A STUDY ON THE EFFECTS OF BODY DEFORMATION ON THE PERFORMANCE OF EXTERNAL GEAR MACHINES

Ajinkya Pawar*, Andrea Vacca[1], Manuel Rigosi[2]

[1]*Maha Fluid Power Research Center, Purdue University, Lafayette, IN, USA*
[2]*Casappa S.p.A., Parma, Italy*

* Corresponding author: Tel.: +1 765-426-1654; E-mail address: pawar10@purdue.edu

ABSTRACT

The energy efficiency of external gear pumps (EGPs), similar to all positive displacement machines used for high-pressure applications, is significantly influenced by the power losses occurring in the lubricating interfaces that seal the internal displacement chambers. Therefore, it is crucial to account for these interfaces accurately, when developing predictive simulation tools. However, the literature has suggested various modelling approaches for EGPs, with different assumptions regarding the analysis of these interfaces. This makes it challenging for a designer or a researcher to determine what are the essential physical domains needed for properly modelling the lubricating interfaces and assess the EGP performance.

This paper addresses the above research question by leveraging a comprehensive simulation tool (Multics-HYGESim) developed by the authors' research team to compare the effect of different modelling assumptions. HYGESim includes tribological considerations pertaining to the meshing of the gears, the lubricating films at the tooth tip interfaces, at the journal bearings, and at the lateral interfaces. It also considers realistic fluid properties, including the effects of cavitation and aeration, mixed lubrication effects, as well as material deformation effects for the gears, lateral bushings and the EGP housing. Deformation of the internal parts of an EGP is related to the internal balancing features and it is strongly coupled with the instantaneous pressurization of the pumping volumes. For this reason, a realistic quantification of these effects is difficult in simulation.

Using a commercial EGP design as a reference, with known experimental volumetric and hydromechanical efficiency, this paper demonstrates how predictions can vary based on different simulation assumptions regarding body and lubricating film behaviours. Results are discussed starting from a basic rigid-body assumption that considers only body motion and analytical formulations of lubricating interfaces, to simulation model cases of progressively increasing in complexity to account for deformations of gears, bushings and housing. The results show that consideration of deformation effects allow more accurate prediction of power losses and efficiencies of the pump while simulations carried out without deformation considerations approximate the leakages and the power losses at the lateral lubricating interface though can predict the fluid dynamic performance. These findings will offer valuable insights to EGP designers, enabling them to understand the strengths and limitations of different modeling assumptions on the prediction of EGP behavior, especially regarding the effects of body deformation.

Keywords: External gear pumps, Pump Efficiency, Simulation, Power loss, Body deformation

1. INTRODUCTION

Despite the basic concept for external gear pump (EGP) dates back centuries, EGP technology has been constantly evolving to follow technical trends. In fact, the EGP design is among the most cost-effective ones for positive displacement machines [1]. EGPs also have good performance features, in terms of efficiency, durability, resistance to different forms of contamination. It is therefore natural for an engineer or a researcher to consider application of an EGP to address new applications. For this reason, EGPs can be seen in automotive, aerospace, industrial, mining, construction and agricultural application. And their design is constantly adapting to new application requirement. A significant example is the recent electrification trend in mobile applications, which is bringing to new EGP designs that can better cope with electric prime movers [2]. Therefore, there is a clear need of providing the technical community with the most accurate possible simulation tools, that are able to properly account for the key physical aspects affecting the operation and the energy efficiency performance of EGPs.

Figure 1 shows a typical bearing-block type pressure-compensated EGP design used for high pressure operation. Other EGP designs, with or without lateral compensation, do exist, as mentioned in [1,3], but still involving the same fundamental principles. The fluid is displaced across a pressure difference using rotation of externally engaging spur gears. The radial loads acting on gears are supported using journal bearings while lateral compensating bearing blocks are pressure against the lateral surface of gears to minimize the leakages in axial direction. From a physical perspective, the operation of an EGP can be divided into three domains. First, the fluid domain comprising of the volumes inside the machine such as the inlet and outlet volume, spaces between the gear teeth through which the main displacing action occurs. Second, the solid domain, which comprises of the floating bodies such as gears, the lateral bushings and the housing. Third, the lubricating interface domain, which comprises of thin fluid films between floating bodies which function as load support mechanisms. Additionally, these domains interact with each other leading to a multi-domain coupled operation of an EGP which is challenging to model using simulation techniques.

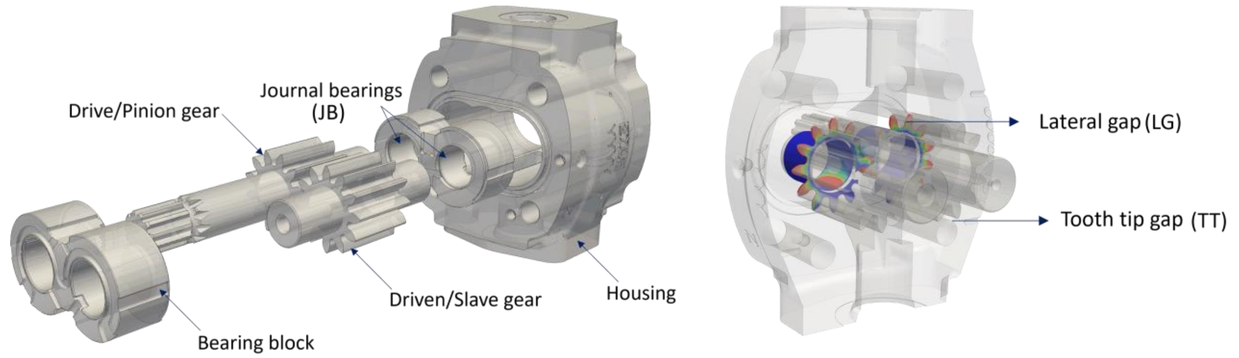

Figure 1: Illustration of a typical pressure compensated EGP and its lubricating interfaces

Over the past few decades, various simulation methodologies of varying complexity have been proposed, that aim to analyse the physical phenomena in one or more operating domains of an EGP as well as the interactions between them. The related papers, as it will be further discussed, shows good correlation with experiments for all these approaches. Therefore, it can be challenging for a designer to understand the strengths and the limitation of each approach.

