



Conference Article

Design Model and Analysis of a Hydrostatic Bearing for Hydraulic Rotary Actuators

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Abstract

Hydraulic rotary actuators are actuators that enable the piston, which is moved linearly by hydraulic fluid, to rotate the shaft to which it is connected through an involute gear system inside and outside, between certain angles. In this study, hydrostatic bearing that use a fluid film for load support and movement precision in rotary actuators is implemented in place of standard bearing. These bearings work on the principle of hydrostatic lubrication, in which oil is pressurized and used to separate the surfaces from each other. In this way, it minimizes friction and wear, increases the efficiency and life time of the machine in which it is used. This article provides a brief overview of Hydrostatic bearing systems and hydrostatic bearing brake system and focuses on our work at HKTm on the application of these systems in rotary actuator.

Mathematical modeling, flow analysis and structural design have been carried out in this study. By mathematical modelling, design parameters of the hydrostatic bearing under a determined load, such as film thickness, land length, orifice diameter of capillary restrictor, and operating



parameters such as supply pressure, pad pressures, stiffness and flow rate have also been determined. Flow analyses have been performed to verify the fluid flow in the hydrostatic bearing and the required pressure within the bearing. This paper provides a detailed description of our research findings and conclusions.

Keywords: Hydraulic, Rotary, Actuator, Hydrostatic, Bearing, Brake

1. Introduction

Hydrostatic bearings are special bearings used in industrial machines and provide bearing with the help of hydraulic fluid pressure. Hydrostatic bearings absorb vibration and have low friction at high speeds. In this way, they help systems heat up less and operate more comfortably. They also enable high weight carrying and precise control. These bearings are mostly used in hydraulic machines, aviation, rail transportation vehicles and maritime. Other advantages of hydrostatic bearings are that even at zero speed, there is a load-bearing oil layer between the surfaces thanks to the hydrostatic bearing, and since there is continuous oil circulation in the system, heating of the bearing is prevented. As with every system, hydrostatic bearings have disadvantages. First of all, since the system is fed with externally pressurized hydraulic fluid, there is a need for a hydraulic pressurization system that must operate continuously, which increases the cost of idle operation of the system. Another disadvantage is that since hydrostatic bearings are not standard products, a special design must be made for the system and the system must have oil inlet and outlet holes suitable for the hydrostatic bearing. This increases the initial installation cost of the system.

As HKTM, the design, analysis, testing and integration studies of the hydrostatic bearing we developed for use in the Rotary actuators in our company's product catalogue were carried out within our company with the support of TUBITAK within the scope of the TUBITAK TEYDEB 1501 program number 3200574, Development of Innovative Hydrostatic Bearing and Hydraulic Rotary Actuator with Brake System project. Within the scope of these studies, first concept and literature research studies were carried out. Following concept and literature studies, a mathematical model was created to determine the necessary dimensions for the design of the hydrostatic bearing. The measurements determined through the mathematical model were used as preliminary design parameters and design studies were carried out using computer programs. Validation studies were carried out on the preliminary design through computational fluid dynamics (CFD) analysis. With the information obtained from the analysis results, the necessary arrangements were made and the manufacturing and testing process of the



hydrostatic bearing was started. Design changes were made on the data obtained as a result of the tests, CFD analyses were performed again, and this process was repeated until the final product was created.

In parallel with the hydrostatic bearing testing and verification studies, hydrostatic bearing studies with brake system were carried out within the scope of the same project. By utilizing the experience and data obtained during the development of standard hydrostatic bearings, studies were carried out to develop hydrostatic bearings with brake systems for rotary actuators. In this context, design and analysis studies have been carried out, the first product manufacturing has been completed and testing studies are continuing. A patent application has also been made for the relevant product within the scope of protection of intellectual property rights.

In addition, during the literature review of the hydrostatic bearing development project, some scientific articles were used to determine design parameters and create a mathematical model. Design of a low cost hydrostatic bearing (Wong Anthony R., 2012), A review of hydrostatic bearing system: researches and applications (Liu et al., 2017), Analysis of static and dynamic load on hydrostatic bearing with variable viscosity and pressure (Srinivasan V., 2013), Modeling and control of hydraulic rotary actuators (Hera et al., 2009). In all of these articles, points to be considered in hydrostatic bearing design parameters and innovative perspectives are explained.

In our article, the design parameters and working principles of standard hydrostatic bearings and hydrostatic bearings with brake system will be explained. We will also support our article with the data we obtained as a result of CFD analyses.

