OPTICAL SENSOR FOR JOURNAL BEARING OIL FILM PRESSURE MEASUREMENTS

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ABSTRACT

The oil film pressure is one of the fundamental parameters influencing the operation of journal bearings. The oil film pressure is estimated by theoretical calculations, since the measurement of oil film pressure has been a demanding task in journal bearings, especially in bearings carrying dynamic loads. In this study a new approach to experimentally measure the oil film pressure has been developed and tested.

The sensor design utilizes the optical fibre technique and the sensor is integrated in the sliding surface of the bearing thus providing the possibility to measure the actual oil film pressure under load without disturbing the contact conditions. The finite element method (FEM) calculations have been used for optimizing the design of the sensor and for ensuring the appropriate mechanical performance of the sensor design.

The optical sensor was integrated into a hydrodynamic journal bearing made of bronze and a versatile bearing test rig was used for testing the operation of the optical sensor. The tests were carried out using both static and dynamic loading conditions with different loads and speeds. The experimental data was compared with the simulated one. The results showed that the optical sensor was capable to measure the oil film pressure in journal bearing at real operating conditions and the sensitivity of the sensor was good enough to verify the speed and load effects on the oil film pressure.

According to this work, it is possible to increase the knowledge of true operating conditions of journal bearings by using the optical sensor for oil film pressure measurement. The knowledge can be utilized in the development work of safer and more efficient machines and engines with journal bearing carrying high and dynamic loads. This optical sensor configuration can be used also in other applications for measurement and control of pressure.

KEY WORDS

Optical sensor, journal bearing, oil film pressure

INTRODUCTION

The journal bearings are frequently used to carry radial loads in machinery, like thermal engines, turbomachinery and power generating units. A journal bearing system consists of two elements; a loaded, rotating shaft (journal) and a bearing with a slightly larger diameter than that of the journal. The operation of the journal bearings is dependent on the hydrodynamic film generated in the bearing and the oil film pressure is one of the key parameters in operation of journal bearings [1, 2]. The determination of the oil film pressure generated in the bearings has been based on equations and numerical calculations [3]. The experimental determination of the oil film pressure in journal bearings has been earlier based on the use of conventional pressure sensors mounted in a borehole drilled through the journal bearing surface. This type of configuration has one major disadvantage, since it effects the contact situation and the actual oil film pressure in the bearing. Even though the measurement of the oil film pressure has been a demanding task, Mihara and co-workers have succeeded to measure oil film pressure by using a thin film sensor deposited on the bearing surface [4, 5, 6]. He has carried out oil film pressure measurements as well as temperature and strain measurements of the bearing surface in engine tests. The sensors have been deposited by PVD techniques onto the bearing surface. Using the pressure sensor e.g. at the bottom of the main bearing of a diesel engine the maximum oil film pressure of 45 MPa at full engine load has been measured [6].

Another functional parameter of interest in journal bearings is the oil film thickness. The eddy current cap sensors have been used to measure the oil film thickness and shaft trajectories in engine bearings by Moreau et al. [7]. The in situ measurements of elastic engine bearings showed that for some bearings good agreement with measured films thickness values and the theoretical calculations was found, but for some cases significant variation between calculated and measured values was observed. The difference between the calculated and measured values were at the minimum less than 10 µm, but reached the values up to 25 µm in some cases. Also optical sensors have been earlier used for oil film thickness measurements in hydrodynamically lubricated bearings. The optical sensor has been typically mounted flush with the bearing surface and the light is transmitted through the lubricant film and reflected from the shaft surface back to the optical sensor [8, 9, 10]. In these sensor applications the sensor on the bearing surface influences the contact conditions in the bearing. Sensors based on optical fibre technology have been developed also for strain and temperature measurements in different applications. These embedded sensors typically utilize advanced techniques like Fibre Bragg Grating [11] or Fabry-Perot interferometry [12] and are thus more complicated and expensive to produce.

In this study a novel method for the experimental determination of the oil film pressure in journal bearings has been developed and verified in versatile journal bearing tests. The sensor for oil film pressure measurement is integrated in a journal bearing in a way which leaves the bearing surface untouched. The sensor utilizes the optical fibre technique which provides benefits, such as insensitivity to electromagnetic disturbances and capability to transmit the information long distances even from difficult operational circumstances without electrical wiring.

OPTICAL SENSOR

The sensor developed for the oil pressure measurement is based on the optical fibre technology. An optical sensor head is mounted in a cavity machined in the journal bearing from behind in a way that the contact surface of the journal bearing remains untouched and acts as a measurement membrane of the sensor design. This means that the oil pressure acting on the contact surface can be measured without disturbing the contact area or the actual contact conditions. The optical sensor head developed consist of two optical fibres fixed inside a sensor head. One fibre is used to illuminate the measurement membrane, and the other one to receive the reflected light. The principle of the sensor is shown in Fig. 1. The light source used is a broadband halogen lamp with a wide optical spectrum eliminating the harmful interference effects, which are present when using a coherent source, such as laser. The detected intensity of the reflected light changes according to the deflection of the measurement membrane, which is caused by the oil pressure acting on the bearing surface.

