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Influence of hydrostatic pump operation period on performance of a thrust bearing of a 125 MW pump-turbine

Leszek Dabrowski and Michal Wasilczuk[a]

Faculty of Mechanical Engineering, Technical University of Gdansk, Narutowicza 11/12, 80-952 Gdansk, Poland

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Abstract – A special instrumented pad was installed at hydrodynamic thrust bearing of 125 MW pump turbine in one of Polish power plants. “Spring mattress” type thrust bearings of these machines are quite heavily loaded and have caused many problems so far. It was intended to assess bearing present state more thoroughly than with the use of standard monitoring system and to assist in bearing research and development attempts. Instrumentation of the pad comprises 16 thermocouples for measurements of temperature distribution in the pad and 3 proximity probes to evaluate the pad position and film thickness. The pump-turbine with an instrumented bearing was tested at various operating conditions including steady state and transient conditions. One of the examples of the research carried out with the use of the described instrumentation was the research into the influence of hydrostatic jacking pump operation period on bearing performance in transient states which is presented in the paper. The results showed that current practice of pump operation is far from optimum, and that bearing reliability could be improved by changing the current start-up and coasting procedures. The results also showed that pad position during operation is not satisfactory and also some improvement could probably be achieved by rearranging the support of the bearing pad.

Key words: hydrodynamic thrust bearing / spring mattress bearing / hydrostatic jacking / transient conditions / water turbine.

Résumé – Influence de la durée de fonctionnement de la pompe hydrostatique sur les performances d’une butée d’une turbopompe de 125 MW. Un patin spécialement instrumenté a été installé sur une butée de groupe pompe-turbine de 125 MW d’une centrale de production d’énergie polonaise. Les butées de type patin sur support compliant de ces machines sont assez fortement chargées et ont été la cause de nombreux problèmes jusqu’à présent. Il a été entrepris d’évaluer l’état présent de ces butées de façon plus approfondie qu’en utilisant un dispositif standard de pilotage et d’aider à la recherche sur les paliers et aux tentatives de développement. L’instrumentation comporte 16 thermocouples pour mesurer la distribution de la température dans le patin et trois capteurs de déplacement pour déterminer la position du patin et l’épaisseur du film. Le groupe pompe-turbine équipé du palier instrumenté a été testé dans différentes conditions de fonctionnement en régime établi et en régime transitoire. L’étude de l’influence de la durée de fonctionnement de la pompe alimentant la poche hydrostatique (poche de soulèvement) en régime transitoire présentée dans cet article est un exemple des recherches développées avec l’instrumentation décrite. Les résultats montrent que les pratiques usuelles sont éloignées du fonctionnement optimal et que la fiabilité de la butée pourrait être améliorée en modifiant les procédures usuelles de démarrage et de revêtement. Les résultats montrent aussi que la position du patin en fonctionnement n’est pas satisfaisante et que des améliorations pourraient probablement être obtenues en modifiant le support du patin.

Mots clés : butée hydrodynamique / patin sur support compliant / poche de soulèvement / régime transitoire / turbine à eau.

1 Introduction

Hydrodynamic thrust bearings of 125 MW pump turbines of one of Polish major pumped storage power plants are shown in Figure 1. The bearing is a tilting pad type with pads (1) supported on springs (5) evenly distributed under each pad. Thrust plate (2) fixed to the thrust collar (3) rotate together with the vertical shaft (4). The thrust bearing carries the weight of the machine rotating

[a] Corresponding author: mwasilcz@pg.gda.pl

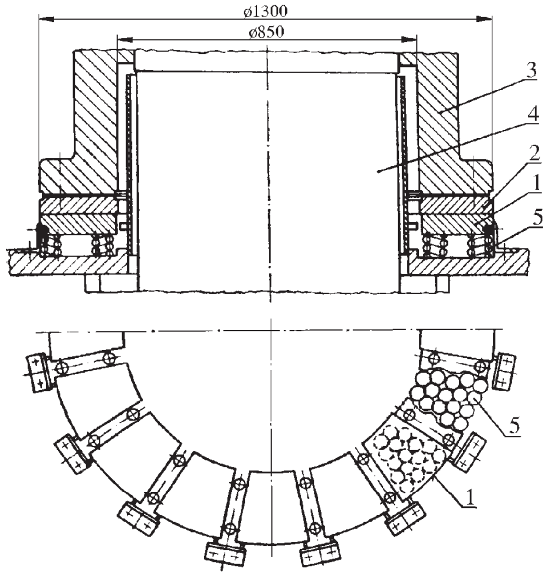

Fig. 1. Thrust bearing of Francis-type reversible machine installed in pumped storage power plant.

