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Optimization of the Cylinder Block-Valve Plate Interface Considering Coupled Interaction from Piston Dynamics and Shaft Deformation

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Abstract
Cylinder Block/Valve Plate interface ideally operates with a thin fluid film separating the running surface, preventing contact and wear. At the same time, the film seals the interface, preventing leakage of high-pressure fluid in the displacement chamber. This thin film is maintained by balancing the hydrodynamic/hydrostatic pressure distribution with the external loads applied on the cylinder block. Extending the operating speeds and pressure of the pump can disrupt this balance, preventing the interface from sealing effectively, or generating wear that causes early failure of the machine. The factors limiting the operational range are therefore coupled physical phenomena, where the performance of the piston/cylinder block interface or the shaft-cylinder block spline connection may lead to the failure of the cylinder block/valve plate interface. Current state-of-the-art simulation tools focus on individual lubricating interfaces, which is not sufficient to accurately model physical behavior for finding the operational limits of the cylinder block/valve plate interface at extended operating conditions.
This paper proposes a coupled simulation method for the cylinder block/valve plate interface that includes consideration of the physical behavior at other lubricating interfaces. The paper presents simulation results when the cylinder block/valve plate interfaces is coupled with the piston/cylinder block interface and the shaft spline interface and demonstrates the significant difference in simulation results between the proposed coupled simulation method and the standalone simulations. Furthermore, the paper includes experimental test observations that validate the findings from the coupled model simulation. The coupled simulation is then used to find optimized designs for extended operating conditions, at higher pressures and higher speeds. The paper reports experimental results with the optimized design prototypes, which demonstrate performance improvement.

Keywords. Axial Piston Pump, Tribology, Lubricating Interface, Design Optimization

1. INTRODUCTION

Axial Piston Machines (APM) are among the most widely used hydrostatic pumps and motors. They are known for their ability to provide varying displacements, as well as high efficiency even at high operating speeds and pressures. Current trends in applications of hydraulic pumps and motors show continued demand for an increase in performance capabilities as well as longer operational lifespans. Therefore, it is important to understand the behavior of APM when pushed to the limits of the operational window, to find the physical factors restricting performance, and to develop design solutions for further improvement of the machine's operation.

The cylinder block/valve plate interface is critical to the performance of an axial piston machine. The valve plate is responsible for regulating flow through the machine, and the design allows control over several key behaviors such as the flow ripple and noise generated during operation [1]. The lubricating film at this interface also regulates the leakage from the pressure ports, as well as providing hydrodynamic balancing against the loads acting on the cylinder block. Studies like Manring [2] have shown that improving the design of this interface could therefore address several issues affecting machine behavior at extremes of the operational range and improve overall performance. However, the far-reaching impact of valve plate design also increases the complexity of the design process.

Simulation models enhance the process of designing axial piston machines, reducing the need for expensive and time-consuming experimental runs, which can now be restricted to validating the final designs. Thanks to the simulation models, various design features can be parameterized and used in conjunction with optimization algorithms to generate several iterations of highly tuned efficient designs.

The lubricating interface performance of axial piston machines depends on interactive physical phenomena such as hydrodynamics, thermodynamics, heat transfer, elastic deformation due to pressure and thermal load, the micro motion of the moving parts, and fluid and solid properties. Various simulation methods have been developed targeting different aspects of this complex system.

Given the complex nature of flow within an axial piston machine, a full-scale CFD model would be particularly useful in understanding the flow behavior. Frosina et al. [3] demonstrated the use of commercial CFD models to predict flow behavior in axial piston pumps with complex design features to reduce flow ripple. Boland and Shang [4] used an axial piston pump model implemented using the CFD tool Simerics MP+ to study cavitation behavior and its scalability. CFD models can provide very detailed fluid behavior and can be very useful for studying the fluid dynamics within the pump. However, using a full-scale CFD model is computationally expensive. Ignoring or simplifying the fluid flow behavior at the lubricating interfaces can speed up the simulation but can ignore crucial flow behavior at these interfaces which can affect the accuracy of the results. Additionally, CFD approaches are restricted to fluid flow behavior, and often do not provide any further understanding on the dynamics of the solid components themselves.

Lumped parameter modelling approach is also widely used for positive displacement machines. This approach greatly reduces the computational cost of predicting flow behavior by considering the fluid volumes inside the machine as several lumped volumes, ignoring any spatial variation of fluid properties and any flow within the volume. Roccatello et al. [5] developed such a model for simulating axial piston machines and demonstrated its use in predicting pump characteristics like flow ripple and torque. Corvaglia et al [6] compared Lumped Parameter simulations to results provided by a full–scale 3D CFD model and found a good agreement between them. Lumped models are simple to develop and can provide quick results for a large variety of pump designs, compared to the speed of CFD models. They can also be used in conjunction with dynamic models to understand the motion of solid components within the machine. But the lumped volume assumption means there is no way to model detailed fluid behavior, particularly at the lubricating film interfaces.

