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An experimental investigation on the influence of deactivation of a groove on the performance of a twin groove journal bearing

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Abstract

Laboratory tests have been carried out in order to assess the influence of groove activation and deactivation on the performance of a twin axial groove steadily loaded hydrodynamic journal bearing. Temperature distribution at the oil–bush interface, oil outlet temperature, total oil flow rate, partial oil flow rate (at each groove), and motor consumption were measured for several journal speeds and loads under constant feeding pressure (p_f) and constant feeding temperature (T_f), at five different loading angles (Γ). In this study, the corresponding groove was deactivated whenever negative oil flow rate was observed in it and results were compared. It was found that the groove deactivation strategy has profound influence on the bearing performance when negative flow rate occurs at one groove, preventing such undesirable effects as lubricant starvation at the loaded region of the bearing. Groove deactivation in the event of negative flow rate may be easily implemented by incorporating a check valve to the feeding system of each groove. Such strategy seems to be highly recommended for the safe operation of bearings subjected to high loads and load angles deviated from 90°.

Keywords

Hydrodynamic journal bearings, supply conditions, thermal behavior, groove deactivation

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Introduction

Hydrodynamic journal bearings are machine elements which are typically used for the support of radially loaded rotating shafts in different machines. Due to their simplicity, reliability, efficiency, and low cost, they are widely utilized and can be considered as the only practical choice for the support of high speed and/or high loaded rotating shafts. Very often in practical applications, the bush is mounted with two diametrically opposed lubricant supply grooves allowing for shaft rotation in both directions.

A correct prediction of journal bearing performance under realistic operating conditions is vital for a reliable machine design. It requires accurate test data for its validation. Reputable works have been presented along time, which have been extensively used in model validation.[1–6] But operating conditions should be characterized not only by the nominal load and speed but also by the conditions under which the lubricant is fed to the bearing, such as the feed pressure, feed temperature, lubricant feed groove configuration, and load angle relative to the groove plane. From the aforementioned works, only Ref. 4 included the variation of feeding pressure and another one load angle,[6] although only for the case of high speed bearings. In the meantime, several works by the authors have highlighted the importance of these feeding conditions.[7–13] In fact, the thermohydrodynamic (THD) characteristics of journal bearings have been theoretically and experimentally examined over many decades, but often the influence of these feeding parameters has been neglected or overlooked. In fact, the incorporation of the influence of groove geometry and configuration requires the use of mass conservative algorithms incorporating film rupture and regeneration, as well as groove mixing models. These are

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difficult to implement and thus they are frequently avoided, despite their relevance.

The influence of the direction of the load relative to the groove plane (in the present work called simply load angle, Γ) can be easily apprehended. In fact, slight changes in load direction will affect the clearance at the inlet of grooves, consequently affecting the oil flow fed to the bearing and, therefore, the bearing thermal behavior. Also, the location of the hydrodynamic pressure generation zone relative to grooves will deeply affect the flow patterns, which are pressure driven besides being drag driven.

Until recently, there has been little experimental information concerning the influence of the load direction angle on the thermal behavior of twin groove journal bearings. One of the few existing works was the one made by Gethin and El-Deihi[6] where they found that besides speed and load, loading direction had also a significant effect on film temperature excursions. Unfortunately, their work was limited to high speed bearings under the turbulent regime.

Recently, Arab Solghar et al.[9] have dealt with the analysis of twin groove journal bearings under different loading direction angles. Nine different loading angles were chosen in that study from 50° to 130° for the interval of 10° with respect to the load line. The influence of loading angle on journal flow rate, bush inner surface temperature, and outlet temperature was investigated. The occurrence of negative oil flow rate in grooves, which had been firstly reported by Brito et al.[13] for journal bearings with ±90° to the load line, was now observed for a wide range of operating conditions and load angles. It was found that negative flow rate happens preferentially in the downstream groove at light loads and in the upstream groove at high loads. This negative flow, in which the groove starts acting as a lubricant sink instead of a lubricant source, happens whenever the hydrodynamic pressure buildup zone gets too close to the groove regions being sufficiently strong so as to overcome the effect of lubricant feed pressure. This causes the reversing of the normal direction of the lubricant feed flow. The reversed flux of hot lubricant which exits the bearing through the groove eventually mixes with the fresh feed lubricant at the feed piping before reentering the bearing via the opposite groove. This kind of *hot lubricant feedback* phenomenon causes an effective raise of the temperature at which the lubricant is fed to the bearing, standing as a virtual, nonintended rise in lubricant feed temperature. This latter effect is highly counterintuitive and absent in literature but has been extensively reported in the authors' previous works.[8,9,13]

The effect of negative flow rate was found to be deleterious for bearing performance, as it would contribute for lubricant starvation ahead of the active bearing region and would increase journal eccentricity and maximum bush temperature. Moreover, this would happen preferentially under heavily loaded conditions, further rising seizure risk. The aforementioned works by the group concluded that a higher inlet pressure might indeed suppress the negative oil flow rate in some cases.

More recently, Brito et al.[10] have conducted some experimental tests in order to compare the performance of a single ($\Gamma = 90°$) and a twin groove ($\Gamma = \pm 90°$) journal bearing with identical geometry. In reality, they used a twin groove bearing for the tests, shutting down the downstream groove in order to resemble a single groove bearing. In this way, the authors were able to maintain virtually the same exact geometry (e.g. clearance) for both bearings, something which would be impossible to obtain using different bearings. They observed that although the total flow rate was very similar for both groove configurations, the distribution of flow rate among grooves varied markedly with load for twin groove bearings. In the higher load range, the flow rate at the upstream groove decreased with the increase of load and was nearly zero under the highest load tested. Unfortunately, it was not possible to reach loadings where negative flow rate would be attained at this groove and compare it with the single groove case.

