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Review Paper on Performance of Porous Ceramic Hydrostatic Journal Bearing

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Abstract

Porous-ceramic hydrostatic bearings have been recently developed. These bearings have demonstrated an exceptional overall performance when compared with conventional technology bearings. However, despite all the benefits, porous-ceramic hydrostatic bearings have yet to find widespread acceptance due to the problems found in tailoring the bearings geometry and size to suit precision engineering applications, while producing porous-structures with consistent and reproducible permeability.

Keywords: *porous, ceramic, journal bearing, hydrostatic.*

I Introduction

About

In a hydrostatic bearing, an external source of pressurized fluid forces lubricant between two surfaces, thus enabling non-contacting operation and the ability to support a load. Hydrostatic bearings can support large loads without journal rotation and provide large (accurate and controllable) direct stiffness as well as damping (energy dissipation) coefficients. Hydrostatic bearings rely on external fluid pressurization to generate load support and a large Centering stiffness, even in the absence of journal rotation. The load capacity and direct stiffness of hydrostatic bearings do not depend on fluid viscosity, thus making them ideal rotor support elements in process fluid pumps. Current applications intend to replace oil lubricated bearing with hydro static bearings to improve efficiency with shorten rotor spans and less mechanical complexity. Current cryogenic liquid turbo pumps implement hydrostatic bearings enabling an all fluid film bearing technology with very low number of parts.

Porous hydrostatic bearings utilize a porous material as one of the bearing surfaces. They are externally pressurized, and by carefully controlling the porosity it is possible to have a large number of integrated feed restrictors throughout the bearing material. This results in a more even pressure distribution at the bearing surface which, generally improves its load carrying capacity.

Fig. 1.1 Porous Ceramic Hydrostatic Bearing

The main requirement for the ultra precision spindle bearings was very low radial error motions. Porous Ceramic bearings are ideal for this application as they are not limited by some of the geometric design features inherent in traditional fluid film bearings. Traditionally, air bearing spindles have been preferred over oil hydrostatic designs because of the lower asynchronous noise, however extremely low radial error motions and carefully tuned hydrostatic oil systems allow for high load capacity, extremely low radial error motion with minimal asynchronous noise.

Background

By virtue of their overall performance, porous-ceramic hydrostatic journal bearings present themselves as a viable solution to the newest severe demands for higher accuracy and overall performance levels required by spindle bearing systems.

Amongst the currently available bearing technologies, oil hydrostatic bearings are the precision engineers' preferred choice for applications requiring maximum stiffness. However, their medium term accuracy is limited by heat generation caused by the oil viscous shear. To this effect, thermal distortion and drift are considered major sources of error in higher precision manufacture.

