Analytical and Numerical Multibody Dynamic Modeling and Constraint Force Analysis in an Axial Piston Pump

Milind.Thambu*,Mira.Mitra#

* Senior Engineer
Eaton India Engineering Center
Kharadi, Pune, India
TRMilind@eaton.com

Associate Professor
Department of Aerospace Engineering
Indian Institute Technology Bombay
Powai, Mumbai, India
mira@aero.iitb.ac.in

Abstract

In the present work, the methodology of modeling an swashplate type axial piston pump in a multibody dynamics framework is developed. The swashplate type axial piston pump is a type of rotating machine which is widely used in hydraulic power systems for industrial and mobile applications. There are several studies carried out on modeling and analysis of axial piston pumps. The 1D flow models are developed to study the pressure ripples and leakage. The 3D modeling of the fluid flow using Navier-Stokes or Reynolds equations and CFD or finite difference solution techniques is used to study the flow behavior at a specific interface. The coupled 3D flow and mechanical dynamic models at a specific interface are helpful in lubrication studies. The dynamic modeling of the pump using 1D models or Bond-Graph techniques enables the study of the swashplate motion and the controls performance [1,2]. In addition to the above, the structural design and optimization, estimation of fatigue life, and improvement in noise and vibration are important considerations in the pump design. The 3D dynamic modeling and analysis of the constraint reaction forces is critical for addressing these issues. The kinematic modeling [3,4] of the pumping mechanism is an important step in the overall dynamic modeling of the pump. The multibody dynamic method provides an ideal framework for modeling the dynamics of the pump [5,6].

The dynamics of the pumping mechanism is studied using analytical modeling which is validated through numerical simulations. The modeling is carried out using a multibody dynamics framework considering the 3D dynamics of the major components in the pumping mechanism and the pressure forces acting due to the hydraulic fluid. The equations of dynamic equilibrium for the different components are developed using the augmented Newton-Euler formulation [7]. The pumping mechanism dynamics is formulated as an *inverse dynamic* problem and *closed-form solutions* for the constraint reactions are obtained. The analytical models are developed for the general case of the axial piston pump mechanism having N pistons. The numerical model is developed using the equations of motion in the augmented Newton-Euler formulation with Lagrange multipliers. The closed form solutions are compared with numerical simulations. The time variation and the frequency spectrum of the constraint reactions are studied for the case of single pumping piston and nine pumping piston configurations. Also, the influence of swashplate angle, pressure ripple, and rotating group design parameters are being studied.

The dynamic modeling is carried out by developing the differential EOMs using the augmented Newton-Euler formulation where the constraint reaction forces are explicitly considered. The equations are developed for the individual components in the form,

$$\left[M^i\right]\left\{\ddot{q}^i\right\}-\left\{Q_c^{\ i}\right\}=\left\{F_e^{\ i}\right\} \tag{1}$$

Where $\left[M^i\right]$ is the mass-inertia tensor, $\left\{\ddot{q}^i\right\}$ is the vector of generalized coordinates, $\left\{Q_c^{\ i}\right\}$ is the constraint force vector and $\left\{F_e^{\ i}\right\}$ is the external force vector.

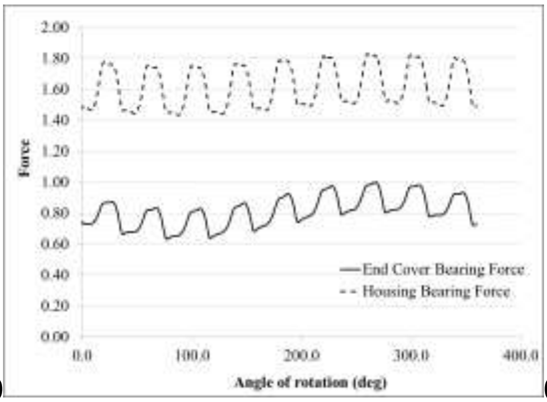
A numerical model is developed to validate the analytical closed form expressions. In the numerical modeling of the pump dynamics, the governing dynamic Equations are developed using augmented Newton-Euler formulation with Lagrange multipliers. This formulation leads to symmetric coefficient matrices with a sparse structure.