It would therefore be valuable to assess the effect of shutting down a groove in which negative flow rate is occurring and observe if an improvement of bearing behavior may be achieved with this operation. This was the aim of the present study, which therefore is a sequel of Refs. 9, 10. It endeavors to contribute to a more clear examination of the effects of groove activation and deactivation under different load direction angles and to add results to the stock of thermohydrodynamic data currently available for journal bearings. Thus, the influence of load angle and journal speed on bearing performance characteristics such as inner bush surface temperature, oil outlet temperature, and groove flow rates are discussed.

Test rig, measurements, and bearing details

The present work was done at the test rig from the Machine Elements and Tribology Laboratory of the University of Minho. This apparatus has already been used for several works[8–13] and has had significant updates along time.

Rotational speed, applied load, load direction, oil feed pressure, and feed temperature are the parameters which may be regulated. The measured performance parameters were the temperature at the oil–bush interface, the oil outlet temperature, the oil flow rate at each groove, the total oil flow rate, and the shaft locus.

The geometric parameters, operating and supply conditions, as well as lubricant properties, are presented in Table 1. An uncoated bronze twin groove bearing has been used along with a stainless steel journal, which was rigidly mounted between two preloaded conical rolling bearings to ensure a suitable stiffness for the system, as shown in Figure 2(a). The bush diameter, the shaft diameter, and cylindricity were measured using a coordinate measuring machine with a resolution of 0.1 μm. The oil used was ISO VG 32 (Galp Hidrolep 32—see Table 1 for details).

Table 1. Main bearing characteristics, lubricant properties, and operating conditions.

Parameter		Units	Value/span
Geometrical bearing characteristics			
Groove length/diameter ratio	a/b	–	0.5
Bush width/diameter ratio	b/d	–	0.8
Bearing diametric clearance	C_d	μm	107
Inner bush diameter (nominal)	d	mm	50
Outer bush diameter	D	mm	100
Groove circumferential extension/diameter ratio	w/d	–	0.2
Operating conditions			
Rotational speed	N	r/min	2000–4000
Applied load	F	kN	0.4–4
Specific load	P	MPa	0.2–2
Load angle	Γ	°	60–120
Supply conditions			
Oil supply temperature	T_f	°C	40
Oil supply pressure	P_f	kPa	300
Ambient temperature	T_a	°C	30–55
Lubricant properties			ISO VG 32
Dynamic viscosity at 30 °C	μ_f	N s/m^2	0.0467
Dynamic viscosity at 75 °C	μ_f	N s/m^2	0.0083
Specific mass	ρ	kg/m^3	875
Specific heat	c_p	J/kg°C	1943
Thermal conductivity	k	W/m °C	0.13
Ambient temperature	T_a	°C	30–55

The loading arrangement relies on a cantilever system on which weights are applied. A closed loop steel cable was used to apply the load to the bush body, as shown in Figure 2(b). The loading system was calibrated using a high precision load cell with an error of less than ±0.5 N. A 0.95 kW variable speed motor was used to drive the shaft via a transmission belt. The speed was regulated through an inverter drive and kept within a range of ±10 r/min of the nominal speed.

The regulation of the feed pressure (P_f) was made through a restricting valve and monitored with the aid of pressure transducers located at the interior of each groove, as shown in Figure 1(b). P_f was kept within an interval of variation of ±10 kPa.

The regulation of the feed temperature (T_f) was made with the use of a thermostatic bath with outer circulation. This primary circuit passed through a plate heat exchanger in order to transfer the heat to the feeding oil. T_f was monitored by three thermocouples, one located in the main feeding pipe, immediately upstream of the point where the flow is separated in two branches to feed each groove, as shown in Figure 2(a). T_f was kept within a range of ±1 °C from the set point. Two other thermocouples, one for each groove, were also located at the groove entrance.

All measurements were performed under steady state.

Three gear flow meters (repeatability 0.03%), suitable for low flow rate measurements were used for the measurement of flow rate. A flow meter was attached to the main feed line (see Figure 1(a)), while two others (see Figure 2(c)) were located along each branch in order to measure partial (groove) flow rates. Rectangular wave signals were recorded

