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CURRENT DEVELOPMENT FOCUSES OF THE HYDROSTATIC BEARING DESIGN AND OPTIMIZATION

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Abstract: The number of scientific articles dealing with hydrostatic bearings has jumped significantly over the last decade due to the huge increase in the development of the Far East industry. With new numerical calculations and simulations, the shape of the bearing pads, the fluid film thickness can be optimized and the behaviour of special hydrostatic bearing designs can be tested. Considering the research results revealed, new directions for optimization, new applied fluids and further development directions are emerging.

Keywords: *hydrostatic bearings, hydrostatic guideways, Reynolds equation, optimization*

1. INTRODUCTION

Hydrostatic bearings could be one of the most important elements of machine tools due to their long service life and rotational precision, but their application is greatly haltered by their complex design, manufacturing precision sensitivity and the difficulty of describing their complicated mechanical properties compared to rolling bearings. For this reason, until the 1990s, the design of hydrostatic bearings was mostly based on previous measurements and experiences with analytical and numerical calculations. While hydrostatic bearing design companies in Europe are becoming increasingly obsessed, in the Far East, due to the large industrial developments, more and more publications are being dealt by developing hydrostatic bearings.

New publications – in the design and analysis of hydrostatic bearings – now consider engineering applicability. During the 1990–2018 period nearly 200 new publications were published on this topic. Some of the theoretical research deals with the improvement of the Reynolds equation, while a larger proportion of publications can be categorized by the shape of the bearing recesses, the pressure control method and the bearing design.

2. NEW GOVERNING EQUATIONS FOR HYDROSTATIC BEARINGS ANALYSIS

For studying hydrostatic bearings, the Reynolds equation provides a suitable base equilibrium, which can be used to determine the pressure distribution in a thin fluid flow, while for thermal analysis, the energy equation can be selected. By combining the energy equation and the Reynolds equation, M. Khlifi [1] dealt with (1),

$$u\frac{\partial T}{\partial x}+\left(v-u\frac{\partial h}{\partial x}-w\frac{\partial h}{\partial z}\right)\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=$$
$$\frac{k_c}{\rho c_p}\frac{\partial^2 T}{\partial y^2}+\frac{\eta}{\rho c_p}\left(\left(\frac{\partial u}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right) \tag{1}$$

in which *u, v, w* is the liquid velocity at *x*, *y* and *z* direction, *T* is the temperature of the fluid, η is dynamic viscosity, ρ is density, k_c is thermal conductivity, and c_p is specific heat *(at given pressure)*. The Reynolds equation is a second order differential equation, which can be solved analytically solely for Newtonian liquids. Rheological and other non-Newtonian fluids' flow behaviour was described by E De la Guerra Ochoa [2], who used the Reynolds equation for non-Newtonian fluids, using Carreau's dynamic viscosity function (2),

$$\eta=\eta_0\left(1+\left(\frac{\tau}{G}\right)^2\right)^{\left(\frac{1-\left(\frac{1}{n}\right)}{2}\right)} \tag{2}$$

where η_0 is the dynamic viscosity at steady state , τ is fluid shear stress, *G* is the shear modulus of elasticity, *n* (0.2 ... 1) is the Carreau exponential ratio that characterizes the given non-Newtonian fluid. The Reynolds equation was written for all currently applied bearing pads. The analytical solution of the Reynolds equation can be used to express the effects of each bearing design parameters, but complex mathematical calculations and simplifications are required. Employing CFD software, specific engineering problems are easier to simulate, but the interpretation of new models is difficult, therefore most theoretical research is based on numerical computation.

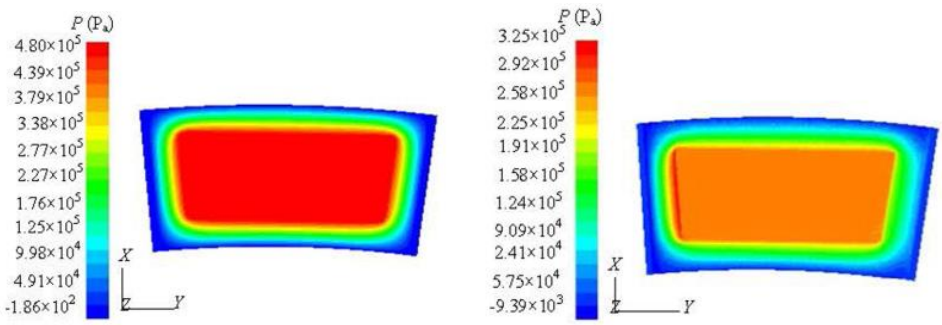

Figure 1. Fluid pressure distribution on a single pad bearing at different (2 and 20 1/min) rotational speed

Significantly fewer attempts were made to validate computational results and new models with experiments. Zhang Y. G. [3] verified the correlation between speed and pressure distribution by simulation with experimental and finite differential techniques.