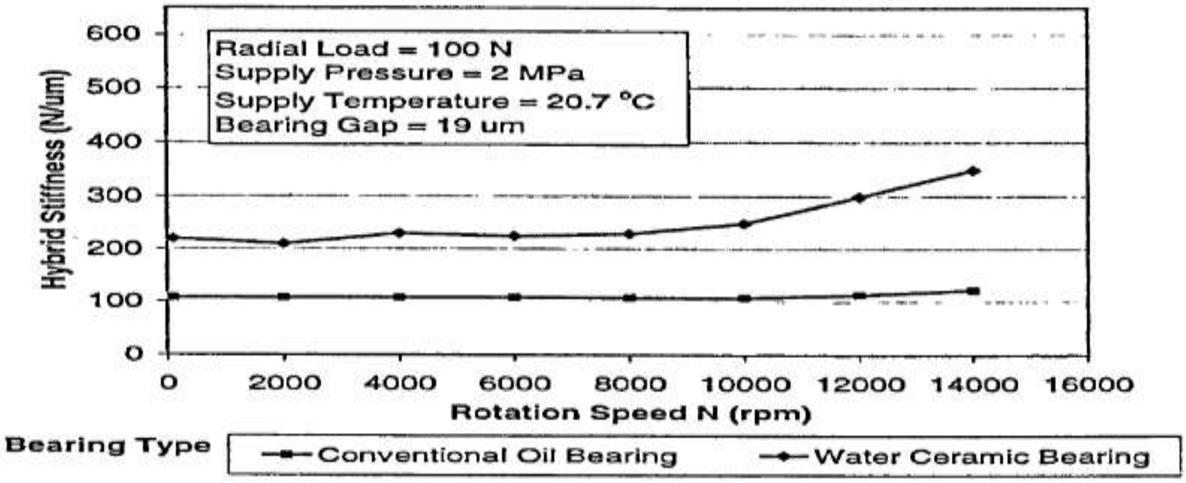

Fig.1.2. Direct stiffness comparison: Porous ceramic water hydrostatic bearing v/s a conventional hydrostatic bearing[2].

Recently developed porous-ceramic hydrostatic journal bearings have demonstrated an optimized overall performance when compared to conventional oil hydrostatic journal bearings. For example, Figure I illustrates a direct stiffness comparison between these two bearing technologies, as presented by Almond [2].

The use of a porous material as a bearing material allows a multitude of feeding restrictors to be uniformly distributed over the entire surface of the bearing, providing the best pressure distribution and thus the highest load capacity and stiffness, as is shown in Figure 1.2. Superior damping characteristics also result from the use of a porous material, due to its ability to absorb energy oscillations.

Unlike hydrostatic bearings, and as a result of their improved pressure distribution, porous-ceramic hydrostatic bearings do not require hydrostatic 'pockets'. Hence, their stiffness via their hydrodynamic-component is maximized; while simplifying their design. In addition, the absence of pockets permits the spindle to reach higher speeds before the onset of turbulence. The effect of the stiffness hydrodynamic component can be observed in Figure 2, being particularly noticeable above 10,000 rpm.

A further advantage of porous ceramic hydrostatic bearings is that they can be lubricated with water without corroding; offering the following benefits:
1. A lower viscosity than typical hydrostatic bearing oils, which directly reduces friction and heat generation.
2. A higher specific heat than oils, making it easier to control the temperature of the bearing assembly and machine.
3. Water lubrication overcomes environmental concerns associated with the use of oil and its disposal.

As a result of a comprehensive research programmed and a performance comparison study, Almond [2] examined the benefits of porous-ceramic hydrostatic journal bearings over conventional oil hydrostatic journal bearings, clearly demonstrating the potential benefits from this new technology. A summary of his findings is presented.

Parameter	**Conventional Hydrostatic bearing**	**Porous Ceramic Hydrostatic bearing**	**Improvement factor (%)**
Static stiffness	113	188	66
lubricant flow rate(lpm)	7.5	1.4	80
Pumping power Requirement (W)	875	47	95
Friction Power (KW)	1.2	.33	72
Lubricated temperature rise(°C)	6.5	2.5	62
Hybrid stiffness((N/µm))	113	286	52

Table 1: Bearing performance comparison: conventional hydrostatic Vs porous-ceramic water hydrostatic at 10,000 rpm

1.3 Problem identification

Despite the numerous and significant advantages offered by porous-ceramic water hydrostatic journal bearings, these have not yet been completely embraced by precision engineers and machine tool designers. Certain aspects of both their manufacture and operation must be further developed or improved before their wide spread acceptance and application.

The first problem is concerned with the porous bearings' manufacturing method. The current method consists of the vibration packing of powders followed by hot isostatic pressing (HIPing). This has proved to be successful for the production of 50 mm ID x 50 mm long journal bearings. However, a significant level of machining is required and HIPing is a relatively expensive process. Also, it is difficult to process fine powders and avoid agglomeration, which results in a non-uniform permeability. The ability to use a range of powders is important in order to control pore size and pore distribution. In addition, it becomes more difficult to achieve uniform permeability as the size of the components increase. Hence there is a need to establish an optimized alternative porous ceramic manufacturing route that would enable larger and more cost effective bearings to be produced.