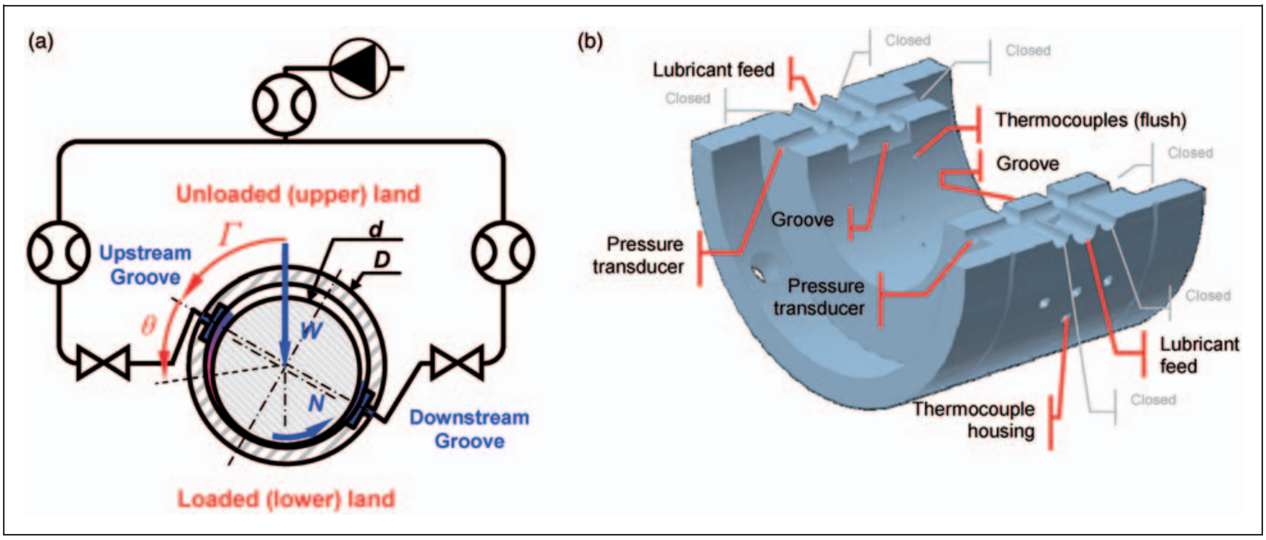

Figure 1. (a) Schematic overview of the bearing system, including flow meter system, (b) detail of the bush body (lower half).

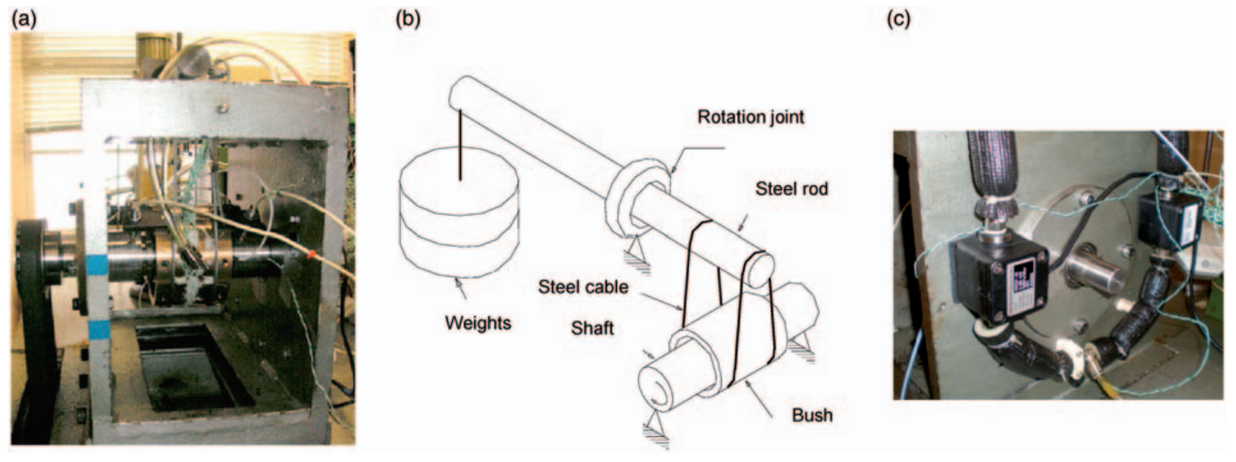

Figure 2. (a) Detail of the test rig showing the bearing system, (b) outline of the loading system, (c) detail of the gear flow meters used for measuring the flow rate of lubricant feeding each groove, including thermocouple for feed temperature measurement at the main feed pipe.

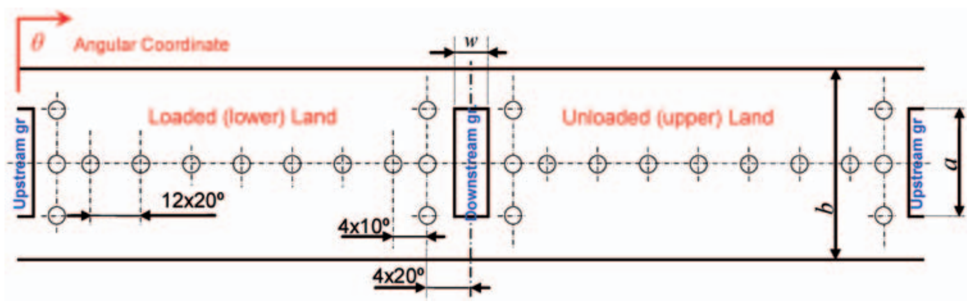

Figure 3. Angular location of the thermocouples at the inner surface of the bush (unwrapped view).

during 35 s so that even feeble flow rates could be recorded. The differences between the total flow rate and the sum of the partial flow rates measured were generally below 1.5%.

Type K thermocouples were used to monitor temperature field. The repeatability of the measurements was within ±1 °C. Figure 3 outlines the locations where the temperature at the oil–bush interface was measured. The thermocouples were placed inside fully drilled holes, flush with the inner bush surface as depicted in Figure 1(b). An additional set of thermocouples was used to measure the oil outlet temperature and the ambient temperature in the vicinity of the bearing system.