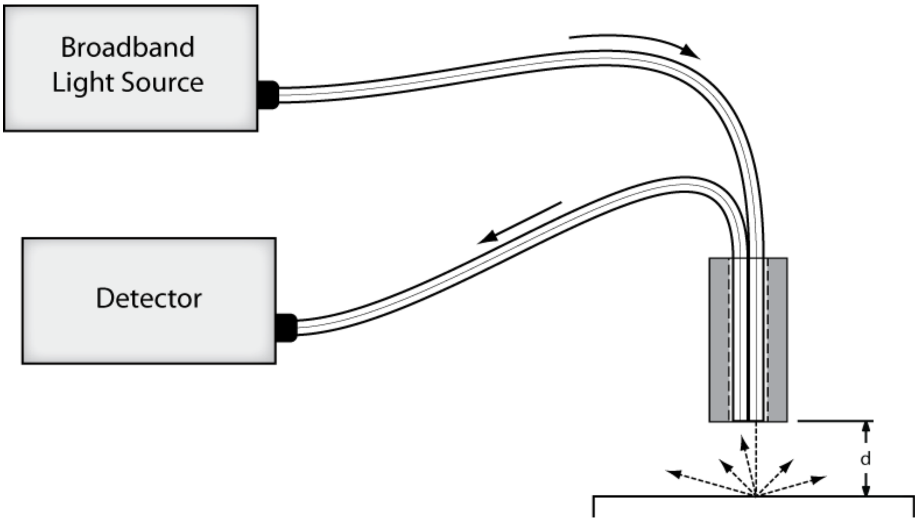

Figure 1. The operational principle of the optical sensor. One fibre is used to illuminate the surface. Part of the reflected light is coupled to the other fibre, and its intensity is measured using a photodetector. The measured signal depends on the width of the gap (d) between the sensor head and surface.

To test the functionality of the optical sensor head, optical test measurements were carried out. Figure 2a shows the measured optical signal as a function of distance between the sensor head and a highly reflected mirror surface. The sensor was moved accurately using a motorized translation stage with a minimum detectable movement is 100 nm. When the gap was small no light was detected. As the gap increased, some of the reflected light was captured by the receiving fibre. The maximum signal was detected at the distance of 400 µm. Further increase of the gap decreased the signal. The optimum measuring distance was about 270 µm, because the gradient of the curve is highest at this position. This value was used for the operational distance between the measurement membrane and the sensor head. The maximum movement of the membrane to be measured is designed to be typically under 4 µm. In this range the change of the signal is linear and the minimum detectable movement is 100 nm, as can be seen in Fig. 2b. The degree of reflection influences the intensity of the detected optical signal, but does not affect to the functionality of the sensor. The lower reflection degree can be compensated by increasing the input power.

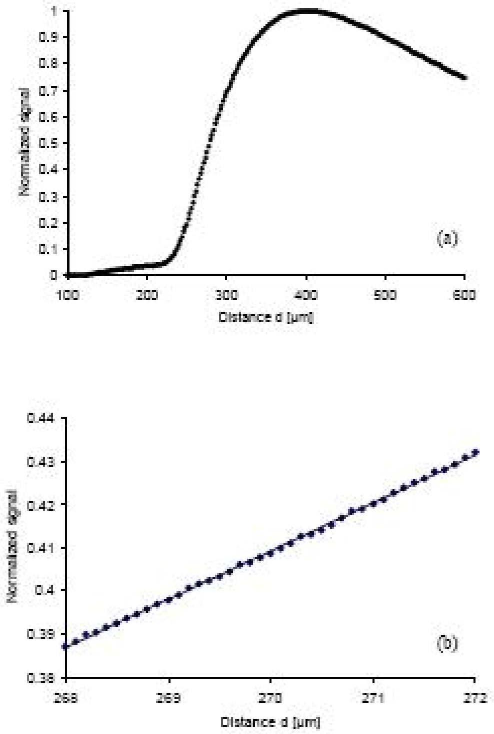

Figure 2. (a) Measured signal as a function of the distance between the sensor head and the Au mirror. The sensor operates optimally at a distance of 270 µm, since the gradient of the curve is highest. (b) The signal change is linear in the typical measurement range.

The Finite Element Modelling (FEM) was used for the optimization of sensor design and for the characterization of the mechanical functionality of the sensor. An axisymmetric model with parabolic elements was generated by Abaqus 6.6-2 program. The uniform pressure of 100 MPa was used in modelling and the material input depicted the properties of bronze covered (0.5 mm) steel structured bearing. The modelling described the displacements, von Mises stresses, the maximum and minimum principal stresses generated by the sensor in the bearing structure. The FEM results showed that the sensor structure was mechanically applicable and the design could be further improved by using modelling approach.

OPTICAL SENSOR IN A JOURNAL BEARING

The optical sensor head was integrated in a hydrodynamic journal bearing having a steel shell and inner bearing surface made of bronze alloy. The outer diameter, inner diameter, width and wall thickness of the bearing were 91 mm, 85 mm, 32 mm and 3 mm, respectively (Fig. 3). The bearing consisted of two half-shells and the optical sensor was integrated in the upper shell in the middle of the bearing width.

