

An Analysis of Lubricating Gap Flow in Radial Piston Machines

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ABSTRACT

Radial piston units find several applications in fluid power, offering benefits of low noise and high power density. The capability to generate high pressures makes radial piston pumps suitable for clamping function in machine tools and also to operate presses for sheet metal forming.

This study is aimed at developing a comprehensive multidomain simulation tool to model the operation of a rotating cam type radial piston pump, with particular reference to the lubricating gap flow between the pistons and the cylinder block. The model consists of a first module which simulates the main flow through the unit according to a lumped parameter approach.

This module evaluates the features of the displacing action accounting for the detailed evaluation of the machine kinematics and for the mechanical dynamics of the check valves used to control the timing for the connection of each piston chamber with the inlet and outlet port. The estimation of the instantaneous pressure within each displacement chamber is utilized in a second module dedicated to the prediction of the lubricating gap flow between the pistons and the cylinder. This lubricating gap flow module is based on a fluid-structure interaction algorithm in which the fluid film pressure is calculated by using the Reynolds equation and accounting for hydrodynamic terms due to material deformation and micro-motions of the pistons.

The results shown in the paper highlight the potentials of the simulation approach for determining the main performance parameters of the unit (i.e. outlet flow oscillations, instantaneous piston pressures, etc.) including the evaluation of possible contact and of the power losses due to leakages or fluid shear at the piston/cylinder lubricating interfaces.

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1. INTRODUCTION

Radial piston pumps and motors are widely used in many fluid power machines. A key feature of these units is the capacity to generate high pressures at a wide range of shaft speeds. They are also characterized by a compact arrangement with high energy conversion efficiency. Due to these aspects, these units

are widely used in mobile applications, in particular to realize hydrostatic transmission systems, as well as in stationary applications such as hydraulic presses. The specific unit considered in this work ([Figure 1](#)) finds application as a hydraulic power supply for portable tools such as clamping devices, cutting tools, mini presses and rock splitters.

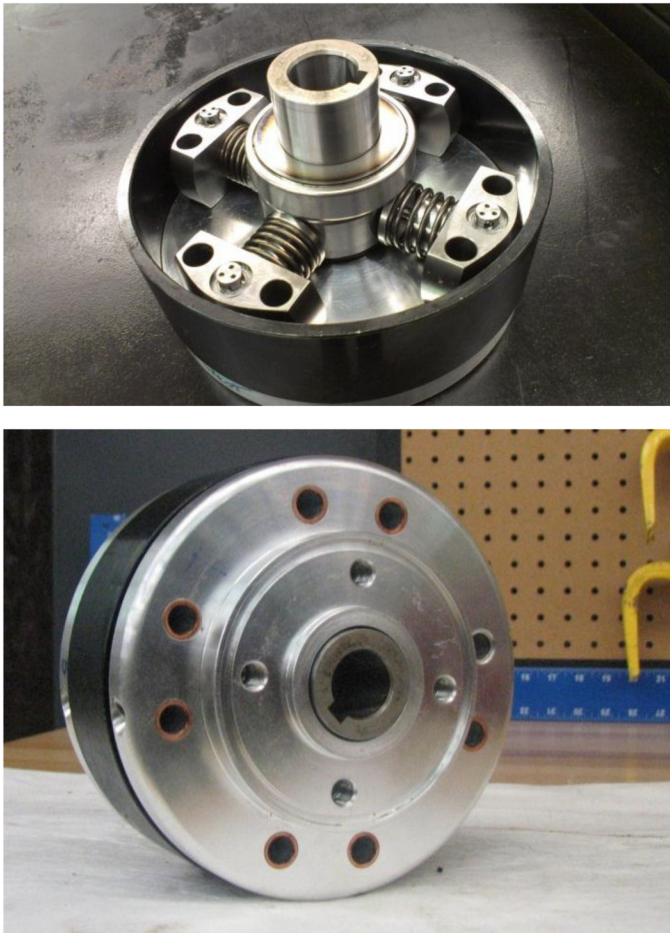


Figure 1. External view of the rotating cam type radial piston pump. (Displacement = 1cc/rev, Maximum operating pressure = 700bar, Speed range = 1200-1800 rpm)

Figure 2 shows the sectional view of the reference unit, which is a rotating cam type radial piston pump. The unit consists of 4 pistons radially arranged around an eccentric cam. Due to the eccentricity, a rotating motion in the cam generates a reciprocating motion in the pistons that causes pumping of the fluid in and out of the displacement chambers.