A second problem exists in the scepticism found in using water as a lubricant. Although water lubrication benefits are widely acknowledged, there is certain hesitancy for their use because water is feared to promote corrosion within the spindle assembly and auxiliary equipment components. The addition of corrosion inhibitors may potentially alleviate this problem. However, corrosion inhibitors are also feared to induce certain non-desired secondary effects such as foaming or bacterial growth. Thus, a thorough assessment of the effects of water lubrication including corrosiveness, the addition of corrosion inhibitors, foaming and bacterial
growth in porous ceramic hydrostatic bearing systems must be conducted.

II Literature Review

J. Corbett, R.J. Almond, D.J. Stephenson, Y.B.P. Kwanza (1) has described the medium term accuracy of oil hydrostatic bearings has traditionally been limited by the thermal effects and although aerostatic bearings have relatively good thermal characteristics they suffer from a low relative stiffness and load capacity. New concepts are therefore required, and the authors describe a programmer which is using fundamental principles to develop a new improved generation of porous bearings. The processing methodology required to produce reliable porous ceramic bearings has been established, and the relationship between fluid flow properties, porous microstructures and processing conditions has been quantified. Bearings of high standard have been produced and will form the basis for further optimization, using the new high specification test rig. the next phase will utilize the results gained to date to manufacture and test a range of optimized journal bearings, in collaboration with the industrial partners.

Jerry T. C. Su, K. N. Lie (3) described an approximate solution for a hydrostatic porous journal bearing is developed. The analytical approximation is valid for low eccentricity, low permeability length to diameter ratio as compared with numerical solution of the Reynolds equation. The approximate solution can be simplified into a linear function of the eccentricity ratio ε. The approximate and numerical solution match well and maximum range of deviation is under 10% for $\varepsilon < .5$, $\lambda < 10$ and $l/d < .5$. The predicted load capacity by the approximate solution greater t6ha than those of the numerical solutions. The power required and the flow rate are weak function of the eccentricity ration and decrease slightly as e increase ε.

I S Durazo-Cardenas, J. Corbett, And D.J. Stephenson (4) has described the performance of a porous-ceramic hydrostatic journal bearing manufactured by the starch consolidation (SC) technique has been examined using a highly instrumented test rig. The results have been compared with those of a 5-recess hydrostatic bearing of the same size and comparable design, under the same testing conditions. The SC porous-ceramic bearing showed an improved performance over the conventional hydrostatic bearing. Static and rotational stiffness were 95 per cent and over 150 percent higher, respectively. In addition, the porous ceramic bearing exhibited a more economic performance with a 64 per cent lower flow rate and pumping power than the hydrostatic bearing. In terms of heat generation, the porous ceramic bearing showed 50 per cent lower temperature rise.

Isidro S. Durazo-Cardenas, David J. Stephenson, John Corbett (5) has described a series of fine grade alumina powders has been used in combination with maize starch granules to produce porous structures for porous hydrostatic journal bearing applications. A comprehensive series of tests were conducted to characterize porosity in terms of density, pore size and permeability. Porous ceramic structures suitable for a variety of ultra-precision applications can be successfully produced by the starch consolidation technique. The journal bearings produced with this technique exhibited well defined, reliable and reproducible permeability. Porosity of the bearings increase so result larger pores and this is turn resulted in more permeable bearings and also cost effective, flexible, reproducible and environmentally sound.

Dinesh Dhande, Dr. D.W. Pande, Vikas Chatarkar(6) has described hydrodynamic journal bearings are analyzed by using computational fluid dynamics (CFD) and fluid structure interaction (FSI) approach in order to find deformation of the bearing. Journal bearing models are developed for different speeds and eccentricity ratios to study the interaction between the fluid and elastic behavior of the bearing. the nodal fluid forces computed by CFD are used in order to find deflection of the bearing. Cavitations in the bearing are neglected by setting all negative pressures to ambient pressures. the CFD results were compared in order to validate the model with the experimental work. the elasto hydrodynamic study of the hydrodynamic journal bearing using computational fluid dynamics (CFD) and fluid structure interaction (FSI) approach. The simulation result of pure fluid model has a good agreement with previous experimental work done. This technique gives the deformation of the bearing due to action of hydrodynamic forces developed which is important for accurate performance of the bearings operation under severe conditions it is observed that there is substantial amount of deformation of the bearing.