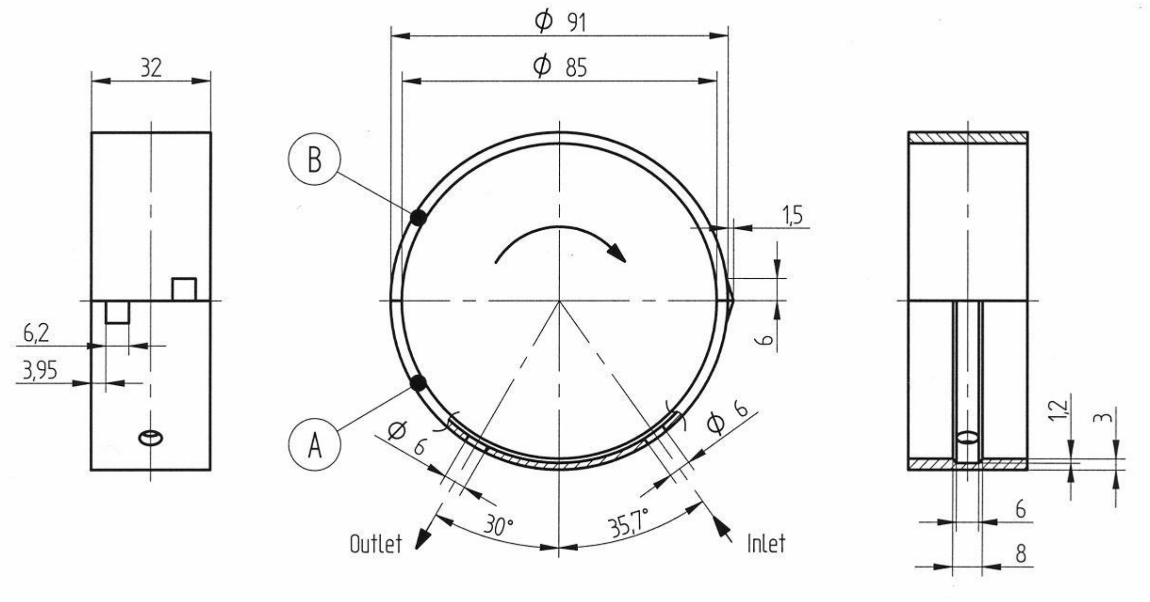

Figure 3. Bearing used in the study. The optical sensor was integrated in the upper bearing shell.

The mounting of the optical sensor in the bearing was carried out after the bearing was installed in the housing. The optical sensor was calibrated by using a specially designed device for sensor in-bearing calibration. The calibration device provided a controlled fluid pressure on the sensor area which allowed the sensor calibration in a step-wise manner in the range 5 to 50 MPa. The measured optical signal showed repeatedly linear dependence on the calibration pressure with a standard deviation less than 1 % between the calibrations.

JOURNAL BEARING TESTS

The journal bearing with integrated optical sensor was tested in a versatile bearing test rig (Fig. 4). The bearing test rig consisted of a frame, test bearing unit and the systems for loading, driving, lubricating, controlling and measuring the test equipment. The lubricating system provided lubricant for the test bearings and the loading system generated both static and dynamic bearing loads resembling for example the load patterns typical for engines. The sliding speed of the shaft used in these tests was in the range 1 to 5 $ms^{-1}$and the bearing load in the range 5 to 15 kN. The above mentioned sliding speeds and bearing loads resemble roughly the ones found in main bearings of high-speed diesel engines at idle running. The main tribological variables related to operation of the bearing were recorded during the tests.

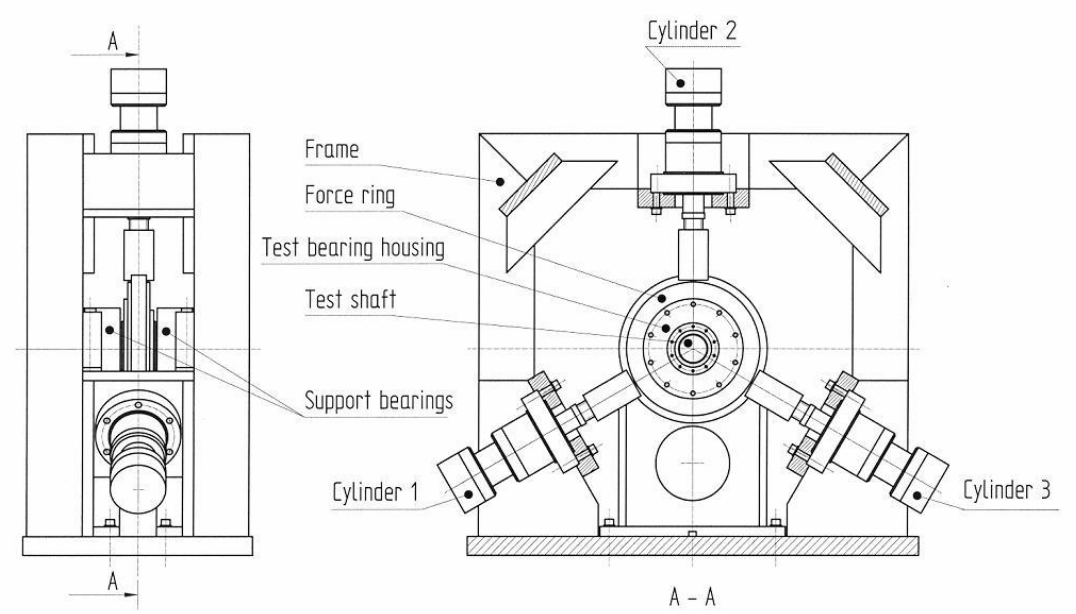

Figure 4. Versatile bearing test rig with hydraulic cylinders generating the bearing load.