2. Materials and Methods

In a hydrostatic bearing, two surfaces are separated from each other by a high-pressure fluid film between them. They are also described as "external pressure bearing" because the pressure is generated by an external pump.

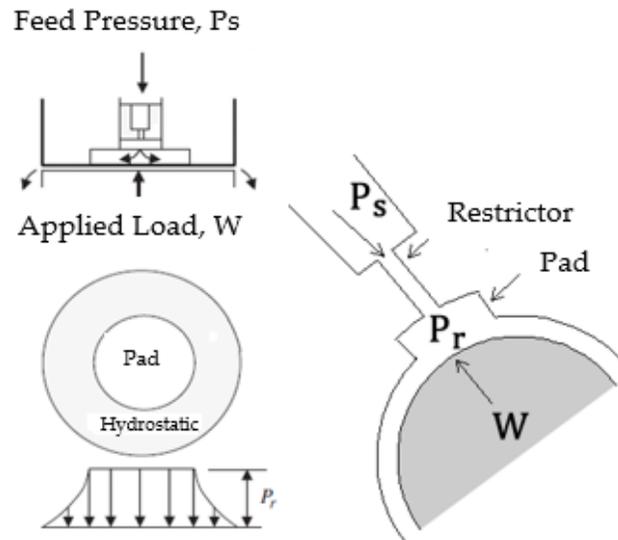


Figure 1. Hydrostatic bearing with a restrictor control

In the working principle of the hydrostatic bearing, the fluid is pumped towards the bed with a constant supply pressure " P_s ". Then, due to its working principle, it passes through the restrictor hole to provide pressure drop before the hydrostatic bearing pad. The oil pressure in the bearing pad is " P_r ". The thickness of the bearing pad is greater than the oil thickness that will form between the shaft and the bearing, and the pressure on the pad is considered constant. The thin oil layer formed in the hydrostatic bearing resists the applied load and ensures the separation of the surfaces from each other, thus forming bearing. One of the basic rules for the formation of bedding in a hydrostatic bearing is that the inlet pressure is always higher than the pad pressure, that is, it must be $P_s > P_r$. Advantages of hydrostatic bearing over other bearing types.

- Hydrostatic bearings do not experience wear as the pressure is released before starting and ensures complete physical separation of the bearing surfaces.
- Hydrostatic bearings have the ability to operate at zero speed and high speed.
- Besides the advantages of low starting torque, high positional accuracy, good dynamic stability and cold running, material selection is generally less critical than most other bearing types.
- Hydrostatic bearings can be used successfully for many years in large and low-speed machines that require high load support and low friction to achieve high precision in positioning.



In the process of developing hydrostatic bearings for rotary actuators, we benefited from some articles and papers. In the first of these articles, Patil examined the use of hydrostatic bearings for actuators in their study and carried out geometric optimization in the system to allow the highest load capacity in the mathematical model they developed (Patil et al., 2018). In another article, Yuan introduced the principle of using a spherical hydrostatic bearing in rotary forging presses. They stated that they have advantages such as greater rigidity, longer service life and easier valve selection compared to traditional hydrostatic bearings. The main design parameters were indentation area, pressure ratio (Yuan et al., 1997). In another article, Xu investigated the effects of liquid film thickness on the force supported by the hydrostatic bearing using computational fluid dynamics simulation and verification experiments. Experimental results show that the practical resistance of the rotor can be well reflected by the changing trend of the experimental rotor speed at the operating pressure from 0.1 MPa to 6.0 MPa, and is incompatible with the theoretical resistance calculated using simulation results. Simulation results showed that the resultant force increased linearly with increasing both the working pressure and the thickness difference between the upper and lower fluid films (Xu et al., 2016). In another article used during the project process, Kowalski and Tadeusz developed a formulation to obtain the pressure in the variable narrow bed gap of a hydrostatic thrust bearing with a rotating upper wall, on the basis of the Navier-Stokes equations and the continuity equation. They also analysed the influence of geometric parameters and usage conditions on the distribution of environmental pressure around the smallest height of the cavity (Kowalski and Tadeusz, 2014).

2.1. Determining Design Parameters

After literature research, our project continued with the analytical calculation of geometric parameters for the design.

Hydrostatic bearings are divided into single pad beds and mutual pad beds. For single pad bearings the film thickness depends on the applied load and can therefore be considered self-adjusting. This means that the supply pressure or pad size can be adjusted to achieve the optimum pressure ratio for any applied load. For opposing pads, bearing clearances and tolerances must be specified. In all cases, the design procedures consist of two main parts: first, the design of restrictors for flow-based flow control and, finally, the design of the bearing geometry for flow and stiffness.

