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Fail-safe design of journal bearing hybrized with passive magnetic levitation

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Abstract- The best tribological performance, in terms of reduced friction and almost negligible wear, of a journal bearing is achieved when it operates in hydrodynamic lubrication regime. However, during starting as well as stopping, sudden impact/dynamic loading and/or due to severity of operating conditions, the journal contacts the bearing which increases the friction and causes wear. The sudden/uneven wear of the bearing may modify the bearing geometrical parameters that may render it unsuitable for use in the required application. Therefore, there is a need to provide a fail-safe design of a journal bearing that maintains the desired level of bearing performance under all imposed operating conditions during its service life. The fail-safe design of a journal bearing is achieved without the addition of any redundant element. In the present research, hybridization of passive magnetic levitation with a hydrodynamic journal bearing has been proposed to obtain a fail-safe design of journal bearing. In order to overcome the limitations of the passive magnetic bearing, an arrangement of radial and axial polarized magnets stacked alternatively over one other is proposed. An experimental setup has been designed and developed for performance evaluation of the proposed hybrid bearing. The experimental results indicate that the proposed hybrid bearing qualifies as a fail-safe design.

Keywords- *Friction, Wear, Rotation Magnetized Direction, Tribological Considerations, Redundant Elements, Hybrid bearing*

1. Introduction

Fail-safe designs are generally understood to be the designs that incorporate various techniques to mitigate losses due to system or component failures with an implicit assumption that failure will eventually occur but the system will fail in a safe manner with due warning before failure. The traditional method of fail-safe design is the incorporation of redundancies by providing backup systems. However, this feature makes the system heavier and increases initial and running costs. The present paper proposes a fail-safe design of a journal bearing without the employment of any redundancies.

The hydrodynamic journal bearings under suitable operating conditions experience negligible friction, zero wear and high damping. During starting/stopping/impact loading or operating under high load and/or low relative speed conditions, wear of the bearing occurs. The consequences of wear are numerous and may render the system unsuitable for use leading to failure. A fail-safe bearing that may continue to function under all odd (starting/stopping/impact/heavy-load) conditions will be preferable compared to conventional journal bearing. A fail-safe bearing can be obtained either by incorporating redundancy (two bearings in place of one bearing) or hybridizing two different bearing mechanisms (i.e. hydrodynamic hybridized with hydrostatic, active magnetic bearing hybridized with rolling element bearing). In the present study, a fail-safe design of hydrodynamic journal bearing is realized by hybridizing it with permanent magnetic bearing technology.

2. Proposed fail safe bearing

A properly designed journal bearing can tolerate some degree of misalignment, fluctuations in speed/load and unexpected light dirt. In addition, with changes (sudden or gradual) in the operating conditions like increase in the load, decrease in the speed, impact loading, high operating temperature that reduces lubricant viscosity and during starting and stopping, the thickness of fluid film decreases and the journal may contact the bearing with consequent increase in friction and wear. The hybridization of passive magnetic levitation with the hydrodynamic journal bearing has been successfully utilized to prevent this condition [1,2]. In such hybrid bearing, the static load is carried by passive magnetic bearing and dynamic load by hydrodynamic bearing. Tan et al [3] used separate full ring magnetic bearing to bear the static load and adjoined journal bearing to carry the dynamic load, however this arrangement requires more space. Hirani and Samanta [1] proposed an improved design that utilized the surface of the magnet itself as the journal bearing in order to reduce the space requirements. Hirani and Samanta [2] also proposed a combined action of a half ring magnet at the bottom and a 45° sector magnet at the top for enhancing the load carrying capacity of the hybrid magnetic bearing. The experimental studies of Muzakkir et al [4] on a hybrid bearing showed the formation of crack along with wear marks on the surface of stator magnet. Their investigation revealed the formation of different poles on the inner surface of the magnet which occurred due to the contact between rotor and stator magnets. The reason for the failure of the hybrid bearing was attributed to the presence of both attractive and repulsive forces on the bearing surfaces which resulted in increased load on the bearing. Lijesh and Hirani [5] proposed a stator of metallic (aluminum) sub-structure with small sized pieces of magnetic material for containing the brittleness of permanent magnets (ceramic material). It was experimentally shown that the reduced sized magnets are less prone to cracks, as the impact toughness of ceramic materials is inversely proportional to the length and height of the material. The metallic substructure with slots to accommodate the pieces of permanent magnet also provided good damping properties[6]. The structure proposed by Lijesh and Hirani [7] increased the structural damping of bearing but at the cost of reduced load carrying capacity. The enhancement in the load carrying capacity of the magnetic bearing was proposed by Yonnet et al [8] by stacking of the axial magnet rings in a back to back arrangement as shown in figure 1.