Shigang Wang, Xianfeng Du, Mingzhu Li, Zhongliang Cao, Jianjia Wang (7) has described the effect of oil states (sufficient state and deficient state) on temperature field distribution and temperature rise of heavy hydrostatic bearing as the starting point, simulation research is conducted with the fluent 6.5. The results show that the temperature of heavy hydrostatic bearing has a linearly increase in both oil state with the spinal velocity speeding up. However the temperature rise is lower in sufficient oil state than that in the opposite state. In addition, the oil state has an effect on the distribution of temperature filed at the same rotational speed. The obtained data supply the theory basis for the safe operation of the hydrostatic bearing.

Qiyin Lin, Zhengyingwei, Ningwang, Weichen (8) has described transient analysis method combining computational fluid dynamics and fluid–structure interaction was applied based on actual physical model. both thermal influence and cavitations were studied in rotor bearing. By using cfd-fsi method shown the eccentricity, temperature rise and pressure increased with increasing the exerted external load the temperature rise became higher and higher as the rota- tional speed increased. At the same time, the cavitations problem became more and more severe. so the bearing structure in high-speed rotor-bearing system must be well designed. The temperature rise and cavitations volume fraction would decrease linearly as the number of groove increased. In addition, the oscillation of journal and the eccentricity decreased with increasing the groove number and it also had beneficial effect. Consequently, in order to decrease temperature rise and inhibit cavitations, high-speed rotor-bearing system should use bearings with multiple grooves and select high pressure mode for lubricant supply.

J.R. Lin, P.J. Li, And T.C. Hung (9) has described Shliomis Ferro fluid model together with the micro-continuum theory of stokes, the influences of Non-Newtonian ferro fluids on the steady-state performance of long journal bearings have been investigated. Analytical solutions for bearing performances are obtained from the Non-Newtonian Ferro fluid Reynolds-type equation. comparing with the Newtonian non-ferrofluid case, the effects of Non-Newtonian Ferro fluids under external magnetic fields provide increased values of the zero pressure-gradient angle and the load capacity, and result in decreased values of the friction parameter especially for a larger Non- Newtonian couple stress parameter and magnetic Langevin's parameter. For the long journal bearing lubricated with non-Newtonian ferrofluids and operating at larger values of the couple stress parameter and magnetic langevin's parameter (for example, n=0.3, x =50), increasing the volume concentration parameter gives slight change in the friction parameter, but results in the further increments in the bearing load.

K. M. Panday, P. L. Choudhury, and N. P. Kumar (10) has described a thin film lubricated journal bearing are investigated by means of three-dimensional computational fluid dynamics analysis. The 3D navies stokes compressible equations were integrated to simulate the flow. Turbulence effects were included in the computation of unsteady transient analysis of journal bearing, taking into account gravity. the journal bearing is designed in gambit software, the journal is modeled as a ''moving wall'' with an absolute rotational speed of 3000 rpm. The flow is simulated using Ansys fluent software. design parameters like relative eccentricity, dimensionless load carrying capacity, dimensionless wall shear stress, friction coefficient, Reynolds number, Somerfield number, strain rate, pressure distribution, temperature distribution and lubricant flow properties like turbulent viscosity, and velocity magnitude are considered for the analysis. Transient dynamic behavior of thin film lubricated journal bearing system have been studied and presented. From pressure plots, it is observed that the maximum pressure, the bearing can withstand is increasing with increase in l/d ratio. The maximum pressure is noted at minimum oil film thickness. It can be observed that the shear stress developed on the walls of journal and bearing is steady after 0.04 seconds and it is decreasing with increase in l/d ratio. The dimensionless load carrying capacity is observed to be good with l/d ratio 1. Turbulent viscosity of the lubricant increases with increase in l/d ratio and the level of turbulence at the minimum oil film thickness is low.

