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Hydrostatic journal bearing and pressurized seals for machine tool spindles based on active magnetic fluids: magnetorheological fluids and ferrofluids

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Abstract
The research work presented in this paper is focused on the development of actively lubricated journal bearings (hydrostatic and hydrodynamic lubrication) and advanced sealing rings for high precision spindles in machine tools. In both cases, bearing and seals, two commercial magnetic fluids were applied as active fluid: ferrofluids from FERROTEC (mod. s10n) and Magneto Rheological Fluids (MRF) from LORD Corp (MRF122-2ED). Reynolds' thin film lubrication equation was modified for non-Newtonian fluids, and magnetic model and calculations were carried out for bearings and seals performance evaluation. In the case of complex hybrid journal bearings, where Reynolds is not applicable, Computational Fluid Dynamics (CFD) simulations were computed with Herschel-Buckley model for MRF. On the other hand, a test bench was designed and set up for testing the prototypes of next three devices: active hydrodynamic journal bearings, active hydrostatic bearings with magnetorheological valves, and magnetic fluid based pressurization seals. Active hydrodynamic lubrication showed an improvement in the load capacity and stiffness of around 50% for middle coaxiality values. In the case of active hydrostatic journal bearings four MR valves were developed, and by a close loop control, quasi-infinite stiffness was demonstrated at low frequencies values, below 5 Hz. Sealing rings based on ferrofluids have demonstrated a high pressurizing capacity, around 9 kPa per ring. With a serial design as proposed in this research, around 100 kPa pressurization capacity has achieved with negligible friction in the spindle at studied rotational speeds, up to 200 r/min. Summarizing, it has been demonstrated the feasibility of actively lubricated journal bearings and sealing rings based on MRF and ferrofluids for high precision spindles in machine tools.

Journal bearing, sealing ring, magnetorheological fluid, ferrofluid, active bearing, hydrostatic lubrication, hydrodynamic lubrication.

1. Introduction

Pressurized lubricated bearings, hydrostatic or hydrodynamic bearings, are widely used by manufacturers of high-precision machine tools. Most influencing authors in the machine tool building field [1], agree that between the available technologies for guiding systems, namely sliding, rolling and pressurized lubricant technologies, the latter offers better properties, considering resolution, damping and smoothness in the movement. The application of magnetic fluids in actively lubricated bearings was studied in some previous works with two main approaches: Hydrodynamic and hydrostatic. In the case of hydrodynamic bearings the magnetic field is applied directly into the bearing, modifying the rheology of the fluid in the pressurized thin film. Notorious changes in the Stribeck curve were observed experimentally with the use of ferrofluids [2]. The use of ferrofluids in lubricated bearings design was also studied on the static and dynamic response [3]. A deeper approach about magnetic fluids as lubricants was developed by Uhlmann [4]. More recent works in this matter [5], aimed at the study of the free boundary laws and the effect of surface roughness. In the case of hydrostatic lubrication, the flowrate and pressure under variable external loads, vibrational response and damping was explored [6]. Valves (or restrictors) with magnetic fluids for hydrostatic bearings determine the pressure drop in function of flowrate and applied magnetic field [7]. Finally regarding bearings lubrication, considering that ferrofluids are highly stable but show very low magnetoviscous effect as bearings lubricant [8]; the research presented in this paper was conducted exclusively with MR fluids.

On the other hand, seals based on those magnetic fluids were studied. Magnetic fluids based seals were presented in the early 1980's where the basic design parameters were established [9], such as the gap, size and the distance between the rings. Simulations of those seals with non-linear models to consider the real magnetization curve were discussed [10]. The use of MRFs for sealing applications was considered, where the pressurization and the wear generated in the rings by the magnetic fluids with strong yield stress was studied. Finally a deep theoretical and experimental study of ferrofluids based seal was presented in [11], discussing the maximum pressure achieved by the rings and the recovery pressure after the fluid seal has achieved the limit.

Summarizing, this work was focused in the use of magnetic fluids as lubricants for bearings and pressurized seals. Section 2 presents the experimental characterizations of the fluids, section 3 is related with bearings and section 4 with seals.

2. Fluids experimental characterization

Indicated two fluids were experimentally characterized in a rheometer, Thermo HAAKE RheoStress RS150. The data given by the manufacturers are approximate, and they cannot be considered for this kind of research work. Therefore, magnetorheological response in function of temperature, magnetic field and shear stress were determined. With those results, the models from bibliography were adjusted, Herschel-Buckley for MRF and viscosity tuning for ferrofluis.

3. Lubricated bearings

Two bearings were studied in this work, a hydrodynamic and a hydrostatic one, where MR valves were developed for the second one. In both cases the bearings were modelled by CFD tools, together with Finite Elements Method (FEM) simulations for magnetic field induction in the fluid by the coils. In the Figure 1 the final results are shown for pressure distributions into the journal bearing at two orientations of the pockets, four pockets bearing.

