free bearings and supports, including steam bearings and liquid bearings technology, are described in the paper.

2.1. *Steam bearing technology*

The compressibility and the low viscosity of gas is an important factor and must be included in the analysis of various forms of gas bearings. The advantages of gas–lubricated bearings over liquid–lubricated bearings are well known:

- cleanliness – elimination of the contamination caused by typical lubricants,
- stability of the lubricant – no vaporization, cavitation, solidification, decomposition under extreme temperatures,
- very low friction (low viscosity).

The main disadvantages of gas–lubricated bearings are recognized as resulting from low viscosity of the gas:

- reduced unit load carrying capacity,
- closer control of manufacturing tolerances.

The development of gas bearings is connected with the fact that they can be often used where the application of well–known traditional design solutions of bearings is troublesome (i.e., high–speed cryogenic expanders or high–speed microturbines).

Actually, two kinds of gas bearing systems are developed simultaneously for the project needs:

- an aerostatic gas bearing system (externally pressurized),
- an aerodynamic "bump foil" bearing system (self–acting).

2.1.1. *Aerostatic bearings*

The design of aerostatic (externally pressurized) jet fed journal bearings is shown in Fig. 1. The bearing consists of a cylindrical bush into which two rows of gas feed holes spaced evenly around the bearing circumference are drilled [5]. Compressed gas is supplied from an external source to the reservoir surrounding the bearing. From the reservoir, the gas flows through the feed holes into the clearance between the shaft and the bush and then axially to the ends of the bearing where it exhausts to atmosphere. With no load applied to the shaft, there is no variation of pressure circumferentially around the bearing so that the pressure forces balance on the shaft. When a load is applied to the shaft in the vertically downward direction, the shaft deflects in that direction so that the clearance at the top of the bearing is increased, and at the bottom it is reduced. A difference of pressure now exists across the shaft to balance the applied load. A great advantage of aerostatic bearings is the relatively large load capacity and the correct operation even without rotation.

The main problem connected to the aerostatic bearing application is additional energy needed to pressurize the supply orifices spaced uniformly in two ranges of the bearing sleeve. From the viewpoint of energy consumption, one should analyze thoroughly the total mass flow of the incoming pressurized steam through the aerostatic bearing system. Especially as the bearing mass flow reduces the total mass flow of the turbine and, consequently, decreases the efficiency of the turbine.