The shaft used in the tests was made of steel with nominal diameter and length 85 mm and 600 mm, respectively. The shaft had one radial oil-feeding hole with a diameter of 6 mm, which was used to provide lubricant into the middle of the bearing with a inlet pressure of 0.3 MPa.

The bearing housing consisted of two half-rounds and thick-wall conical sleeves with flanges (Fig. 5). The upper sleeve was equipped with drillings for the optical sensor and one thermoelement, which was used for the operating temperature measurements.

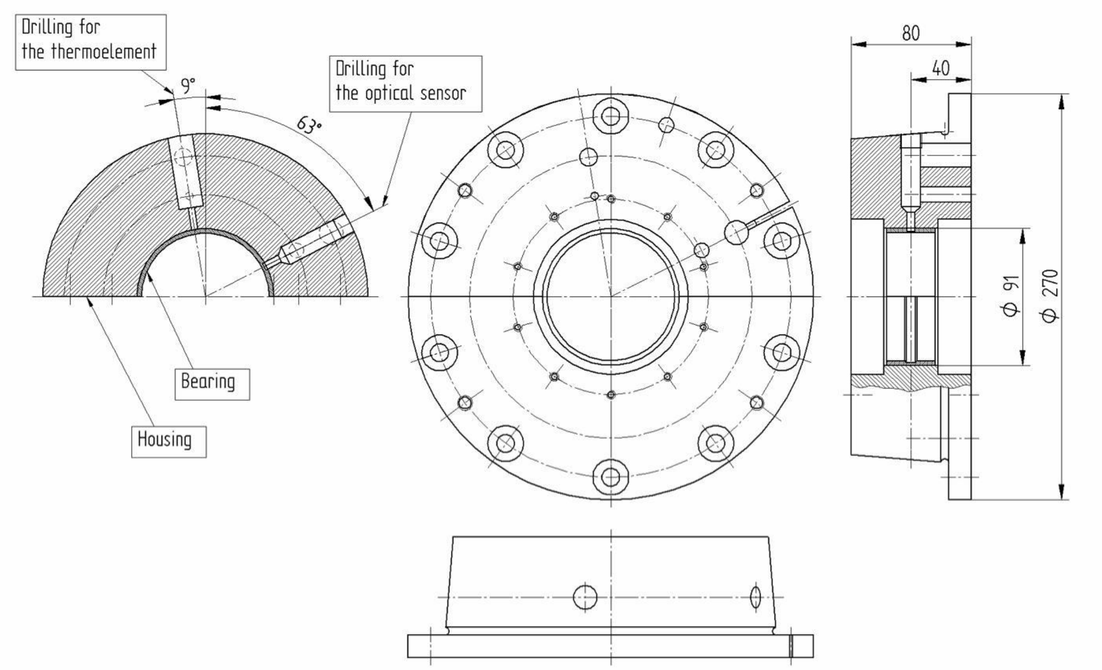

Figure 5. Bearing housing with the bearing and drillings for the optical sensor and the thermoelement.

The lubricant used in the tests was a mineral oil based lubricant blended to SAE 40. It was formulated to be used as a combined cylinder and crankcase lubricant in medium speed marine diesel engines. The Density of the lubricant was 916 kgm^{-3} (at 15 ^{o}C) and the kinematic viscosity 139 mm^{2}s^{-1} at 40 ^{o}C and 14.9 mm^{2}s^{-1} at 100 ^{o}C.

Both rotating and the static bearing load conditions were used in the tests. The bearing loads were generated by the hydraulic load system that had three hydraulic cylinders. The generated cylinder forces F_1, F_2, and F_3 were synchronized with the rotation of the shaft by using a pulse sensor and a pulse counter. Outputs of the sensor and pulse counter were used as input data for the computer with a signal processor to control the load system. The resultant of the cylinder forces was the load L and the bearing load F was the counterforce for the load L (Fig. 6).

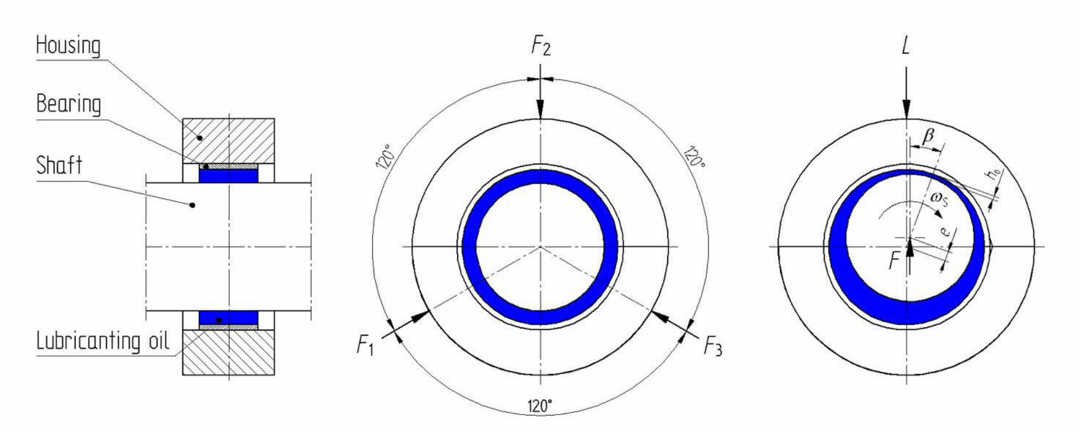

Figure 6. Cylinder forces F_1, F_2, and F_3, resultant L, and bearing load F pushing the bearing against the test shaft. The shaft rotates clockwise at angular velocity ω_S. The shaft has a certain eccentricity e.