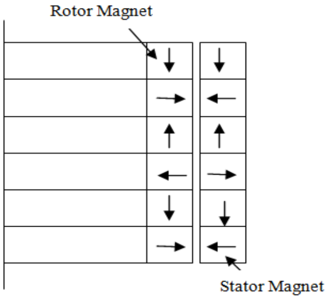


Fig 1 Schematic Diagram of back to back arrangement of magnets

In another arrangement termed as Rotation Magnetized Direction (RMD) and shown in figure 2, the radial and axial polarized magnets are stacked alternatively one over the other to increases the stiffness of the bearing.

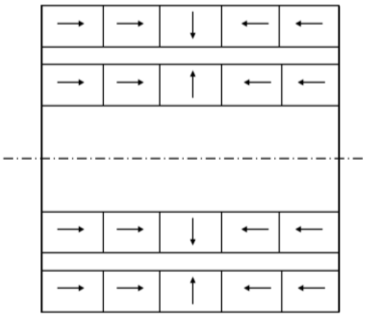


Fig 2 Schematic Diagram of RMD arrangement of magnets

The figure 3 shows the model of the RMD arrangement of magnets.

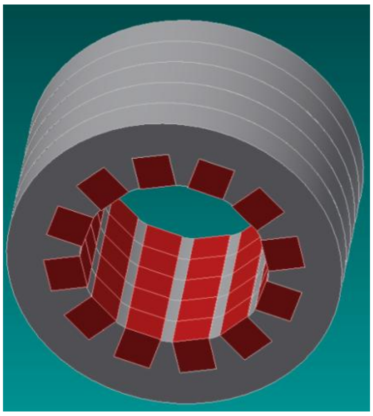


Fig 3 Model of RMD arrangements of magnets

The RMD arrangement of magnets is hybridized with the journal bearing to achieve a fail-safe design. The experimental verification of the proposed RMD hybrid bearing is required to establish it as a fail-safe design. The next section describes the design and development of the experimental setup for conducting experimental validation of the proposed fail safe design.

3. Design and development of experimental setup

An experimental setup was designed and developed to conduct experiments on the conventional journal bearing, conventional passive magnetic bearing and proposed hybrid bearing that qualifies as fail-safe design. The figure 4 depicts the schematic arrangement of the experimental setup.

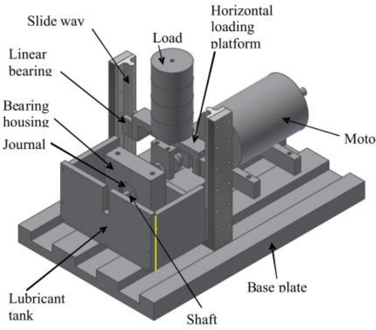


Fig 4 Schematic arrangement of the experimental setup

The experimental setup rig consists of an induction motor (AC, 3 phase, 1.5 kW) rigidly mounted on a base plate. The motor speed is controlled by an ABB frequency drive (IP20/ul open type) from 25 to 3600 rpm. The experimental setup consists of a stainless steel (grade 303) shaft having one end free, while the other end connected to motor via a spiral coupling. The loading arrangement consists of a horizontal loading platform supported on linear bearing mounted on vertical slide-ways of circular cross section. A (shielded) deep groove ball bearing transfers the load from the loading platform to the shaft. A maximum of 500N of load can be applied using this arrangement. Two accelerometers (Type: KS 76C-10, voltage sensitivity: 1.032 $mV/m/s^2$), one connected at the top and other at one side of the bearing housing provide data. Data acquisition (DAQ, National Instruments) was used to acquire data and store in the computer using Lab VIEW© interface.

The arrangement for achieving radial polarization is implemented on the middle-magnet of the rotor as shown in figure 5(a). The fabrication of RMD in stator is shown in figure 5(b).

(a) Rotor (b) Stator

Fig 5 Fabricated RMD arrangement of rotor and stator

For conducting experiments on conventional journal bearing, the experimental setup is arranged to have one stainless steel journal (48mm diameter) fitted at the free end of the shaft and supported in the bearing (50mm diameter) housing which in turn is rigidly fixed to the base plate. A lubricant tank consisting of heater and thermal cut-off switch maintains the lubricant at the desired temperature. The journal bearing is operated under extreme conditions (heavy load of 373 N and slow speed of 27 rpm) for 6 hours.