Hasko et al [7] showed that film interfaces are a major contributor to power loss in an axial piston machine. Therefore, a representative numerical model should be able to include the effects of lubricating films. A fluid structure interaction model for the cylinder block -valve plate interface was introduced by Zecchi and Ivantysynova [8], and for the piston-cylinder block interface by Pelosi and Ivantysynova [9]. These models involved coupling the lumped parameter model with a fluid simulation for the lubricating interfaces and demonstrated the improvement in modelling pump behavior without excessive computational cost. A tribological cylinder block/valve plate interface model was developed at IFAS and used to optimize the design geometry of the interface [10] to reduce wear due to fluid and solid friction. The benefits of detailed film modelling in developing new designs were demonstrated by Geffroy et al. [11] and the model was further validated experimentally in [12] A numerical lubricating film model was also used by Li et al. [13] to study wear characteristics at the cylinder block/valve plate interface under different operating conditions. More recently, Han et al. [14] used a cylinder block/valve plate lubricating film model to study the effects of hydrostatic pockets in reducing solid body contact in a floating piston pump.

It is clear that simulating the cylinder block/valve plate lubricating film interface would be useful in understanding how the interface performs in extreme operating conditions. However, isolated simulation models do not accurately capture the behavior of APMs. For example, the behavior at the cylinder block/valve plate interface would be affected by the forces created by the lubricating film along the piston interface. While analytical assumptions can be made for specific test cases, a general use simulation model should be able to model this coupled interaction accurately. Ransegnola developed a coupled model for an axial piston machine and used it to study the piston and slipper spin [15]. This model was able to extend methods previously used for singular lubricating interfaces, and couple them with a lumped parameter model for fluid volumes and a solid dynamics solver that resulted in a highly accurate simulation model of the entire axial piston machine assembly. Mukherjee et al. demonstrated the benefits of a coupled modelling approach by showing an improvement in estimation of power losses at lubricating interfaces with the new approach [16]. Gärtner et al. [17] developed and compared coupled models for the piston/cylinder interface, to better include the effects of the slipper/swashplate film and the slipper-piston ball joint dynamics. Coupling of multiple interfaces creates a more accurate model for the complex interactions in the APM and ensures better accuracy in studying the behavior of the cylinder block/valve plate interface.

The goal of this work is to extend the operational limits of axial piston machines through improved design of the cylinder block – distributor plate interface. The paper describes the physical behavior of the interface in extreme conditions such as high speeds and high pressures. A novel numerical modelling approach is proposed to simulate this behavior, addressing the limitations of previous numerical modelling methods for axial piston machines. Experimental validation of the improved model is done with two test cases, where the model is used to better understand the limiting factors of the interface design, and to test design changes addressing the limitations.

2. THE CYLINDER BLOCK/VALVE PLATE INTERFACE

The interface between the cylinder block and the valve plate serves three primary functions: to reduce friction between the stationary control plate and the rotating section of the APM, to for an effective seal preventing fluid from the high-pressure ports leaking out, and to provide hydrodynamic balancing for the forces and moments acting on the cylinder block

[1]. Since the film thickness distribution is primarily affected by the pressure load. the running surfaces of the cylinder block and the valve plate need to be carefully designed to ensure the lubricant film layer can sufficiently balance the load on the cylinder block. An ill-designed surface can disrupt the functioning of the film and affect its other functions.

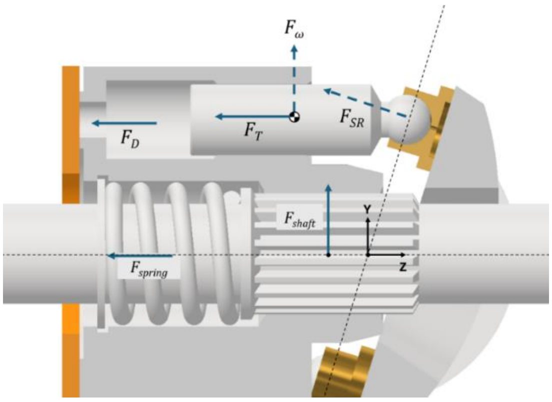

Figure 2.1. Overview of Cylinder Block Forces

Simulation models for use in understanding the behavior of the valve plate interface need to accurately include the effects of the forces and moments acting on the cylinder block. There are two main types of forces acting on the cylinder block [8,18]: forces that are directly applied on the cylinder block and reaction forces from other components transmitted through lubricating films. Figure 2.1 shows the locations where these forces are applied on the cylinder block. The direct forces are shown with dark arrows and the forces applied through film are shown in dashed arrows

Studies like Geffroy et al. [10] have shown that a numerical model of the forces on the cylinder block can be used to calculate the gap height distribution at the valve plate interface. While state of the art models can accurately include most forces, there are some factors which represent a challenge. The friction force acting on the cylinder block is a result of the lubricating interface between the block bore and moving piston surface. The friction includes both viscous losses generated by the fluid, and solid-solid friction when the surfaces are in contact with each other. Since these forces are primarily a result of lubricating film behavior, the best way to accurately calculate these forces is by simulating the films at each of the interfaces between the pistons and the cylinder block. Additionally, to properly simulate complex interactions, these film models would need to be coupled with the numerical model of the valve plate interface. This adds a high level of complexity for the model.

