

A CFD study of an Electronic Hydraulic Power Steering Helical External Gear Pump: Model Development, Validation and Application

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ABSTRACT

External gear pumps are positive displacement devices which perform with excellent efficiencies over a wide load and speed range. This wide range of performance is primarily due to micron-level leakage gaps in such machines which prevent large leakages at increasing loads. The present paper details a novel approach implemented in the commercial CFD tool PumpLinx that can capture the details of the micron level gaps, and model such machines accurately. The steps in creation of the model from original CAD geometry are described. In particular, the CFD mesh is created using a specialized template structured meshing method within PumpLinx especially created for external gear pumps and motors. This makes process of mesh creation and flow solution through complicated geometries of a gear pump efficient and streamlined. The above approach is used to create a model of an electronic hydraulic power steering gear pump and the model is validated by comparing the flow rate predictions with experimental measurements for a range of speeds and loads and an excellent agreement is observed.

The validated pump model is then used to create design improvements on the component level. Design features are introduced within the simulation environment to demonstrate a reduction in the cavitation and pressure ripple, thereby providing directions for a pump with reduced noise. A novel method of using PumpLinx simulations together with test result for system level optimizations, including dynamic response and efficiency performance is also introduced with examples. The efficiency of model creation and the speed of the solver within PumpLinx enable the integration of CFD analysis of gear pumps into the product design and development process.

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INTRODUCTION

External gear pumps (EGP) are positive displacement machines, where the fluid is displaced from the suction to the delivery port due to the intermeshing of the teeth of the drive and slave gears. Due to their reliability, compactness, low comparative costs and good efficiencies EGPs are one of the most commonly utilized positive displacement pumps in automotive and commercial vehicle applications. A view of the chief components of EGPs and the principal of operation can be seen in Fig.1. Due to their widespread popularity, development of analytical methods that can improve the performance of such machines has a great importance. The present work details the creation of a 3D CFD model of a high pressure helical external gear pump which is used in an electro-hydraulic steering assist system in a passenger vehicle.

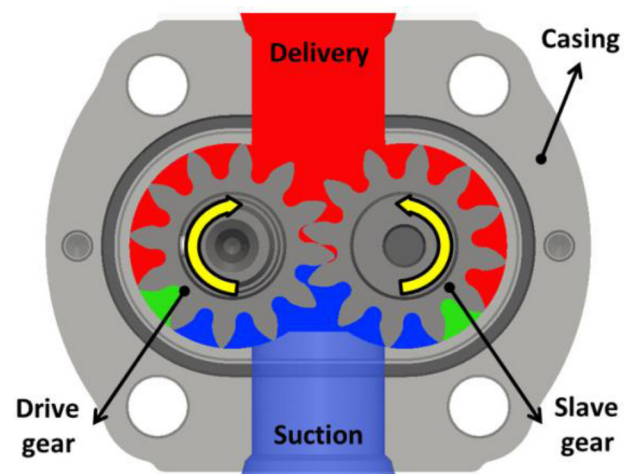


Figure 1. Principle of operation and components of EGPs.

Analytical methods of the delivery flow ripple from EGPs started by using a graphical method [1] and then using analytical approaches using energetics methods [2, 3]. EGPs have also been studied extensively using 0 and 1 dimensional models such as those presented in [4, 5, 6]. A few studies using CFD programs have also been performed. Wustmann et al. [7] looked at the flow reversing process inside an external gear machine and del Campo et al. [8] studied some considerations due to cavitation in an external gear pump. However, both approaches were highly simplified using a two dimensional (2D) geometry and mesh. The geometry of a gear pump and all internal phenomena are three dimensional in reality due the presence of 3D features such as relief grooves and the ports and pipes through which the fluid enters the pump, and phenomena such as cavitation and aeration are also inherently three dimensional. Important as the 3D effects are in a spur gear pump, their importance is even greater in a helical gear pump where the geometry of the gear teeth themselves are varying in all 3 dimensions.