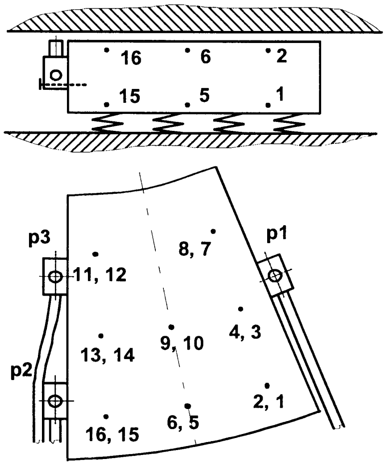

Fig. 2. Distribution of thermocouples (1–16) and displacement probes (p1–p3) in the instrumented pad installed in unit 1.

elements (approx. 2.25 MN) and hydraulic load, which varies for different operating regimes. During start up and shutdown when hydrodynamic load-carrying capacity of the bearing is inadequate because of lower speed, hydrostatic pump supplies high pressure oil to the pockets made in each pad.

Thrust bearings in these machines are heavily loaded and their operation has shown problems typical for thrust bearings of reversible machines. These problems have been discussed in more detail in [1]. The main difficulty is that that reversible machine requires bi-directional bearings because the shaft rotates in one direction in generating mode and in the opposite direction in pumping mode whereas tilting pad bearings with symmetrically supported pads suitable for bi-directional operation are generally inferior to off-set pivoted bearings [2]. The other problem typical for big bearings is the control of thermal deformation [3]. Since the commissioning of the power plant in 1979 thrust bearings have caused many problems, but due to careful maintenance some improvement of bearings reliability has been achieved. Special instrumented pads are being installed in the thrust bearings in order to be able to assess their performance and to evaluate the effects of various R&D projects, as well. Research into the bearing performance under various operating conditions ordered by the power plant owner – Pumped Storage Power Plants – was carried out by the Technical University of Gdansk and G&S Expert Company.

2 Instrumentation pad

Instrumentation installed in one of the bearing pads comprises 16 thermocouples and 3 eddy-current proximity probes. Their distribution is shown in Figure 2. Thermocouples were arranged in pairs (1, 2; 3, 4; 7, 8 etc.) with one thermocouple of each pair situated close to the sliding surface and the other close to the bottom of the pad so as to be able to evaluate sliding surface temperatures at 8 selected locations. Type T (Cu-CuNi) thermocouples of 2 mm diameter were used. The temperature was evaluated with the use of the standard coefficient for T-type thermocouples, no special calibration was carried out. Three proximity probes (p1, p2, p3) were fixed to the sides of the pad so that pad position with respect to the collar could be monitored in various operating regimes. After further processing the data from the proximity probes can also be used to evaluate film thickness. During the research, simultaneously with the instrumentation pad, monitoring system installed in the power plant was used to measure other quantities determining thrust bearing operating conditions, such as:

- Machine output;
- Rotational speed;
- Hydrostatic pump pressure;
- Shaft axial displacements which are proportional to bearing axial load changes.

Most of the data was recorded at 2 s intervals apart from steady state operation when data was acquired only when any of the temperatures changed by more than 0.5 °C, or, if the temperature changes were smaller than 0.5 °C, at 30 s interval. The method of recording proximity probes output, because of its dynamic (fast changing) character was different. Data was first recorded with high frequency and then an average value of each shaft revolution was calculated and recorded.