Another important factor governing the overall moment acting on the cylinder block is the shaft reaction force. The forces acting on the cylinder block perpendicular to the shaft axis are balanced by a reaction force provided by the shaft itself. This reaction force acts on the cylinder block on the region where it is in contact with the shaft, known as the crowning region. The location of the crowning region is important, as it determines the moment generated by the shaft reaction force on the cylinder block. The crowning region is defined by a characteristic curve added to the spline of the shaft, the peak of this curve considered as the center where the shaft would be in contact with the cylinder block, and the point where the transmission of forces and torque occurs.

The surfaces of the cylinder block and shaft in contact here can deform, as a result of the large forces acting on the cylinder block. This deformation increases if the axial piston machine is functioning at the limits of its operational range. The deformation can affect the nature of contact between the two surfaces. Figure 2.2 illustrates the effect that such deformation can have on the location of the crowning point.

Figure 2.2. Shaft Contact Behavior due to deformation

To understand better the exact behavior of contact between the shaft and the cylinder block considering deformation, a finite-element method simulation was conducted. A representative model of the Axial Piston Machine was constructed, and the simulation was conducted using Ansys Mechanical. Studying the contact region under the loads applied on the cylinder block, it is observed that contact is indeed not restricted to a single point but is instead a long region along the edge of the area of contact on the shaft spline, as shown in Figure 2.3.

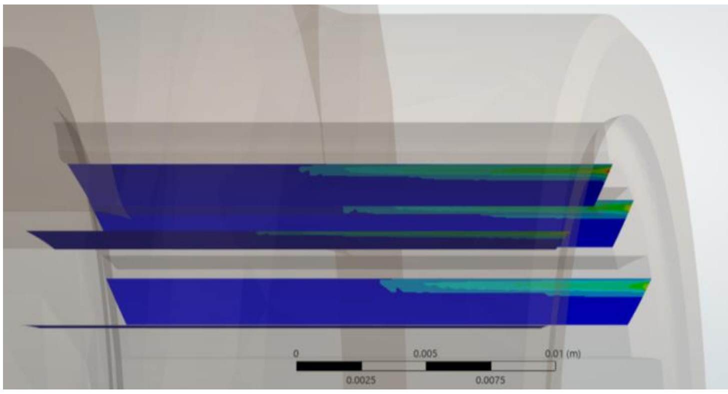

Figure 2.3. Shaft contact region from FEM Simulation

To calculate the contribution of shaft reaction moment on the block, and to accurately model the tilting of the cylinder block, it's important to define a single contact point. This point can be the center of the entire contact region, the ideal point at which the net contact force can be considered to be acting. To calculate this point, the net moment generated by the contact region on the cylinder block $\vec{M}$ is extracted from the Ansys model. Additionally, the contact pressure can be integrated with the contact area to calculate the net contact force $\vec{F_c}$. This contact force has two components, one contributing to the moment on the block, and the other countering the forces in the axial direction. To find the components of contact force normal to the moment $\vec{F}$, a simple vector calculation is performed, as described in equation 1.

$$\vec{F} = \vec{F_c} - \frac{\vec{F_c}.\vec{M}}{|\vec{M}|^2}\vec{M} \tag{1}$$

Using equations 2 and 3, the length of the normal moment arm $\vec{r}$ required by the contact force to generate the moment is calculated, which gives the location of the point at which the net contact force is acting. This is the ideal center of the contact region.

$$\vec{r} \times \vec{F} = \vec{M} \tag{2}$$

$$\vec{r}\,.\hat{F} = 0 \tag{3}$$

The inclusion of the effects of shaft deformation on the cylinder block moment, as well as the coupled modelling of piston films, represents the novelty of the modelling approach used in this study. As shown in the case studies in Section 4, the consideration of shaft deformation proves critical in the APM behavior at operational limits and ensure that design solutions proposed are indeed effective in improving performance.

3. SIMULATION MODEL

The primary goal of the simulation model for this study is to accurately capture the behavior of the cylinder block/valve plate interface. As described in section 2, the major factor affecting the behavior of this interface is the dynamics of the cylinder block, and the best way to accurately model this is using a coupled simulation model involving both the cylinder block/valve plate interface, and the piston/cylinder block interface. For this study, the lubricating interfaces are modeled using a modified version of the Reynolds equation [13], to include the effects of mixed lubrication and surface deformation, as shown in equation 4.

$$\nabla.\left(\phi_P \frac{Kh^3}{12\mu}\nabla\rho\right) = \nabla.\left(\rho v_m\left(\phi_R R_q + \phi_C h\right)\right) + \nabla.\left(\rho\frac{\phi_S}{2}R_q(v_t - v_b)\right) + \frac{\partial\rho\left(\phi_R R_q + \phi_C h\right)}{\partial t} \tag{4}$$

These modifications are necessary to account for the forces developed in the film due to varying flow regimes, and the effects of deformation on the gap height and the resulting balancing force produced by the film. To model the fluid chambers and hydraulic components like orifices, a lumped parameter fluid model is implemented to reduce computational cost. The kinematics of the various solid components in the APM are determined using a body dynamics solver.