The relative scarcity in available literature on full 3D CFD methodologies and analyses in gear pumps in particular, and all positive displacement devices in general, is because of the extremely complex geometry of such machines features double curved contiguous surfaces and extremely small gaps between solids. Over the past several years the commercial CFD software PumpLinx has been developed to address this challenging problem and studies on positive displacement devices such variable displacement vane pumps [9], gerotor pumps [10], piston pumps [10], crescent oil pumps [11] and spur gear pumps [12] have been published using this platform. The present work, also performed using the 3D CFD code PumpLinx, is the first to be published detailing a full transient 3D simulation of a helical external gear pump along with a detailed experimental validation.

The helical gear pump examined in the present work is a critical component of electronic hydraulic power steering (EHPS) system - one of the most popular applications of such pumps in automotive vehicles. A typical EHPS hardware include software driven electronic controller, motor, gear pump, and other key components such as assembly body, harness and connector to CAN, reservoir and hoses, mounting isolator, etc. As a major vehicle component output function, the EHPS output assistant forces to steering gear through fluid outflow from gear pump outlet. The gear pump continuously takes steering gear side load information to feedback to software and controller, which communicate with CAN and ECU and combine other information for dynamic vehicle control. This information usually includes vehicle speed, steering angle and speed, environmental temperature, fluid temperature, motor speed, etc. The performance of an EHPS system will be tuned during the vehicle dynamics development stage to meet handling objective and subjective attribute targets.

As the frontier direct interface of EHPS with steering gear, a clear understanding through CFD modeling of gear pump with the operating hydraulic fluid is vital important to the successful design and optimization of EHPS system. For example, accurate flow and torque ramp up curve, gear pump efficiency and dynamic response performance at different temperature is desired by software and hardware design team to optimize algorithm and PCB design to improve overall system efficiency and NVH performance.

In EHPS system design and optimization, results from CFD modeling of gear pump can be very helpful. At helical gear pump component level, the CFD modeling can help the design of gear pump itself. The cavitation caused pressure ripple analyzed both at time and frequency domain can be used to optimize helical gear geometry and tooth shape to reduce noise and improve volumetric efficiency.

At system level some topics of interest include, flow rate at different RPM and load, volumetric efficiency at different RPM and load, system dynamic response, the extreme low temperature start problem due to fluid resistance caused by increased viscosity, system power and torque consumption information both at pump inlet and outlet. When combined with test results, the CFD results can also be used to calculate gear pump mechanical efficiency through equations and thus open the opportunity to trade off system attributes, including overall efficiency, performance and NVH.

Furthermore, combined with test, gear pump CFD simulation can enable virtual component design optimization and validation process. Due to the timing and cost constraint, ideal design and validation process usually cannot be achieved in a fast vehicle build program. A well correlated CFD model to experimental data with high accuracy can provide high level results for high standard component design process, such as the design for six sigma.

MATHEMATICAL MODEL

The governing equations for the mass and momentum conservation laws for the system of liquid, non-condensable gas and vapor may be expressed, in the integral form, as follows:

$$\frac{\partial}{\partial t} \int_V \rho dV + \oint_S \rho(\mathbf{u} - \mathbf{u}_g) \cdot d\mathbf{s} = 0 \quad (1)$$

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \rho \mathbf{u} dV + \oint_S \rho \mathbf{u}(\mathbf{u} - \mathbf{u}_g) \cdot d\mathbf{s} \\ = \oint_S \boldsymbol{\tau} \cdot d\mathbf{s} - \oint_S p d\mathbf{s} \\ + \int_V \mathbf{F} dV \end{aligned} \quad (2)$$

where $\mathbf{u}_g$ is the grid velocity; V is the control volume and S is its enclosed surface. The terms on the right side of the momentum equation (2) represent, respectively, the viscous shear force, the pressure force and the body force. *For oil pump flows cavitation is*

often encountered and is an important factor of design considerations. In the present work the vapor mass fraction f_v is solved via

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \rho f_v dV + \oint_S \rho f_v (\mathbf{u} - \mathbf{u}_g) \cdot d\mathbf{s} \\ = \oint_S \mathbf{D}_f \nabla f_v \cdot d\mathbf{s} + \int_V (R_e \\ - R_c) dV \end{aligned} \quad (3)$$

with the evaporation and the condensation source terms expressed as [13]:

$$R_e = C_e \frac{\sqrt{k}}{\sigma_l} \rho_l \rho_v \left[\frac{2(P_v - P)}{3 \frac{\rho_l}{\rho_v}} \right]^{0.5} (1 - f_v - f_g) \quad P < P_v \quad (4)$$

$$R_c = C_c \frac{\sqrt{k}}{\sigma_l} \rho_l \rho_v \left[\frac{2(P - P_v)}{3 \frac{\rho_l}{\rho_v}} \right]^{0.5} f_v \quad P > P_v \quad (5)$$