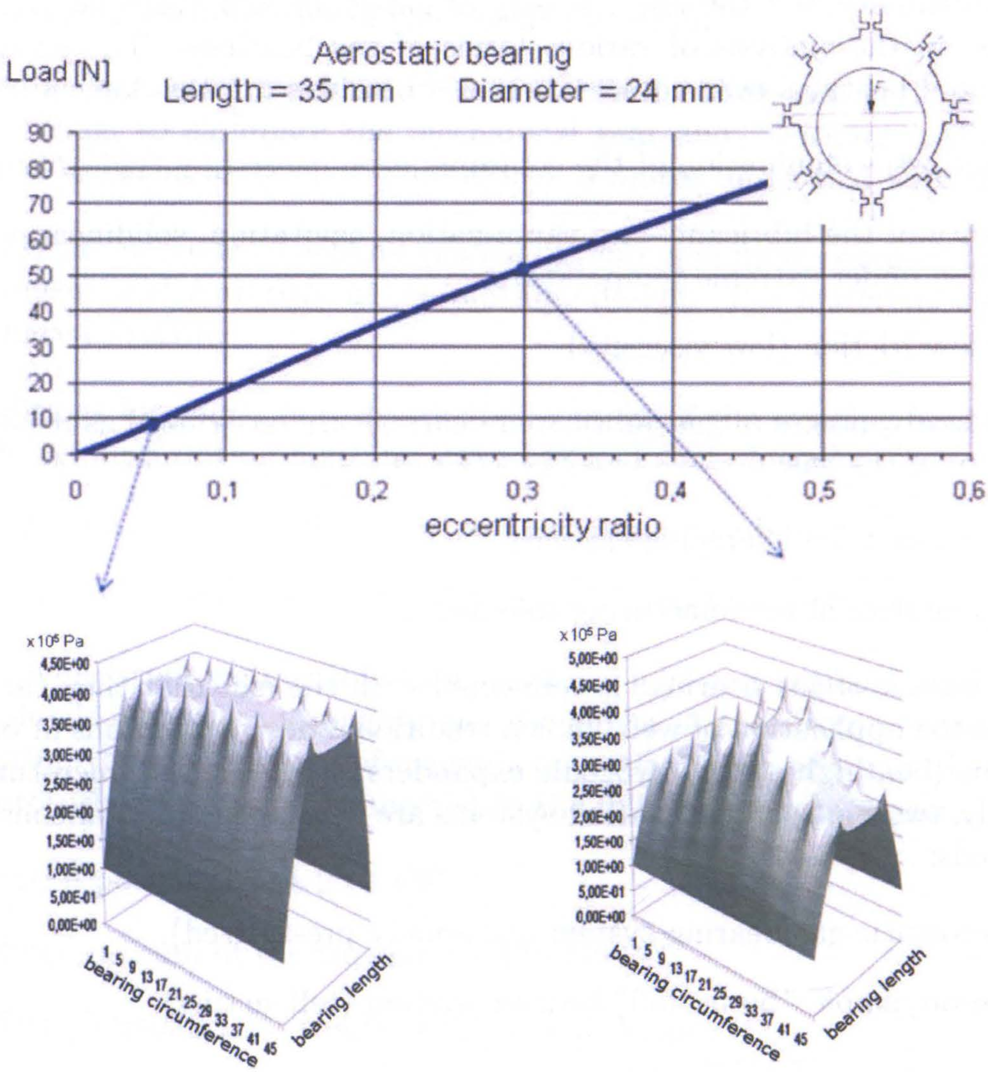

Figure 1 Design of the aerostatic bearing and the calculated load characteristics and a gas film pressure distribution of the externally pressurized gas bearing

Fig. 1 shows a calculated load capacity of this journal bearing and a pressure distribution in the gas film for the supply pressure equal to $p_s = 500$ kPa

The calculations have shown that the total mass flow of the incoming steam through the bearing system is less than 1 g/s. It is about 0.5% of the nominal turbine flow and probably it is acceptable from the point of view of hermetic machine efficiency.

2.1.2. *Aerodynamic foil bearings*

The design of the experimental foil bearing as well as the calculated aerodynamic pressure distribution are shown in Fig. 2. The uniqueness of foil bearing operation results from the fact that the *top foil* is clenched during the bearing operation on the rotating journal by means of the elastic *bump foil.* The aerodynamic film geometry of a very low thickness, theoretically close to the cylindrical one, is generated by the viscosity effects. A great advantage of aerodynamic bearings is that they require no external pressurization system for the working fluid.