Models to analyse of fluid displacing action of EGPs in the fluid domain can be classified into three main categories namely analytical models, lumped parameter models and computational fluid dynamics (CFD) models. *Analytical models*, similar to the work by Manring and Kasaragadda [4], Ivantysyn and Ivantysynova [1], provide a theoretical description of fluid flow inside EGPs and can estimate the kinematic flow ripple using the geometrical information, but do not consider the effects of compressibility of the fluid. The lumped parameter models, such as the works by Vacca and Guidetti [5], Borghi et. al [6], divide the fluid domain into a number of control volumes, and solve mass conservation as well as fluid transport equations to determine the fluid flow and pressurization behavior inside the pump. *Lumped parameter models* are very powerful in simulation of EGPs as they are computationally inexpensive and can help estimating physical phenomena such as outlet pressure ripple, loads acting on the floating components due to fluid pressure, effects of cavitation and aeration etc. The estimation of loads on gears also allows coupling of the fluid domain pressures with the micromotion of gears which can affect the fluid domain predictions significantly. One of the major drawbacks of these models is that they significantly approximate the behavior of lubricating interfaces inside the pump and use analytical approximations as well as lubricating film gap assumptions while estimating the power losses arising from these interfaces. Therefore, when it comes to torque efficiency prediction, these models cannot be considered most accurate. *CFD models*, as seen in the works of Castilla et. al [7], Frosina et al. [8], divide the fluid domain into infinitesimal meshes and solve the partial differential equations in a distributed mesh domain using numerical techniques and can accurately estimate the fluid flow and pressure behavior inside an EGP. These studies allow accurate estimation of fluid-related phenomena such as cavitation and incomplete filling of the machine, local effects of fluid inertia as well as bubble collapse and damage at the cost of higher computational resources. 3D CFD models can also approximate the lubricating interface behaviour with fixed geometry film gap to obtain better estimation of the volumetric losses in the EGPs. Although 3D CFD models can show capability of coupling the micromotions and deformation effects with fluid dynamic evaluation, the CFD studies on EGPs do not consider these effects.

The modelling of lubricating interface domain in EGPs including the above aspects is crucial to accurately predict both the volumetric and the torque losses, as well as to assess the durability of a given design. The behavior of the lubricating interfaces is significantly affected by the film gap height distribution which is a function of the motion and the deformation of the floating bodies forming these interfaces and thus is highly coupled with the solid body domain behavior of the pump. For this reason, models addressing only the fluid domain might not be sufficient, and *tribological models* should be introduced. Different models of this kind have been developed with different assumptions while analysing the behavior of various lubricating interfaces. Taking an example of the lateral gap lubricating interface in EGPs, studies such as the ones by Borghi et al. [9] assume a predefined gap height distribution to determine the film pressure distribution from solution of Reynolds equation. Dhar and Vacca [10] showed the effect of coupling the axial motion of the lateral bushing on the lateral film behavior assuming that the lateral bushing is always under the state of force balance. The same authors (Dhar and Vacca [11]) extended the model to include the effects of pressure and thermal deformation of lateral bushing in the lubricating film analysis. Thiagarajan and Vacca [12] extended this work to include the mixed lubrication regime modelling and effect of surface roughness on the lateral lubricating film power losses. A recent work from the authors' team [13] introduced the multi-domain simulation tool Multics-HYGESim, which allows the simultaneous/coupled analysis of different domains of an EGP. The tool, which will be further described in Section 2, has a modular structure, and can accommodate new modules such as the housing deformation and the gear meshing ones presented respectively in [14,15].

The current study aims to leverage the capabilities of Multics-HYGESim to analyse effects of different physical aspects associated with the operation of an EGP in terms of simulations. Simulation options of Multics-HYGESim, purposely introduced in this research, allows changing the complexity of the assumptions taken to carry out the analysis of the EGP on various levels.

For example, the model can analyse only the fluid domain along with consideration of gear micromotion, whilst simplifying the lubricating domain with analytical solutions of the journal bearing and using a constant gap height laminar equation to model lateral gap interface. While, the most physically and computationally complex simulation possible involves consideration of lubricating interfaces using solution of the Reynolds equation, along with effects of linear and tilting motions of gears and bushings, deformations of gears, bushings and the housing.

Using this flexibility of the simulation tool, four simulation cases with increasing complexity will be considered. The overall behavior of the reference pump will be compared across these four cases in terms of various parameters that are important for the EGP designers and manufacturers to prototype new high performing units. These parameters include comparison of differences in housing wear, overall Tooth Space Volume (TSV) pressurization, outlet flow/pressure ripple, volumetric and frictional losses from lubricating interfaces across four cases. Based on the comparison, the authors aim to establish a correlation between the effects of motion and deformation of different bodies on the performance characteristics of the machine. Finally, the results from the simulation tool in all four cases will be compared with experimental data of volumetric and hydromechanical efficiency, outlet pressure ripple and housing wear to understand the importance of consideration different physical effects during simulation, on the EGP performance prediction. This should help a designer to make proper decisions on the assumptions to make when simulating an EGP.