3 Experimental data processing

3.1 Evaluation of sliding surface temperatures

Temperatures of the pad-sliding surface in selected locations were evaluated as shown in Figure 3. Linear extrapolation of temperatures in the thermocouple location

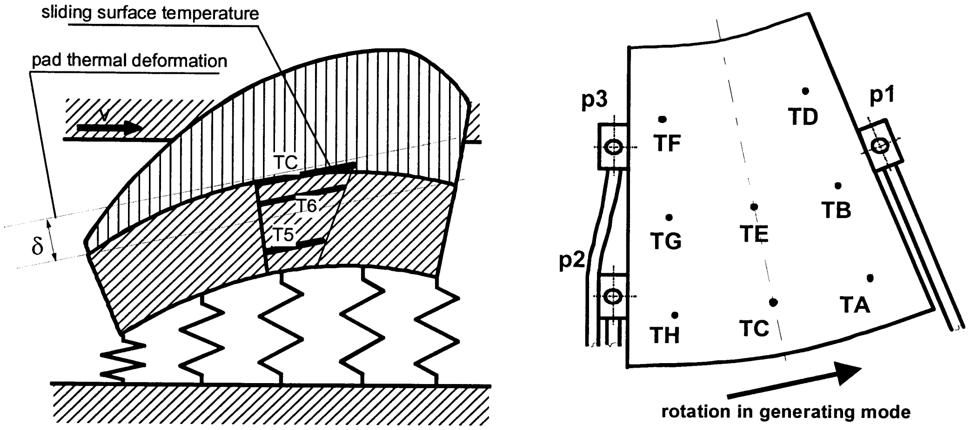

Fig. 3. Method of sliding surface temperature evaluation, sliding surface temperature symbols.

(e.g. 5 and 6) was carried out to give temperature on the sliding surface in the point situated above these two thermocouples (e.g. TC).

The assumption of linear distribution is true (i) for the pad which thickness is small in comparison with length and width, (ii) for heat flux uniformly distributed over the pad surface. Additional discrepancy of linear theory with real temperature distribution occurs in transient states. Then some of the heat is not conducted to the bottom of the pad and oil bath but is heating the pad (or some additional heat is conducted to the oil bath when the pad is cooling down). A method of evaluating the temperature distribution in the pad without the above simplifying assumptions is being prepared, but for the research described in this paper simple linear extrapolation (which is a method typically utilized in the literature – e.g. [4]) was used. Thermal distortion (δ – see Fig. 3) of the pad was evaluated on the basis of average temperature difference between the pad face and bottom assuming for simplicity that pad is a circular plate.

3.2 Minimum measured film thickness

Minimum film thickness was evaluated on the basis of measurements of proximity of the thrust collar carried out with the use of eddy current proximity probes. The probes were of 6 mm diameter and 2 mm measurement range. During installation of the instrumentation pad to the machine proximity probes were calibrated with the use of real thrust plate and purposely prepared sets of distance washers of different thickness to set the distance between the bearing pad and the collar. Standard coefficients given by the probe manufacturer could not have been used because the probes were installed at a smaller distance from the pad than specified by the manufacturer. Difference between proximity probe output signal during operation and at standstill (when the gap between the pad and the thrust collar is zero) was used to evaluate pad distance from the thrust collar. Because of thermal expansion of the pad the difference is not equivalent to film thickness. In order to evaluate real film thickness near

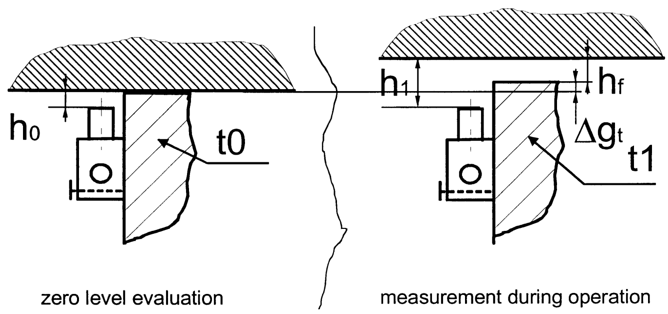

Fig. 4. Influence of temperature on film thickness measurement.

the probe the thermal expansion effect illustrated in Figure 4 had to be considered. Left figure shows calibration of the zero film thickness, which was carried out at standstill when the pad temperature (t_0 – see Fig. 4) was about 50 °C. The situation during operation is shown in the right figure – then the distance between the probe and the thrust plate is increased to h_1. The increase of the distance between the probe and the collar is the result of two phenomena – generation of fluid film between the pad and the collar and increase of pad thickness because of its thermal expansion. During operation pad temperature (t_1) was about 90 °C as compared to 50 °C during standstill, therefore a significant thermal expansion component (Δg_t) must have been taken into account and film thickness was evaluated with the use of the following formula (nomenclature according to Fig. 4):

$$h_f = h_1 - h_0 - \Delta g_\mathrm{t} \tag{1}$$

Thermal expansion component cannot be evaluated very precisely because (i) the temperature of the pad in the vicinity of proximity probes was not measured, (ii) pad temperature within the pad is not constant, and (iii) it also varies in time. Evaluation of the thermal expansion effect showed that its value was 11–14 μm in probes installed at trailing edge side of the pad (oil outlet from the gap) depending on the operation regime.

