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A lumped parameter and CFD combined approach for the lubrication analysis of a helical gear transmission

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Abstract. This paper proposes a combined 1D-3D approach for the lubrication analysis of a standard transmission including two helical gears. A lumped parameter model of the entire lubrication system is developed to predict the flow distribution within the circuit and the localized pressure drops along the lines. This model considers the geometrical features of the real system, and it combines the experimental characteristic curves of the main hydraulic components. The steady-state condition is investigated, and the corresponding lubrication flow is provided as a boundary condition for a three-dimensional CFD model. The overset mesh method is employed to address the instantaneous position of the gears in the contact region and the Volume of Fluid (VOF) model assesses the multi-phase phenomenon. The turbulent behavior of the flow is described by the two-equation realizable k-ε model, and the incompressible assumption is made for both oil and air. The effect of different nozzles configurations on the lubrication efficiency is analyzed and the internal system fluid-dynamics is investigated to point out the oil path. The numerical results are discussed in terms of the volume fraction of oil on the gears teeth, the passive torques at the shafts and the associated power losses under specific operating conditions.

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1. Introduction

A helical gear transmission represents a fundamental part of a vehicle since it transforms the rotation of the engine shaft into the longitudinal movement. Recently, many analyses have been done to improve these kinds of systems. In [1], a detailed optimization of the component has been performed to enhance the efficiency by reducing both weight and noise emissions.

Transmission performance have been largely investigated in terms of wear, lubrication, noise, and thermal phenomena. In [2], different experimental studies compare the wear behavior of the gear teeth, considering many specific material treatments. In [3], a platform for transmission testing vibration was assembled to achieve the influences of heat, load, and rotational speed on the dynamic behavior under different working conditions. A specific worm gear pair has been experimentally analyzed in [4] to predict the effect of different lubricating conditions on several tribological properties like wear and friction. A poor quality of these parameters negatively affects the efficiency of the system in terms of both high energy losses and frequent maintenance.

However, the experimental approach may not always represent the best solution for the lubrication analysis due to intrinsic difficulties in the sensor placing. Therefore, numerical approaches have gained more and more importance in the last decade, thanks to the very high computational power of modern computers.

In [5], a FEM (Finite Element Method) simulation of a spur planetary gear for high-speed applications provides the influences of flexibility and fitting status on the stresses and elastic deflections of the internal ring gear. A similar approach is exploited by [6], where a two-dimensional finite element analysis highlights the contact between two loaded gear teeth to estimate the heat generated by friction.

Nevertheless, a fundamental part in the gear transmission design is to ensure the proper lubrication of the teeth in the meshing region. For this reason, the CFD (Computational Fluid Dynamic) approach can be successfully exploited to investigate the internal oil distribution. In [7], the lubrication and temperature characteristics of a standard gearbox are studied through an appropriate CFD model, which exploits the multiple reference frame (MRF) method to simulate the flow field produced by the gears' rotation. In [8], the entirely three-dimensional domain of a novel concept for axle dry braking system is discretized and the flow turbulent characteristic is implemented by the two-equation realizable k-epsilon model. Moreover, the multi-phase nature of the flow is addressed by means of the VOF (Volume of Fluid) approach. A similar analysis is shown in [9], where the CFD simulation of a cogeneration system highlights the reaction of liquid aluminium and water steam.

Beside the three-dimensional CFD approach, the 0D-1D methodology provides a huge support during the design phase of complex hydraulic systems, and it finds several applications in the automotive and agriculture industries. In [10, 11], the authors suggest a lumped parameter model for the optimization of specific lubrication circuits, while in [12], the heat transfer results from a CFD analysis are exploited in a 0D-1D model of a three-piston water pump.

This paper deals with a combined lumped parameter and CFD analysis of the lubrication process in a helical gear transmission for automotive applications. The main target of the simulation is to investigate the effects of different nozzle layouts on the internal oil distribution as well as to predict the corresponding viscous losses produced by the gears' rotation.

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2. Materials and methods

A lumped and distributed parameter model of the entire lubrication system was implemented within the Simcenter Amesim software, [13]. In Figure 1, the layout of the hydraulic circuit is shown as an interconnection between multiple Amesim components.