The remaining part of the paper is divided into three sections. Section 2, describes the simulation tool and the details of analysis of different domains in brief, followed by description of cases considered along with the underlined assumptions and level of complexity of physical effects that are evaluated during simulation. Section 3 describes the simulation operating conditions and gives detailed comparison of reference machine performance parameters and provides insights into correlation of physical aspects considered in simulation with the results. Section 4 talks about important conclusions and provides recommendations regarding physical aspects to consider during simulation to predict the different components of the EGP performance.

2. METHODOLOGY

2.1. Multics – HYGESim overview

Figure 2 shows the schematic of different solvers of the simulation tool and the domains of the machine they model.

Fluid Domain Modeling

The evaluation of fluid dynamic behavior takes place using the fluid dynamic solver where the pump domain is divided into multiple control volumes or tooth space volumes. Using a lumped parameter approach, pressure build-up equation (eq. 1) is solved for each control volume to predict the pressurization inside the pump. The flow between the control volumes through various geometrical connections such as the ones due to grooves on the bushings is modelled using orifice equation (eq. 2). The fluid dynamic solver also models the leakages at the gear tip – housing interface using a Couette-Poiseuille equation (eq. 3). A geometrical pre-processor is run to determine the variation of TSV volume, the time derivative of TSV volume, connection areas and diameters between different control volumes, and other geometrical parameters required by the simulation model as a function of rotation angle of the shaft gear. More details regarding the approach can be found in [5, 13].

$$\frac{dP_i}{dt} = \frac{K_T}{V_i}\left(Q_{in} - Q_{out} - \frac{dV_i}{dt}\right) \tag{1}$$

$$Q_{i,j} = sign(p_i - p_j)C_f\Omega\sqrt{\frac{2(p_i - p_j)}{\rho}} \tag{2}$$

$$Q_{i,j} = \left(-\frac{h_{i,j}^3(p_i - p_j)}{12\mu L} + \frac{v_{i,j}h_{i,j}}{2}\right)b \tag{3}$$

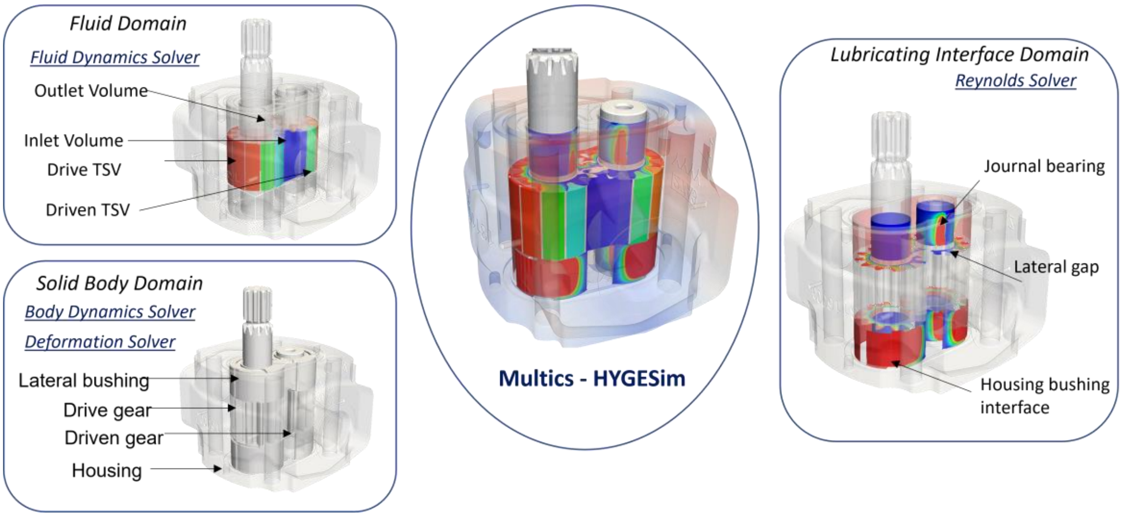

Figure 2: Different solvers in Multics-HYGESim simulation tool

Lubrication Domain Modeling

The behavior of lubricating films at journal bearing, lateral gap and casing-bushing interface is modelled by the Reynolds solver, which solves the universal mixed Reynolds equation (eq. 4). To estimate the contact forces based on the roughness profile of the bodies, an approach proposed by Lee and Ren as described in [13] is used which relates the gap height information of the film to the contact pressure in the regime of asperity contact. The mixed lubrication modelling allows evaluation of viscous as well as asperity friction (eq. 5) and accurate evaluation of power losses from the lubricating interfaces. To evaluate the meshing losses, a curve-fit relation proposed by Manne et al. [15] is used, to obtain which the authors simulated the EHL contact considering mixed lubrication effects.

$$\nabla \cdot \left(\phi_p\left(\frac{K_T h^3}{12\mu}\nabla\rho\right)\right) = \nabla \cdot \left(\rho\overrightarrow{v_m}(\phi_R R_q + \phi_c h)\right) + \nabla \cdot \left(\rho\phi_s R_q\left(\frac{\overrightarrow{v_t} - \overrightarrow{v_b}}{2}\right)\right) + \frac{\partial\left(\rho(\phi_R R_q + \phi_c h)\right)}{\partial t} \tag{4}$$

$$\overrightarrow{F_{fric}} = \int_{\Omega_{JB}}\left(\frac{\mu\overrightarrow{V_D}}{h}(\phi_f + \phi_{f,s}) + \frac{\phi_{f,p}h\overrightarrow{\nabla P}}{2}\right)dA + \mu_{Asp}p_C dA\overrightarrow{v_D} \tag{5}$$