As the rotating load was used, the level of the bearing load F was constant as a function of the angle of rotation and the bearing load was rotating with the shaft around the bearing at rotational speed. The direction of the bearing load, F, was synchronized with the position of the radial oil-feeding hole in a way that the oil-feeding hole pointed to the unloaded side of the shaft as presented in Fig. 7.

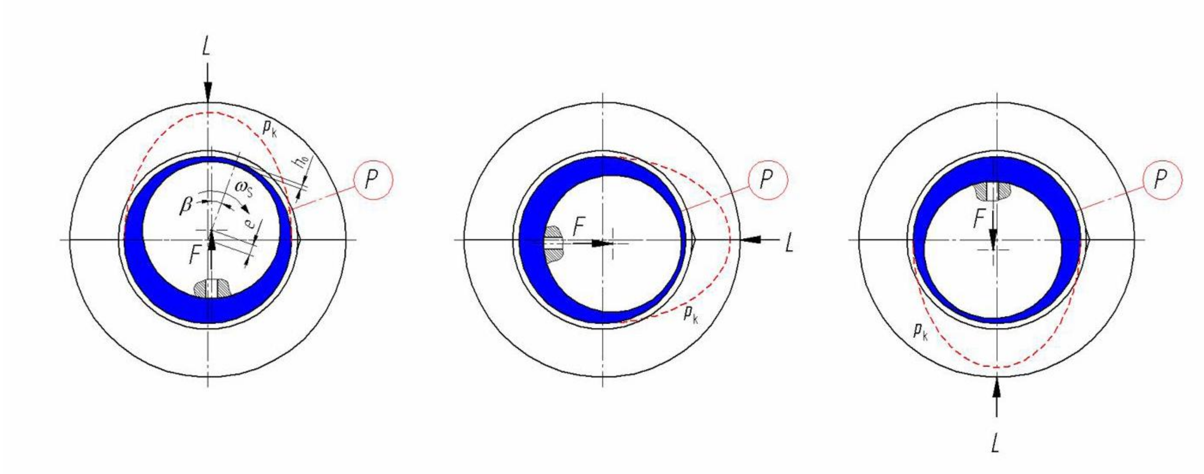

Figure 7. Load L and bearing load F in three consecutive phases of the revolution of the shaft when a rotating load is used. The shaft rotates clockwise. The radial oil-feeding hole in the shaft points to the unloaded side of the shaft. The oil film pressure generated under load crosses the measurement point (P) once per revolution.

When the continuous static load was used, the level of bearing load F was constant as a function of rotation angle and the direction of the bearing load was fixed pointing upwards (Fig. 8). The radial oil-feeding hole in the shaft crossed the measurement point once per revolution.

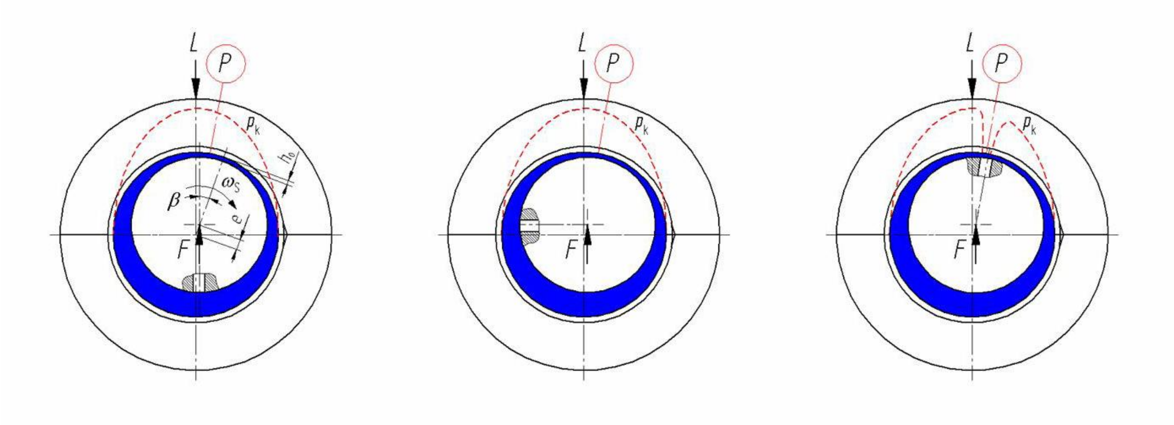

Figure 8. Load L and bearing load F in three consecutive phases of the revolution of the shaft when a static load was used. The shaft rotates clockwise. The radial oil-feeding hole in the shaft crosses the measurement point (P) once per revolution.

For comparison to experimental data the bearing simulations were carried out by the AVL EXCITE simulation software. The software used the finite element method (FEM) to simulate the dynamic response of engine parts connected by a set of nonlinear joints. The simulation model used was based on elastohydrodynamic (EHD) bearing calculation. The model of the bearing had 19 nodes in axial direction and 121 nodes in circumferential direction. The bearing dimensions and operating parameters applied in the tests were used as input data in simulations. The lubricating oil temperature was assumed to be constant and equal with the measured operating temperature of the bearing.

TEST RESULTS

Journal bearing tests carried out with different loads and sliding speeds showed that the optical sensor performed well in journal bearing tests with different bearing loads, speeds and temperatures. Typically, the measured oil film pressure varied linearly as the bearing load was varied. The signal of the optical sensor had a good signal to noise ratio.

