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Research Paper

Numerical simulation of three-dimensional external gear pump using immersed solid method

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ABSTRACT

External gear pumps are typically used as positive displacement machines that are capable of developing high pressures while operating at low suction pressures in hydraulic systems. Considerable attention has paid recently been given to investigating the flow characteristics and enhancing pump efficiency using theoretical, numerical, and experimental approaches. In this study, three-dimensional (3D) numerical simulations of an external gear pump were conducted to study the effects of 3D geometrical design parameters on pump performance characteristics such as the flow rate. The characteristics of internal flow are also presented with respect to the internal pressure peak, local cavitation, and delivery pressure ripple. The immersed solid method (ISM) was used to simulate the operation of a gear pump under extreme conditions of high rotational speed. We found that the maximum flow rate of the gear pump is a strong function of the gear tip clearance and lateral clearance. Using the 3D model, the effect of the lateral clearance on flow rate is highlighted.

1. Introduction

External gear pumps are one of the most common types of pumps for hydraulic fluid power applications (e.g., industrial and mobile machines). These pumps have advantages of a wide range of operating conditions, structural simplicity, high reliability, and low manufacturing cost. Generally, gear pumps are designed to operate over a wide range of rotational speeds and high delivery pressures as positive displacement units in hydraulic systems. The working principle is also very simple.

Continuous research and development have resulted in improved gear pump performance. In recent years, many researchers have focused on analytical, experimental, and numerical analysis for predicting and improving the performance of gear pumps [1,2]. Borghi et al. [3] developed a mathematical model to predict volumetric efficiency in gear pumps and compared numerical results with experimental results. Vacca and Guidetti [4] describe a fluid dynamics model to analyze the effect of the main design parameters on factors such as efficiency, internal pressure peak, local cavitation, and flow fluctuation. They compared the numerical results with data available from experiments. In other studies, the characteristics of the complex flow pattern of a gear pump system were investigated experimentally with time-resolved particle image velocimetry (TRPIV) to help improve the overall performance [5].

When designing a gear pump, a good design for the lateral bushings with proper axial balance is crucial [6]. For this reason, many studies have focused on the analysis of certain geometrical parameters that characterize the lateral bushing design in order to evaluate their effect on the volumetric efficiency of the pump [3]. The effects of parameters such as the tilt angle of the lateral bushing have also been studied [6,7]. Other researchers have investigated inter-teeth pressure transients during the gear meshing cycle of the gear pump [8]. Recently, Magnusson [9] and Dhar and Vacca [10,11] highlighted the leakage flow and the forces on lateral lubricating gaps in a spur gear pump.

High-performance computers and the development of efficient parallel algorithms make it possible to simulate complex flow behavior and allow for various challenging trials. However, most studies published so far have performed two-dimensional (2D) approximations based on computational fluid dynamics (CFD) using techniques for mesh deformation and remeshing [12,13].

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Nomenclature

A	area [mm^2]
D	distance [mm]
E	eccentricity [mm]
P	total pressure [Pa]
L	length [mm]
O	center
Q	flow rate [L/min]
R	radius [mm]
W	width [mm]
h	clearance height [mm]
k	turbulence kinetic energy [m^2/s^2]
n	rotational speed [rpm]
u	fluid velocity [m/s]
x, y, z	cartesian coordinates

Greek symbols

ε	turbulent dissipation rate [m^2/s^3]
μ	dynamic viscosity of fluid [kg/m s]
ρ	fluid density [kg/m^3]
φ	rotational angle [°]

Subscripts

1	gear 1 (driving gear)
2	gear 2 (driven gear)
CR	casing radius
G	gear
IA	inlet area
IG	inside radius of gear teeth
IL	inlet length
IR	inlet radius
OA	outlet area
OL	outlet length
OG	outside radius of gear teeth
TSV	tooth space volume
WC	width of casing
WG	width of gear teeth
avg	average
d	delivery
eff	effective
i, j	index of fluid velocity
max	maximum
t	turbulent
th	theoretical

Abbreviations

CFD	computational fluid dynamics
FSI	fluid structure interaction
ISM	immersed solid method
TSV	tooth space volume

The rotational speed of the pump is also limited from approximately 500 to 3000 rpm. Moreover, 2D numerical simulation does not exactly predict the internal flow characteristics and flow rate. During the operation of an external gear pump, the flow phenomena are complex and include three-dimensional (3D) flow, turbulent flow, and two-phase flow due to cavitation. Therefore, 3D simulation of an external gear pump is challenging, and the computing time is much longer than for a 2D simulation due to complexities in geometry and flow phenomena.

Very recently, Castilla et al. [14] simulated the internal flow of an external gear pump using a complete 3D model running on a LINUX cluster with a solver developed with the OPENFOAM Toolbox. They focused on the overall 3D flow, principally in the chamber, and on the meshing zone. The numerical model included a decompression slot, which cannot be simulated with a 2D approximation, but no leakage in the lateral gap was considered. However, simulation of the leakage flow in the lateral gap is crucial because this leakage is one of the main factors for lower pump efficiency. The rotational speed of the pump was 500 rpm. No model was used for turbulence and cavitation.

In the present work, 3D numerical simulation of an external gear pump was performed for more realistic prediction of pump performance and internal flow phenomena by considering leakage in the lateral gap. We focused on the effects of design parameters on the flow rate and flow characteristics. A small gear pump designed to cool electric devices which generates heat in fighter aircraft was used to develop the numerical model. High cooling performance is essential for these cooling systems of the aircraft and motor vehicle [15]. For validation of the model, experiments were performed under the same conditions of high rotational speed as the numerical simulation. Flow rates were compared for theoretical, numerical, and experimental results. We used a commercial computational fluid dynamics code, ANSYS CFX 14.5, to simulate the extreme operating conditions of the pump.

The main components of the gear pump are shown in Fig. 1. The pump is required to operate at an extremely high rotational speed of 10,000 rpm. To consider flow phenomena in the gear pump, the fluid flow was assumed to be turbulent. Prediction of the internal flow is highly complex due to the rotation and meshing process of the gears. Furthermore, the flow pattern shows unsteady fluid flow.

The mesh deformation and remeshing method utilizes an algorithm that generates a new mesh during run-time depending on the gear position and local mesh quality. At each time step the grid is deformed due to the new gear positions, and a routine automatically decides whether this grid needs to be remeshed or not depending on the mesh quality. Compared to the ISM, the gear surface is accounted for in a way that the near wall region can be treated more accurately by turbulence models. Also, multi-phase flows can be calculated. However, the main disadvantage is that remeshing in small gaps is almost unavoidable for almost every angle increment [16]. The time step size needs to be small in order to compute the mesh deformation accurately. Every remeshing needs interpolated results from the previous time step, which can result in interpolation errors. Furthermore, the remeshing method must use an automatic grid generation program. Such programs usually use unstructured mesh elements that result in high elements numbers within the gaps or in poor mesh quality within the gaps. Thus, it can be very difficult to obtain a converged solution for extreme operating condition of 10,000 rpm using the mesh deformation and remeshing technique.

The immersed solid method (ISM) was used to overcome the numerical difficulties. The ISM simplifies calculation of small gap problem saving computing time significantly. During the simulation the region of overlap is determined each time step and momentum sources are applied to force the fluid there to follow the motion of the gear. The advantage of this method is that the initial grids can be used for the whole simulation as remeshing