After determining the type of bed to be used in hydrostatic bearing design, the parameters of the system in which the hydrostatic bearing will be used are determined. Payload, size and speed. Then, the parameters to be calculated and selected in the bed

design are determined. For example, the maximum flow rate to the bed according to the pump power and flow rate. After the parameters are determined, the design phase begins.

The ratio between pad pressure and restrictor pressure in hydrostatic bearings is generally 0.5, which is generally the optimum value for hydrostatic bearings and design parameters are optimized to approach this ratio because this value allows the maximum load range. For this ratio, a bearing clearance tolerance range can be selected in fixed resistance limiters. This provides a pressure ratio of 0.4 to 0.7 when the maximum and minimum clearance limits are in the ratio 1.5:1. The choice of these tolerances means that restrictors manufactured to produce a maximum pressure ratio at minimum clearance will subsequently result in a minimum pressure ratio at maximum clearance.

First, let's start with the process of calculating the flow rate, diameter and pressure of the restrictor channel.

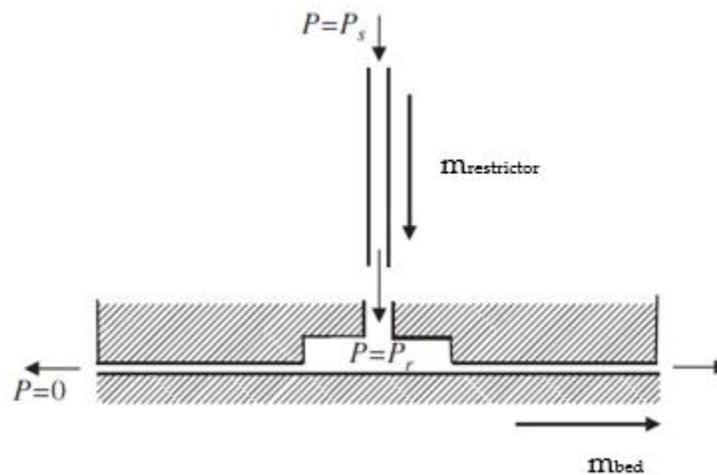


Figure 2: Circular pad mattress with restrictor

Flow through bed areas can be calculated using a specific pad pressure (P_r). Pad pressure can be calculated by applying the mass-flow continuity condition.

$$\dot{m}_{restrictor} = \dot{m}_{pad} \quad (1)$$

The flow rate in a capillary channel restrictor is;

$$q = \frac{(P_s - P_r) \pi d_c^4}{128 \eta l_c} \quad (2)$$

where " l_c " is the length of the capillary channel and " d_c " is the diameter of the capillary channel, if possible the ratio " $\frac{l_c}{d_c}$ " should be greater than 100. For laminar flow, the Re number should be less than 2000.

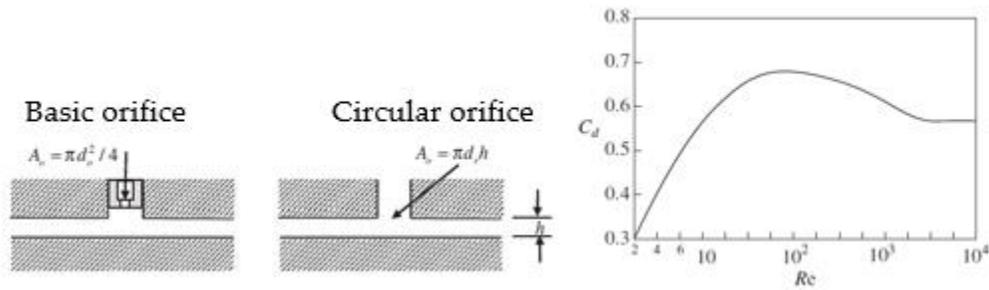


Figure 3: a. Cross-sectional area in Basic and circular orifice b. Variation of c_d coefficient with Re for liquid flows

If it is a restrictive orifice, the flow rate is;

$$q = c_d A_0 \sqrt{\frac{2(P_s - P_r)}{\rho}} \quad (3)$$

From equality;

$$q_{in} = q_{out} \quad (4)$$

Figure 4 is a schematic diagram showing flow through an orifice. On the left, an arrow labeled $q_{in} = c_d A_0 \sqrt{\frac{2(p_s - p_r)}{\rho}}$ points into the orifice. On the right, an arrow labeled $q_{out} = \frac{P_r \pi h^3}{6\mu \ln(R_2/R_1)}$ points out of the orifice.