M. Frycz, P. Anioł, (10) has described numerical calculations of temperature distribution, load carrying capacities, friction forces and coefficient of friction in the gap of Ferro fluid-lubricated slide bearing for different concentrations of magnetic particles. Reynolds-type equation has been derived from the equations of momentum and continuity of the stream for laminar, steady and isothermal flow so viscoelastic model Rivlin Ericksen type of lubricant has been adopted. It has been adopted also that the dynamic viscosity depends generally on the magnetic field. Reynolds-type equation by which the hydrodynamic pressure distributions can be determined has been solved numerically using program - MathCAD 14 professional. On the base of these calculations have been designated values of the friction forces and coefficient of friction, and temperature distributions in the oil gap of sliding journal bearing which is presented in the form of graphs. Increase in the number of magnetic particles causes an increase of load. Carrying capacities with the presence of the same value of external magnetic field. Increase in the number of magnetic particles results in a slight increase in friction force with a large increase in load carrying capacities and a slight growth in friction force, conventional friction coefficient decreases with increasing concentration of magnetic particles in Ferro Fluid. The presence of magnetic particles in Ferro Fluid reduces the maximum temperature in the gap of slide journal bearing. it should be clear that the quoted values are the result of computer simulation. the actual value of changes of temperature, load carrying capacities, friction force and friction coefficient will depend on the type of magnetic particles, the type of base fluid, the concentration of magnetic particles, the value of an external magnetic field, temperature and value of Ferro Fluid's hydrodynamic pressure, which depends inter alia on the load bearing, rotational speed, radial clearance, and the geometric dimensions of the bearing.

S. S. Gautam1, S. Quamar, M. K. Ghosh (11) has described a numerical study has been done for externally pressurized circular step thrust bearing lubricated with incompressible fluid with finely dispersed air bubbles taking into consideration the variation in lubricant physical properties due to temperature and pressure variation in the fluid film. effect of misalignment / tilt and coning on cavitation region has also been investigated. Bubbly oil improves the performance of the bearing when the air bubble content is low. Higher air bubble content does not alter the performance. There is thus an optimum value of air bubble content in the oil (x=0.01) up to which performance improves. Temperature increases from leading edge to trailing edge. There is a surge in temperature at the recess edge due to discontinuity in the film thickness. load carrying capacity improves initially with increase in the air bubble content and then asymptotically attains a constant value when air bubble content becomes high. region of cavitations diminishes with increase in the air bubble content. Due to centrifugal inertia effect cavitations zone increases. The frictional power loss and lubricant mass flow rate decreases with the air bubble content. cavitations region is reduced by misalignment and coning.

F.P. Brito , A.S. Miranda , J.C.P. Claro , J.C. Teixeira , L. Costa , M. Fillon (12) has described a thermo hydrodynamic(THD) model for the analysis of hydrodynamic journal bearings with realistic lubricant feed conditions has been proposed and used to assess the role of lubricant feeding conditions on the performance improvement and friction reduction of hydrodynamic journal bearings. the model is based on the simultaneous solution of the generalized Reynolds equation through a mass conserving algorithm and the energy equation within the fluid domain, as well as the Laplace equation within the bush body domain. the feeding pressure proved to be a critical factor in reducing the temperature level of the bearing and in preventing the occurrence of hot oil reflux (negative flow rate in a groove), even if it was at the expense of a higher power loss. the increase of the lubricant feeding temperature proved to be beneficial under low loads (it decreased power loss) but especially dangerous under high loads as it strongly increases the eccentricity, Tmax, Pmax, and the thermal and mechanical distortions, while lowering the critical load for which hot oil reflux starts occurring. the increase of w/d induced a decrease in power loss and maximum bush temperature without a significant decrease in load carrying capacity. However, the critical load for which hot oil reflux starts occurring was lowered.