When rotating load was used in the tests the rotating shaft was moving on the contact surface around the bearing at sliding speed generating the oil film pressure to circulate around the bearing surface. As the shaft passed the optical sensor once per revolution, the oil film pressure measured by the sensor increased reaching the maximum value characteristic for the load applied. After the shaft moved further from the sensor area the pressure signal decreased steeply. Figure 9 shows the data of tests carried out with 15 kN bearing load and with 4 ms^{-1} sliding speed. The oil inlet temperature was 70 ^{o}C and the operating temperature of the bearing 80.4 ^{o}C. The maximum pressure value measured was about 20 MPa and the pressure signal levelled to zero before and after the pressure peak.

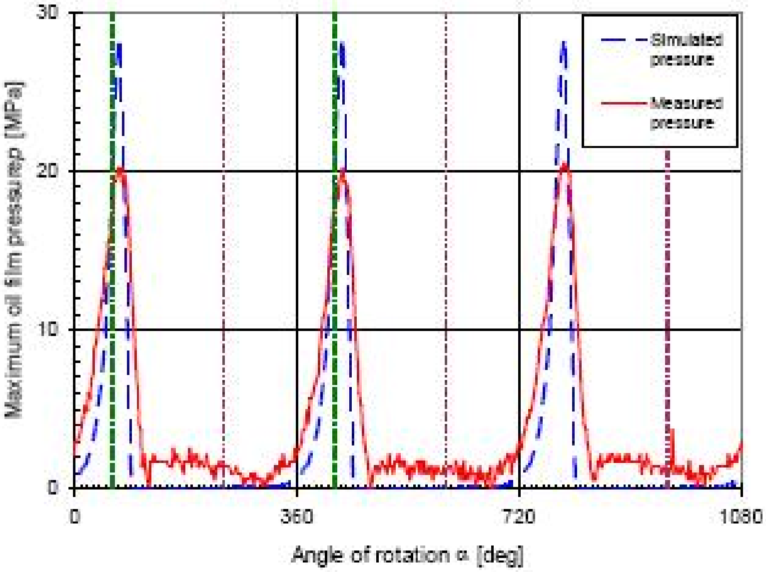

Figure 9. Measured and simulated oil film pressure p as a function of the angle of rotation at rotating load. The bearing load in test was 15 kN and the specific load 5.5 MPa. The rotational speed was 899 rpm and sliding speed 4 ms^{-1}. The oil inlet temperature was 70 ^{o}C and the operating temperature of the bearing was 80.4 ^{o}C during the test.

Figure 9 also represents the simulated oil film pressure with rotating load. The calculated pressure showed similar performance compared to the measured data, but the maximum pressure was higher compared to measured one. The measured pressure peak was slightly broader than the calculated one due to averaging effect in the sensor. When comparing the integrated areas of the measured and calculated pressure peaks, they showed values close to each other.

When the tests were carried out with different bearing load values increasing from 5 to 15 kN, an increase in maximum oil film pressure was observed. Figure 10 represents the effect of load on the measured oil film pressure showing increase of maximum oil film pressure from a few MPa to 20 MPa as the bearing load was increased from 5 to 15 kN. The dependence of the pressure on the load was close to linear. However, more tests are needed to accurately verify the correlation.

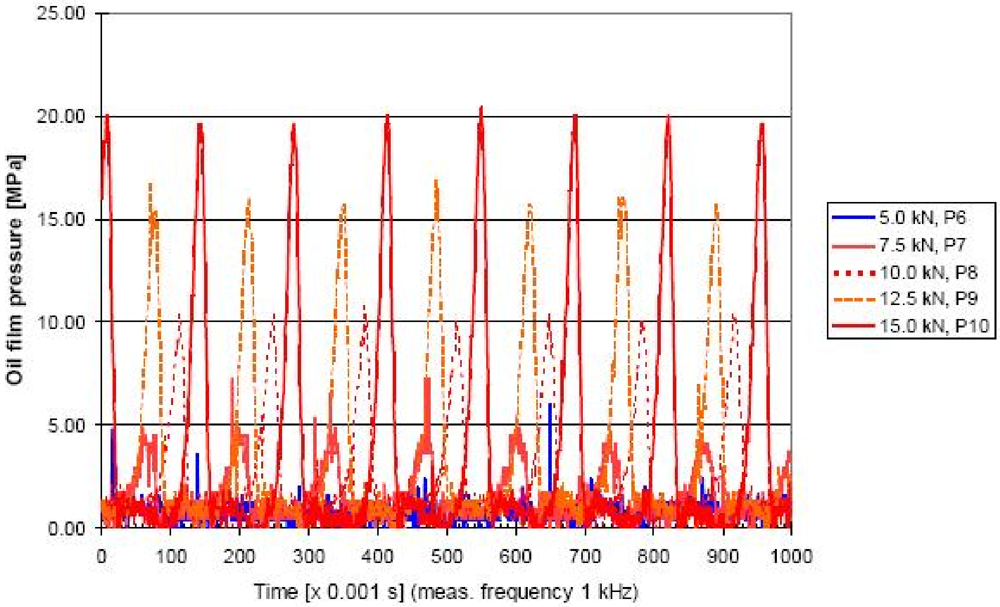

Figure 10. Measured oil film pressure p as a function of time at rotating load. The bearing load was varied in the range 5 to 15 kN representing specific bearing load of 1.8 to 5.5 MPa. The sliding speed was 4 ms^{-1} and the oil inlet temperature 70 ^{o}C.