Figure 4: Flow mass equality law schematic

$$P_r = \frac{\sqrt{1 + 4P_s K_0 \left[\frac{Bh^3}{\eta} \right]^2} - 1}{2K_0 \left[\frac{Bh^3}{\eta} \right]^2} \quad (4)$$

Here, $K_0 = \rho / [2(c_d A_0)^2]$ is the orifice coefficient.

3. Result and Discussion

Before geometric design, design parameters were determined and calculated. According to this, the load, feed pressure, pad pressure, flow rate, rigidity, required power, temperature change and viscosity of the hydraulic oil values of this hydrostatic bearing are calculated or selected as in the table below.

Table 1: Calculated and defined values for geometric design

W (N)	8137.25
P_s (bar)	89.42
P_r (bar)	62.594
q (m ³ /h)	1.127



q_n (m ³ /h)	0.188
λ (MN/m)	187.48
H_p (W)	2798.60
H_r (W)	48.89
ΔT (°C)	5.50
η (Pas)	0.0400

After determining the restrictive measures analytically, a verification study is carried out with CFD analysis of the design and the mathematical model accuracy is measured by comparing the analysis results with the analytical results. If it is necessary to make changes to the bearing geometry as a result of the analyses, geometric verification must be made with re-analysis studies after the changes made.

Our main goal in the CFD analysis, the results of which are given below, is to determine the inlet and outlet hole diameters of the restrictor and the flow rate that should occur accordingly.

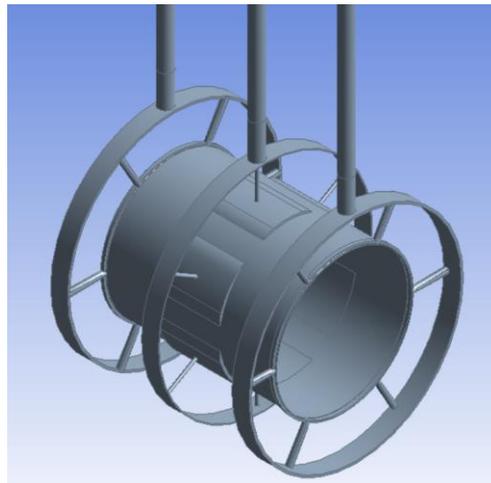


Figure 5: Hydrostatic bearing flow volume

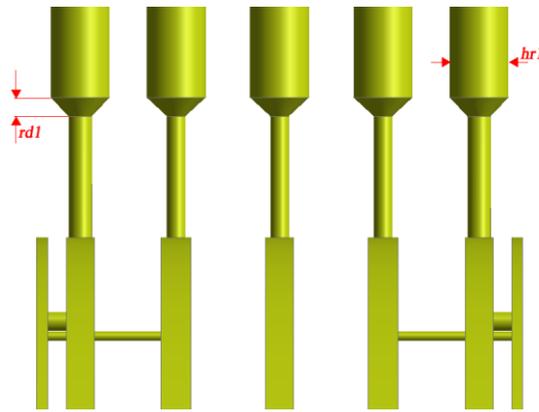


Figure 6: Hydrostatic bearing restrictor inlet and outlet dimensions

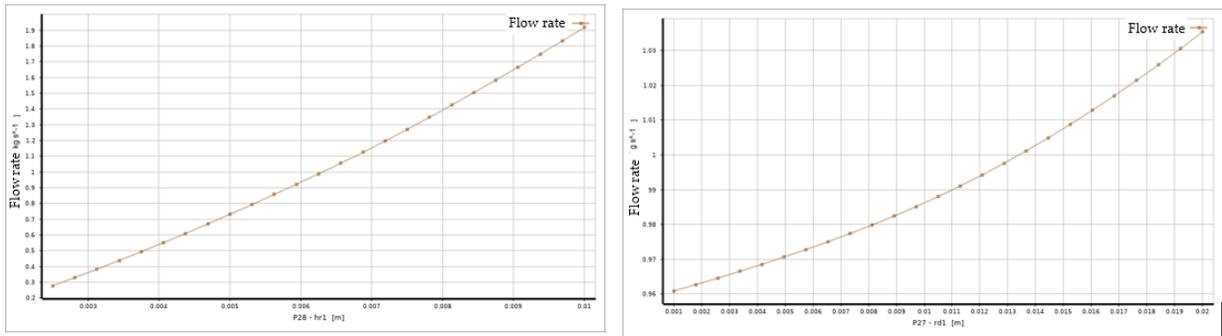


Figure 7: Flow rate vs restrictor inlet diameter graph

The flow rate increases with the increase of both rd1 and hr1 parameters.