To simulate the interaction between physical domains, the models are coupled with each other. This coupling is implemented through continuous information transfer between the models, simulating physical behavior in an APM. The lumped parameter and the solid body dynamics need to be solved with a much smaller timestep compared to the interface models, and forcing the interface model to be solved on this small timestep increases computational cost. So, the simulation is divided into independent timelines: one for each of the lubricating interfaces and one main timeline for the lumped parameter and body dynamics model. Information about the interface is interpolated between timesteps to be used by the lumped parameter and the body dynamics solver, ensuring continuous transfer of data between the models and improving the solution time.

The coupled model used in this study was built using Multics, a Multiphysics simulation tool developed by the Maha Fluid Power Research Center. Multics was first introduced by Ransegnola et al. [19] and used to perform a fully coupled simulation for external gear machines. It included multiple models for various physical features such as tooth space volumes, floating bodies and lubricating interfaces. It also introduced the asymmetric timeline method used to improve simulation times with coupled models. The tool was further used to develop a coupled Swashplate APM model to study piston – slipper spin [15]. The flexible structure of Multics also allows for the addition of new models, which allows new physics to be introduced for various positive displacement machines. Mukherjee et al. further developed the Swashplate APM model to include the effects of thermal behavior across various physical domains in [20].

The simulation model proposed in this paper uses Multics to develop a fully coupled model consisting of the Cylinder Block/Valve plate and Piston/Cylinder Block interfaces, with mixed lubrication and deformation considerations at the interfaces, along with floating body models for moving components and lumped parameter modelling for the chambers. Additional considerations are also made to include the effects of shaft deformation in the dynamics of the cylinder block. Figure 3.1 shows an overview of the proposed model.

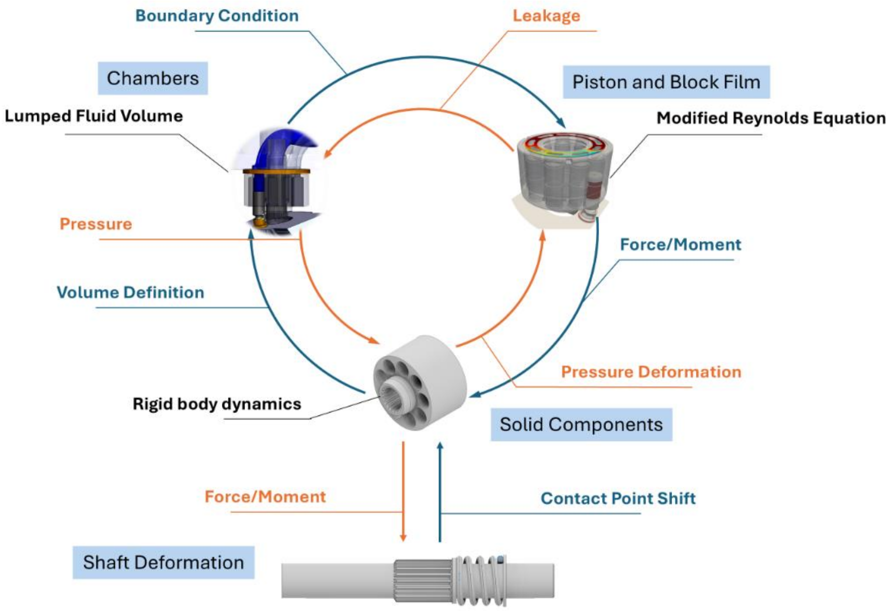

Figure 3.1. Overview of Swashplate APM Model

4. Validation and Case Studies

The proposed coupled model is used in simulating the behavior of the cylinder block/valve plate interface of an axial piston machine near operational limits. Two test cases considering two different kinds of limiting behavior at the extremes of the operational range were considered:

- The first case studies the factors that define the maximum pressure capability of the pump, beyond which wear begins to appear on the valve plate running surface
- The second case studies the maximum power of an axial piston motor, beyond which the cylinder block begins to separate from the valve plate

For the two cases, simulation results for the baseline designs are validated with observations from experimental tests. Further, the simulation results are analyzed to determine the underlying factors, and to test design changes aimed at improving performance at higher pressure and operating speeds. Finally, the design solutions are validated experimentally. Additionally, the benefits of the novel considerations in the simulation model are highlighted for each of the test cases.

4.1. Study of Valve plate Wear at High Pressure

The cylinder block/valve plate interface is designed to hydrostatically balance the loads acting on the cylinder block. The lubricating film at this interface has a gap height in the order of microns, making it sensitive to the deformation of the running surfaces. When the machine is operated at high pressures, the surfaces can be deformed from the nominal plane, where 'bump' (local reduction of the film thickness) increases the change for contact and wear, and 'dent' (local increase of the film thickness) increases the leakage. This study will focus on the wear, which is a critical factor that determines the maximum operation pressure of an axial piston machine. Contact pressure is used as a parameter to measure and compare the degree of wear between the baseline design and test cases.