The tests were also carried out with different sliding speeds in the range 1 to 5 ms^{-1}. The pressure varied slightly as the speed was changed showing decreasing trend as the speed was increased as shown in Fig. 11.

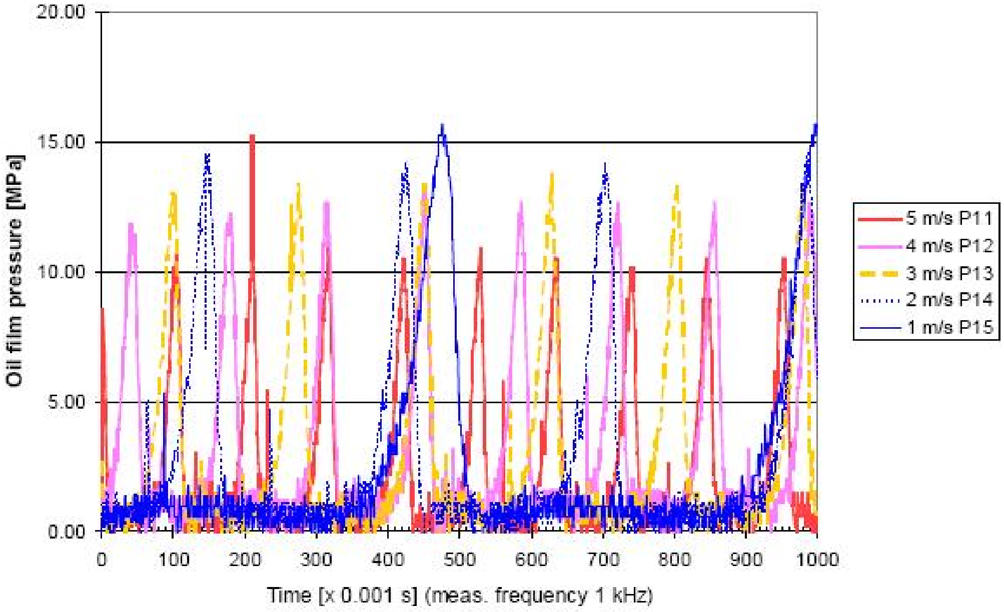

Figure 11. Measured oil film pressure p as a function of time at rotating load. The sliding speed was varied in the range 1 to 5 ms^{-1} with the rotating bearing load of 10 kN (3.7 MPa). The oil inlet temperature was 70 ^{o}C.

The static load of the bearing caused basically a steady pressure on the sensor when the shaft generating the oil film pressure was acting on the area where the sensor was mounted. However, a rapid drop in oil film pressure to the zero level was observed as the radial oil-feeding hole in the shaft crossed the measurement point of the optical sensor once per revolution as observed in Fig. 12.

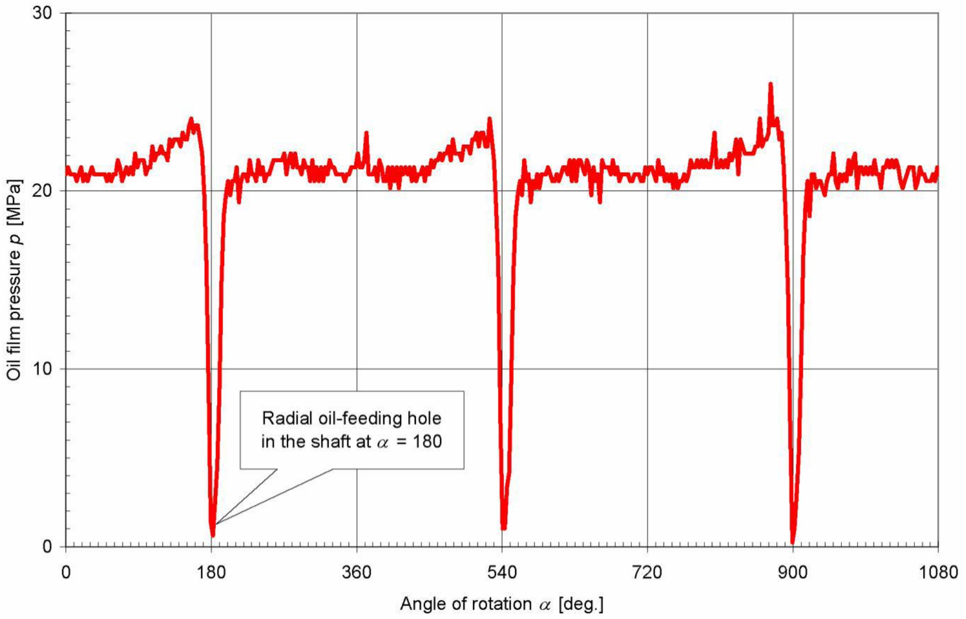

Figure 12. Measured oil film pressure p as a function of the angle of rotation at static bearing load. The bearing load was 13 kN and specific load 4.8 MPa. The rotational speed was 899 rpm and sliding speed 4ms^{-1}*. The oil inlet temperature was 70* ^{o}*C and the operating temperature of the bearing 80.9* ^{o}*C.*

When the load and the sliding speed in the bearing tests were varied, the operational temperature of the bearing changed accordingly as expected. The measured pressure had a tendency to drift due to temperature change in the bearing. It was observed that the change in operational temperature of the bearing from 50 to 65 ^{o}C caused variation in the optical signal corresponding of about 6 % increase in pressure.

