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THEORETICAL ASPECTS REGARDING THE DEVELOPMENT OF A METHOD FOR INTERNAL VOLUME DETERMINATION OF EXTERNALLY GEARED PUMPS

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Abstract: *The article is focused on the literature study of determining the capacity of an external gear pump by applying Computational Fluid Dynamics (CFD) technology. The solution proposed by the authors involves theoretical research and early numerical simulations on the gear pump to evaluate its performance under various conditions such as suction and discharge. The pump housing was modeled using Autodesk Inventor and the simulation was performed with ANSYS software. The theoretical model proposed by the authors is complemented by CFD simulations, which provide insights into how factors such as suction and discharge affect flow. The obtained results through mathematical modeling correlated with the simulations results allows a comprehensive understanding of the pump's behavior and characteristics, thus validating and refining the flow determination model through empirical data.*

Keywords: *Externally geared pump, computational fluid dynamics, mechatronic system*

1. Introduction

Gear pumps are one of the most common types of pumps and are used in a wide range of applications because of their reliability, compactness, reduced purchasing costs and good efficiency. The two main types of gear pumps are external and internal gears, which can be divided into several categories based on the profile of the teeth. One significant benefit of externally geared pumps is their ability to handle a wide range of fluid viscosities and temperatures, making them suitable for diverse applications across various industries, from automotive to aerospace.
These pumps are often used in hydraulic systems where precise control of fluid flow and pressure is required, such as in heavy machinery, industrial equipment, and hydraulic power units. Overall, externally geared hydraulic pumps are valued for their reliability, efficiency, and versatility, making them a crucial component in many hydraulic systems where consistent fluid power is essential.
High efficiency and overall performance in these systems stands to benefit from a much better understanding and modelling of the pump being used. As such, a clear characterization of the pump’s internal capacity will be the starting point of any model that might allow it to be included in an Industry 4.0 capable system, such as a digital twin or digital shadow. However, given the difficulties encountered in estimating characteristics and mostly incomplete documentation, such a model, especially one that allows for high precision, is usually hard to include. A method for determining key parameters is described in this paper. To this end, a study of current developments in the field has been conducted, with some of the results being listed below.

2. Previous and related works

An external gear pump is a positive displacement device that transfers the fluid from the suction port to the discharge port by means of the gear of the drive and the secondary gear. In the gap between the teeth of the two gears, the fluid is transferred from the suction to the discharge of the

pump [1-3]. Several studies have been conducted in the last few years to develop simulation procedures for describing pump fluid dynamics, with numerical methods becoming more prevalent for modeling fluid problems. Current CFD simulations use the finite volume method (FVM) and the finite element method (FEM). They allow the analysis of complex technological processes and the stimulation of various starting and boundary conditions [1,3]. According to Močilan et al. [1], the use of advanced CAD and CFD techniques for product design and simulation has significant applications in the fields of mechanical, automotive and aeronautical engineering. In their paper a strong emphasis was performed on CAD simplification. Their results show that it is possible to predict the dynamic behavior of a pump with an external gear, with good approximation of the phenomena that occur during the operation of these devices such as fluid pressure distribution on, torque in gear movements and many others. A novel approach to capture detailed micron gap information and accurate model of these machines is described in a paper [2], using the commercial CFD tool PumpLinx. Analysis of gear pumps can be integrated into the product design and development process by using PumpLinx simulations in conjunction with test results for system level optimization, including dynamic response and efficiency performance.
Another methodology was adopted in paper [4], where attention was given to structuring the simulation in three iterative calculation phases with great emphasis on the correct characterization of the involute gear tooth profile. To comply with the space requirement and the tooth production constraints, it is designed to ensure proper volumetric displacement. The second calculation step therefore provides the design of the driving shaft and corresponding dimensions for journal bearings based on an analysis pressure load estimation coupled with operating parameters. Lastly, the third part of the procedure will lead to an estimation of clearance for gear tip and housing by means of a power failure approach. The application of this methodology to a case study of a multistage gear pump used in a dry sump lubrication system for an automotive heavy-duty engine illustrates the potential of this methodology. Each calculation step shall be laid down in accordance with the proposal for an analytical formulation and results of parameter calibration shall be disclosed. In this context, a CFD analysis shall be used to assess the procedure. The accuracy of the methodology for the estimation of the required flow rate is highlighted in the results. In addition to being accurate, flexible and reliable, the procedure stands out as an innovative tool in a multistage gear pump system.
The authors in [5] use advanced CFD models of hydraulic gear pumps to study their performance. The focus is put primarily on the numeric aspects, with a view to defining strategies for simulating oil dynamics in gear pumps. Two rotary pumps of fixed displacement type belonging to a family of gear pumps are proposed to be investigated. Three main steps, namely preprocessing, process and post-processing, form part of the study carried out to analyse these pumps as in classical computational fluid dynamics simulations. Another method is presented in paper [6]: a prediction of cavitation at high speed in helical gear pumps, to develop a hydrostatic dynamometer system. The fluid movement is described by means of several stages of fluid transfer from the pump inlet to the outlet, using a variety of meshes and densities.
In [7] the leakage past the tooth flanks of the gears in transition contacts in involute external toothed gear pump is analyzed in detail using CFD in Fluent®. The experimental flow diagrams are supported by analytical results. More rigorous analyses are carried out, considering the actual gear data of the pump and the full cycle of contact, to extend the approach of the earlier investigation.
By using the powerful ANSYS 16 CFX module, the authors of the paper [8] investigate the hydrodynamic behavior of the 8/9 teeth annular gear pump. Until the advent of Ansys immersed solid technology, it was difficult to solve solids that were evolving inside liquids. Reliable results can be obtained by using this technology in very specific areas such as CFD analysis of micro annular gear pumps, which can lead to more detailed studies such as geometrical optimization of functions and existing equipment.
A CFD model of an external gear pump is presented in [9]. One of the commercially available CFD software packages has been chosen to study fluid flow phenomena that occur when external gear pumps are used. To simulate the flow caused by the rotation of the gears, the immersed solid method has been used. The results of simulation studies performed for the different operating