The other problem of evaluation of real film thickness is evaluation of zero reference level. Measurement at standstill is carried out with the probe situated against one particular point of the thrust collar. Eddy current proximity probes are sensitive to magnetic properties of the observed material and the level of output signal is dependent not only on the distance of the probe from the collar but also on magnetic irregularities of the collar. In order to evaluate relevant zero reference level the output signal at standstill in many angular shaft positions should be measured and then averaged, which is possible in a test rig but was not possible in a real machine. Zero reference level for the described tests was evaluated on the basis of eight random angular positions of the shaft. According to the authors' experience in film thickness measurements described in detail in [5] the effect of thrust collar irregularity can be of the order of magnitude of film thickness. Irregularity of the collar did not affect measurements during operation because in the data acquisition system used for measurements the results of many measurements carried out with high-frequency sampling is averaged from each shaft rotation thus minimizing the effect of irregularities of the collar.

All the problems of film thickness evaluation based on a measurement in a real large bearing discussed above bring an issue of the results uncertainty. It can be concluded that direct comparison of measurement results acquired during operation for various operating regimes are more reliable than the film thickness values themselves because most of the uncertainty is connected with evaluation of zero reference level. In authors opinion the direct measurement error does not exceed the resolution of the data acquisition system, which was about 2 μm, while film thickness value error is higher and can be assessed as 5–8 μm.

One should also remember that the smallest of the film thicknesses evaluated in the vicinity of three proximity probes is not equal to minimum thickness of the oil gap over the whole pad because of pad thermal deformations. In order to evaluate the minimum oil gap thickness one should also precisely evaluate deformed shape of the pad during operation, which was not within the scope of the presented research.

4 The effects of variations of hydrostatic pump operation period

One of the elements of the research program carried out with the use of the instrumentation pad was testing the influence of hydrostatic pump operation period on thrust bearing performance. As mentioned above the hydrostatic jacking system increases bearing load carrying capacity during transient states by supplying high-pressure oil to the circular pockets, which are manufactured in the pad faces. The reason for that is inadequate hydrodynamic load-carrying capacity of the thrust bearing during start up and shutdown because of slow sliding speed [6]. To make matters worse, during start up and shutdown of a Francis reversible turbine axial load carried by the bearing is considerably higher than at steady state operation. On the other hand, during start up oil in the oil gap (and the pad) can be considerably cooler and thus of greater viscosity than in steady state operation. In order to assess the influence of these opposite effects on the thrust bearing measurements of the bearing temperature, film thickness and axial load has been carried out for all typical transient states. In the tested pump turbines hydrostatic jacking system is activated before the start and operates until the shaft rotational speed reaches 85% of the nominal speed, during shutdown the system is activated when the speed falls below 85% of the nominal speed and operates until the shaft is completely stopped. As some earlier observations suggested that it might be beneficial for the bearing if the system worked for a longer time, it was decided to test machine operation at four different periods of hydrostatic jacking system operation:

1. pump is activated at the beginning of the start up and stopped at 75% of the nominal speed; during shutdown pump is activated at 75% of the nominal speed and is working until the shaft rotates;
2. pump is activated at the beginning of the start up and stopped at 85% of n_n; during shutdown pump is activated at 85% of n_n and is working until the shaft rotates – it is the normally used regime of hydrostatic system operation;
3. pump is activated at the beginning of the start up and stopped at full speed (100% of n_n); during shutdown pump is activated at the beginning of slowing down (100% of n_n) and is working until the shaft rotates;
4. pump is activated at the beginning of the start up and stopped 30 s after the end of start up (n_n +30 s); during shutdown pump is activated at the first step of the shutdown procedure and is working until the shaft rotates.