For conducting experiments on passive magnetic bearing, the experimental setup is arranged to have one journal consisting of four neodymium magnetic discs (ID 10 mm, OD 48 mm and thickness 8 mm) fitted at the free end of the shaft and supported in the bearing consisting of two cylindrical magnets (ID 50 mm, OD 100 mm and thickness 15 mm) which in turn is rigidly fixed to the base plate.

For conducting experiments on the proposed RMD arrangement, the stator and rotor used are shown in figure 5(a) and (b) respectively.

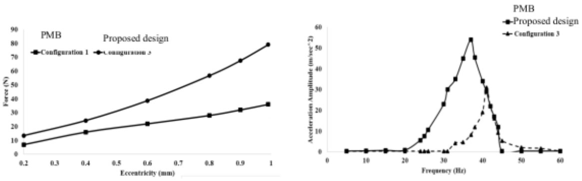
4. Experimental Results and Discussion

The experimental performance evaluation of a conventional journal bearing indicates wear of the bearing to the tune of 60 mg weight loss after the 6 hour test, indicating a 0.033% weight loss of the bearing material. The bearing was operated at 27 rpm which is much smaller than the lift-off speed of 529 rpm (corresponding to a specific film thickness of 3). This indicates that the journal was in contact with the bearing and hydrodynamic conditions could not be achieved due to the severity of the operating conditions. Therefore, a journal bearing fails to operate successfully under the given extreme operating conditions.

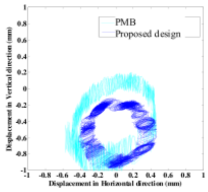
The experimental performance evaluation of a passive magnetic bearing indicates that the levitation of the journal could not be achieved under the similar operating conditions as that of the conventional journal bearing. The maximum static load capacity of the passive magnetic bearing was determined to be 52.8 N which is not sufficient to levitate the rotor.

The experimental performance evaluation of the proposed RMD configuration indicates that the bearing is able to operate under the extreme operating conditions. The levitation of the journal is achieved with the use of RMD structure. The static load capacity of conventional passive magnetic bearing and proposed RMD configuration, as shown in figure 6(a), indicates a larger static load capacity for the proposed design. The acceleration response of conventional passive magnetic bearing and proposed RMD configuration is shown in figure 6(b). It is observed that the acceleration response of the proposed design is reduced and occurs at a higher frequency due to increase in the stiffness of the system.

From figure 6(c), it is can be inferred that with proposed RMD configuration design, the shaft is rotating in lifted position and span of the orbit plot is reduced compared to PMB configuration. Therefore based on the experimental investigations it may be concluded that the proposed design qualifies as a fail-safe design.



(a) Static Load Comparison (b) Acceleration at different frequencies



(c) Orbit plot

Fig 6 Comparison of Passive magnetic bearing and proposed design

Conclusions

The fail-safe design of the hybrid bearing is achieved by the use of hybridization of journal bearing and passive magnetic levitation employing RMD structure. This RMD structure enhances the bearing damping without compromising the load carrying capacity. It has been found experimentally that the proposed RMD structure enhances the load carrying capacity of magnetic bearing. Based on the experimental studies performed on the proposed hybridization of journal bearing and passive magnetic levitation employing RMD structure, it is concluded that the proposed hybrid bearing is able to operate under varying operating conditions, thereby providing a fail-safe design. The fail-safe design is achieved without the introduction of any redundant elements.

References

[1] P. Samanta, H. Hirani, 2008, Magnetic bearing configurations: Theoretical and experimental studies Magnetics, IEEE Transactions on Magnetics, 44(2), 292-300.
[2] P. Samanta, H. Hirani, 2007, Hybrid (Hydrodynamic + Permanent Magnetic) Journal Bearings, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 221(J8), 881-891.
[3] Q. Tan, W. Li, and B. Liu, 2002, “Investigations on a permanent magnetic–hydrodynamic hybrid journal bearing,” Tribol. Int., 35(7), pp. 443–448
[4] S M Muzakkir, Lijesh KP, Hirani H. 2014, Tribological failure analysis of a heavily-loaded slow speed hybrid journal bearing. Eng Fail Anal;40:97–113.
[5] H. Hirani and K.P. Lijesh, “Stator”, Patent application, 259883
[6] Y.P. Yonnet, G. Lemarquand, S. Hemmerlin and E.O.-Rulliere, 1991, “Stacked structures of passive magnetic bearings,” J. Appl. Phys., 70(10), pp. 6633-6635

[7] K.P. Lijesh, and H. Hirani, “Stiffness and damping coefficients for rubber mounted hybrid bearing,” Lubrication Science, 26(5), pp. 301-314

[8] Samanta, P., Hirani, H. An overview of passive magnetic bearings, 2008 Proceedings of the STLE/ASME International Joint Tribology Conference, IJTC 2008, pp. 465-467.