parameters to assess the influence of rotation speed and pressure in the outlet channel on the cavitation intensity, a prepared 2D CFD model has been used.

The current design of external gear fuel pumps shows that flow processes at the meshing zone have an important impact on performance and lifetime, according to analysis provided [10]. In the opening and closing of the cavity in the meshing zone, the incorrect geometry of the truss plate and the compensation system leads to an increase in velocity, which results in intense cavitation. This approach does not give an objective result, although it is possible to determine the true values of pressure and load in relation to angle of rotation. However, as a basis for validation of the flow model, high speed scanning can be applied.

Another effort is described in paper [11] where a moving-deforming grid study was carried out using Fluent®, a commercial CFD solver. The goal was to quantify the level of mixing of a lower viscosity additive (at a mass concentration below 10%) into a higher viscosity process fluid in a big metering device pump configuration, common in plastics manufacturing.

A new method for simulation and evaluation of hybrid external gear pumps using Modelica has been presented [12] and is currently being tested. The authors modeled the entire working process of an external gear pump. The pump chamber is divided into a set of control volumes, the effective volume of which changes with the rotation of the gears. The CVs take in fluid from the inlet port and squeeze fluid out at the outlet port. Flow ripple, pressure distribution, leakage age, meshing conditions and so on are also considered in the overall design of the pump. Details are provided for each com portent of the entire pump. From pressure distribution in the gear tooth space, the radial force on the shaft can be calculated, based on which shaft movement can be simulated.

For fluid power applications, [13] presents a computational fluid dynamics simulation of an external gear pump. The objective of this study shall be to test the model's ability to evaluate pressures within a tooth space for both total shaft revolutions as well as lowest inlet pressure in all filling. The model considers leakage from the internal fluid system and two different configurations of thrust plates have been considered. A proper high dynamic transducer measuring the internal pressure in the tooth space for the entire shaft revolution has been used to validate the simulations in different operating conditions. To determine the drop-in flow rate, due to incomplete filling of tooth spaces when the pressure at the upstream is decreased, stable simulations have also been performed. It was shown that significant results could be obtained despite the need for compromise to overcome limitations on considering fixed axes of gear and thrust plates, which make a CFD approach very suitable for such analysis.

According to [14] it is difficult to obtain an accurate CFD simulation of a component due to its geometric complexity and high-pressure gradients, which characterize the design of flow fields for gears. In general, assumptions are made about the geometrical characteristics and physics to be considered in the analysis. In 3D CFD simulations, due to the intrinsic limitations of dynamic meshing techniques that can hardly effectively cope with a zero or near zero gap point formed during gear rotation, contact between teeth is an essential factor for proper functioning of these pumps. CFD analysis is complex, due to geometric complexity and sharp gradients in the gear pump flow field that characterize it, therefore avoiding contact with gears' teeth is a crucial feature. In [14], a gear pump composed of inlet and outlet pipes was considered, and the contact between the gear’s teeth was modeled in two different ways, one where it is effectively implemented and one where it is avoided using distancing and a proper casing modification.