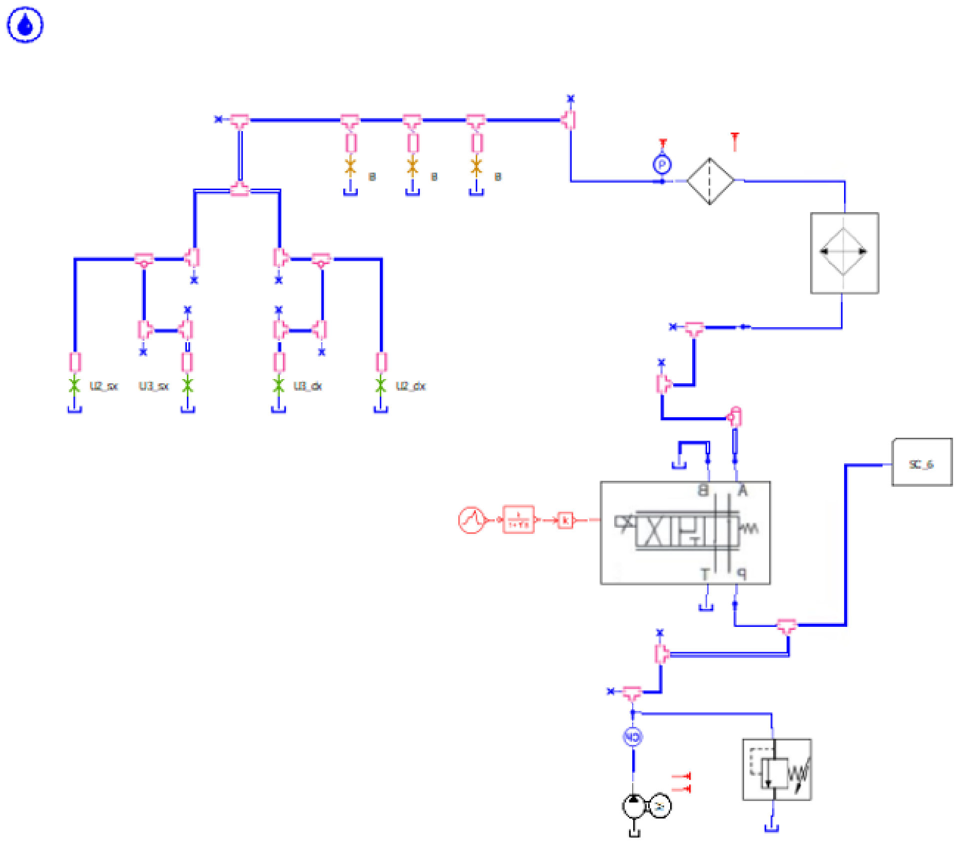

Figure 1. Hydraulic circuit lumped parameter model

The oil jet lubrication of the entire transmission was achieved by means of seven parallel nozzles, whose diameters were chosen as to meet the flow rate requirements at both gears and bearings, thus ensuring a proper lubrication of the components. The oil was supplied by a fixed displacement pump while a pressure relief valve was installed to set the maximum working pressure of the system. The numerical models of these components were previously validated against experimental results under different working scenarios. Similarly, the actual characteristic curves of both the filter and the cooler were included in the simulation. A proportional distributor was finally adopted to adjust the flow direction. In this paper, the lubrication condition was only addressed, which corresponds to a null excitation of the solenoid. Nevertheless, different tasks could be performed by switching the directional valve to the other positions. The fluid properties were evaluated at constant temperature of 85°C. The flow rate Q through the nozzles was the main result of the simulation as it represented the boundary condition for the three-dimensional CFD model.

The proposed CFD analysis was performed on the STAR-CCM+ platform, licensed by Siemens [14]. This study focused on a limited portion of the entire transmission, and it considered only two helical gears, i.e., the driving gear and the driven gear, and a single lubrication nozzle. In Figure 2, a transparent representation of the external case reveals the geometry of the internal components.