Next, by solving equation (1), the closed form expressions for the different constraint reactions viz., horizontal swashplate bearing force(R_{sbX}), the vertical swashplate bearing force(R_{sbZ}),

control piston force(R_c), horizontal swashplate bearing moment(M_{sbX}), vertical swashplate bearing moment(M_{sbZ}), reaction forces at driveshaft-cylinder barrel interface(R_{bsZ} , R_{bsY}), and moments at the driveshaft-cylinder barrel interface(M_{bsY} , M_{bsZ}) are obtained. The Equation (2) gives the expression for the force exerted by the swashplate on the bearings.

$$R_{sbX} = \sum_{i=1}^{N} -(m_p^i + m_{sh}^i)\omega^2 \frac{D}{2} \tan(\alpha) \sin\theta_i + F_{pr}^i(t) \quad (2)$$

Figure 1 shows the variation in the forces for the nine piston configuration. Figure 1(a) show the variation in the bearing forces and Figure 1(b) shows the variation of the control piston force.

(a) 

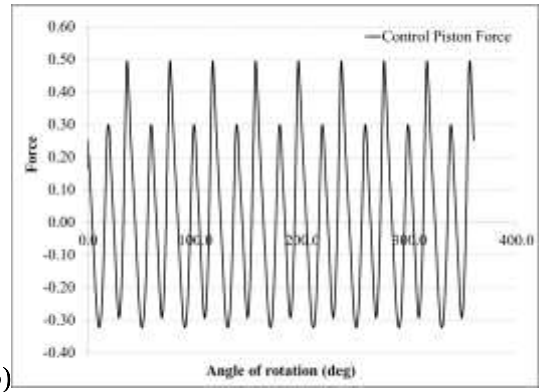
(b) 

Figure 1 Bearing and Control piston forces in a nine piston configuration

The frequency spectrum of the constraint forces are studied using fast fourier transforms (FFTs). Based on the study the dominant forces and their orders are identified. The parametric studies are being conducted to evaluate the influence of design (swashplate angle, pressure variation, rotating group design parameters) and operating conditions on the dynamic excitation forces produced by the pump.

References

[1] Kaliafetis, P., Costopoulos, Th., 1995, “Modelling and simulation of an axial piston variable displacement pump with pressure control”, Mechanism and Machine Theory, 30(4), pp. 599-612.

[2] Manring, N. D., Johnson, R. E., 1996, “Modeling and Designing a Variable Displacement Open-Loop Pump”, ASME Journal of Dynamic Systems, Measurement and Control, 118, pp. 267-271.

[3] Abuhaiba, M., Olson, W. W., 2010, “Geometric and kinematic modeling of a variable displacement hydraulic bent axis piston pump”, Journal of Computational and Non-linear dynamics, 5, pp. 041010-1 to 041010-12.

[4] Shi, Z., Parker, G., Granstrom, J., 2010, “Kinematic Analysis of a Swash-Plate Controlled Variable Displacement Axial-Piston Pump With a Conical Barrel Assembly”, Journal of Dynamic Systems, Measurement and Control, 132, pp. 1-8.

[5] Roccatello, A., Mancò, S., Nervegna, N., 2007, “Modelling A Variable Displacement Axial Piston Pump In A Multibody Simulation”, Journal of Dynamic Systems, Measurement and Control, 129, pp. 456-468.

[6] Deeken, M., 2002, “Simulation of the reversing effects of axial piston pumps using conventional CAE tools”, Ölhydraulik und Pneumatik, 46, pp. 1-11.

[7] Shabana, A. A., Computational Dynamics, Third edition, John Wiley & Sons Ltd, 2010.