In the previous study by the group,[9] the flow rate in each groove was measured for nine different loading direction angles (Γ) separated by 10° intervals ranging from 50° to 130°. In that study it was found that negative oil flow rate occurred at the downstream groove for the lightly loaded bearing at $\Gamma \leqslant 70^\circ$ and at the upstream groove for the heavily loaded bearing at $\Gamma \geqslant 100^\circ$. This phenomenon was called the hot oil reflux since the groove starts acting as a lubricant sink instead of a lubricant source. In the present work, an attempt is made to analyze the influence of hot oil reflux on the THD characteristics of the journal bearings by shutting off (with a valve) the lubricant feed at the corresponding groove whenever this phenomenon appears and comparing the results with the open groove case. Therefore, five loading direction angles (those where negative oil flow rate was observed) were considered in this study, namely $\Gamma = 60^\circ$, 70°, 100°, 110°, and 120°. For the sake of simplicity, the analysis of tests with $\Gamma = 50^\circ$ and 130° has been disregarded because of their similarity to journal behaviors for loading angles 60° and 120°, respectively. In addition, no hot oil reflux was observed for loading angles 80° and 90° for the load ranges from 0.4 to 4 kN, therefore these cases are not investigated here, but can be found for similar test conditions in Ref. 7. In this study the feeding pressure was kept constant at 300 kPa. To investigate the effect of hot oil reflux, each groove is equipped with a butterfly valve. To stop the occurrence of oil reflux from the grooves, the valve is turned off.

Results concerning the oil–bush interface temperature profile at the mid-plane of the bearing are presented in Figure 4 for shaft rotational speeds of

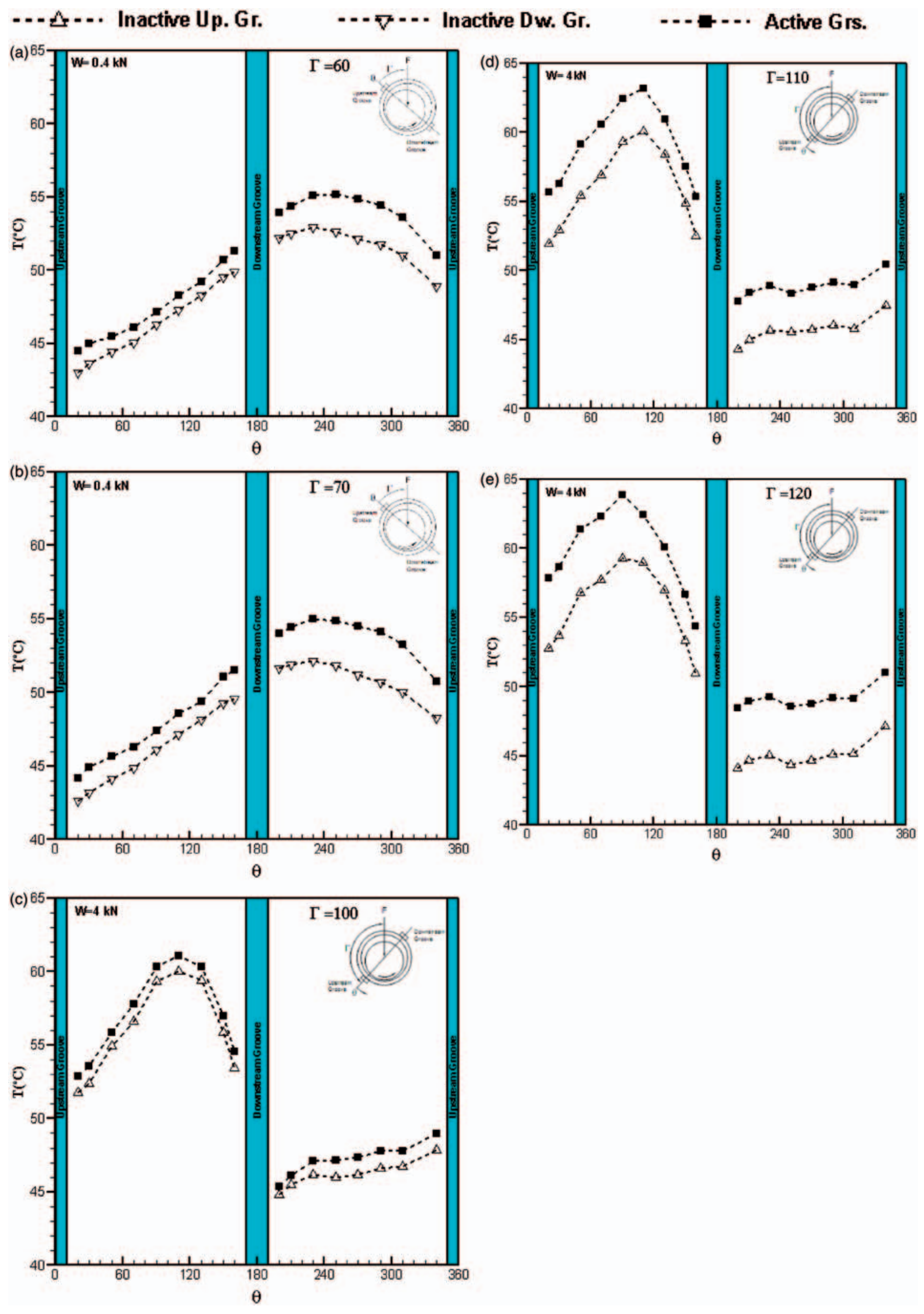

Figure 4. Effect of shutting off the oil feed to the groove where negative flow rate is occurring on the bush–oil temperature distribution at mid-plane for different values of load and load direction angle.