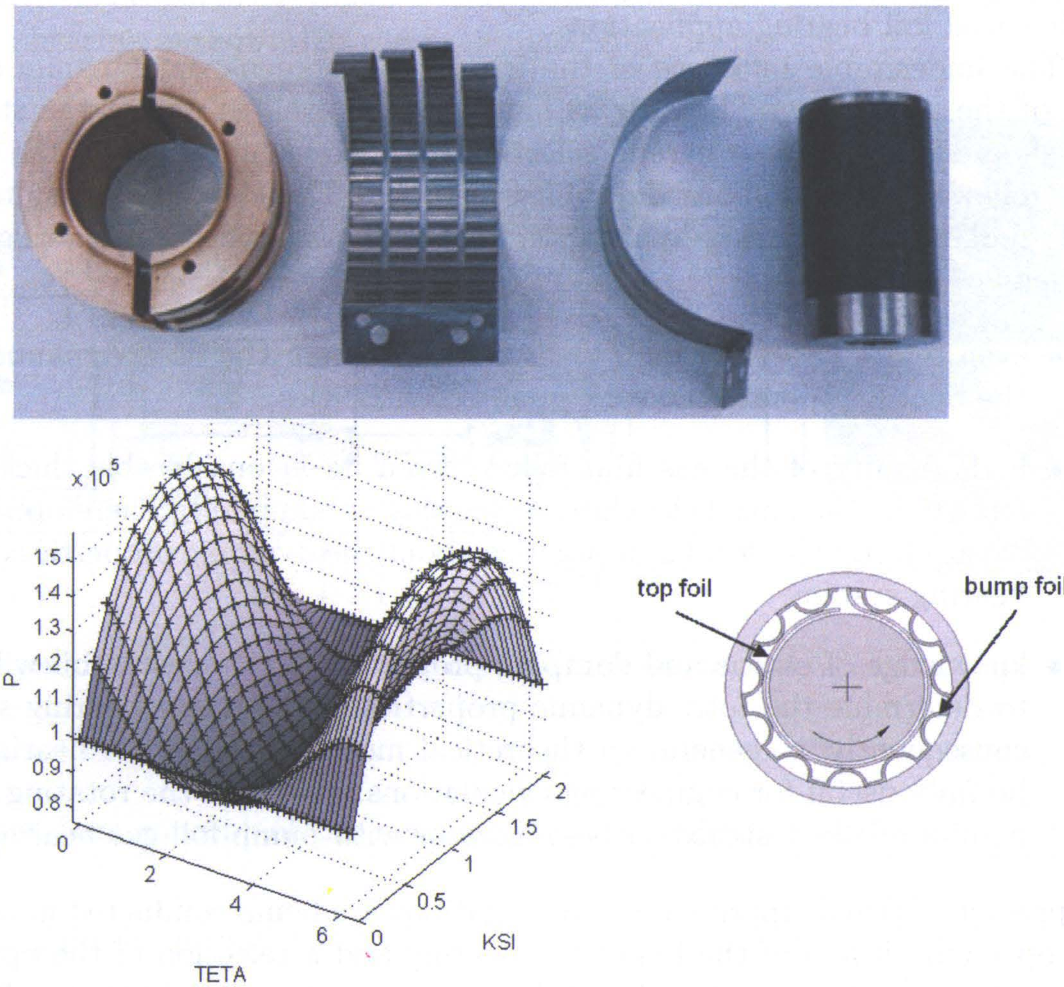

Figure 2 Aerodynamic foil bearing developed for the project needs

The important problem of the aerodynamic gas bearing application is connected to the start–up and the shut–down in contact with the shaft surface and thus:

- a high drive moment for the start–up (disputable from the viewpoint of the turbine mechanical characteristics) is needed,
- there is a limited number of start–up/shut–down cycles (wear).

Furthermore, the analysis of gas foil bearings is difficult due to the interaction between the gas film pressure and the complicated deflection of the top foil and the underlying bump strip support structure. Dynamic properties of aerodynamic gas bearings, according to the linear theory, are usually represented by a set of eight coupled dynamic coefficients, linearised around the static equilibrium position of the bearing. It is necessary, however, to limit the scale of the excitation forces in order to fulfill the basic condition of small displacements around the equilibrium point. The motion of movable, but non–rotating parts of variable–geometry bearings is inevitably connected with friction. It is evident that the nature of elastically supported bush motion can dramatically affect dynamic characteristics of the bearing. Therefore, nonlinear modeling of dynamic properties, including design characteristics of the support and the generated friction forces, becomes indispensable in high–speed foil bearing applications.