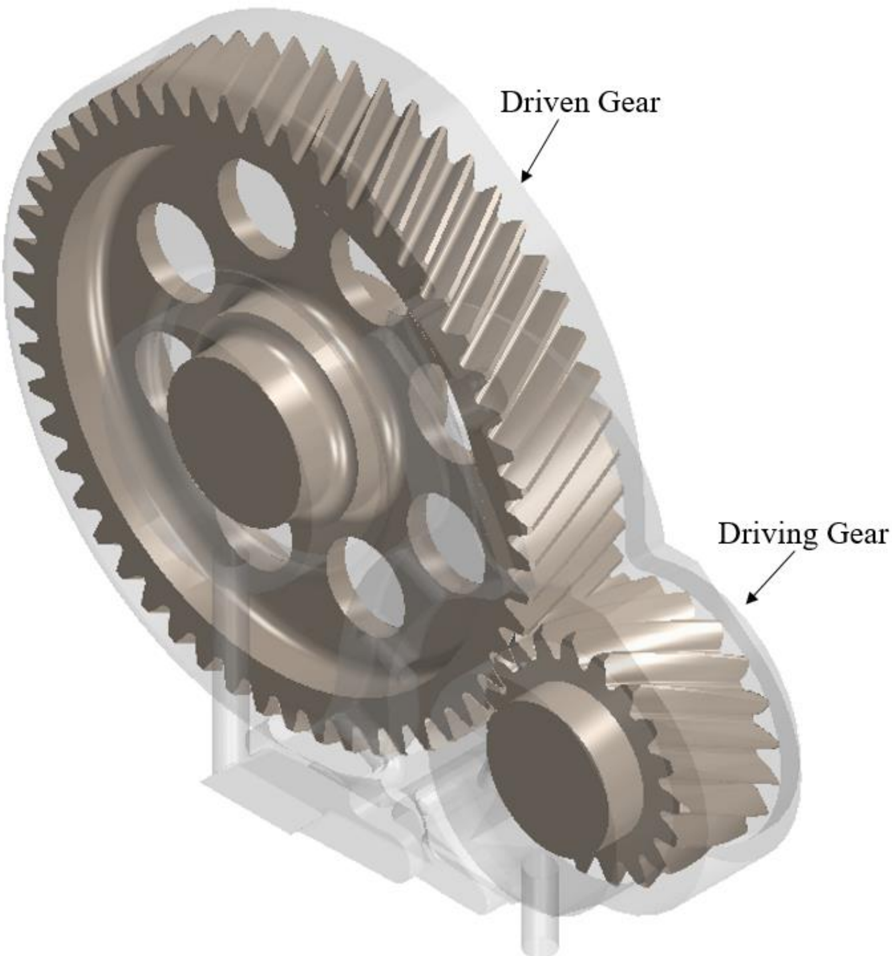

Figure 2. 3D helical gear transmission geometry

This work is based on the overset mesh approach, a characteristic tool of the software which allows simulating the motion of one or more objects within a limited computational domain by means of different overlapping meshes. In details, this procedure requires a background region which encloses the entire solution domain, while separate overset regions surrounding the moving bodies are used to instantaneously update the geometrical features of the system.

For this reason, an overset region was implemented for each single gear, while a common background region was created to define the outer limit of the fluid domain. The trimmed cell mesher was chosen for the full geometry discretization and a mean base size of 0.7 mm was selected for both the background and the overset regions. The prism layer mesher was farther included to improve the results accuracy within the viscous boundary layer and a first-layer absolute thickness of 0.25 mm proved necessary to reach a high defined mesh. in the teeth meshing area. Moreover, local mesh refinements were performed to ensure a proper coupling between the overset and the background regions. In particular, different volumetric controls were set in the gears meshing region and in front of the nozzles. Finally, a frontal section of the mesh is shown in Figure 3a, while the overset hole-cutting process appears from Figure 3b, where the fluid domain after the interfaces initialization is highlighted. In Figure 3c, a zoomed view of the computational grid in the teeth meshing area is reported.