3. Research results of hydrostatic thrust bearing

Hydrostatic thrust bearings generally are employed with a circular and annular bearing recesses. Due to circumferential geometry, the calculation of Reynolds equation can be made simpler with the cylinder coordinate system, and due to its lightweight manufacturability, most of the publication is concerned with this type of bearing. The publications are categorized into four theme groups: design and development of thrust bearings, surface texturing researches, bearing optimization, and studies about dynamic behaviour. Antoon van Beck [4] found that flexible bearing surfaces *(maintaining the thickness of the liquid film)* have a positive effect on the bearing load capacity. Moreover, the load capacity of the elastic support was derived analytically. Convex deformation should be avoided in this case, but a slight concave deformation is allowed. Later, the model was used by many studies in linear modelling and new numerical models that consider surface frictions too.

Y. Kang [5] investigated the dynamic behaviour of a rotational table supported by closed thrust bearings has been studied in the case of capillary compensation and constant oil pump. The stiffness of the hydrostatic thrust bearing regulated with the pump is much higher than for the capillary control. In addition, the static load significantly influences the dynamical characteristics of the hydrostatic bearing.

T. A. Osman [6] investigated the dynamics of axial hydrostatic bearing rings. Based on its calculations, an optimum flow rate can be determined for bearing load capacity, stiffness and damping. In addition, it can be stated that the bearing pad properties are greatly deteriorated if the bearing surfaces are not parallel to each other. F. Shen [7] studied multiple bearing recess shape *(rectangular, circular, ring, ellipse)*, based on the results the highest stiffness can be achieved with the circular bearing recess, while the highest load capacity can be provided with the annular recess bearing.

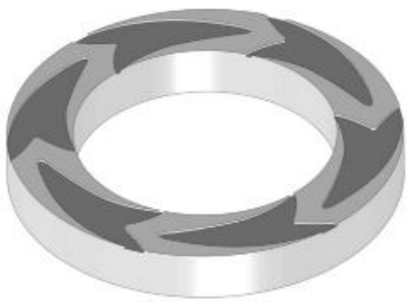

Figure 2. Standing pad of hydrostatic thrust bearing allocated with optimized grooves

The centrifugal inertia force causes a high speed limit for hydrostatic thrust bearings. To compensate this effect, the spiral texturing of bearing surfaces is studied, and the applicability of streamlined bearing grooves [8] is examined. At present, these specially designed bearings are only employed for micro-manufacturing and aerostatic bearings.

4. RESEARCH RESULTS OF HYDROSTATIC JOURNAL BEARING

The number of publications about hydrostatic journal bearings is considerably lower than for thrust bearings, mainly due to the more complex bearing geometry. Most of the publications deal with the simulation of steady loads in bearings, with a smaller fraction of the description of dynamic behaviour, and the combination of journal-thrust bearings.

The utilizing of hydrostatic journal bearings is greatly influenced by their speed limitations. In the case of compressible liquids, the damping capabilities of the journal bearing decreases at low speeds, while at high speeds whirl instability appears [9]. S. C Jain compared the various recess pressure control methods with an analytical solution. Based on the calculations, the maximum permissible bearing loads and stiffness can be achieved by regulating the diaphragm flow control valve *(Figure 3)*.

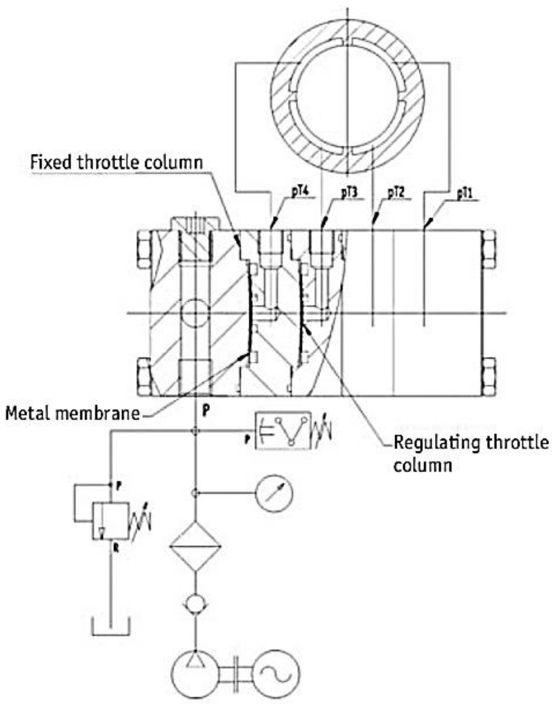

Figure 3. Hydraulic circuit diagram of the diaphragm constant flow valve (Hyprostatik)