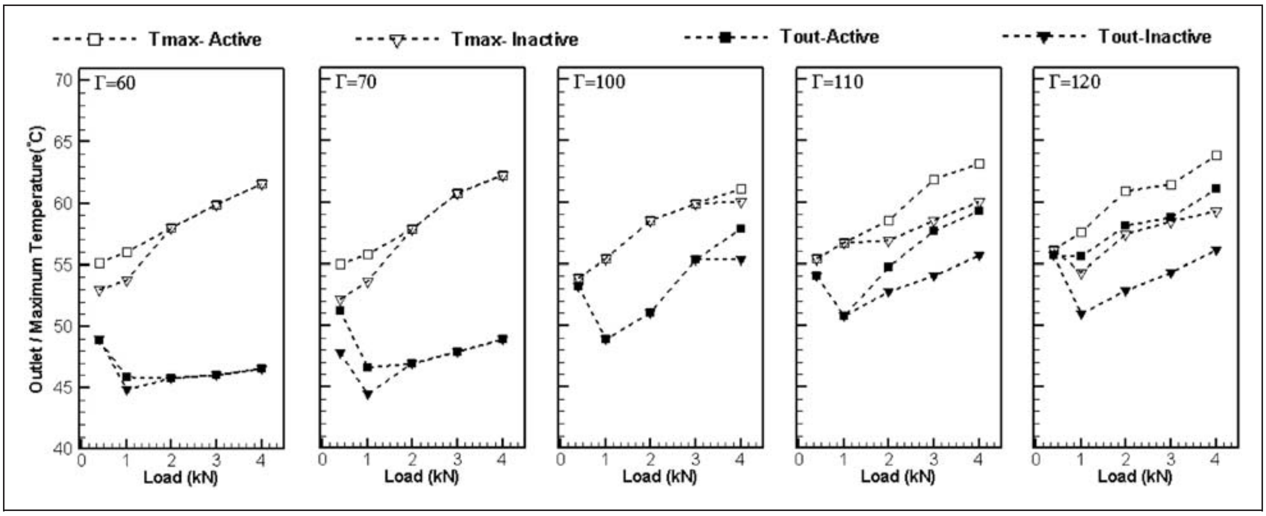

Figure 5. The influence of load and orientation angle on the outlet and maximum temperature.

4000 r/min and several combinations of load and load angle. Each plot contains two profiles, one for the case where all valves are open (with oil reflux occurring in one of the grooves) and the other one corresponding to the case where the oil reflux groove has been deactivated. As shown in Figure 4, the global temperature level of the circumferential temperature profiles is lowered for all loading angles when hot oil reflux is eliminated by shutting off the corresponding groove.

For $\Gamma = 60^\circ$ and 70° and low load (0.4 kN—see Figure 4(a) and (b)), negative flow rate occurred at the downstream groove. It can be seen that shutting this groove provoked a global temperature reduction, which was more pronounced in the unloaded land of bearing where maximum temperature occurs. Specifically, the maximum temperature difference between the case with all grooves active and the one with the downstream groove deactive was observed to be 2.73 and 3.40 °C for loading angles of 60° and 70°, respectively. This global temperature reduction effect is beneficial for bearing performance since maximum bush temperature is one of the main limiting factors in bearing design. This global lowering of the temperature level may be explained by the fact that when the oil reflux groove (in this case the downstream groove) is deactivated, the hot lubricant feedback phenomenon which has been described in the introduction (hot refluxing oil mixing with fresh feeding oil at the feeding piping and effectively raising the feed temperature) ceases to occur. Consequently, when hot oil reflux occurs, the operation of the bearing will become cooler if just one groove (the upstream groove) is active and reflux is eliminated. Or in more practical terms it can be clearly stated that the single groove journal bearing runs cooler than the twin groove bearing for light loads at $\Gamma \leqslant 70^\circ$.

Similar results were obtained for loading angles 100°, 110°, and 120°. However in these cases, the negative flow rate occurred at the upstream groove. Here the temperature fall due to negative flow groove shutting was similar for both lands. As illustrated in Figure 4(c) to (e), the increase of the loading angle amplifies the temperature difference between active and inactive upstream groove. Specifically, differences of 1.17, 3.19, and 4.60 °C for loading angles 100°, 110°, and 120° were obtained. This amplification is due to the fact that the value of negative oil flow rate rises for $\Gamma \geqslant 100^\circ$ with the increase of loading angle, as it will be seen when analyzing the flow rate charts.

Plots concerning maximum bush temperature (T_{max}) and oil outlet temperature (T_{out}) as a function of applied load are presented in Figure 5 for $N = 4000$ r/min. Clearly, both maximum and outlet temperatures are decreased with the elimination of oil reflux, with the effect on T_{out} being sometimes even more pronounced than the effect on T_{max}.

The variation of temperature profiles is compatible with the total and groove flow rate results, which are displayed in Figures 6 to 10 for various load angles. It can be apprehended from Figures 6 to 10 that the negative oil flow rate at high speed is more intense, because the increase of shaft rotational speed tends to broaden the generated hydrodynamic pressure buildup zone for a given load.[7] Increasing speed causes the adverse pressure gradient at the groove edges to be even more intense, amplifying the negative flow rate through this groove.