[9] K. P. Lijesh, H. Hirani, 2015, Optimization of Eight Pole Radial Active Magnetic Bearing, ASME, Journal of Tribology, 137(2),

[10] K. P. Lijesh, H. Hirani, 2015, Development of Analytical Equations for Design and Optimization of Axially Polarized Radial Passive Magnetic Bearing, ASME, Journal of Tribology, 137(1).

[11] Lijesh, K.P., Hirani, H. Design of eight pole radial active magnetic bearing using monotonicity (2015) 9th International Conference on Industrial and Information Systems, ICIIS 2014,

[12] Lijesh, K.P., Hirani, H. Design and development of Halbach electromagnet for active magnetic bearing (2015) Progress In Electromagnetics Research C, 56, pp. 173-181

[13] S M Muzakkir, K P Lijesh, H Hirani, and G D Thakre, 2015, “Effect of Cylindricity on the Tribological Performance of Heavily-Loaded Slow Speed Journal Bearing, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology, 229(2), 178-195.

[14] S M Muzakkir, H Hirani and G D Thakre, 2013, “Lubricant for Heavily-Loaded Slow Speed Journal Bearing”, Tribology Transactions, 56 (6), 2013, 1060-1068.

[15] S M Muzakkir, H Hirani, G D Thakre and M R Tyagi, 2011, “Tribological Failure Analysis of Journal Bearings used in Sugar Mill”, Engineering Failure Analysis, 18(8), 2093-2103.

[16] H. Hirani, K. Athre, S. Biswas, 1999, Dynamic Analysis of Engine Bearings, International Journal of Rotating Machinery. 5(4), 283-293.

[17] H. Hirani, K. Athre, S. Biswas, 1998, Rapid and Globally Convergent Method for Dynamically Loaded Journal Bearing Design, Proc. IMechE (UK), Journal of Engineering Tribology. 212, 207-214

[18] H. Hirani, K. Athre, S. Biswas, 2000, A Hybrid Solution Scheme for Performance Evaluation of Crankshaft Bearings, Trans. ASME, Journal of Tribology. 122(4), 733-740.

[19] H. Hirani, K. Athre, S. Biswas, 2000,Transient Trajectory of Journal in Hydrodynamic Bearing, Applied Mechanics and Engineering. 5(2).

[20] H. Hirani, K. Athre, S. Biswas, 2001, A Simplified Mass Conserving Algorithm for Journal Bearing under Dynamic Loads, International Journal of Rotating Machinery. 1, 41-51.

[21] H. Hirani, K. Athre, S. Biswas, Lubricant 2001, Shear Thinning Analysis of Engine Journal Bearings, STLE, Journal of Tribology Transaction, 44 (1), 125-131.

[22] H. Hirani, K. Athre, S. Biswas, 2002, Comprehensive Design Methodology for Engine Journal Bearing, IMechE (UK), Part J, Journal of Engineering Tribology. 214, , 401-412.

[23] Hirani, H., 2004, Multi-objective Optimization of a journal bearing using the Pareto optimal concept, Proc. Institute Mech. Engineers., Part J, Journal of Engineering Tribology. 218 (4), 323-336.

[24] H. Hirani, Multiobjective optimization of journal bearing using mass conserving and genetic algorithms, Proc. Institute Mech. 2005, Engineers., Part J, Journal of Engineering Tribology. 219(3), 235-248.

[25] H. Hirani, N.P. Suh, 2005, Journal Bearing Design using Multi-objective Genetic Algorithm and Axiomatic Design Approaches", Tribology International, 38(5), 481-491.

[26] H. Hirani, M. Verma, 2009, Tribological study of elastomeric bearings of marine shaft system, Tribology International, 42(2), 378-390.

[27] T. V. V. L. N Rao, H. Hirani, K. Athre, S. Biswas, 2000, An Analytical Approach to Evaluate Dynamic Coefficients and Non-linear Transient Analysis of a Hydrodynamic Journal Bearing, STLE Tribology Transactions, 23(1), 109-115.