The undesirable influence of the friction phenomena on dynamic characteristics of the aerodynamic bearing at high speed as well as during the start–up and the shut–down requires a careful selection of different materials for the bearing design followed by scrupulous durability tests [4]. The simulation results allow one to formulate the following hypotheses related to the bump foil bearing operation, namely:

- even under relatively high loads of the journal, the "aerodynamical" part of the bearing operates at very small eccentricities,
- high rigidity of the gas film follows from its inconsiderable thicknesses "enforced" by the initial clenching of the elastic bump foil. Therefore, the rigidity of the elastic foil decides in practice about the dynamic properties of the whole bearing system,
- knowledge of elastic and damping properties of the elastic foil will allow one to determine the total dynamic properties of the whole bearing system and, consequently, to generate a theoretical model of the whole bearing that will be fully useful for engineering calculations related to the rotating system dynamics of the designed turbo-generator with bump foil gas bearings.

At present, further experimental investigations are being conducted in order to find the optimum design of the bump foil bearing and a selection of the optimum pair of materials (a journal material and a foil coating material) that will ensure its sufficient durability under unstable operation conditions.

2.2. *Liquid bearing technology*

Liquid bearings are fluid film bearings that rely on a film of oil or other liquid lubricant to create a clearance between the moving and stationary elements. When comparing liquid and gas bearings, there are two fundamental differences in the lubricant properties. First, the oil can be considered to be incompressible, and secondly, its viscosity is usually from 100 to 1000 times greater than the viscosity of air.

These two factors mean that in practice that the load capacity of any liquid lubricated bearing is much higher than the load capacity of an aerostatic bearing of the same size and shape. In consequence, the operation of the liquid lubricated bearing is also much safer. Theoretically two types of liquid bearings, hydrostatic bearings (externally pressurized) and hydrodynamic bearings, can be used in hermetic, oil free machines devoted to operation in the ORC cycle. The both types of bearings employ liquid fraction of the ORC cycle as a working medium. However, the problems connected with use of a liquid lubricant need to be highlighted, they are higher friction power losses and higher costs, especially for small size bearings. In practice, hydrostatic bearings are an interesting solution for machines in ORC systems producing above 20 kW of electric power.

3. Turbogenerator dynamics

In Fig. 3 a general design of the micro–turbo–generator for the ORC cycle supported in the steam bearing is shown [2].

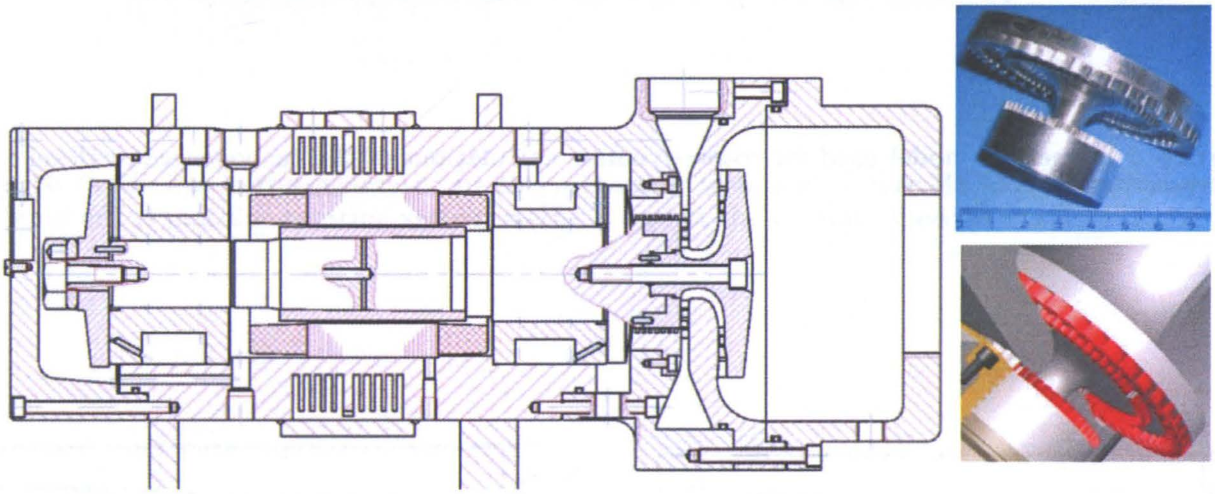

Figure 3 General design and overall dimensions of the turbogenerator developed for the project needs

The presented here concept of the machine is connected to the following assumptions:

- electrical power output 2÷4 kW,
- oil–free aerostatic or aerodynamic steam bearing system,
- a turbine shaft integrated with an electrical generator.