In addition, it can be observed that the total flow rate is somewhat lowered with the deactivation of the refluxed downstream groove and it is risen with the deactivation of the refluxed upstream groove. The explanation for this ambivalent behavior does not seem to be straightforward, since there are strange phenomena when hot oil reflux occurs, such as the oil feedback from the refluxed oil groove to the opposite one. Nonetheless, the explanation should be linked with the weighing of several factors. On one hand, there is the elimination of the hot oil feedback flow occurring between grooves through the feeding

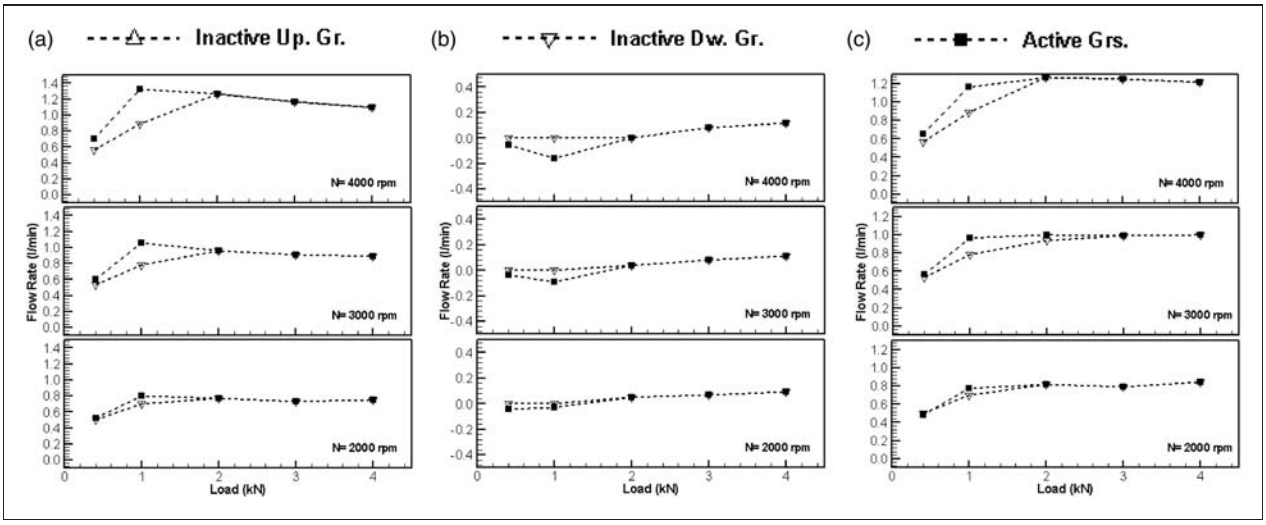

Figure 6. The effect of shaft rotational speed and load at $\Gamma = 60^\circ$ on (a) upstream flow rate, (b) downstream flow rate, (c) total flow rate.

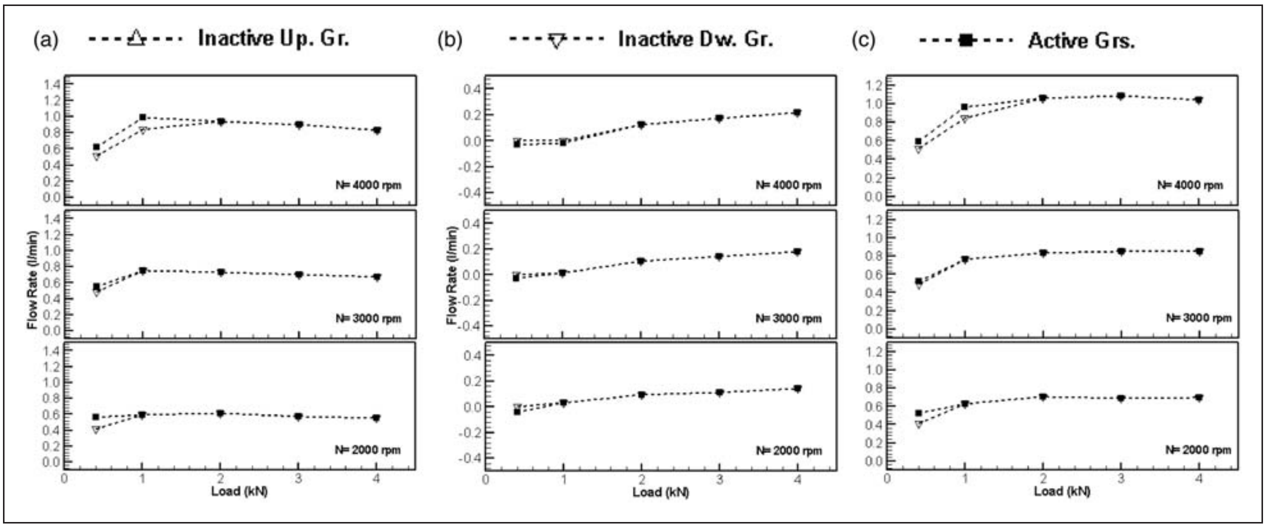

Figure 7. The effect of shaft rotational speed and load at $\Gamma = 70^\circ$ on (a) upstream flow rate, (b) downstream flow rate, (c) total flow rate.