DISCUSSION

The operation of power transmitting components, like bearings, is important for the reliable and effective operation on machinery. The operation of components like journal bearings has been based on calculations and experimental studies, since the accurate measurement of the bearing parameters, like oil film pressure, has not been possible. The further increased requirements for higher power densities are pushing the operational limits of components even further which makes it important to increase the information of the components and of the parameters influencing their performance in actual operational situations. Also the reliable operation of components and machines is becoming more and more important due to the demand for productivity and continuous production.

Generally the condition monitoring of components and machines has been carried out with different techniques by using sensors mounted on the outskirts of the components, like bearing cases that are far away from the actual contact of interest. However, the sensors integrated in the actual point of interest would bring more valuable information on the parameters influencing the performance of components and machines. A new type of sensor developed in this study, is integrated into the component in a way that the real operational surface is acting as a part of the sensor. The optical sensor developed is based on commercially available optical fibres and components, and therefore it is possible to produce the integrated sensor with a reasonable price. The preliminary journal bearing tests carried out with the integrated optical sensor show the feasibility of the sensor design.

The results from the journal bearing experiments showed that the optical sensor operated well in journal bearing tests when high bearing loads, speeds and operating temperatures were used. At rotating load, the measured oil film pressure varied dynamically when the pressure wave crossed the measurement once per revolution. At static load, the measured oil film pressure was stable, except the change in pressure when the oil-feeding hole of the shaft crossed the sensor once per revolution. This showed the capability of the sensor to rapidly respond to the pressure changes. It was also observed that the measured pressure level increased as the bearing load was increased and decreased as the sliding speed was increased, which is in accordance with the theoretical calculations. Thus the sensor could be used for studying the operational parameters of journal bearings.

The sensitivity of the sensor was good enough to distinguish the bearing loads in the range 5 to 15 kN and the measured pressure signal followed the increase in bearing load in a linear way reaching pressure values up to 20 MPa. The signal to noise ratio of the sensor was high enough to depicting clearly the changes in pressure. When the bearing load was kept constant, some noise was observed in the measured oil film pressure as shown in Fig. 9 to 12, which was obviously related to turbulence in the lubricating oil inside the bearing and to instabilities in the test equipment operation. The repeatability of the measurement results was considered good in the range studied.

The changes in the operational temperature had an influence on the sensor signal showing some fluctuation of the pressure signal as the temperature of the bearing system changed even though the test parameters were kept constant. The pressure signal tended to increase as the bearing temperature was increased. This was obviously caused by the thermal instability of the sensor design and therefore the design was re-evaluated and modifications in the design were made in order to increase the temperature stability of the sensor. The updated version of the sensor with a more stable materials and sensor design will be used in the future tests.

Results from a comparison between measured and simulated oil film pressure data showed that the shape of the measured and simulated oil film pressure peaks resembled each other and the measured oil film pressure level correlated reasonably well with simulated one. Therefore it can be assumed that the optical sensor was able to measure the actual oil film pressure. The maximum value of the measured pressure peak was lower than the calculated one. However, since the measured peak was somewhat broader due to averaging effect of the sensor, the integrated area of the measured and calculated pressure peaks were similar. The difference between the peak values of the measured and the calculated pressure is anyway an interesting feature that needs to be verified with a larger amount of experimental results.

In Figures 9 to 11 the zero level of pressure is set on the minimum pressure value measured. However, this causes of about 2 MPa oil film pressure on zero load in the angle of rotation. If the zero level would be set on a higher level comparable to the 2 MPa level shown e.g. in Fig. 9, the pressure peaks pointing below zero level would represent negative pressure in the oil film. This is possible, since the measurement membrane can deform in the opposite side of the bearing surface owing to the negative pressure. The sensor thus provides a practical means to study the different pressure effects in the journal bearings.

When comparing the results obtained with this optical sensor to previous studies of Mihara et al. [4, 5, 6], the both techniques are feasible for pressure measurements in journal bearings. However, the thin film sensor consisting of brittle ceramic materials is vulnerable in journal bearing applications where certain amount of conformability and embeddability during operation is required. An integrated sensor leaving the contact surface of the bearing untouched will probably be able to operate in more versatile conditions. Basically the optical sensor can be integrated into other components and can thus be used also in other applications for pressure measurements.

The integrated sensors can provide valuable information on the operational parameters influencing the performance of machine components. This can enhance the development of bearing and component designs for more effective and reliable operation. In the long run new integrated sensor technologies can enable new approaches for smart operation and control of components and machinery.

CONCLUSIONS

The optical sensor integrated in a journal bearing was used in journal bearing tests. The developed sensor was able to measure oil film pressure at dynamic operating conditions in test rig environment. The measured pressure signal followed the increase in bearing load systematically, reaching values up to 20 MPa with bearing load of 15 kN. In the tests with static bearing load the pressure signal was stable, but dropt to zero level as the oil-feeding hole of the shaft passed the sensor area.

According to this work, new integrated sensor designs, like the optical oil film pressure sensor, can be used to increase the knowledge of operating conditions of journal bearings. The knowledge can be used in development of safer and more efficient machines and engines with journal bearings carrying high and dynamic loads.

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