One of the basic problems connected with a practical application of the above mentioned high–speed machine concept equipped with non–conventional gas (steam) lubricated bearings, is the machine operational reliability under various working conditions, which requires an adjustment of the machine design at the early stage of the study. The main factors of this adjustment connected to the oil–free technology specificity are as follows [1]:

- possible diminution in thrust and lateral loads of the bearings by a correct design of the turbine flow structure,
- correct selection of the gas bearing type.

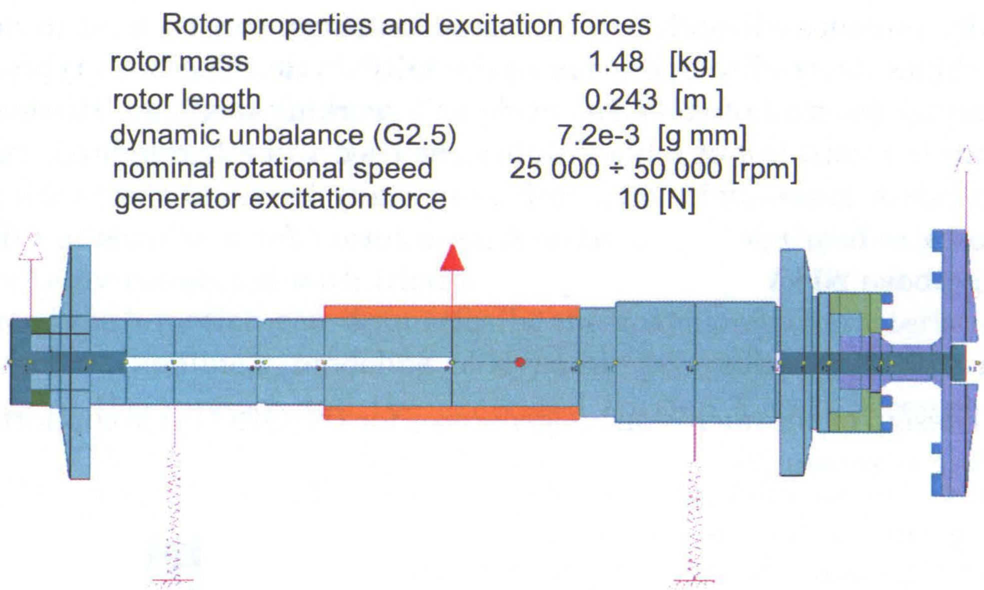

Figure 4 Numerical model used for rotor–dynamic calculations of the turbogenerator developed for the ORC cycle