To achieve energy savings, partial electrification of hydraulic circuits requires increasing the angular velocity of positive displacement pumps with a risk for incomplete filling. In this context, the paper [15] deals with the development of a computational fluid dynamics CFD model using SimericsMP+ for two external gear pumps, namely helical and spur type pumps. The study's objective shall be to analyze phenomena occurring on the Suction side under conditions where the fill is not completed at fast speeds.

A methodology is presented in [16] to predict the motion of a gear pump within its operational range. Complete pump parameterization was done through standard tests, and these parameters were used to create a bond graph model to simulate the unit's behavior. In field tests, this model has been validated on an experimental basis. To do so, experimental data were compared with a simulation of the volumetric behavior in the same conditions where the pump was used for auxiliary movements on the drilling machine. This paper describes a method for classifying each hydrostatic pump as a black box model predicting its behavior in all operational conditions. The novelty of this method is based on the correspondence between the variation of the parameters and the internal changes of the unit when working in real conditions, that is, outside a test bench.

3. Material and method

Externally geared hydraulic pumps are devices used to generate fluid flow within hydraulic systems. These pumps consist of two gears, an input gear (driven by a motor or engine) and an output gear, enclosed within a housing. The gears mesh together and rotate, creating suction at the inlet side and forcing hydraulic fluid out of the outlet. Starting from the suction phenomenon of the hydraulic fluid, caused by the depression produced by the teeth coming out of the gear, to the discharge phenomenon produced by the gear teeth entering the gear of the pump construction. The aim is to determine the flow supplied by the pump at a speed, n, and the power generated. The pump flow is obtained by taking a quantity of fluid in each impeller tooth space and conveying it from suction to discharge. It is determined by the volume of hydraulic fluid conveyed at one complete rotation of the impellers.
The authors propose the following approach to determine the flow rate of the gear pump by integrating two methods (mathematical modeling and numerical simulation) to obtain more accurate and robust results.

3.1 Analytical method

The flow rate in a gear pump can be determined analytically by a mathematical model that integrates the fundamental principles. Gear pumps belong to the category of positive displacement pumps, which transfer a fixed volume of fluid with each revolution of the gears. Flow rate can be affected by many factors such as: gear dimensions, rotational speed, distance between components and fluid properties. To determine the mathematical model some assumptions are made: fluid incompressibility, that is usually true for most hydraulic oils; steady-state operation conditions; gear imperfections and wear are excluded, if necessary, they can be considered by changing the efficiency parameters.
According to literature the following flow rates are determined analytically: theoretical flow rate, theoretical instantaneous flow rate and theoretical average flow rate. Notation from the theory of fine mechanics mechanisms (fig. 1) will be used to describe the areas of the tooth crowns that contribute to the pump backflow. Using the theory of mechanisms to determine the geometry of the gears in gearing the following expression was obtained:

$$Q_t = b\left\{n_1\pi\left[r_{e_1}^2 - \left(A - r_{e_2}\right)^2\right] + n_2\pi\left[r_{e_2}^2 - \left(A - r_{e_1}\right)^2\right] - n_1 z_1 H\right\} \tag{1}$$

where:
Q_t - theoretical flow; b- the length of the contact line for a pair of teeth; n_1- speed for gear 1; r_{e_1}- radius of the tooth pitch circle (for gear 1); A- gear center distance; r_{e_2}- radius of the tooth pitch circle (for gear 2); n_2 - speed for gear 2; z_1 - teeth number of gear 1; where:
The theoretical instantaneous flow rate is expressed as a function of the angle of rotation, φ, resulting in the following relationship [17]:

$$Q_{ti} = \pi \cdot n \cdot b\left[r_{e_1}^2 + i \cdot r_{e_2}^2 - \frac{i}{i+1}A^2 - (i+1)r_{b_1}^2\varphi_1^2\right] \tag{2}$$

By integrating on a circular arc of length $\frac{\pi}{z}$, we obtain the mean theoretical flow rate with the expression:

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$$Q_{tm} = \pi \cdot n \cdot b \left[r_{e_1}^2 + i \cdot r_{e_2}^2 - \frac{i}{i+1} A^2 - (i+1) \frac{\pi^2 m^2 cos^2 \alpha}{12} \right] \quad (3)$$

For pumps with gear ratio, $i = 1$, the equation becomes:

$$Q_{tm} = \frac{\pi n b}{2} \left[d_e^2 - A^2 - \frac{\pi^2 m^2}{6} cos^2 \alpha \right] \quad (4)$$

where: α – angle of engagement; m – module.