Solid Domain Modeling

The solid domain modelling includes the body dynamics solver and the deformation solver. Body dynamics solver computes the linear and angular rigid body motion of floating bodies, i.e. the gears and the lateral bushings, by solving Newton's second law. The loads acting on bodies from TSV pressures, lubricating interfaces, contact forces as well as frictional forces are considered while evaluating the motion of the bodies. The deformation solver uses the influence matrix approach, which is based on finite element analysis under reference loads and scaling the obtained deformation based on actual loads as described in [10, 13], to determine the elastic deformation of the gears, bushings as well as the housing. The deformation of the gears can also be determined analytically by using Euler-Bernoulli beam theory and is chosen for this work as it is more computationally inexpensive.

The next section describes the simulation cases that are considered for the purpose of this study and the assumptions as well as physical phenomena considered for each case and the method of evaluation. It will also try to provide reasoning behind choosing these particular cases.

2.2. Simulation cases analysed

Figure 3 gives an overview of the simulation cases considered for the proposed study. For each case, the reference EGP will be simulated at corner operating conditions encompassing the overall operating region of the machine.

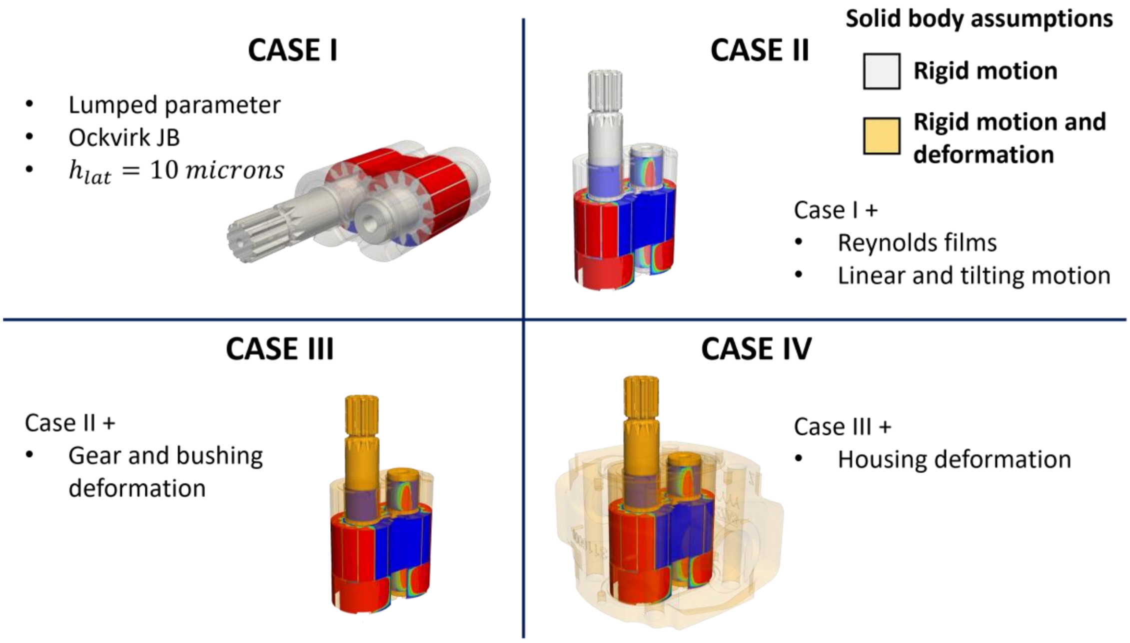

Figure 3: Overview of simulation cases considered

Case I: Lumped parameter simulation with analytical films

This case considers only the evaluation of fluid domain with rigid body micromotion of gears. The assumptions under this case indicate simulation framework used for multiple previous studies in analysis of EGMs using lumped parameter models [5, 6], which has been shown to predict the performance behaviour of the machine including the hydromechanical [16] and volumetric efficiency, housing wear [5] etc. As the simulation framework in this case uses only 0D equations, the analysis is computationally inexpensive and can be used for quick performance prediction of the machine with considerable accuracy and therefore is considered as one of the cases analysed in this study. Important assumptions involve the maximum discharge coefficient of orifices, which is considered as 0.7, and the constant lateral gap height of 10 microns, which is equivalent to average gap height at the lateral gap interface considering deformation and tilting effects. All other parameters are evaluated either based on geometry (such as areas and hydraulic diameters of orifice connections) or analytical equations (friction force evaluation at lubricating interfaces).

Case II: Rigid simulation considering lubricating domain

This case considers Reynolds films to model the film behavior at journal bearing, lateral gap and housing bushing interface. The simulation can estimate linear and tilting motion of the lateral bushing in addition to the motion of gears due to accurate pressure force and moment evaluations from the lubricating interfaces. This simulation case does not consider deformation effects, but can allow comparison with case I, with more accurate consideration of leakages and viscous losses, especially from the lateral gap interface without assumption of any rigid gap height. One of the advantages of this case is accurate estimation of forces and moments on the lateral bushing from the gear side, allowing accurate design of balancing features.

Case III: Simulation considering deformation of gears and bushings

This case estimates the pressure deformation of gears and lateral bushings and their effects of the lubricating interface behavior. Consideration of deformation of these bodies allow accurate estimation of the power losses from journal bearing and lateral gap interfaces as it does not involve any assumptions pertaining to lubricating film behavior except consideration of symmetric behavior of top side and bottom side films.