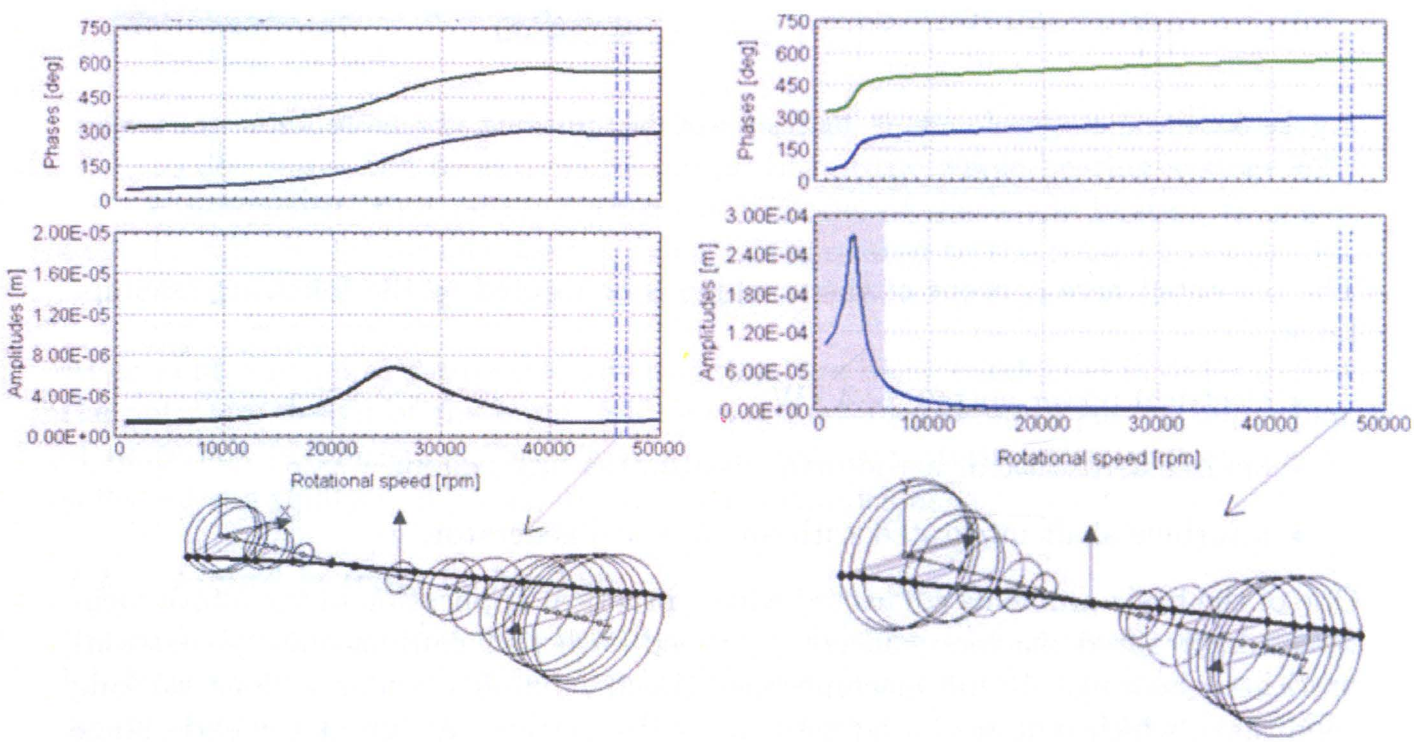

Figure 5 Theoretical Bode plot of the ORC turbogenerator rotor supported in aerostatic and aerodynamic /bump foil/ bearings