For a unit transmission ratio, the theoretical displacement V_t, the theoretical displacement of the pump can be written as follows:

$$V_t = 2 \cdot z \cdot b \cdot f \quad (5)$$

where: $f = 0{,}5 \cdot p \cdot 2m$ and $p = \pi \cdot m$

From the above relations the equations for theoretical displacement and theoretical flow rate can be written as follows:

$$V_t = 2\pi \cdot m^2 \cdot b \cdot z \quad (6)$$

$$Q = 2\pi \cdot m^2 \cdot b \cdot z \cdot n_0 \quad (7)$$

Through observations made over time by specialists and researchers, it has been found that this type of pump also exhibits a displacement and flow unevenness, which at a unity transmission ratio has the frequency, $v_0 = z \cdot \frac{n_0}{60} [Hz]$

where: $n_0 \left[\frac{rot}{min}\right]$ – instantaneous operating speed; z – number of gear teeth;

Therefore, the non-uniformity coefficient can be expressed as follows:

$$\delta_Q \% = \frac{\pi^2 m^2 cos^2 \alpha}{d_e^2 - A^2} \quad (8)$$

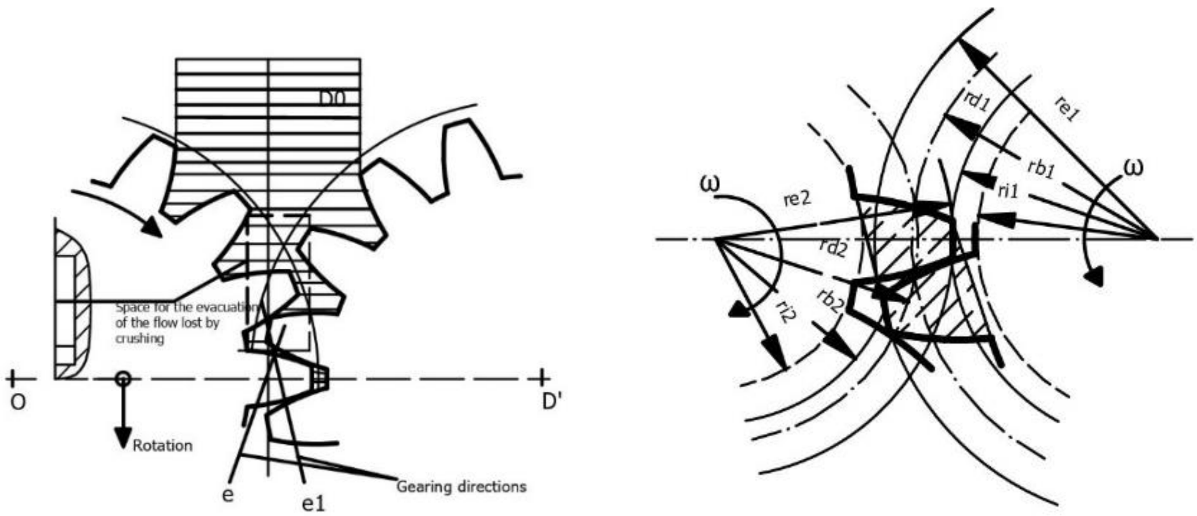

Fig. 1. Gear calculation parameters

3.2 Simulation method

CFD can be used to study and determine the fluid flow behavior inside the gear pump, particularly fluid dynamics influence on performance, efficiency and design. Computational fluid dynamics is based on numerical methods to solve complex equations governing fluid flow. Partial differential equations describe the manner in which momentum, energy and mass transfer occur in the fluid. Precise boundary conditions that define inlet and outlet pressures, flow rates and gear rotation speeds are imposed. Hydraulic fluid properties and thermal effects are taken in consideration in the gear pump model. Gear pump geometry is modeled by dividing the structures into smaller elements. The pump consists of two interlocking gears enclosed in a housing, the hydraulic fluid trapped and pressurized between the gear teeth and the walls. Fig. 2 illustrates a test conducted on a 2D model of a hydraulic gear pump. The geometry of the pump was initially modeled in Autodesk Inventor and then imported into Ansys Fluent. Design Modeler was used to extract the surface of the face and generate the mesh. In the first step, the network was created with default values. In the subsequent stage, element dimensioning was performed and to enhance the mesh quality, the triangle method was employed. Named selections were established for each component of interest, including the two gears, inlet, outlet and fluid. Improvements to the mesh quality in the toothed areas of the gears were achieved through additional element dimensioning in those regions. General simulation settings were configured, specifying the solver type, time and 2D space. Following this, model settings were adjusted in the viscous model sub-menu. The fluid and its composition were selected from the materials database. The cell zone status was set to fluid based on the chosen database entry. Boundary conditions were defined for each pump component in the model. To define the motion of the gears, a User Defined Function (UDF) was created for each gear.