Case IV: Simulation considering deformation of gears, bushings and housing

In addition to gears and bushings, this case estimates the pressure deformation of the housing body of the machine. In the current study, this case aims to analyse the effect of housing deformation on pump performance parameters such as housing wear, frictional losses and leakages at lubricating interfaces. Compared to case III, this case removes the symmetric assumption of top and bottom side films, and simulates all 12 lubricating interfaces shown in **Figure 2**, providing the complete picture of EGP operating under isothermal conditions, but results in the most computationally expensive simulation.

3. RESULTS AND DISCUSSIONS

The reference unit, PHP20QW20.20 is simulated at 5 different operating conditions shown in **Table 1**. ISOVG-46 is considered as the operating fluid while the temperature is assumed constant at 50^o C. Nominal dimensions of the unit are considered for simulation. **Table 2** presents the EGP parameters. The simulations consider an initial wear-in simulation (at operating conditions suggested by the manufacturer), to derive a wear-in housing profile that is be used for the subsequent simulations of **Table 1**.

Table 1: Parameters of the reference EGP

EGP parameters	Value
Displacement	22.38 cc/rev
Type	Spur involute
Maximum operating speed	3500 RPM
Maximum operating pressure	250 bar, 300 bar (intermittent)

Table 2: Operating Conditions

Terminology	Operating speed and pressure
Low Speed Low Pressure (LSLP)	500 RPM, 50 bar
Low Speed High Pressure (LSHP)	500 RPM, 250 bar
Medium Speed Medium Pressure (MSMP)	1500 RPM, 150 bar
High Speed Low Pressure (HSLP)	2500 RPM, 50 bar

High Speed High Pressure (HSHP)	2500 RPM, 250 bar

3.1. Housing wear-in and fluid dynamic comparison

Figure 4a indicates the housing wear predicted by the simulation model and comparison with experimentally measured wear profile. Consideration of deformation is important as seen from case III and case IV results to predict the amount of wear on the housing surface. Case IV considers deformation of internal housing surface while determining the wear, allowing estimation of worn region at different axial sections as shown in **Figure 4b**, leading to a better prediction of the trend of housing wear with angle. Both cases III and IV overestimate the wear, though the magnitude of the wear lies within manufacturing tolerance region. There is a possibility that model is overpredicting the deformation of the lateral bushing and journal bearings which dictate the positions of gears inside the housing and the magnitude of the wear, as the influence matrix approach assumes a linear dependence of deformation of applied pressure. The contact zone between lateral bushing and the housing, as well as the journal bearing liner and the bushing can exhibit non-linear deformation effects, which the proposed model does not consider.

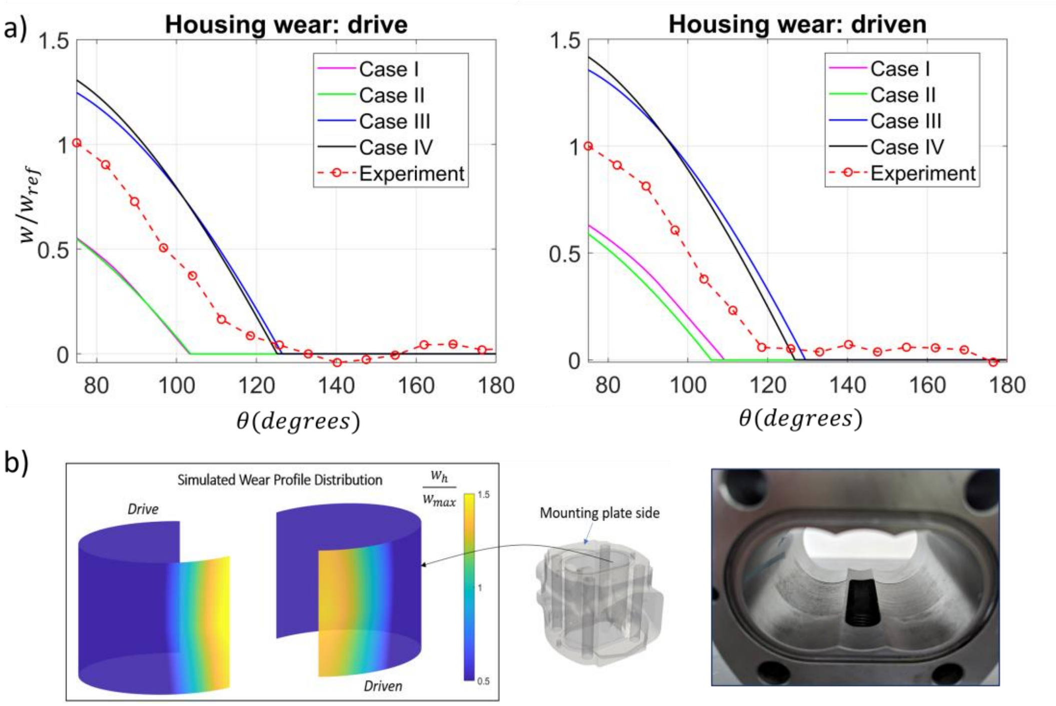

Figure 4: a) Comparison of housing wear for all cases **b)** 3D worn region prediction from case 4