In this paper because limitations of space only the start to pumping mode is shown in the diagrams. Diagrams showing the changes of characteristic quantities in time are presented in Figure 5. Quantities for the shortest pump operation mode are not shown in Figure 5, for better readability.

Film thickness in the diagram is the smallest of the three – for pumping mode it was film thickness measured at p2 position – see Figure 3, temperatures are described according to Figure 3, as well. Additional load is the increase of the bearing axial load caused by flow phenomena in the turbine runner – for all regimes of hydrostatic jacking system operation it was practically identical, that is why only one is shown in the diagram.

Start up to the pumping mode is the longest of the transient states, it lasts for almost 5 minutes, compared to 70 s required for start up to generating mode and 3 minutes for shutdown from generating and pumping modes. During start up to the pumping mode conditions of bearing operation are difficult because of the bearing overload equal to about 700 kN (compared to 2250 kN of the weight of the rotating parts). The start up lasts for such a long time that the bearing highest temperature is higher than in steady state operation by approx. 5 °C.

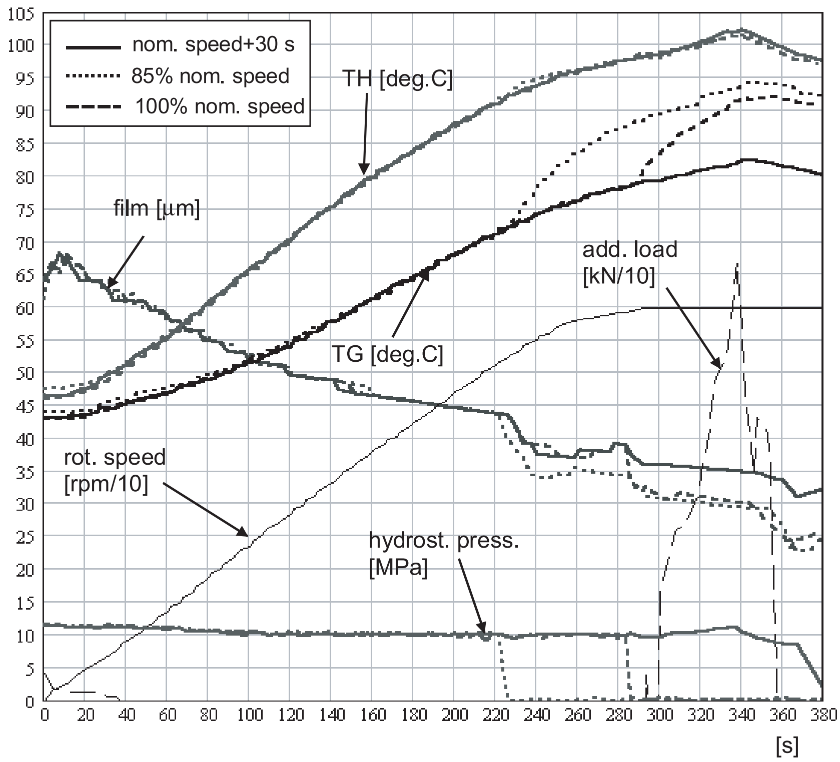

Fig. 5. Changes of characteristic quantities during start up to pumping mode for various regimes of hydrostatic system operation.

The influence of hydrostatic system operation regime can be clearly observed: turning off the hydrostatic pump causes immediate increase of temperature in the middle of the trailing edge (TG) and sudden drop in minimum measured film thickness. On the other hand pump operation regime has no influence on the temperature in the outer corner of the pad (TH). It can also be observed that bearing overload which occurs just after achieving full rotational speed can be carried with an aid of the hydrostatic system only when the system is working for 30 s after achieving full rotational speed by the machine. The result of this assistance is higher film thickness and lower temperature in the middle of the trailing edge.