M.M. Khonsari, D.E. Brewe (13) has described the performance parameters for a journal bearing of finite length lubricated with micro polar fluids is undertaken. Results indicate that a significantly higher load carrying capacity than Newtonian fluids may result depending on the size of material characteristic length and the coupling number. it is also shown that although the frictional force associated with micro polar fluid is in general higher than that of a Newtonian fluid, the friction coefficient of micro polar fluids tends to be lower than that of the Newtonian. a study of the lubricating effectiveness of micro polar fluids in a finite journal bearing is presented. Micro polar fluids are a subclass of micro fluids in which the fluids exhibit micro rotational effects i.e., the fluid is considered to possess microstructure that can rotate independently of the micro volume but the deformation (micro stretch) is not allowed. These fluids have potential in describing the effect of polymeric additives as the classical Navier-Stokes theory has no provision for the effects of microstructure in fluids. the results presented in this paper indicate that for a steadily loaded finite journal bearing, the micro polar fluids do indeed exhibit a beneficial effect in that the load carrying capacity is significantly increased and the friction coefficient is less than that of the Newtonian lubricant.

III Research Work

Aim of Research

- Developing an Optimized Manufacturing Route Capable of Producing Reproducible, Uniform Porous Structures for Larger Bearings, Suitable for their Incorporation.

- The Assessment of Water Lubrication Robustness for Porous-Ceramic Hydrostatic Bearing Systems.
- Employing Low Viscosity oils as Lubricant in Porous-Ceramic Hydrostatic Bearing Systems.
- Analysis of the failure in hydrostatic bearing and optimize solution for that. And also calculate Effect of surface roughness, slip velocity, etc.
- In thermal analysis Design parameters like relative eccentricity, dimensionless load carrying capacity, dimensionless wall shear stress, friction coefficient, Reynolds number, Somerfield number, strain rate, pressure distribution, temperature distribution and lubricant flow properties like turbulent viscosity, and velocity magnitude are consider for the analysis.

Objectives

- Increase life of bearing.
- To increase Long Term Dimensional Stability And Stiffness, Compared to Traditional Materials, over a Wide Temperature Range - Less Wear than Traditional Bearing Materials
- To decrease Coefficient of Linear Expansion which Reduced Problems of Thermal Drift
- The Non Corrosion of most Ceramics in Water.
- To decrease Viscosity Hydrostatic Bearing oils, which directly Reduces Friction Power And Heat Generation.
- To increase Specific Heat than oil, making it Easier to Control the Temperature of the Bearing Assembly and Machine.
- To overcoming Environmental Concerns Associated with the use of oil.
- Increase Uniform Pressure Profile at the Bearing Surface which Provides an Increased Load Capacity and Stiffness
- Improved Utilization of the Hydrodynamic Pressure in the Lubricant Film With the Elimination of the Hydrostatic Bearing Pocket (Recess).
- Elimination of the Hydrostatic Bearing Pocket also Permits Higher Speeds Before the onset of Turbulence.
- Improved Damping Due to the Permeable Surface Adjacent to the Bearing Gap and the Squeeze Film Effect.

Scope of Work

Bearing is the main components of any machinery. If bearing will be failing all part fail and Machinery will be stop. Following example are related bearing:
In the Case of Steam Turbines, Airfoil theories may attract much attention, But the role of Journal Bearings Supporting the Turbines are also Very Important. If Seizure occurs in a Bearing, the Turbine will stop. In other Words, a Bearing determines the fate of the whole Machine. In this Connection, Bearing Technology is very important in a Completely Different way from Airfoil Theory, which may improve turbine efficiency by 2% Or 3% by changing the Airfoil of turbine blades.
In case of a Magnetic Disk Memory Device, Hydrodynamic Lubrication Develops between a Slider and the Magnetic Disk, with the surrounding air as Lubricant. If Seizure (or a Crash) takes place there, It's all over. All records will be Lost. All High Technologies In The other Parts of The System Will Be Useless. The Importance of Tribology cannot be overstated."
So bearing is important part and it's use in any machinery.