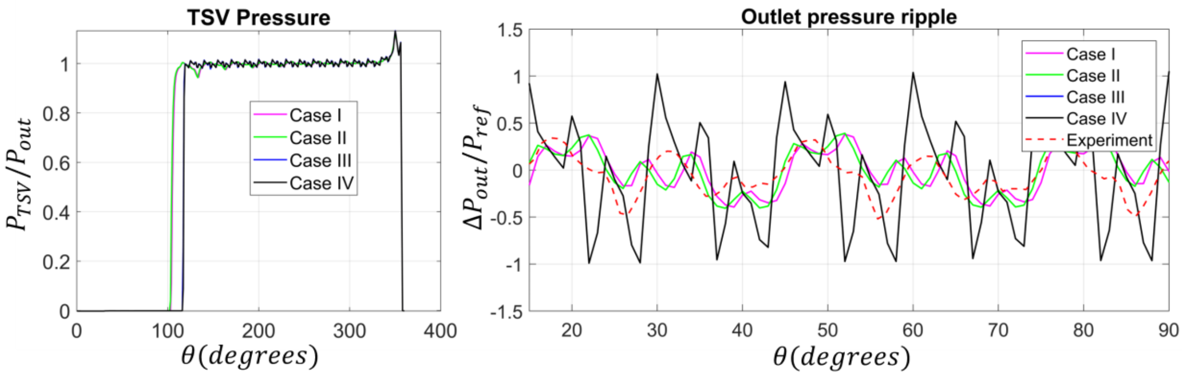

Figure 5: Comparison of TSV pressure and outlet pressure ripple for all cases

The housing wear profiles obtained from simulation are given as input to the model for corresponding cases. Figure 5 shows comparison of TSV pressurization and outlet pressure ripple of the pump at HSHP operating condition. Clearly, cases I & II, and cases III & IV show very similar fluid dynamic behavior. The positions of the gears inside the housing affect the fluid dynamic behavior significantly. Due to deformations of the bushings and the housing, the gears in cases III and IV are pushed towards the suction side by a larger magnitude. Additionally, the deformations of bodies negate the journal bearing effect seen in cases I and II at high speed, which tends to increase the minimum gap at the journal bearings leading to an inefficient sealing at tip-housing interface. Therefore, cases I and II show early TSV pressurization from tip leakages, while cases III and IV show TSV pressurization when the chamber is exposed to backflow groove leading to different fluid dynamics compared to cases I and II. Comparing the outlet pressure ripple, cases I and II show a peak-to-peak magnitude match of ripple compared to experiments while cases III and IV show higher ripple magnitude. The magnitude of deformation also affects the outlet pressure ripple and can be a reason for overprediction of peak-to-peak magnitudes.

3.2. Power loss and leakage prediction

Figure 6a indicates distribution of power loss predicted from different lubricating interfaces of the EGP at HSHP operation by the simulation model. Case I only involves lumped assumptions but can estimate the tooth tip as well as meshing losses accurately but fails to estimate losses at JB and LG interfaces due to not capturing the mixed lubrication effects and assumptions of constant gap at LG interface. Case II estimates the JB losses on approximately the same level as cases III and IV indicating mixed lubrication effects are more important in JB loss prediction as compared to deformation. Case IV can capture the losses arising from both top and bottom side films including the effects of tilting of the gear and shows a lower JB loss compared to case III, indicating importance of considering the asymmetric effects at this interface. Case II overestimates losses from LG interface. This can be explained from the lateral gap height comparison between cases II and III shown in **Figure 7.** As case II does not consider deformation, the value of gap height is seen to be very small throughout the film leading to higher frictional losses, while case III indicates that the minimum gap height region will be concentrated in the zone towards the suction groove. As case III does not consider tilting of gears, it predicts a higher zone of contact between gears and bushings, while case IV indicates that the losses from the LG interface are on the same order of meshing interface losses at HSHP operating condition.

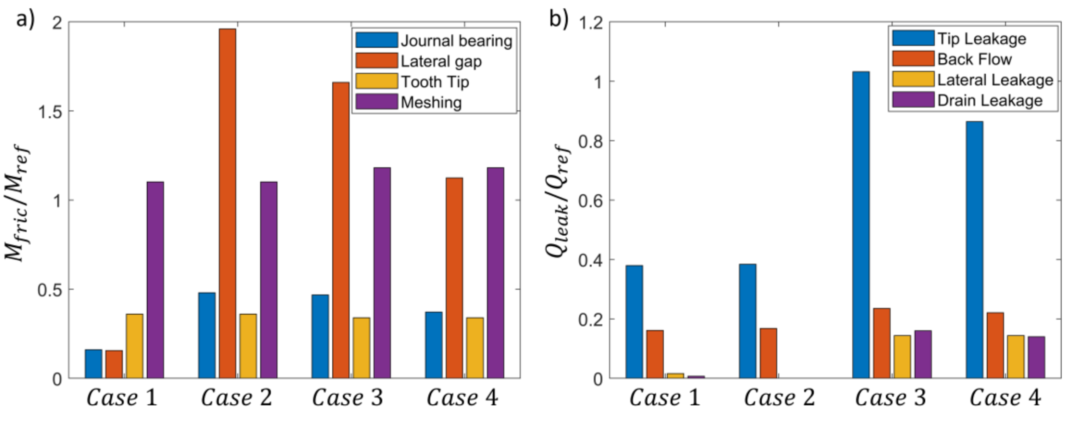

Figure 6: a) Comparison of frictional moment and **b)** leakages for all cases

Figure 6b presents comparison of leakages predicted by the simulation model for all cases at LSHP operating condition. It can be seen that all cases indicate radial or tooth-tip leakages to be the major contributor to volumetric losses in this type of EGPs. As tip leakages are gear position dependent, cases I & II and cases III & IV indicate similar values of radial leakages.