4.1.1. Baseline Design Simulations

The coupled numerical model is used to analyze the baseline design. The model simulates both the piston/cylinder interface and the cylinder block/valve plate interface simultaneously, to ensure the frictional forces and moments generated by the relative motion between the piston and the cylinder block are included when calculating the moments acting on the cylinder block. As shown in Figure 4.1, the simulation results from the proposed model indicate two regions of contact on the outer edge of the interface with a maximum magnitude of 1700 bar. The two contact regions, combined with the high sliding velocity between the running surfaces of the interface results in wear on the valve plate. To validate the simulation results, the location of the contact is compared to the observed location of wear in the experimental tests. As seen in Figure 4.2[A], the valve plate has deep wear marks along the outer edge of inlet and outlet ports, which are the boundaries of the interface with the rotating cylinder block.

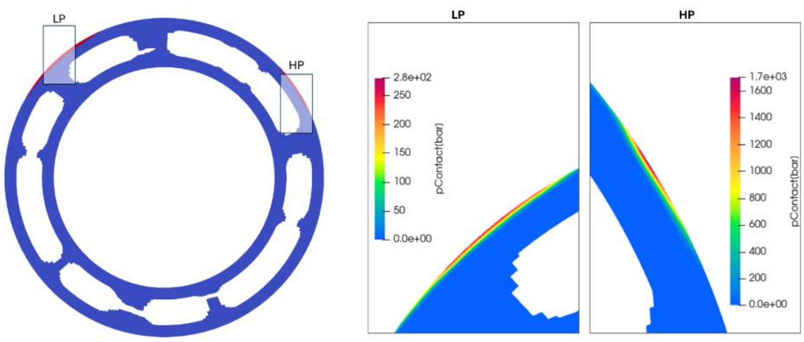

Figure 4.1. Contact Regions on Cylinder Block–Valve plate Interface.
HP and LP indicate areas of film connected to High-Pressure and Low-Pressure ports

[A] [B] [C]

Figure 4.2. Wear observed on valve plate after experimental tests. [A]: Baseline design, [B]: Improved Port Block, [C]: Increased Interface Area

Further investigation of the simulation results indicates that the contact pressure is a result of the combination of high tilting moments on the cylinder block under maximum pressure, the friction between the piston and bore, and the deformation of the solid bodies. Although the effect of the surface deformation of this interface was discussed in Chacon and Ivantysynova [21], the coupled simulation results indicated that the consideration of deformation alone is not sufficient to predict the contact pressure as well as the resulting wear. Figure 4.3 shows the results for the same design without considering the coupled effect from the piston–cylinder block interface. Therefore, the inclusion of the coupled model, despite the added complexity, ensures better representation of the pump's behavior at such extreme operation conditions. With the validation complete, further design solutions aimed at addressing the causes of wear are tested.

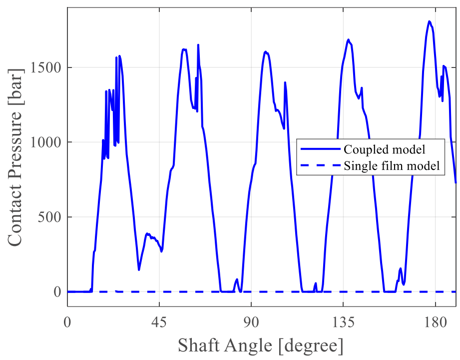

Figure 4.3. Comparison of Simulated Contact Pressure with Single Film Model

4.1.2. Design Improvements

The coupled simulation results indicated the causes of wear on the valve plate. Two design solutions were developed to reduce contact between the running surfaces.

A. Improved Port Block: The first design change was aimed at reducing the deformation of the valve plate surface by redesigning the port block. As shown in Figure 4.4, material added to the chamber walls increases support, which would reduce the deformation caused by the high-pressure fluid in the chamber. This results in lower deformation of the valve plate, reducing contact with the moving cylinder block.

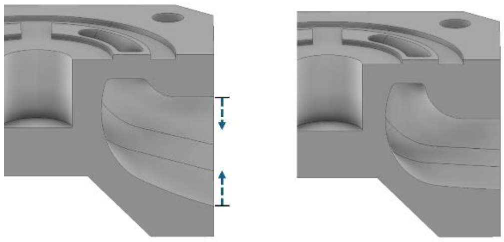

Figure 4.4. Illustration of Port Block design changes to reduce deformation

B. Increased Valve plate Interface Area: The second design change tested is increasing the sealing land area. The baseline design of the cylinder block/valve plate interface is insufficient to balance the large moments acting on the cylinder block at high operating pressures. Therefore, the interface area is increased by increasing the outer diameter and decreasing the inner diameter, as shown in Figure 4.5. This increased surface area can provide more moment balancing the cylinder block, therefore reducing the tilting and the resulting contact with the valve plate.

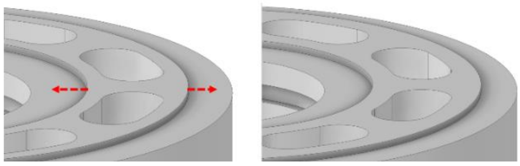

Figure 4.5. Illustration of valve plate interface area changes on Cylinder Block

4.1.3. Results

For the new port block design, simulation results indicate a reduction in maximum contact pressure, as seen in Figure 4.6.[A]. This result is validated by experimental tests for this design. As seen in Figure 4.2[B], the wear markings on the valve plate are still present, but the depth of wear is lower, showing a marginal improvement provided by the new port block.