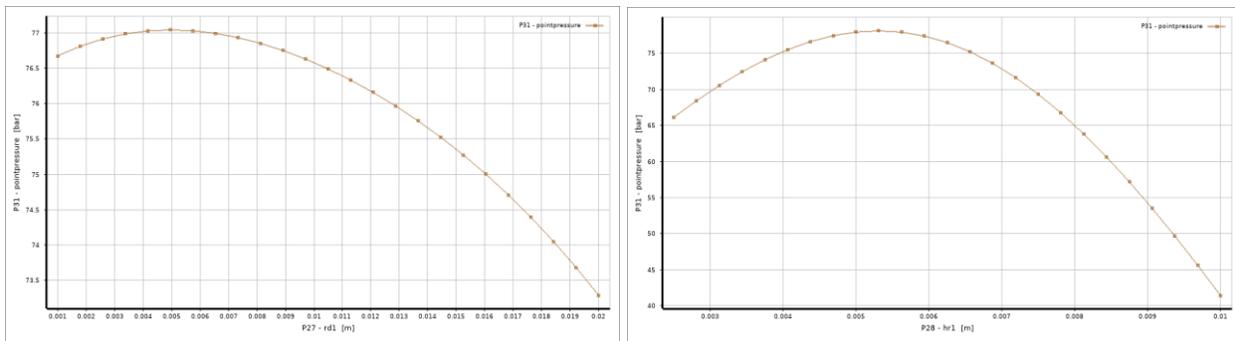


Figure 8: Point pressure vs restrictor outlet diameter graph

As the Rd1 and hr1 parameters increase up to a certain value, the pressure on the radial bearing increases, while at larger values the pressure decreases.

The optimal values for maximum flow rate and bed pressure are as follows.

Table 2: Optimal values for maximum flow rate and bed pressure

Variables	Values
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Rd1(m)	0.0086191
Hr1(m)	0.0078025
Flow rate($\frac{m^3}{h}$)	1.3335
Bed pressure (bar)	67.2

Hydrostatic bearing design was completed and manufactured using the optimal values obtained as a result of CFD analysis and specified in Table 2. After the manufacturing process, hydrostatic bearing verification tests were carried out and our hydrostatic bearing, which we developed for Rotary actuators, showed operating characteristics similar to the bearing rotary actuator.

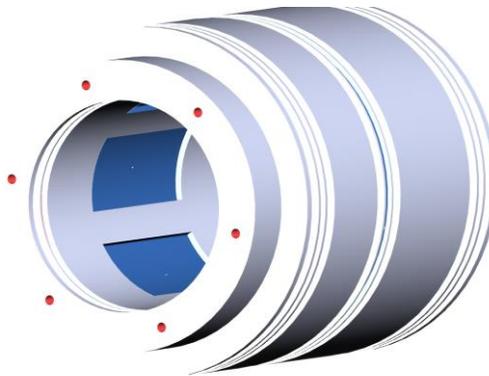


Figure 9: Final Hydrostatic bearing design

As a result of the data we obtained from the hydrostatic bearing development studies, our process of developing a hydrostatic bearing with brake system for rotary actuators has started. In this process, the parameters required for the hydrostatic bearing with brake system, which will work on the same system as the standard hydrostatic bearing, were used exactly the same as the standard hydrostatic bearing. In our study of developing a hydrostatic bearing with braking system for a rotary actuator, we first calculated the braking force required to brake the torque of the rotary actuator by using the remaining surface area on the inner surface of the hydrostatic bearing and selected the material that could reach this force.

Braking torque;

$$M_B = \mu F_N R \tag{5}$$

- F_N = Force from pads (N)
- R = Shaft radius (m)
- μ = Friction force



It is calculated as follows. The force required to provide braking is;

$$F_N = \frac{M_B}{\mu R}$$

can be calculated as . The table below includes the required force calculations for the brake.