Jerry C. T. Su and K. N. Lie [10] investigated hybrid *(hydrostatic/hydrodynamic)* bearing high-speed rotation phenomena. The rotation induces a hydrodynamic effect, the hydrostatic limit of the hydrostatic effect can be extended by several rows of grooved outlets, however, hydrodynamic stiffness deteriorates. The hydrodynamic effect can be improved by increasing the bearing length/diameter *(L/D)*. In the case of high speed operation, it is advisable to construct smaller outlets. S. C. Sharma [11] examined different recess patterns according to selected bearing parameters. The rectangular recess provides the highest loadability depending on the thickness of the oil film. However, the highest bearings stiffness could be achieved with circular recess shape. The triangular recess shape can be used to stabilize for high speed operation. Parallel with these results, experiments with magnetorheological fluids *(containing nano-sized magnetic particles)* have also begun.

5. CURRENT RESEARCHES ABOUT HYDROSTATIC GUIDEWAYS

Among the hydrostatic bearings, the production of hydrostatic guideways is the simplest one because of the design of a regular bearing recess. The main directions of current research are the study and simulation of the dynamic behaviour of hydrostatic guideways, and the research of motion error analysis and optimization possibilities. Much less research has been done in the past on hydrostatic guideways, since the Reynolds equation in the Descartes coordinate system is more difficult to simplify, which complicates analytical computation.

Yikang D. U. [12] investigated the dynamic properties of the hydrostatic guideway systems, considering the fluid compressibility and inertia force, and based on the results, the Maxwell Dynamic Model can be used for liquid lubrication.

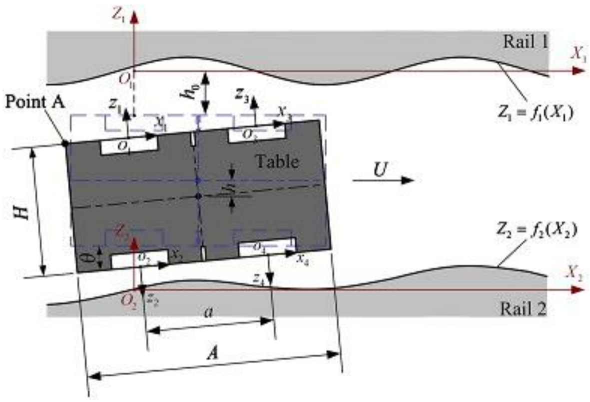

Figure 4. Theoretical model for determining the motion error of the hydrostatic guide [13]

Zhiwei Wang [13] created a new model for determining the motion of the hydrostatic guides *(Figure 4)*. The speed of the table also affects the motion flaw, and by increasing the feed pressure this effect can be reduced. By increasing the thickness of the liquid film, the movement error can be improved.

6. SUMMARY

The following article summarizes the major scientific publications on various hydrostatic bearings. Most publications still be based on the Reynolds equation that can be used to analyse liquid film on the surface of different types of bearings with good efficiency and accuracy but can only provide an approximate result for describing the flow in the bearing recesses. With the appearance of non-Newtonian fluids, the Reynolds equation also needs to be modified to handle changes in its dynamic viscosity.

The simplified analytical solution is computationally developed by numerical calculations. New, more accurate calculation models are laid down, which increasingly consider the relationship between bearing parameters. Due to the shortening of the calculation times and the increase in the calculation accuracy, simulations based on finite differential and finite element methods can be created within the CFD system.

The pressure regulation of the hydrostatic bearing recess can be accomplished by means of a capillary, orifice or a diaphragm flow control valve, with the latter being attained the highest loadability and stiffness at present. Although with the hydrostatic bearing self-regulating system *(servo valves)*, it would be possible to achieve a constant, directly controlled pressure without pressure control elements. Magnetic rheological fluids could also be used to internal regulate by increasing bearing capacity.

Numerous researches deal with the optimization of the shape of the bearing plains and the recesses. The spiral grooves or streamlined bearing recesses are currently present only at hydrostatic thrust bearings. With CFD simulations, the recess shape can be optimized for hydrostatic journal bearings. With new optimization methods, bearing design and dimensioning can also be improved.

Employing hydrostatic guideway systems and bearings in Europe are increasingly peripheral and new research results are still expected from the Far East.

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