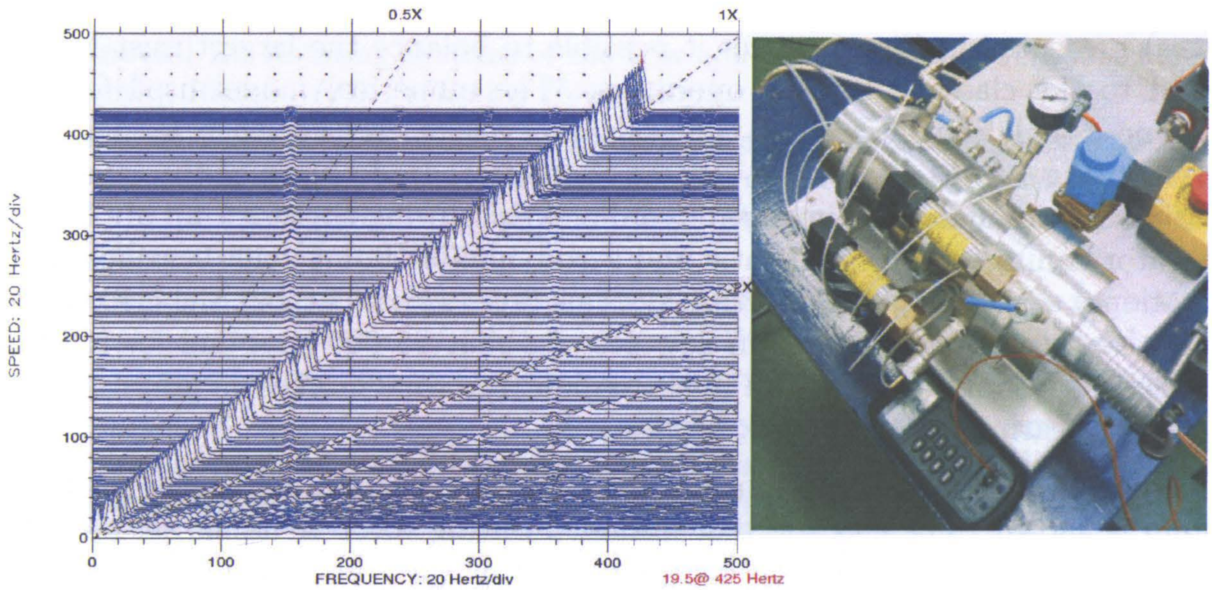

Figure 6 Oil–free turbo–generator prototype during tests and a cascade plot illustrating the stability of the machine rotating system start–up and at the nominal speed

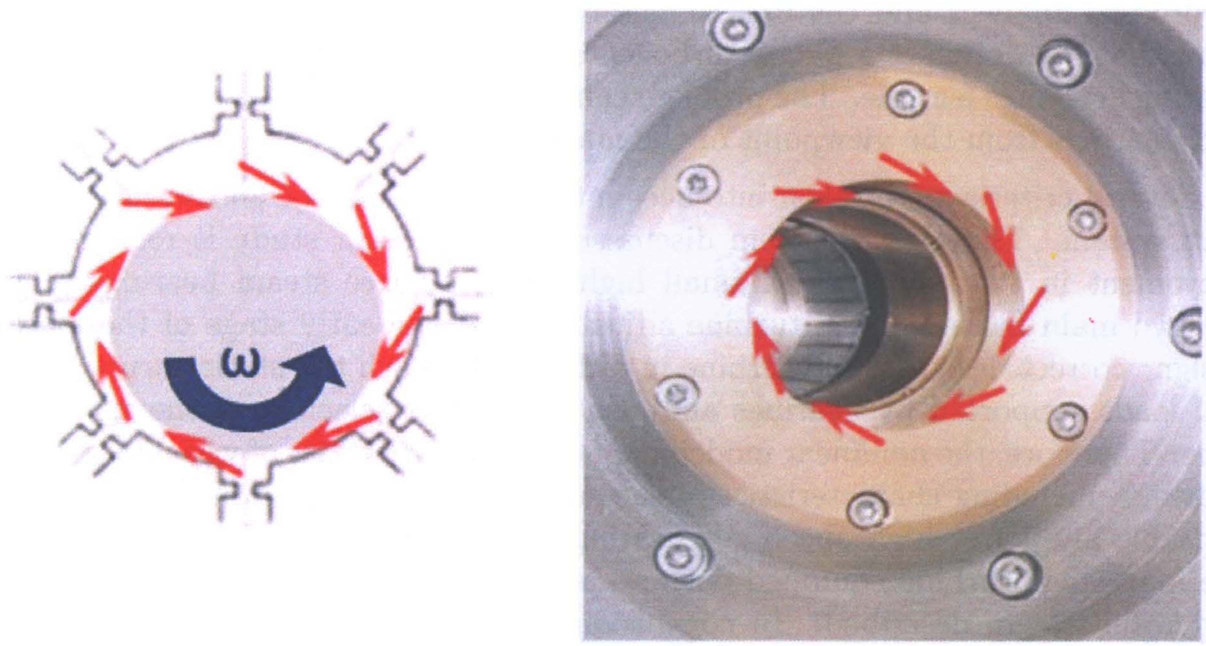

Figure 7 Principle of the anti–swirl steam injection applied in the aerostatic gas bearing system