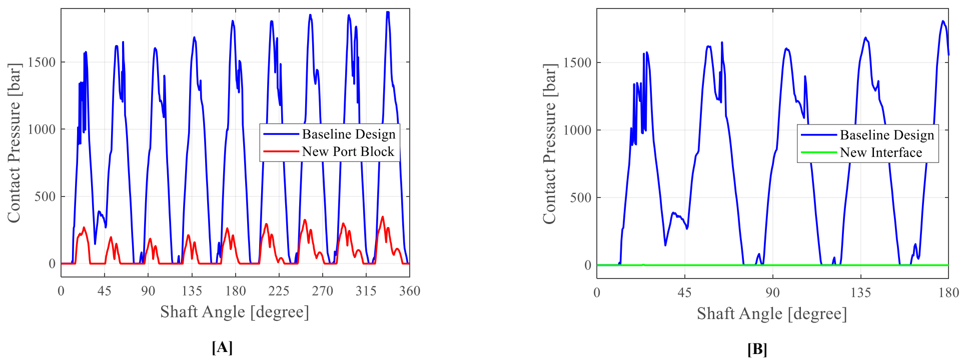

Figure 4.6. Comparison of Contact Pressure with new designs

Figure 4.6[B] shows the simulation results for the new valve plate interface design, with more film area. There is no contact observed, which shows that the cylinder block is sufficiently balanced by the new larger interface. Observing the results of the experimental tests with the new interface design in Figure 4.2[C], a significant reduction in wear is observed, matching the results of the coupled simulation model.

4.2. Study of Cylinder Block Separation at High Speeds

The hydrodynamic force in the lubricating film, the inertia force from the piston and the slipper, and the friction from the piston intensify with the increased piston machine speed. The combination of these effects tends to tilt the block, ultimately resulting in its separation from the valve plate. This failure mode can be observed as the sudden increase of drain flow rate, therefore the sudden increase of case pressure, as well as the sudden loss of high pressure when operating beyond the rated speed.

4.2.1. Baseline Design Simulations

Shaft with crowned spline is often used in piston machines to allow the block to tilt around a designed pivot point. As explained in Section 2, this pivot point may deviate from the shaft crowning point due to deformation. The proposed model considered the shift of the pivot location based on the FEM analysis. Coupled with the friction from the piston cylinder interface, this proposed model faithfully replicates the observation of the behavior of the cylinder block/valve plate interface in this case study. Those are:

- In motoring mode, the block separates from the valve plate when operating beyond the rated speed
- In pumping mode, no separation is observed, and the interface operates normally

The simulated film thickness in the cylinder block/valve plate interface is shown in Figure 4.7, where the block separation can be observed as the diverged film thickness. This figure also demonstrates that this behavior can only be replicated with the consideration of shaft deformation.

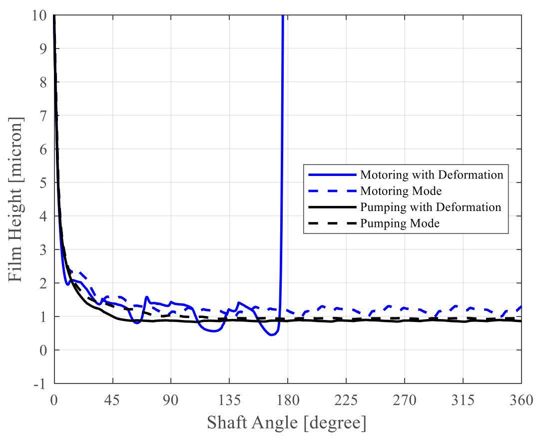

Figure 4.7. Effects of shaft spline deformation on block separation

4.2.2. *Design Improvements*

The coupled simulation results indicated the causes of wear on the valve plate. Two design solutions were developed to reduce contact between the running surfaces.

A. Hydrodynamic Balance Ring: Hydrodynamic balance ring is introduced to provide additional capability to counter the block tilting moments. Figure 4.8 illustrates the change of the geometry of the running surface of the cylinder block.

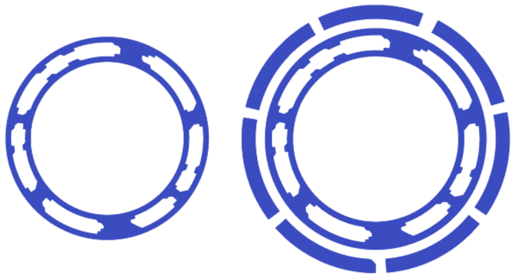

Figure 4.8. Modification of the running surface geometry of the cylinder block

B. Extended piston guide length: The length of the piston guide is defined by the distance between the beginning and end of the cylinder bore running surface. This typically is determined by the geometry of the bore undercut. It is widely understood that the increased length of the piston guide improves the sealing function of the piston cylinder interface and increases the friction due to larger area. However, the length contributes to another significant effect that determines the piston/cylinder performance – hydrodynamics. When operating in motoring mode, the piston moves outwards during the high-pressure stroke, where most of the friction happens. The high pressure tilts the piston in the bore, forming a region of wedge gap around the ends of the piston film.