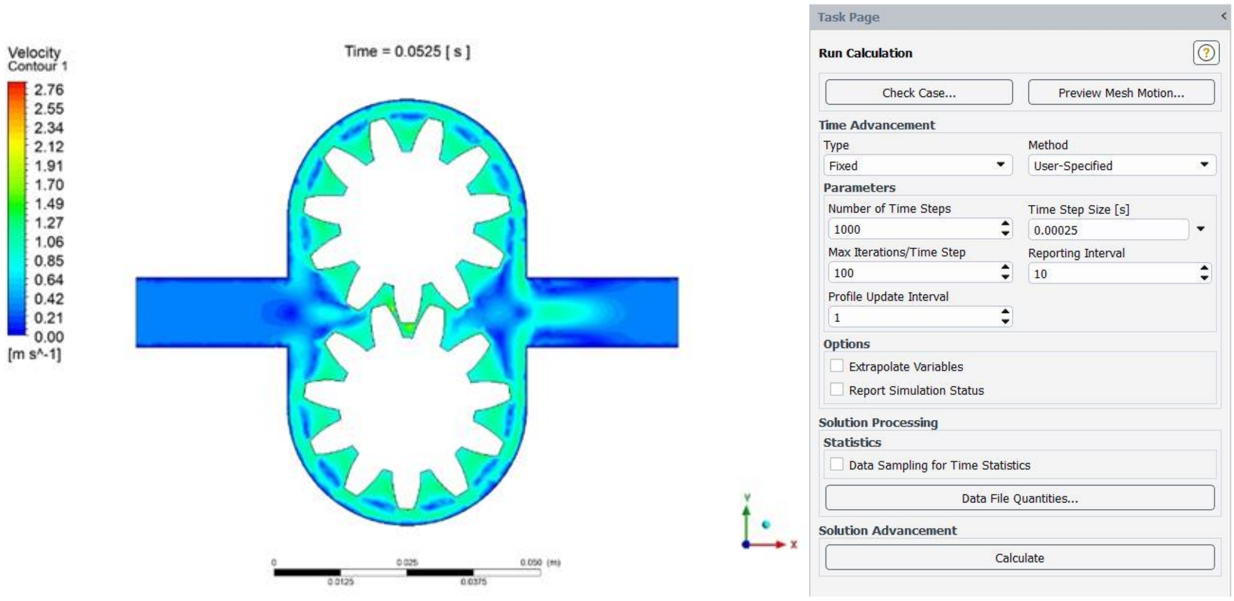

Fig. 2. Simulation parameters

The functions were then loaded into the library from the parameters and customization menu, specifically from the user-defined function section. Mesh methods were selected in the dynamic mesh settings, and the relationships between the UDF functions and the two gears were established. The solution method was chosen for each parameter in the menu. All zones were initialized using the 'Initialize' menu. Simulation parameters, such as the number of time steps, time step size, maximum iterations, and reporting interval, were configured in the 'Run Calculation' submenu, fig. 2. Subsequently, the 'Calculate' option was selected. After simulation, velocity, pressure and residual results were obtained. These simulations are at an early stage, with the phenomena taking place inside the pump to be studied further in more detail.

4. Conclusions

External gear pumps are a tried and tested design in hydraulic systems. However, there are still many aspects of how these mechanisms work that are still either incompletely described or could be improved. Using this aspect as a starting point, the authors tried to propose a methodology that could be applied to better understand and characterize the behavior of this type of pumps, with direct effects on the control of both pressure generation and flow characteristics. By mathematical modeling the flow rate in a gear pump, performance can be predicted under various operating conditions. It is fast, cost-effective and allows designs to be optimized before moving on to more detailed simulations or physical tests. More accurate results can be obtained by using advanced techniques such as CFD for the validation of the model. The fluid interaction with the mechanical components can be better understood with CFD. Valuable information can be revealed about pressure distribution, flow patterns and possible failure causes, such as cavitation or excessive wear. The performance of the gear pump could be optimized before the physical prototype is built by using CFD simulation results correlated with mathematical model result to modify the primary model with improved parameters core. As such, the paper first observes a general survey of how these gear pumps are simulated, with a strong focus on mathematical modeling and CFD simulations being prevalent in the field.

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