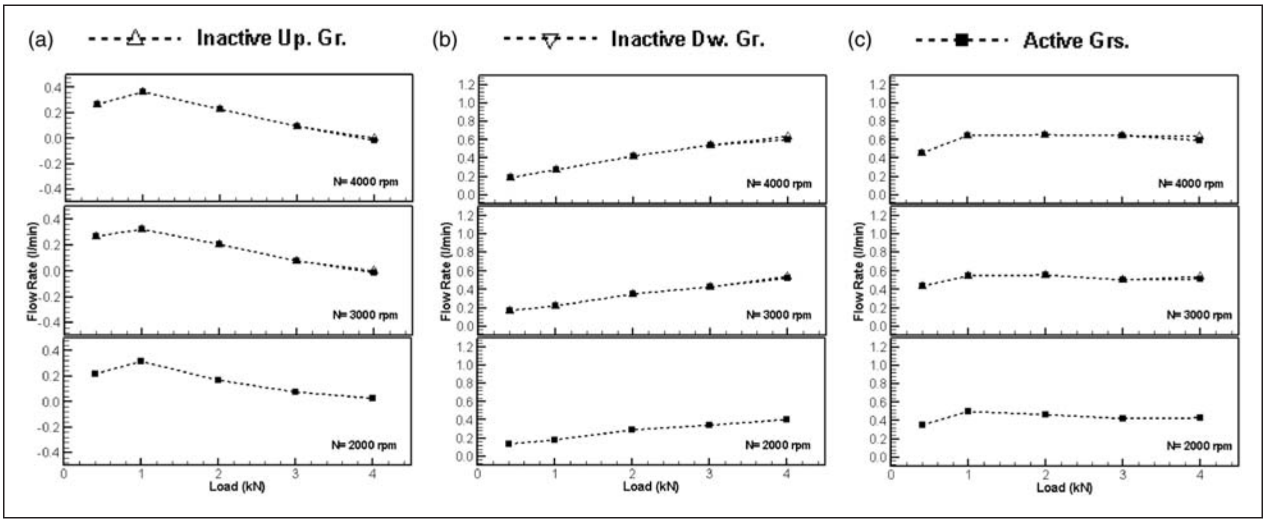

Figure 8. The effect of shaft rotational speed and load at $\Gamma = 100^\circ$ on (a) upstream flow rate, (b) downstream flow rate, (c) total flow rate.

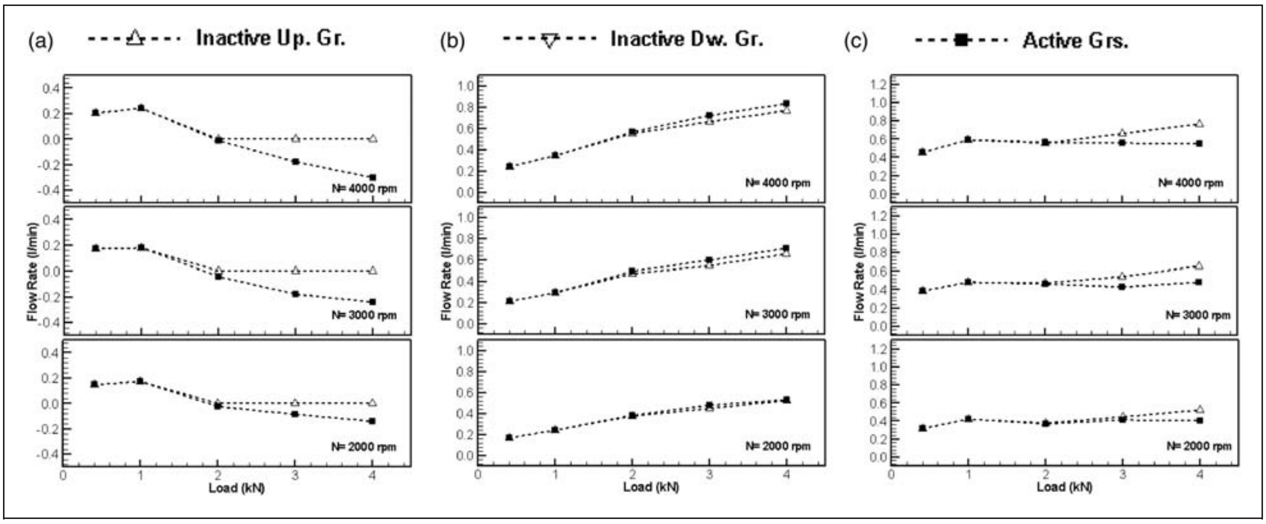

Figure 9. The effect of shaft rotational speed and load at $\Gamma = 110^\circ$ on (a) upstream flow rate, (b) downstream flow rate, (c) total flow rate.

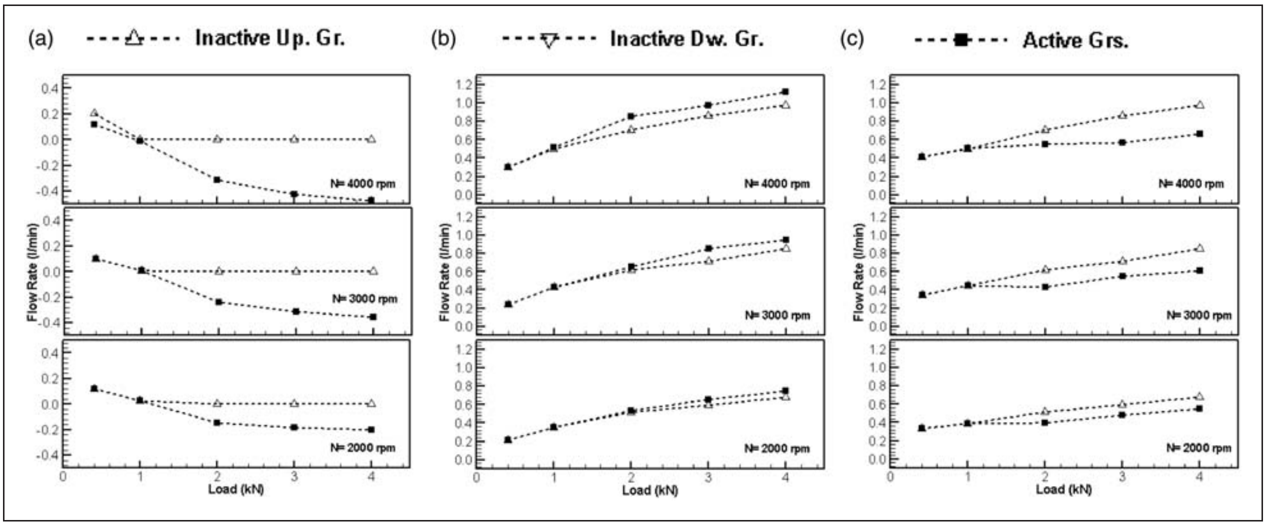

Figure 10. The effect of shaft rotational speed and load at $\Gamma = 120^\circ$ on (a) upstream flow rate, (b) downstream flow rate, (c) total flow rate.