In case of short bore, the film ends at the edge of the bore. The piston moves relative to the wedge gap, where the fluid is dragged out of the contact region, forcing the load to be carried by boundary lubrication. This is illustrated in Figure 4.9[A].

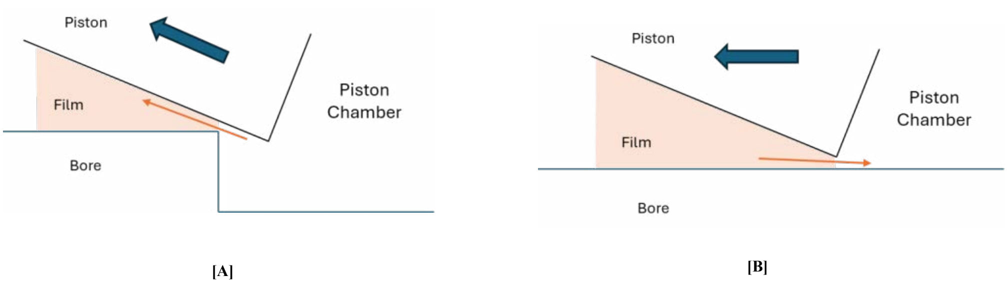

Figure 4.9. Illustration of lubrication behavior with different bore designs

In case of long bore, the film ends at the edge of the piston. The bore moves relative to the wedge gap, where the fluid is dragged into the contact, which helps carry the load hydrodynamically. This is illustrated in Figure 4.9[B]. Therefore, to improve cylinder block/valve plate interface performance through reduction of friction from the piston in motoring more, an extended piston guide is designed as illustrated in Figure 4.10

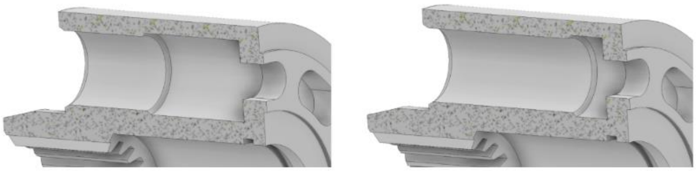

Figure 4.10. Illustration of bore design change

4.2.3. Results

Simulation results for the new interface with the hydrodynamic balance ring design are shown in Figure 4.11.[A]. The film gap heights now stay stable for the entire rotation of the cylinder block, as opposed to the baseline which is shown to separate. This indicates that the added hydrodynamic area reduces the tilting moment on the block and prevents separation.

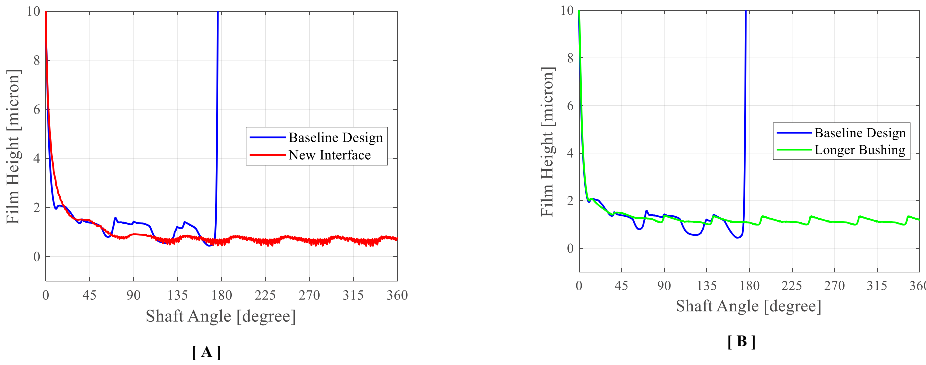

Figure 4.11. Comparison of Gap Height with new designs

Figure 4.11.[B] shows results for the new bore design with longer bushing length. The film gap height at the cylinder block/valveplate interface remains stable for the full rotation, showing that the tilting of the block has been reduced, and separation is prevented. This shows that improvement in performance of the cylinder block/valveplate interface can be achieved by changing the bore design at the piston/cylinder block interface. The coupled model used for this study enables the influence of design changes at other interfaces to be included when simulating the valve plate interface behavior, accurately showing the resulting improvements. Experimental tests show no separation with the new design, which validates the results of the coupled model.

5. CONCLUSIONS

The cylinder block/valve plate interface plays a major role in determining the operational limits of axial piston machines. The behavior of the lubricating film at this interface is dependent on the dynamics of the cylinder block, as well as the behavior of other lubricating interfaces. Accurate numerical models need to include the effects from several interacting physical domains, in order to accurately simulate the behavior. While simplified models permit faster study of a specific parameter, several characteristics can only be understood with a full-scale model. A coupled model approach is proposed as a method to simulate such complex behavior. The proposed coupled model for the axial piston machine uses a fluid-structure interaction model to simulate the piston and valve plate lubricating interfaces, and the model is fully coupled with a body dynamics solver and lumped parameter models to simulate the solid components and the chamber volumes respectively. The effects of deformation of the cylinder block surface at the crowning region are included, to ensure that the effect of the shaft reaction moment is included.