The non-condensable gas mass fraction f_g follows its own conservation equation with no volumetric sources (sinks):

$$\begin{aligned} \frac{\partial}{\partial t} \int_V \rho f_g dV + \oint_S \rho f_g (\mathbf{u} - \mathbf{u}_g) \cdot d\mathbf{s} \\ = \oint_S \mathbf{D}_g \nabla f_g \cdot d\mathbf{s} \end{aligned} \quad (6)$$

The mixture density ρ in the above equations are calculated from

$$\frac{1}{\rho} = \frac{f_v}{\rho_v} + \frac{f_g}{\rho_g} + \frac{(1 - f_v - f_g)}{\rho_l} \quad (7)$$

The above set of equations essentially describes a system of homogeneous multiphase flows. The above equations are discretized using the finite volume approach, and solved using a pressure based solution algorithm.

MODEL ATTRIBUTES AND MESH GENERATION

The fluid volume of the EGP is extracted from the solid CAD of the pump using Boolean operations common in any CAD package and imported into PumpLinX. The model of the EGP consists chiefly of low pressure and high pressure ports, relief grooves and the gear pump internal volume itself. A view of the entire computational domain and the mesh is shown in Fig. 2.

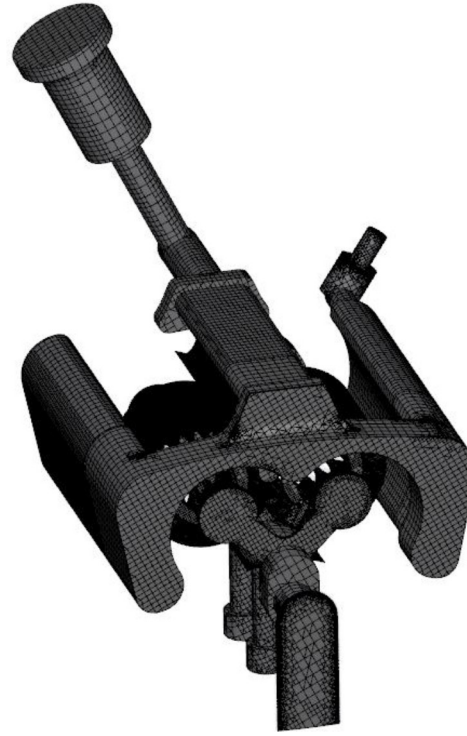


Figure 2. Mesh of the entire computational domain of the EHPS gear pump

For the ports and grooves the Simerics Binary Tree unstructured mesher is used to create a good quality hex-dominant mesh of these domains. For the gear internal geometry mesh the Simerics Gear Template mesher is used. This is a specialized tool within PumpLinX which can create a structured hex-only mesh inside the gear pump domain. The simulation is transient, and the rotor mesh is adapted automatically by PumpLinX according to the angle of the rotation of the gears. A view of the gear internal mesh is shown in Fig. 3. Typically, for high pressure gear pumps the gear experience a micro-motion due to the large loads on the gears from the high pressure side. The gear shaft acts like a journal bearing which causes the gears to operate in an eccentric position toward the low pressure side of the pump, and this causes the tooth tip gap to be much smaller on the low pressure side of the pump and larger on the high pressure side of the pump, thereby creating a good sealing region near the low pressure side of the pump. In order to correctly model this phenomenon, the PumpLinX mesh is created with the gears in an eccentric position leading to larger gaps on the high pressure (delivery) side and smaller gaps on the low pressure (suction) side. Close - up views of the mesh in the tooth tip gaps in these areas are shown in Fig. 3, along with a close-up of the meshing zone of the pump. The tooth tip gaps on the suction side and the gaps in the meshing zone are **of the order of 1 micron**, and are meshed with high quality structured hexahedral cells by the PumpLinX Gear Template mesh generator. As these micron level gaps are responsible for sealing the high pressure side of the pump from the low pressure side, correct modeling of such micron level gaps are essential to have an accurate and useful model of an external gear pump.