5 The effects of variations of hydrostatic pump operation period – summarized

All typical transient states – start up to generating mode, shutdown from generating mode and for pumping mode start up and shutdown, as well – were compared in the same way as start up to pumping mode presented above. Outer trailing edge temperature is not shown in the graphs comparing the results because in all transient states pump operation had practically no influence on its changes. For all transient states this temperature was the highest of all the sliding surface temperatures, which is probably the result of unfavourable pad position. Other results of the research (not shown here) showed that the radial inclination of the pad was almost the same as the circumferential inclination so that film thickness at

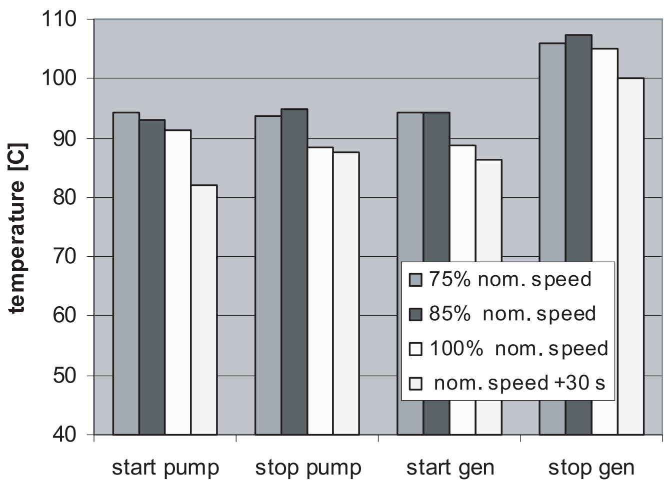

Fig. 6. Influence of hydrostatic jacking system operation regime on the temperature at the middle of the trailing edge.

the outer bearing diameter was considerably smaller than at the inner diameter. Value of each quantity at the bar charts is given at the moment of maximum axial load of the bearing during the start up or shutdown.

The influence of pump operation on the temperature at the middle of the trailing edge (TB for gen. mode, TG for pump mode) can be easily observed (Fig. 6). Difference in temperatures between the shortest and the longest period of pump operation is 8–12 °C. Even though this temperature is not the highest one, the decrease in temperature in case of longer pump operation may considerably

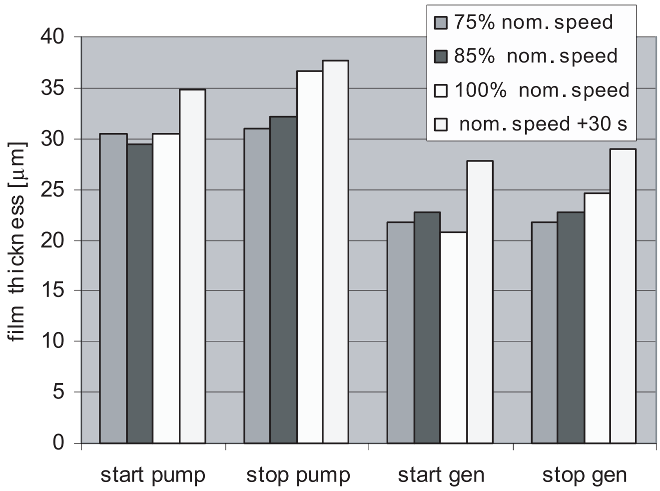

Fig. 7. Influence of hydrostatic jacking system operation regime on the smallest film thickness.

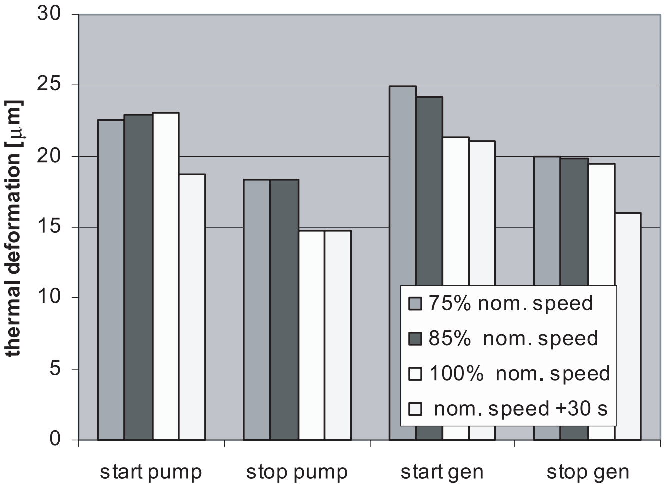

Fig. 8. Influence of hydrostatic jacking system operation regime on the thermal deformations of the pad.

influence bearing reliability because in this area (middle of the trailing edge) the bearing alloy is also subjected to high film pressure. At lower temperature yield stress of the babbit will be greater increasing bearing reliability (and also durability because of higher fatigue strength).