Although their wide utilization in engineering applications, radial piston units have been not deeply investigated by researchers as other positive displacement machines used in fluid power. Only few works were published on aspects related to the flow through these machines: Chapple [1] developed an analytical model of a radial piston motor for evaluation of factors affecting motor performance including friction in ball joints; Kleist [2,3] developed an isothermal model for description of gap flow through radial piston machines. However, this model was based on rigid body consideration and friction forces were not dealt in detail. According to the authors' knowledge, no studies were published on the analysis of thermal and deformation aspects related to radial piston units. These aspects have found to be of high importance in determining the features of operation as well as the performance parameters of other units: axial piston pumps [4, 5], gear pumps [6].

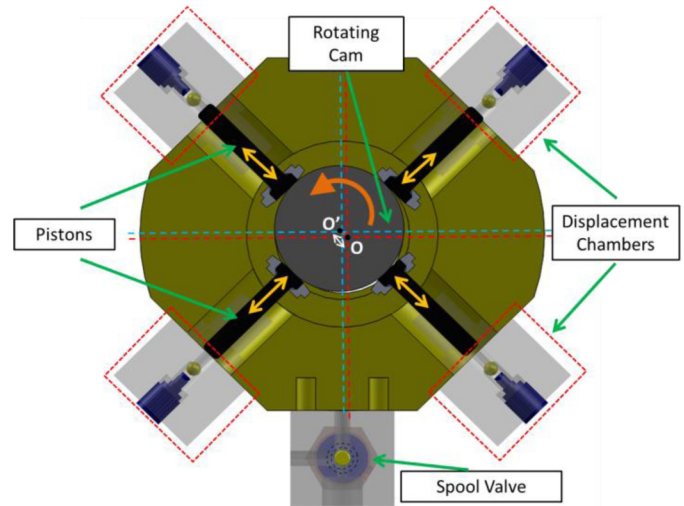


Figure 2. Sectional view of the radial piston pump block.

The present study contributes to fill this knowledge gap related to the modeling of radial piston units by presenting a multidomain simulation tool that can not only model the main flow through the unit but is also capable of evaluating the leakages and the related power losses in the lubricating gap flow existing between the piston and the cylinder.

Figure 3 shows the structure of the simulation tool developed with its individual modules. The main flow through the unit, which includes the evaluation of the pressure inside each piston chamber and the instantaneous flow through the inlet and outlet ports, is modeled through a lumped parameter approach implemented in AMESim®. This kind of implementation permits to easily simulate the unit within a multitude of possible systems by means of the standard libraries of the software. This model, suitable to simulate both rotating cam and rotating piston type units, was detailed in a previous study presented by the authors [7].

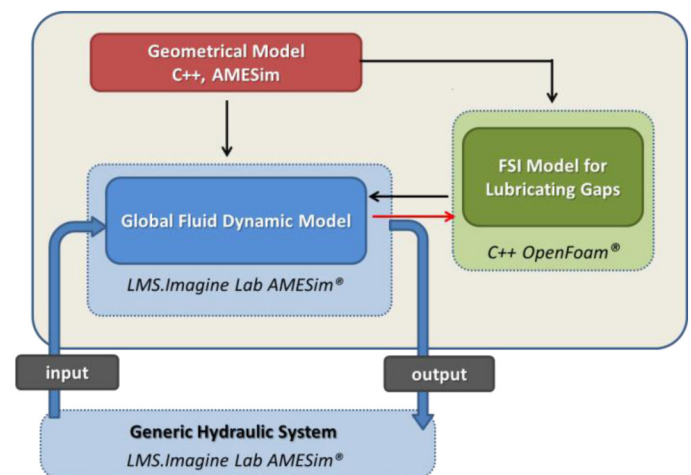


Figure 3. Multi-domain simulation tool for radial piston pump modeling

The focus of the present work is the model for the lubricating gap between the piston and the cylinder, which represents the main lubricating interface in rotating cam type units. A detailed CFD model for the lubricating gap flow is coupled with a structural model that permits to account for the material deformation and is capable of detecting possible material contacts. The models for both fluid flow and solid deformation are based on the finite volume method. As shown in Figure 3, the simulation tool operates on a close interaction between its components. The main flow model (global fluid dynamic model) calculates the instantaneous displacement chamber pressures which are used as boundary conditions for the FSI model to solve for fluid flow in lubricating gap. In return, the leakage flow rates calculated through the gap model are used as inputs in the main flow model to refine the flow parameters through co-simulation.

The paper analyses the effects of material deformation by comparing the results of the model with a simplified version that considers pure rigid bodies for the piston and the cylinder. The following sections detail out the simulation approach used to formulate the different elements of the Multi-domain simulation tool along with the main assumptions used to describe the operation of the considered unit.

2. SIMULATION OF THE MAIN FLOW

As mentioned in the previous section, the main flow model is based on lumped parameter approach wherein the displacement chambers, the suction and delivery volumes are treated as separate control volumes with fluid properties independent of spatial parameters in their domain. Figure 4 shows the complete schematic of the lumped parameter model.