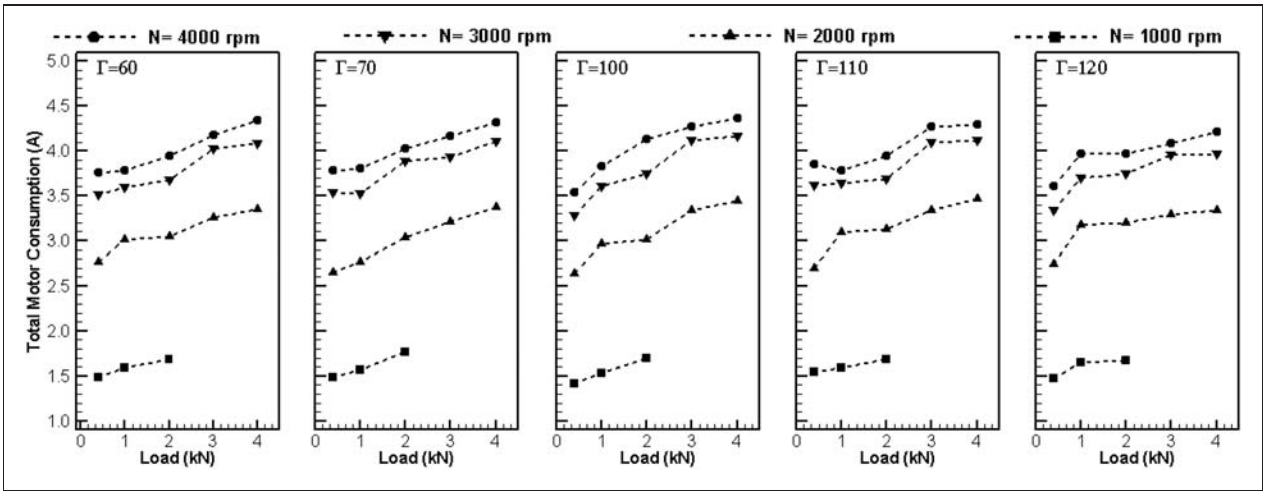

Figure 11. The influence of load and orientation angle on the total motor consumption.

pipings. On the other hand, changes in shaft eccentricity and attitude angle associated with the valve closure and the elimination of oil reflux will occur. These changes, which will vary according to load intensity and angle, will also affect oil leakage in dissimilar ways.

The total motor electrical consumption was measured with a portable multimeter for some of the working conditions. Of course, this consumption corresponds to the whole system, not just the bearing system, but it can be used for comparison purposes. Figure 11 represents the influence of applied load and loading angle on the total motor consumption under different journal speeds. No observable differences were detected when shutting off grooves, so no comparison is made between open and closed valves. As shown in Figure 11, motor consumption increases with both journal speed and applied load remarkably. However, it varies slightly with the variation of loading angle. Under low loads motor consumption seems to be minimized for load angles around 100°. Curiously, this seems to be the angle which maximizes motor consumption for high loads, although differences are slight and difficult to apprehend.

Conclusions

An experimental investigation on the influence of groove deactivation on the performance of a twin axial groove journal bearing subjected to variable loading angle has been carried out. The main goal of this study was to assess the effect of deactivating a groove in which negative oil flow rate occurred, thus eliminating this phenomenon. Results for total flow rate, flow rate at each groove, oil–bush interface temperature, lubricant outlet temperature, and motor consumption were presented and discussed for a range of loads, journal speeds, and load angles (Γ). The following conclusions were drawn:

1. Load angle (Γ) was found to affect deeply the flow rate distribution among grooves but affected motor consumption only marginally. This latter parameter was affected mainly by journal speed and load.
2. Negative flow rate tended to occur at the downstream groove for $\Gamma < 90^\circ$ at low loads and at the upstream groove for $\Gamma > 90^\circ$ at high loads. This phenomenon, in which a groove acts as a sink instead of a source of lubricant, has been reported in other works of the group and is deleterious for bearing performance, contributing for lubricant starvation at the active region of the bearing, raising the global temperature level of the inner bush surface, and increasing bearing eccentricity under high loads.
3. When negative flow rate was eliminated by shutting off the oil feeding to the corresponding groove, a general lowering of the oil–bush interface temperature level and of the oil outlet temperature was observed. This lowering was more pronounced in cases where negative flow rate had been more intense. The decrease of oil outlet temperature due to negative flow rate elimination tended to be even more intense than the corresponding decrease in the maximum temperature of the oil–bush interface.
4. After eliminating hot oil reflux at the downstream groove by shutting it off, a decrease of the total flow rate was observed, while the opposite happened when eliminating hot oil reflux occurring at the upstream groove.

As a concluding remark, it may be stated that the use of nonreturn/check valves positioned upstream of each groove is advisable for twin groove journal bearings, especially in the case of heavily loaded twin groove bearings possessing grooves not located perpendicularly to the load line.

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