Higher film thickness (at p1 position for generating mode and p2 for pumping mode) was another benefit of longer pump operation observed in the research (Fig. 7). The difference was 5–7 μm depending on the mode of machine operation. Because of higher thermal deformations for shorter pump operation (Fig. 8) the differences in minimum film thickness may even be higher. Higher film thickness contributes to the bearing increased reliability – decreasing the risk of metal-to-metal contact and bearing seizure.

Lower thermal deformations observed for longer pump operation have the influence on load carrying capacity of the bearing. According to the fundamental work by Raimondi [7] there is an optimum of deformation that yields highest load-carrying capacity of centrally pivoted

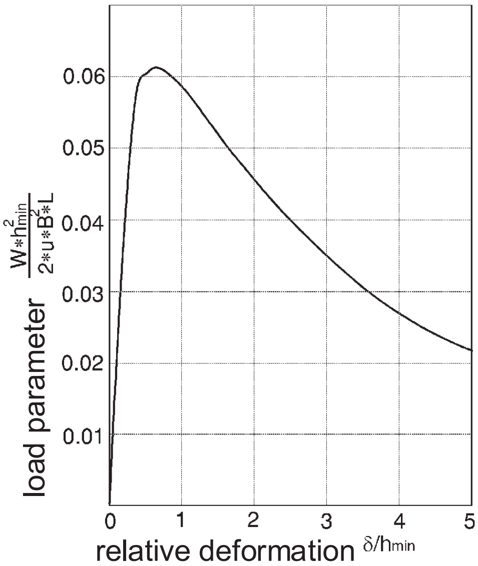

Fig. 9. Load carrying of centrally pivoted pad with spherical deformations.

pad, which is equal to approximately 0.7 of minimum film thickness (Fig. 9).

It should also be mentioned that for a centrally pivoted pad deflections are necessary for generating hydrodynamic load carrying capacity – for zero deflections load parameter is equal to zero. Optimizing pad deflections seems to be a very important problem of the design of large centrally pivoted thrust bearings especially as the deflections should be within an acceptable range not only at steady state operation but also at transient states at which both – axial load and temperature field can differ from these at steady state operation. In the examined bearing one can assess the minimum film thickness to be about 18–20 μm, taking into account the fact that minimum film thickness is smaller than film measured at the proximity probes position. In such a case thermal deformations over 20 μm, observed especially for shorter period of hydrostatic pump operation can be considered as exceeding the optimum values and affecting thrust bearing load-carrying capacity at the moments of excessive bearing load. Moreover at the longest pump operation regime, higher hydrodynamic load carrying capacity due to better profile of the sliding surface (Fig. 9) is further increased by load carrying capacity due to hydrostatic jacking still operating at the moment of maximum axial load.

6 Conclusions

The use of instrumentation pad made it possible to collect detailed information on thrust bearing performance in various modes of operation.

The application of thermocouples of low heat capacity increased safety of bearing operation during research in severe operating conditions. Short response of the thermocouples should encourage the machine operators to introduce thermocouples into the standard monitoring system of the power plant, which should result in increased safety of operation due to shorter reaction time.

Collected data illustrates benefits of introducing longer period of hydrostatic jacking system operation to machine operation procedures, namely:

1. Decreased temperature of center of the pad surface – increasing strength of bearing alloy in the area heavily loaded by oil pressure;
2. Increased film thickness during severe conditions of increased axial force and/or lower speed;
3. Decreased pad thermal deformation increasing load-carrying capacity of the bearing.

The above benefits should encourage machine operators to introduce changes in regime of hydrostatic system operation especially as there is not any evidence of possible threats of longer period of system operation.

Although, according to authors' knowledge, the analysis has been done with the use of methods and models commonly used in the literature, some deficiency of the analysis should be also pointed out:

- evaluation of sliding speed temperature did not take into account heat capacity of the pad and heat;
- thermal deformation of the pad were evaluated with the use of a very simple model;
- effect of thermal expansion of the pad on film thickness measurements was considered in a simplified way.

The authors are now working on improved model of evaluating temperature distribution in the pad, which would take into account realistic model of heat flow including transient state effects. Improved methods of evaluating temperature distribution will make it possible to evaluate shape of the bearing pad and minimum film thickness during operation more precisely – with the use of Finite Element Method programs.

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