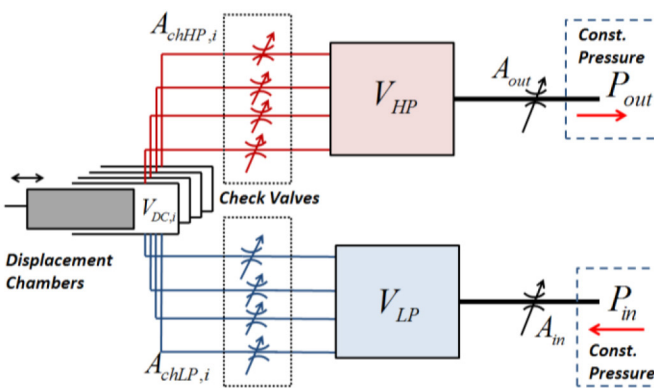


Figure 4. Lumped parameter schematic for the radial piston pump

The pressure in each of these control volumes is described by the pressure built-up equation as follows [Z]:-

$$\frac{dP_{DC,i}}{dt} = \frac{K}{V_{DC,i}} \left[-\frac{dV_{DC,i}}{dt} - (Q_{rHP,i} + Q_{rLP,i} + Q_{pist,i}) \right] \quad (1)$$

In order to solve for flow through the orifice connections shown in the schematic, the orifice flow equation has been used. The equation for the flow from displacement chamber to the HP volume can be written as:-

$$Q_{rHP,i} = \alpha_{HP} \cdot A_{valveHP,i} \sqrt{\frac{2 \cdot [P_{DC,i} - P_{HP}]}{\rho}} \cdot \text{sgn}(P_{DC,i} - P_{HP}) \quad (2)$$

More details about this module can be obtained in [Z] which also contains an experimental validation of the lumped parameter model.

3. PISTON - CYLINDER LUBRICATING GAP MODEL

This section details the numerical approach used to simulate the lubricating gap flow between piston and cylinder. Although the results presented in this study will pertain to the pump design shown in Figure 1, Figure 2, the model presented in this study can be applied to other radial piston units of both rotating cam and rotating cylinder types.

Figure 5 shows the gap domain between the piston and cylinder. The precise evaluation of fluid flow parameters in the gap requires an accurate estimation of the micro-motion of the piston during its reciprocating cycle which facilitates the evaluation of the gap film thickness at every instant. Instantaneous values of film thickness are critical in calculating the pressure distribution in the gap domain.

A quasi-static analysis of piston motion is assumed throughout the study wherein the piston must satisfy the equilibrium condition at each time instant in the cycle and force balance is solved for. The quasi-steady approach has been successfully applied and experimentally validated for other positive displacement machines [4, 6].

The FSI algorithm is illustrated in the next section. This is followed by a detailed description of each of the components and processes that form a part of the solution algorithm.

3.1. FSI Solution Algorithm

The complete scheme for the FSI algorithm is shown in Figure 6. The numerical procedure consists of three main iterative loops:-

- Solution of fluid flow in the lubricating gap.
- Solution of deformation of piston and cylinder.
- Solution of piston micro motion by considering force balance of the piston at each time step.