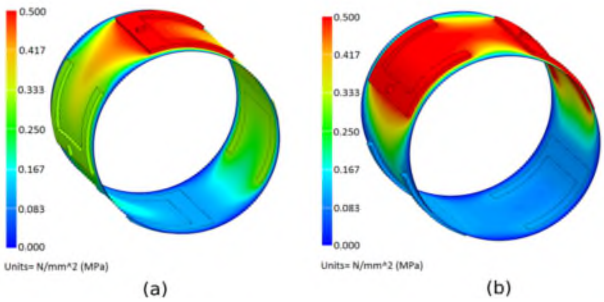

Figure 1. Pressure distribution in the bearing (CFD), a) 0º and b) 45º.

Validation of the model was carried out with a test bench for actively lubricated journal bearings like presented in Figure 2.

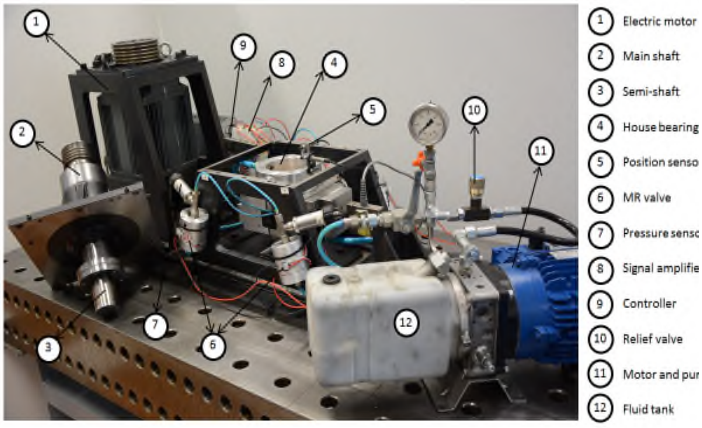

Figure 2. Test bench description for journal bearings.

In the case of hydrostatic bearings, four magnetorheological valves were developed. Like in the bearings, the valves response was simulated by FEM for magnetic field, and CFD for pressure drop and flow rate estimation. The final design of the valve is presented in Figure 3:

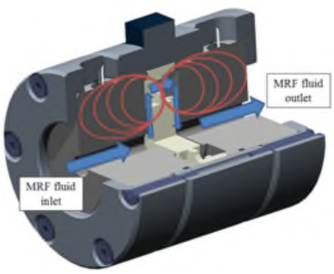

Figure 3. MR valves for hydrostatic active bearing.

As an example of the several kinds of results obtained from the investigation, the load capacity's improvement is presented in Figure 4. In this case, the shaft is rotating at 200 r/min, and the increase of load capacity in working range of the bearing is higher than 100%. There were analysed also attitude angel in hydrodynamic response, where the non linealirity of cross stiffness was reduced more than 80%. Relating dynamic response with MR valves, the time response of overall system for a step input was around 0.06 s, not enough quick for high bandwidth close loop control.

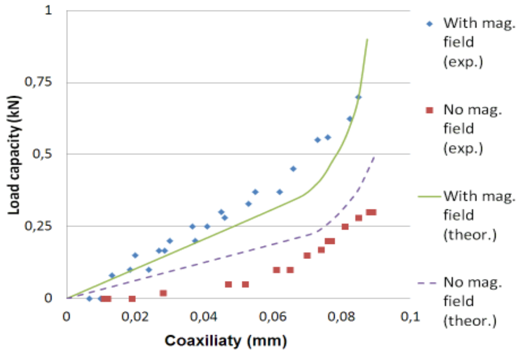

Figure 4. Load capacity of bearing at 200r/min.

4. Sealing rings

Using the same methodology, sealing rings were simulated and designed considering the same test bench of Figure 2, but modifying bearing zone for new sealing prototype, Figure 5.

Figure 5. Prototype of seal based on magnetic fluids.

The results obtained by the experimental set-up and the models are summarized in graphs like presented in Figure 6, which is an example of ferrofluid sealing capacity at 50 r/min.

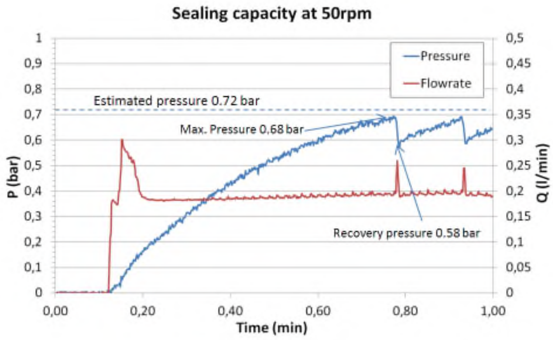

Figure 6. Sealing capacity of ferrofluid at 50r/min.

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