Table 3: Calculates the force required for braking according to different friction forces

Shaft material	Brake material	Friction coefficient	Required brake force
Steel	Bronze	0.16	46153 N
Steel	Cast Iron	0.21	35164 N
Steel	Titanium	0.3	24615 N
Steel	Steel	0.19	38866 N

Table 4: Brake system material analysis

Brake material	Maximum total deformation	Minimum safety factor
Composite	0.084	1.9
Aluminum alloy	0.050	1.11
Bronze,C51000	0.038	1.98
Bronze,C37700	0.040	1.44
Copper,C10100 hard	0.035	0.98
Stainless steel,316	0.026	0.95
Titanium	0.038	3.30

The above analysis was done to determine the material in the first place using the 6.7 mm draft brake system design. When we consider the safety coefficient in the analysis, we see that Composite, Bronze and Titanium provide the desired values, but considering the braking moment calculation and manufacturability in table 3, it is seen that the Titanium structure is suitable.

Table 5: Brake system thickness analysis results

Thickness (mm)	Maximum total deformation	Minimum safety factor
2	0.078	1.42
2.4	0.056	1.81



2.6	0.049	1.99
2.8	0.044	2.19
3	0.039	2.36
3.5	0.031	2.87
4	0.026	3.38

The design was made using titanium material, the thickness was selected as a parameter, and thus analysis was performed at different thicknesses. The changes in diameter and safety coefficient according to thickness were examined. The amount of torque produced by the rotary actuator depends on the desired safety. When we calculate the tight fit between the brake and the shaft required for braking according to the coefficient, it appears that there should be an expansion of 0.034 mm. In order to provide hydrostatic bearing beyond the width of 0.03 mm, an additional expansion of 0.025 mm is required. In this case, the minimum width must be 0.055 mm. Considering the data in Table 5 and the required minimum expansion calculation. The 3 mm thick hydrostatic bearing brake system is analyzed as a whole and the expansion amounts obtained in the radius by applying 100 bar, 150 bar and 200 bar pressure are shown in the analysis.

When 100 bar pressure is applied, we can say that there is an expansion of 56 microns in the radius at the widest place, with an average expansion of 45 microns. When 150 bar pressure is applied, we can say that there is an expansion of 72 microns in the radius at the widest location, with an average expansion of 65 microns. When 200 bar pressure is applied, we can say that there is an expansion of 91 microns in the radius at the widest point, and an average expansion of 80 microns. The material of the brake system must be titanium alloy (Ti-6Al-4V). In addition, according to the analysis results, the wall thickness of the brake system is 3 mm, which is the most appropriate in terms of safety factor and expansion amount.

4. Conclusion

As a result, by using the data obtained as a result of the preliminary design study we made using the information in the literature the calculation and analysis of the required contact area are examined to us, bed recess form and dimension. Data that we obtained are used in the design. The study aimed to determine the most appropriate hydrostatic bearing form and size while ensuring the structural integrity and strength of the bearing.

5. Acknowledge



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References

- [1] Wong, A. R. (2012). Design of a low cost hydrostatic bearing (thesis).
- [2] Liu, Z., Wang, Y., Cai, L., Zhao, Y., Cheng, Q., & Dong, X. (2017). A review of hydrostatic bearing system: Researches and applications. *Advances in Mechanical Engineering*, 9(10), 168781401773053. <https://doi.org/10.1177/1687814017730536>
- [3] Srinivasan, V. (2013). Analysis of static and dynamic load on hydrostatic bearing with variable viscosity and pressure. *Indian Journal of Science and Technology*, 6(sp6), 1–6. <https://doi.org/10.17485/ijst/2013/v6isp6.11>
- [4] La Hera, P. M., Mettin, U., Westerberg, S., & Shiriaev, A. S. (2009). Modeling and control of hydraulic rotary actuators used in forestry cranes. 2009 IEEE International Conference on Robotics and Automation. <https://doi.org/10.1109/robot.2009.5152522>
- [5] Patil, Sumit, et al. "Design of self-compensating hydrostatic bearing for actuators." *Proceedings of TRIBOINDIA-2018 An International Conference on Tribology*. 2018.
- [6] Yuan, Shijian, and Decheng Zhou. "Design procedure of an advanced spherical hydrostatic bearing used in rotary forging presses." *International Journal of Machine Tools and Manufacture* 37.5 (1997): 649-656.
- [7] Xu, Enle, et al. "Investigations on the applicability of hydrostatic bearing technology in a rotary energy recovery device through CFD simulation and validating experiment." *Desalination* 383 (2016): 60-67.
- [8] Kowalski, Konrad, and Tadeusz Zloto. "An analysis of pressure distribution in water and water emulsion in a front gap of a hydrostatic bearing." *Teka Komisji Motoryzacji i Energetyki Rolnictwa* 14.4 (2014).