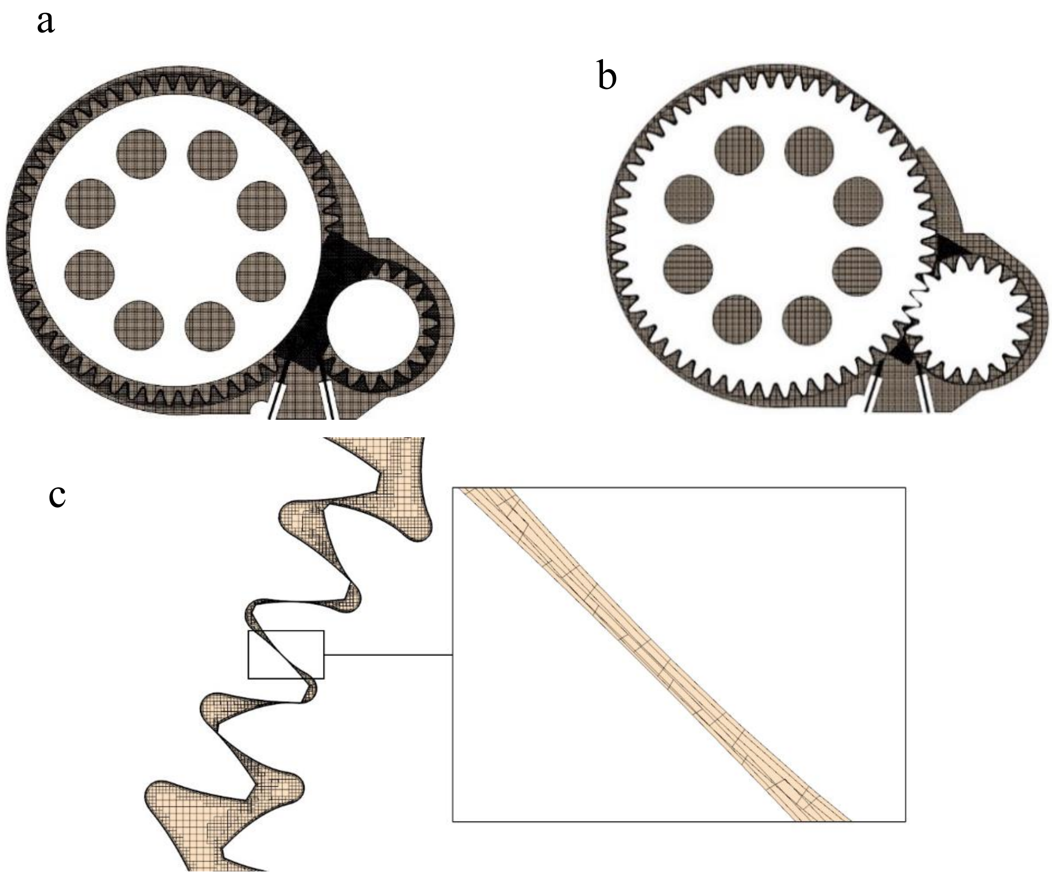

Figure 3. (a) Background and overset mesh; (b) Initialized interfaces' mesh (c) Detail of the helical gears' teeth mesh

Separate local coordinate systems were used to implement the rotational kinematics of the gears and an actual working scenario of the transmission was reproduced in terms of both gears' rotational speeds and directions. Therefore, a clockwise rotation was assigned to the driving gear and a rotational speed ω_1 was set to the corresponding overset region. Consequently, the driven gear was fitted with a counterclockwise rotation while the characteristic gear ratio of the reducer was exploited to derive the rotational speed ω_2 ($\omega_1 > \omega_2$). ω_1 and ω_2 will remain indicated as parameters for the rest of the paper due to a non-disclosure agreement undersigned with the company.

The oil distribution within the gears chamber was addressed by means of the Volume of Fluid (VOF) multiphase methodology, where both oil and air are defined as Eulerian phases. The properties of the fluids were assessed at the working temperature of 85°C and an isothermal flow was considered. The liquid phase was represented by a DCT-F3 incompressible mineral oil typically adopted in automotive applications, while the ideal gas model was assigned to the air phase. Moreover, the interaction between the two phases was included and a surface tension of 0.035 N/m was defined at the interface. A full list of the fluid properties is also provided in Table 1.