IV Conclusion

Based on literature review we were conclude that porous ceramic hydrostatic journal bearing have greater properties such as increase life of bearing, increase long term dimensional stability and stiffness , Increase uniform pressure profile ,increase load capacity, decrease Coefficient of Linear Expansion which Reduced Problems of Thermal Drift as compare to conventional bearing.

Scope for the Future work

- We can increase life of bearing.
- We can increase long term dimensional stability and stiffness.
- We can decrease coefficient of linear expansion which reduced problems of thermal drift.
- We can decrease viscosity hydrostatic bearing oils, which directly reduces friction power and heat generation.
- We can increase uniform pressure profile at the bearing surface which provides increased load capacity and stiffness
- We can improve utilization of the hydrodynamic pressure in the lubricant film with the elimination of the hydrostatic bearing pocket (recess)

REFERENCES

1. J. Corbettl, R.J. Almond, D.J. Stephenson, Y.B.P. Kwanz, "Porous ceramic water Hydrostatic Bearings for improved for accuracy performance" on January 8, 1998.
2. Almond RJ. "The development of a porous ceramic water hydrostatic bearing for ultra high precision applications". PhD theses. Cranfield, U. K.: Cranfield University, 1999.
3. Isidro S. Durazo-Cardenas*, David J. Stephenson, John Corbett,"Controlled Porosity Alumina Structures for Ultra-Precision Hydrostatic Journal Bearings via Starch Consolidation," Journal of the American ceramic Society, vol.93(11),Nov.2010,p.3671-3678.
4. I.S. Durazo Cardenas, J Corbett, and D.J. Stephenson, "The Performance of a Porous Ceramic hydrostatic journal bearing", Proceedings of the institution of mechanical engineers, part j: journal of engineering tribology, volume 224, number 1, 2010, pp81-89
5. Isidro S. Durazo-Cardenas, David J. Stephenson, John Corbett, "Controlled porosity alumina structures for ultra-precision hydrostatic journal bearings via starch consolidation", journal of the american ceramic society, october 2010.
6. Dinesh Dhande, Dr D.W. Pande, Vikas Chatarkar, "Analysis of hydrodynamic journal bearing using fluid structure interaction approach", international journal of engineering trends and technology (ijett) – volume 4 issue 8- august 2013.
7. Shigang Wang, Xianfeng Du, Mingzhu Li, Zhongliang Cao, Jianjia Wang, "Analysis of temperature effect on the lubricating state of hydrostatic bearing", Journal of theoretical and applied Information Technology 20th February 2013. Vol. 48 No.
8. Qiyin Lin, Zhengyingwei, Ningwang, Weichen," Analysis on the lubrication performances of journal bearing system using computational fluid dynamics and fluid structure interaction considering thermal influence and cavitation", tribology international 64(2013)8–15.
9. J.R. Lin, P.J. Li, And T.C. Hung , "Effects of non-newtonian ferro fluids on the performance characteristics of long journal bearings", fdmp, vol.9, no.4, pp.419-434, 2013.
10. K. M. Panday, P. L. Chaudhury, And N. P. Kumar, "Numerical unsteady analysis of thin film lubricated journal bearing", iacsit international journal of engineering and technology, vol. 4, no. 2, april 2012.
11. M. Frycz, P. Anioł," temperature distribution in the gap of slide journal bearings lubricated with ferrofluids for different concentration of magnetic particles", marcin frycz, paweł anioł.
12. S.S. Gautam1, S. Quamar, M. K. Ghosh, "Thermal analysis of externally pressurised step bearing including centrifugal inertia effect for a bubbly lubricant", international journal of engineering, science and technology vol. 2, no. 11, 2010, pp. 147-166
13. F.P. Brito , A.S. Miranda , J.C.P. Claro , J.C. Teixeira , L.Costa , M.Fillon, "The role of lubricant feeding conditions on the performance improvement and friction reduction of journal bearings", tribology international72(2014)65–82.
14. M.M. Khonsari, D.E. Brewe, "on the performance of finite journal bearings lubricated with micropolar fluids".society of tribologiest and lubrication engineers Cleveland.Ohio, May 8-12, 1988.