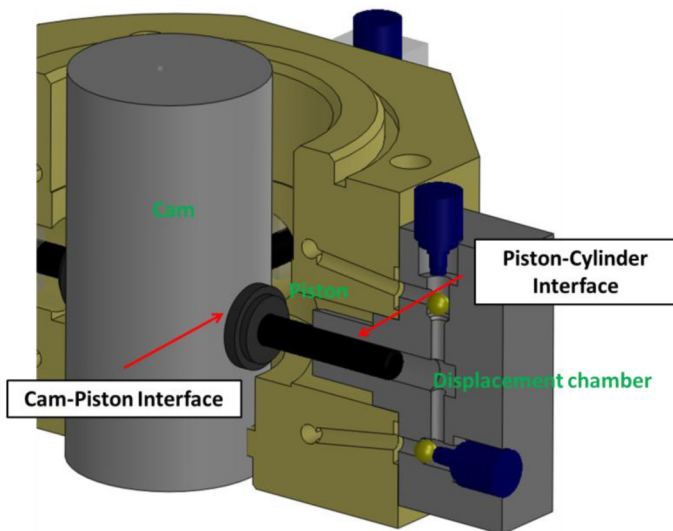


Figure 5. Lubricating gaps in the rotating cam type radial piston pump

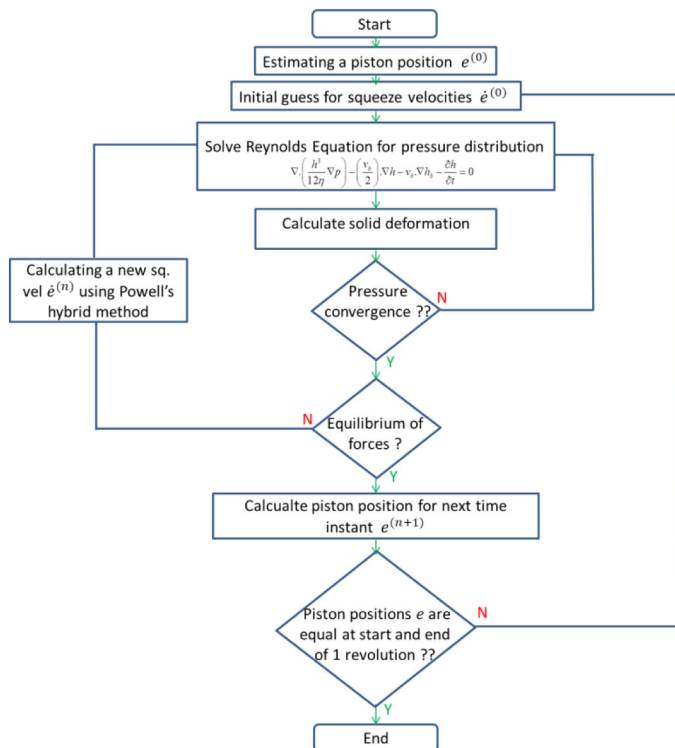


Figure 6. Solution algorithm for the FSI simulation

The simulation process starts by estimating an eccentric position of the piston $e^{(0)}$ for the initial time step. The squeeze velocity of the piston ($\frac{de}{dt}$) is varied through an iterative loop using the Powell's multidimensional root finding method that checks for the force balance of the piston at each successive step until the criteria is met. This forms the main iterative loop for the algorithm. For each value of squeeze velocity in the iterative process, an inner FSI loop is made to run. In this inner loop, the fluid pressure in gap domain is solved using the Reynolds equation and is then used to calculate deformation in the piston and cylinder faces. The new gap film thickness values are used to update the pressure field and these

iterations run until both the fluid pressure and solid deformation values reach convergence. Once the squeeze velocity for a time instant is converged, the eccentric position of the piston is calculated for the next instant by numerically integrating the velocity over a time step using the Euler-explicit method. The criterion for stopping the calculations is the piston position e at a shaft angle of $\varnothing = 0^\circ$ and $\varnothing = 360^\circ$. For the steady state solution, the calculated positions of the piston at $\varnothing = 0^\circ$ and $\varnothing = 360^\circ$ should be same. Therefore, the calculations are done for several revolutions until this convergence is reached.

3.2. Fluid Solver

Figure 7 shows the magnified view of the lubricating gap interface between the piston and cylinder. The pressure distribution in the gap domain is critical in calculating the leakage flow rate and power losses associated with fluid friction. For this purpose, a detailed CFD analysis of fluid flow is performed for the gap domain. The various aspects of the fluid solver are detailed in the following sections:-

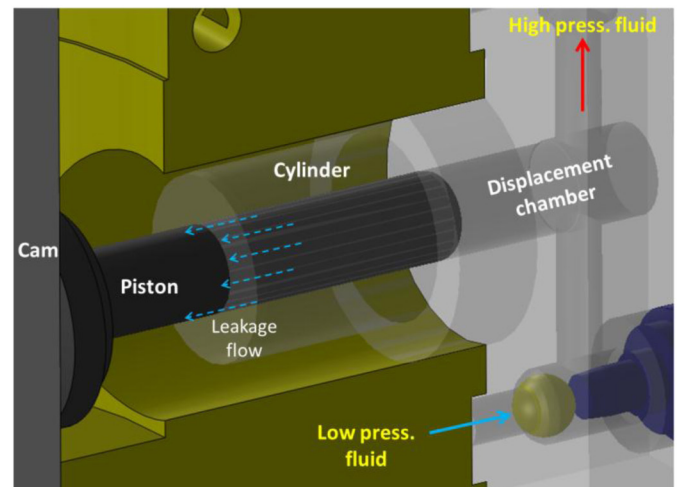


Figure 7. Magnified view of the piston- cylinder lubricating gap showing leakage flow.

3.2.1. Mesh Generation

The lubricant film region consists of the annular region between two cylindrical surfaces of piston and cylinder. However, the curvature of the lubricant film can be neglected since the film thickness is small relative to the piston radius. This implies that the film shape can be unwrapped from the piston circumference and viewed as a periodic stationary profile with length $2\pi r_p$. This reduces the complex film geometry to a simplified rectangular geometry in the Cartesian frame.

Also the gap film thickness is calculated throughout domain as an input to the fluid solver. Figure 8 shows the evaluation of film thickness at an arbitrary point in the fluid domain.