Case IV considers axial variation of housing wear as well as tilting of gears, providing a higher sealing towards the suction side while predicting tip leakages showing a smaller value compared to case III. Case I approximates the lateral and drain leakages using analytical expressions. Case II predicts negligible lateral and drain leakages due to very small gap heights as shown in **Figure 7** while cases III and IV show presence of leakages at the lateral film due to higher gap heights that are resulting due to deformation of the bushings. All cases show similar magnitude of backflow. As seen from **Figure 8a**, for LSHP operating condition, cases III and IV show better prediction the volumetric efficiency of the pump indicating that leakages are captured with higher accuracy. As the leakages at lateral gap interface depend highly on the gap height at these interfaces, the magnitude of deformation can significantly influence the leakages predicted by the simulation model. The same is true for tooth tip/radial leakages.

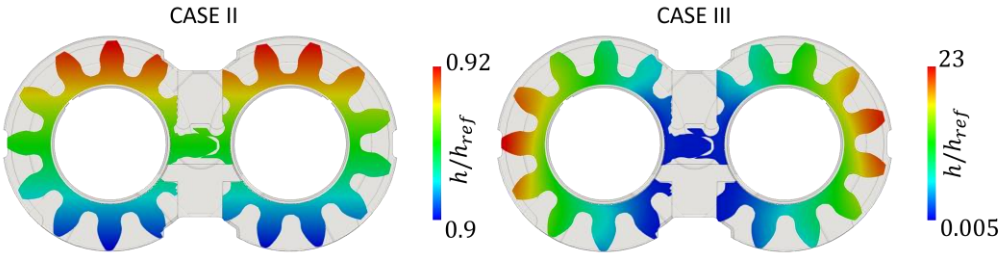

Figure 7: a) Comparison of gap height at lateral gap interface for cases II and III

3.3. Efficiency comparison

Figure 8a shows the comparison of volumetric efficiency with experimental values. Cases I and II overpredict the efficiency at lower speeds and underpredict the efficiency at higher speeds. One of the reasons for underpredicted efficiency by these cases would be smaller amount of movement of gears towards the suction resulting from no deformation considerations can reduce the volume of the fluid the pump actually displaces. The predicted volumetric efficiency from Case I is also a function the value of the lateral gap assumed. Consideration of deformations of all bodies can best help in predicting the volumetric efficiency trends as well as magnitudes. **Figure 8b** indicates importance of considerations of lubricating interface losses while predicting hydromechanical efficiency.

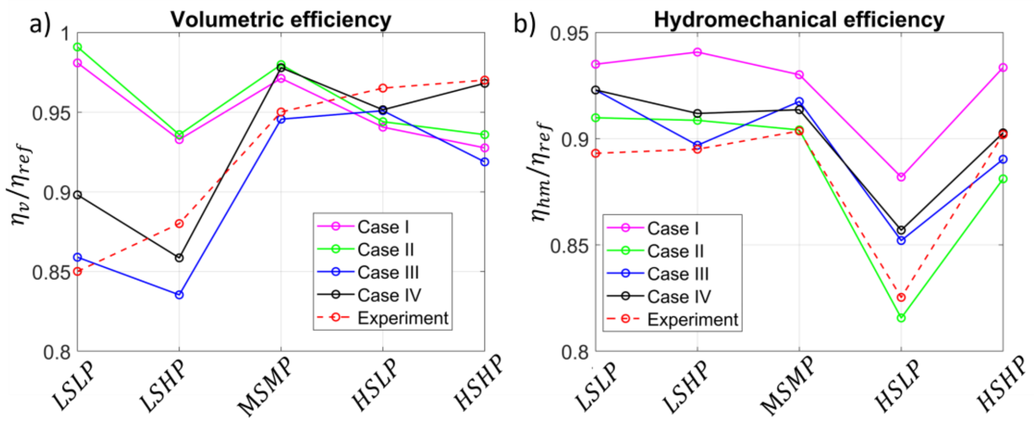

Figure 8: Comparison of EGP efficiencies predicted by simulation model with experiments for each case

4. CONCLUSION AND OUTLOOK

The current study uses the Multics.HYGESim simulation model developed by the authors to drive a study assessing the importance of different modeling assumptions to simulate External Gear Pumps (EGPs). The research intends to provide the technical community insights on the consequences of including or neglecting physical aspects that determine EGP operation. The particular focus is on the different ways the lubricating gaps (i.e. the tooth tip gap and the lateral gap) of an EGP can be modeled. Four different cases with increasing simulation complexity are considered:

Case I: Lumped parameter simulation with analytical films (Average t_{sim} = 2 minutes)

Case II: Rigid simulation considering lubricating domain (Average t_{sim} = 2 hours)

Case III: Simulation considering deformation of gears and bushings (Average t_{sim} = 2 days)

Case IV: Simulation considering deformation of gears, bushings and housing (Average t_{sim} = 5 days)

Although the simulation parameters for each Case could be further refined/adjusted for a better matching with experimental data, in this research all simulations were performed with the same modeling setting with respect to geometrical data, and coefficients to be used in modeling equations (orifice coefficient, transition between laminar and turbulent flow, etc). The main finding is that all the models have more or less pronounced limitations in matching available experimental data. It has to be remarked that the experiments could be reproduced more accurately by using actual measured geometrical clearances, rather than the using the nominal geometry of the reference machine as performed in this study. In particular, case 1 underestimates the losses from both leakages and frictional losses. Case 2, underpredicts the gap height at lateral gap leading to lower leakage and higher frictional losses. Case 3 shows a good prediction of gap height at the lateral gap interface, but considers symmetric assumptions and ignores gear tilting leading to higher tooth tip leakage prediction. Case 4 considers housing deformation which allows simulating the axially asymmetric nature of the EGP with inclusion of gear tilting in the model. These deformation considerations help in getting a good match of volumetric as well as hydromechanical performace of the EGPs.