The improvement of the simulation model is demonstrated in representing physical behavior of the axial piston machine at conditions outside the operational window. Two test cases are considered: valve plate wear at high pressures, and separation of the cylinder block at high speeds. For the two cases, the baseline designs were tested with the simulation model. The predicted behavior matched observations from experimental tests conducted for the same machine designs. Additionally, the results from the simulation model were analyzed to better understand the factors affecting performance, and design solutions were proposed addressing the causes. The improvements were first tested with the simulation model, then validated with experimental results. Table 5.1 summarizes the design changes and the resulting effects. It also highlights the improvement in simulation output with the proposed model's considerations, as opposed to the state of art models.

Designs	Proposed Model	State of Art Models	Experimental Observations
1. Valve plate Wear Study	**Operational Limit: Contact at High Pressure**		
Baseline	Contact	No Contact	Contact
New Port Block	Reduced Contact	-	Reduced Contact
Redesigned Interface	No Contact	-	No Contact
2. Cylinder Block Separation Study	**Operational Limit: Separation at High Speed**		
Baseline	Separation	No Separation	Separation
Redesigned Interface	No Separation	-	No Separation
Longer Piston Bore	No Separation	-	No Separation

Table 5.1. Summary of Test Cases and Design changes

The novel considerations of the simulation model, the coupled films and the shaft deformation, were found to be important in accurately capturing the behavior of the machine at such operating points, and ensuring the improved designs were functioning accurately. The consideration of the coupled film models, as opposed to an individual simulation of the cylinder block/valve plate interface, was found to be necessary for modelling the dynamics of the cylinder block. Additionally, the shift in the crowning point due to deformation at the shaft ensures the simulation model captures the separation of the cylinder block from the valve plate at high speeds.

The simulation results show several cases where the cylinder block/valve plate interface is important in ensuring axial piston machines are operational at extreme operating conditions. Design changes at this interface solve issues like wear and leakage, while changes at other regions of the machine also help in improving the functioning of this interface. Therefore, the study effectively demonstrates that the operational limits of the cylinder block can be extended by optimizing the functioning of the cylinder block interface.

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Biographies

Ishan Suvarna received his Bachelor's degree in Mechanical Engineering from Birla Institute of Technology and Science, Pilani – Goa Campus in 2024, and is currently pursuing his Master's degree in Mechanical Engineering at Purdue University, while working as a graduate researcher at the Maha Fluid Power Research Center. His research interests include the development and application of numerical models to analyze performance of axial piston machines, particularly under extreme operating conditions.

Dr. Lizhi Shang is Assistant Professor of Mechanical Engineering and Agricultural & Biological Engineering at Purdue University. His research interests focus on designing and modeling hydrostatic pumps and motors, hydrodynamic pumps and turbines, fluid power systems, and advanced computational and experimental tribological analysis. His research aims to improve energy efficiency, reliability, and controllability of fluid power systems by conducting interdisciplinary research on both component and system level, and to explore and expand fluid power's use and fluid power technology in new applications. Dr. Shang joined Maha fluid power research center in 2020 as an assistant professor. He graduated as a Ph.D. student in 2018. His Ph.D. advisor is the late professor Dr. Monika Ivantysynova.

Raul Rodriguez received the bachelor's degree in Mechanical Engineering from Instituto Tecnológico de Estudios Superiores de Occidente in 2012. He is currently working as a Simulation and System Engineer at Bosch Rexroth, Fountain Inn, SC, USA. His work primarily involves the simulation and analysis of mechanical components and assemblies, with an emphasis on evaluating structural integrity and mechanical strength. His professional interests include mechanical system modeling, fatigue analysis, and the development of robust simulation methodologies for complex mechanical systems.

Jeemon Kurian brings over 20 years of industry experience as a simulation engineer, with a specialized focus on hydraulics and fluid system applications. Throughout his career, he has played a pivotal role in developing and validating innovative solutions for automotive and mobile machinery systems.

He holds a Bachelor’s degree from Visvesvaraya Technological University and a Master’s degree from Coventry University. Since joining Bosch Engineering in 2005, Jeemon has contributed significantly to technological advancements within the company. Previously, Jeemon Kurian was engineering manager responsible for powertrain development at Bosch Limited India until 2019. He currently leads the Simulation team in Engineering department at Bosch Rexroth in the United States. In this leadership role, he leverages his deep technical expertise to drive innovation and establish new benchmarks in simulation excellence. His work continues to strengthen Bosch Rexroth’s position as a global leader in industrial and mobile applications.

Dr. Enrique Busquets is currently responsible for the Bosch-Rexroth Mobile Solutions business in North America encompassing sales, engineering, product management and manufacturing. In addition to this current role, Enrique has been responsible for engineering with regional product and business development responsibility on hydraulic pumps, valves, electronics, software, telematics, and electrification in North America since April 2021 and the service and aftermarket business since 2024. Additionally, since 2018, Enrique has been responsible for the testing, validation, and vehicle integration infrastructure in North America. Previously, Enrique Busquets was the engineering manager responsible for systems and software development at Bosch Rexroth North America from 2018 to 2021. The technology focus was mobile applications with electronified hydraulics and electrified systems.

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