The four–stage turbine concept (2 radial centripetal and 2 radial centrifugal stages) presented in Fig. 3 makes it possible to balance the large thrust load connected to the classical turbine operation. The numerical model used for rotor–dynamic calculations as well as the excitation forces used for the calculations are shown in Fig. 4. In Fig. 5 we can see theoretical Bode plots of the investigated rotating system under the imposed dynamic load, during the start–up of the turbogenerator equipped with aerostatic and aerodynamic "bump foil" bearings. At the operational speed, both the rotating systems are overcritical, but the critical speed for the aerostatic bearing system appears at about 25 000 rpm and for the bump foil bearing system at 4000 rpm in the region (the zone marked in grey) where the bump foil bearing does not work properly yet.

In Fig. 6 a turbogenerator prototype equipped with an aerostatic gas bearing system is shown. The cascade plot obtained during rotor–dynamic tests confirms the stability of the machine rotating system during the start–up and at the nominal turbine speed.

The anti–swirl gas injections applied in the aerostatic steam bearings shown in Fig. 7 result in a stabilizing effect – the fluid whirl appears at higher speed and the stability margin is greater at the maximal rotational speed.

4. Conclusions

The presented paper is a trial to show the major problems related to the optimal design of the high–speed oil–free turbogenerator developed for the ORC cycle. The theoretical analysis and the experimental tests at the present stage of the study show that the design of a micro–turbogenerator with its aerostatic or aerodynamic bearing system is feasible. The problem consists in the optimal design of the turbine and bearings from the viewpoint of the machine reliability.

Several criteria were taken into account while selecting an unconventional support system. The main problem discussed in the present study is related to improvement in the reliability of small high–speed oil–free steam bearings. There are two main factors of the turbine adjustment at the early stage of the machine design: correct design of the turbine in order to diminish the static thrust and lateral loads supported by bearings and also the correct selection of the gas bearing type. Therefore, the nonlinear modeling of dynamic properties of variable–geometry bearings, including characteristics of the support and friction in it, becomes indispensable in oil–free high–speed gas bearing applications. Finally, the prototype of the four–stage turbine equipped with an aerostatic gas bearing system was tested and results were described. In conclusion, rotor–dynamic tests confirm the stability of the machine rotating system, the additional stabilizing factor being the anti–swirl gas injections. In further project works, the aerodynamic foil bearing support will be implemented to the prototype in order to eliminate the gas supply. It needs to be emphasized that the gas bearing is a good solution for small size, high–speed machines in ORC systems, therefore the hydrodynamic or hydrostatic oil–free bearing design and technology should be analyzed for the sake of an electric power production above 20 kW.

References

[1] **Kozanecki, Z.**: Rotating Systems of the Low and Medium Power Turbomachinery, (in Polish), Radom, *ITE Publishing House*, **2008**.

[2] **Kozanecki Z. and Kozanecka D.**: Theoretical and experimental investigations of oil–free support systems to improve the reliability of industrial turbomachinery, The 8th IFToMM *International Conference on Rotor Dynamics*, September 12–15, KIST, Seoul, Korea, pp. 686–692, **2010**.

[3] **Kozanecki, Z. and Dessornes, O.**, *et al*: Three Technological Bricks for a Micro Power Generation, *Procds. of 5th International Workshop on Micro Technology for Power Generation and Energy Conversion Applications, Power–MEMS*, Tokyo, **2005**.

[4] **Kozanecki, Z. and Miazga, K.**, *et al*: Design, manufacture, assembly and testing of second–generation foil bearings with polymer coatings for high–speed micro ORC turbogenerator, *(in Polish)* , rapport *Institute of Fluid–Flow Machinery PASci*, Gdańsk, **2011**.

[5] **Powell, J.**: The design of aerostatic bearings, Brighton: *The Machinery Publishing Co. Ltd.*, **1970**.