Kinematic Analysis of a Swash-Plate Controlled Variable Displacement Axial-Piston Pump With a Conical Barrel Assembly

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Variable displacement, swash-plate controlled, axial-piston pumps are widely used in applications that require high pressure and variable flow rates. The pump consists of a rotating barrel assembly that houses several pistons in a circular array. A swash-plate is used to control the displacement of the pistons to adjust the output flow of hydraulic fluid. As the barrel rotates, the pistons slide along the angled swash-plate and draw oil from the supply and then discharge oil into the high pressure circuit. This results in an almost constant output flow rate. This paper analyzes the kinematics of a pump based on its geometry dependent characteristics. The analysis assumes an idealized case in which there is no oil leakage and the fluid is considered to be incompressible. It is revealed through the analysis that the piston displacement and the pump output flow are slightly increased by using a conical barrel. Instantaneous and mean flow rate equations are used to describe the output flow characteristics and flow ripple effect. The output flow rate ripple profile is found to be a function of both swash-plate angle and the conical barrel angle. A term defined as the flow rate uniformity coefficient is used to better quantify the flow ripple phenomenon. A frequency analysis is performed on the output flow rate and an additional order is found to be present when using a conical barrel pump versus one with a cylindrical barrel when the pumps have an odd number of pistons. Conical barrel piston pumps are found to have a slight increase in piston displacement, velocity, and acceleration relative to the rotating barrel frame of reference over a pump with a cylindrical barrel. This translates into an increase in the output flow rate for a conical piston pump under the same operating conditions. The conical barrel is also found to have a reduction in the rotational inertia allowing for faster angular acceleration. The presence of an extra order from a frequency analysis for a conical pump with an odd number of pistons has the potential to cause unwanted noise or vibration to the structure or components attached to the pump. [DOI: 10.1115/1.4000067]

Keywords: hydraulic, piston pump, axial-piston pump, variable displacement pump, swash-plate, kinematic analysis, conical barrel, cylinder block, flow ripple

1 Introduction

1.1 Background. Swash-plate controlled, variable displacement, axial-piston pumps are widely used as a power supply in conditions that require high pressure and variable flow rates. The output pressure flow rate is determined by the payload and can be adjusted by changing the angle of the swash-plate. An increase or decrease in piston stroke displacement translates into an increase or decrease in the high pressure oil output flow rate, respectively.

The barrel designs for axial-piston pumps are cylindrical or conical in shape. One of the driving factors behind the conical piston pump barrel design in practice is to decrease the pitch radius at the valve plate. This improves the fluid fill characteristics within the piston bores since the fluid fill velocity is reduced. This helps to keep the inlet pressure as high as possible to avoid cavitation, especially at higher rotational speeds.

For an axial-piston pump that has a conical barrel, the pistons are distributed in a circular array and are angled relative to the centerline of the barrel. When the pump rotates, each piston's velocity and acceleration vectors have three components when a fixed coordinate system is used. This makes the piston's kinematics more complicated when compared with a cylindrical barrel pump, which has piston motion in only one direction.

Works by He [1], Xu [2], and Ivantysyn and Ivantysynova [3] covered kinematics, dynamics, and component design for a variety of different pumps. Piston pump flow rate fluctuation for a cylindrical pump is also discussed in those references. McNamara et al. [4] conducted a brief analysis on kinematics before creating a hybrid neural network model for a variable displacement pump.

Manring and co-workers published several key papers regarding the modeling of axial-piston, swash-plate pumps. Slipper-shoe tipping, with a kinematic analysis of the piston/slipper ball-joint, is discussed by Manring [5,6]. Flow rate ripple and ripple frequency analysis is demonstrated in Ref. [7].

Exploration of piston pump kinematics is covered in papers by Bahr Khalil et al. [8] and Kassem and Bahr [9]. In their work, six coordinate transformation matrices are used to calculate piston displacement, forces, and moments. It should be noted that the piston displacement equation given by Ivantysyn [3] is much simpler than the one developed by Bahr Khalil et al. [8].

A common feature of a piston pump is the generation of flow rate ripple. This is inherent to the design of the pump due to the way multiple pistons are simultaneously pushing fluid into the high pressure circuit at different rates. These ripples also create

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