[28] H Hirani, T Rao, K Athre and S Biswas, Rapid performance evaluation of journal bearings, Tribology international, 30(11), 1997, 825-834.

[29] H Hirani, K Athre, S Biswas, 1999, Dynamically loaded finite length journal bearings: analytical method of solution. Journal of tribology, 121(4), 844-852.

[30] H. Hirani, 2009, Root cause failure analysis of outer ring fracture of four row cylindrical roller bearing, Tribology Transactions, 52(2), 180-190.

[31] H. Hirani, H. S.S.Goilkar, 2009, Design and development of test setup for online wear monitoring of mechanical face seals using torque sensor", Tribology Transactions, . 52(1), 47-58.

[32] H. Hirani, H. S.S.Goilkar, 2010, Parametric Study on Balance Ratio of Mechanical Face Seal in Steam Environment”, Tribology International, 43(5-6), 1180-1185.

[33] H. Hirani, H. S.S.Goilkar, 2009, Formation of Transfer Layer and its Effect on Friction and Wear of Carbon-Graphite Face Seal under Dry, Water and Steam Environments", Wear, 226(11-12), 1141-1154.

[34] S M Muzakkir, Hirani H, Thakre G D., 2012, Performance evaluation of journal bearings used in sugar mills using Taguchi method. Soc. Tribol. Lubr. Eng. Annu. Meet. Exhib. 2012, p. 121–3.

[35] Lijesh KP, S M Muzakkir, Hirani H. 2015, Experimental Tribological Performance Evaluation of Nano Lubricant using Multi-Walled Carbon Nano-tubes (MWCNT). Int J Adv Eng Res:1–8.

[36] Gupta S, Hirani H. 2011, Optimization of Magnetorheological Brake. ASME/STLE 2011 Jt. Tribol. Conf., ASME; p. 405–6.

[37] Hirani H. 2009, Online wear monitoring of spur gears. Soc. Tribol. Lubr. Eng. Annu. Meet. Exhib. 2009, p. 350–2.

[38] Hirani H. 2009, Magnetorheological smart automotive engine mount. Soc. Tribol. Lubr. Eng. Annu. Meet. Exhib. 2009, p. 353–5.
[39] Hirani H, Suh NP. 2005, Journal bearing design using multi objective genetic algorithm and axiomatic design approaches. Tribol Int;38:481–91.
[40] Rao TVVLN, Biswas S, Hirani H, Athre K. 2000, An analytical approach to evaluate dynamic coefficients and nonlinear transient analysis of a hydrodynamic journal bearing. Tribol Trans;43:109–15.
[41] Samanta F, Hirani H, Mitra A, Kulkarni AM, Femandes BG, 2005, Test setup for magnetohydrodynamic journal bearing, Proc. 12th Natl. Conf. Mach. Mech. NaCoMM 2005, National Conference on Machines and Mechanisms, NaCoMM 2005; p. 298–303.
[42] Sukhwani VK, Hirani H, 2008, Design, development, and performance evaluation of high-speed magnetorheological brakes, Proc Inst Mech Eng Part L J Mater Des Appl;222:73–82.
[43] S M Muzakkir, Satish Kumar, 2015, Design of mechanical oil seal and gasket International Journal of Applied Engineering Research, 10 (12), pp. 30911-30926.
[44] H. Hirani, Rao, T.V.V.L.N., Athre, K., Biswas, S. Rapid performance evaluation of journal bearings (1997) Tribology International, 30 (11), pp. 825-832.
[45] Goilkar, S.S., Hirani, H. Parametric study on balance ratio of mechanical face seal in steam environment (2010) Tribology International, 43 (5-6), pp. 1180-1185.
[46] Goilkar, S.S., Hirani, H. Design and development of a test setup for online wear monitoring of mechanical face seals using a torque sensor (2009) Tribology Transactions, 52 (1), pp. 47-58.
[47] Hirani, H., Samanta, P. Performance evaluation of magnetohydrodynamic bearing (2005) Proceedings of the World Tribology Congress III - 2005, pp. 97-98.
[48] Hirani, H., Dani, S. Variable valve actuation mechanism using magnetorheological fluid (2005) Proceedings of the World Tribology Congress III - 2005, pp. 569-570.
[49] Burla, R.K., Seshu, P., Hirani, H., Sajanpawar, P.R., Suresh, H.S. Three dimensional finite element analysis of crankshaft torsional vibrations using parametric modeling techniques (2003) SAE Technical Papers.