What is most important to point out is that the designer should select the simulation assumptions based on the phenomena he/she would like to observe. In case the focus is on pressure ripple or average volumetric efficiency, a simplified simulation such as in Case I can be sufficient. However, it must be understood that there will not be any capability of detecting features such as chances of wear due to material contacts and accurate frictional loss as well as leakage through lubricating interfaces. Increasing the model complexity does not necessarily increase model accuracy in parameters that can be predicted by a simpler model, such as volumetric efficiency, but it can be applicable especially towards accurate modeling and design of lubricating interfaces in EGPs.

NOMENCLATURE

P_i	Pressure of i^{th} TSV
t	Time
K_T	Isothermal bulk modulus of fluid
V_i	Volume of i^{th} TSV
$Q_{in,out}$	Flow entering/exiting i^{th} TSV
$Q_{i,j}$	Flow through flow connections between i^{th} and j^{th} TSV
C_f	Flow coefficient of the orifice
Ω	Area of the orifice
ρ	Density of the fluid
μ	Viscosity of the fluid
L	Width of the tooth tip
$h_{i,j}$	Tooth tip gap height at tooth separating i^{th} and j^{th} TSV

$v_{i,j}$ Tooth tip velocity at tooth separating i^{th} and j^{th} TSV
$\varphi_{P,R,C,S}$ Flow factors for mixed lubrication modeling
h Gap height at lubricating interface
$\overrightarrow{v_{m,t,b}}$ Velocities of surfaces bounding the lubricating interface

REFERENCES

[1] Ivantysyn, J., and Ivantysynova, M., 2003, “Hydrostatic pumps and motors”. New Dehli, India: Tech Books Int.

[2] Zappaterra F., Vacca A., Sudhoff S.D., "A Compact Design for an Electric Driven Hydraulic Gear Machine Capable of Multiple Quadrant Operation," Mechanism and Machine Theory, 177, 10504, 2022.

[3] Stryczek J, Fundamentals of designing hydraulic gear machines, PWN, 2021

[4] Manring, N., D., and Kasaragadda, S., B. 2003, “The Theoretical Flow Ripple of an External Gear Pump," Journal of Dynamic Systems, Measurement, and Control, vol. 125, no. 3, p. 396.

[5] Vacca, A., Guidetti, M., 2011, "Modelling and Experimental Validation of External Spur Gear Machines for Fluid Power Applications," Elsevier Simulation Modelling Practice and Theory, 19 (2011) 2007–2031.

[6] Borghi, M., Zardin, B., Specchia, E. 2009, “External Gear Pump Volumetric Efficiency: Numerical and Experimental Analysis”, SAE Technical Papers, doi: 10. 4271/2009- 01- 2844.

[7] Castilla, R., Gamez-Montero, P-J., Ertrk, N., Vernet, A., Coussirat, M., Codina, E., 2010, “Numerical simulation of turbulent flow in the suction chamber of a gearpump using deforming mesh and mesh replacement”, Int. J. Mech. Sci. 52 (10) 1334–1342.

[8] Frosina, E., Senatore, A., Rigosi, M., 2017, “Study of a high-pressure external gear pump with a computational fluid dynamic modeling approach”, Energies 10 (8) 1113.

[9] Borghi, M, & Zardin, B. "Axial Balance of External Gear Pumps and Motors: Modelling and Discussing the Influence of Elastohydrodynamic Lubrication in the Axial Gap." Proceedings of the ASME 2015 International Mechanical Engineering Congress and Exposition. Volume 15: Advances in Multidisciplinary Engineering. Houston, Texas, USA. November 13–19, 2015.

[10] Dhar S., Vacca A., A novel CFD – Axial motion coupled model for the axial balance of lateral bushings in external gear machines, Simulation Modelling Practice and Theory, Volume 26, 2012, Pages 60-76, ISSN 1569-190X

[11] Dhar S., Vacca A.,, A novel FSI–thermal coupled TEHD model and experimental validation through indirect film thickness measurements for the lubricating interface in external gear machines, Tribology International, Volume 82, Part A, 2015, Pages 162-175

[12] Thiagarajan, D., Vacca, A., 2017, "Mixed Lubrication Effects in the Lateral Lubricating Interfaces of External Gear Machines: Modelling and Experimental Validation," Energies, 10(1), 111.

[13] Ransegnola, T., Zappaterra, F., Vacca, A., 2022, "A Strongly Coupled Simulation Model for External Gear Machines Considering Fluid-Structure Induced Cavitation and Mixed Lubrication," Applied Mathematical Modelling, 104, 721-749.

[14] Pawar A., Vacca A., and Rigosi M., "Prediction of housing wear-in in external gear machines considering deformation effects, ASME Symposium of Fluid Power and Motion Control, 2023

[15] Manne VHB, Vacca A. And Singh K., 2023 A Curve-fit Traction Coefficient Relation of Mixed EHL Line Contact with Hydraulic Fluid and Steel Surfaces, Tribology Transactions, 66:2, 364-380

[16] Rituraj R., Vacca A., Rigosi M., Modeling and validation of hydro-mechanical losses in pressure compensated external gear machines, Mechanism and Machine Theory, Volume 161, 2021