Table 1. Properties of the fluids

Fluid	Physical Property	Value
Oil	Density @ 85°C	802.5 kg/m^3
Oil	Dynamic Viscosity @ 85 °C	0.007 Pa*s
Air	Dynamic Viscosity @ 85 °C	1.855 Pa*s
/	Surface Tension	0.035 N/m

Furthermore, the two equation Realizable K-Epsilon model has been employed to predict the turbulent characteristic of the flow and the all-y+ wall treatment was exploited to improve the mesh flexibility. The temporal discretization of the investigated phenomenon was achieved by the first-order implicit unsteady model and a computational time step of $5.0*10^{-5}$ s was chosen as the best tradeoff between variables' convergence, results' accuracy, and computational demand. The segregated flow solver was finally adopted to separately solve the Navier-Stokes equations. A schematic summary of the CFD model setup is presented in Table 2.

Table 2. Simulation parameters

Parameter	Value
Solver	Segregated
Time step	$5.0*10^{-5}$ s
Driving gear rotation direction	Clockwise
Multiphase approach	Volume of Fluid (VOF)
Turbulence model	Realizable K-Epsilon
Thermal model	Isothermal

In this paper, the effect of the lubrication jet on the system performance was investigated and three different nozzle configurations were analysed to detect the best layout in terms of both power losses and gears lubrication. The standard solution is depicted in Figure 4a, where a single nozzle directs the oil flow towards the teeth meshing area. In Figure 4b, the total flow rate Q was equally split between two separate nozzles with crossed jet directions, i.e., one pointing to the driven gear and the other one pointing to the pinion. Conversely, the third configuration shows two parallel nozzles arranged towards the driven gear. In Figure 4c, a section view of the fluid domain highlights only one of them.

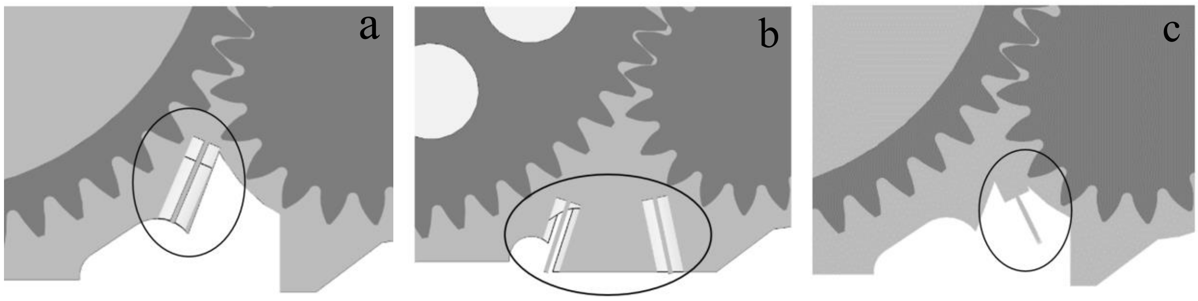

Figure 4. (a) Single nozzle; (b) Crossed nozzles; (c) Parallel nozzles

Finally, the entire set of simulations is reported in Table 3, including the inlet flow rate at each nozzle.

Table 3. List of simulations

Case #	Configuration	Nozzle flow rate
1	Single nozzle	Q
2	Crossed nozzles	Q/2
3	Parallel nozzles	Q/2

3. Results

In this chapter, the numerical results of the CFD analysis are discussed in terms of plots and images to evaluate the oil distribution within the system along with the hydraulic resistive torques and the power losses produced by gears rotation, thus proving the effects of different nozzle configurations. Moreover, this work aims at the definition of the optimal nozzle layout which ensures a quick lubrication of the gears from the very first opening of the hydraulic circuit. For this reason, a specific report was used to monitor the percentage of oil on the teeth of both gears over the simulated time interval, i.e., 0.3 s. In Figure 4, the evolution of the oil volume fraction on the teeth surfaces is reported for each architecture, while an instantaneous comparison at 0.3 s is provided in Figure 5.

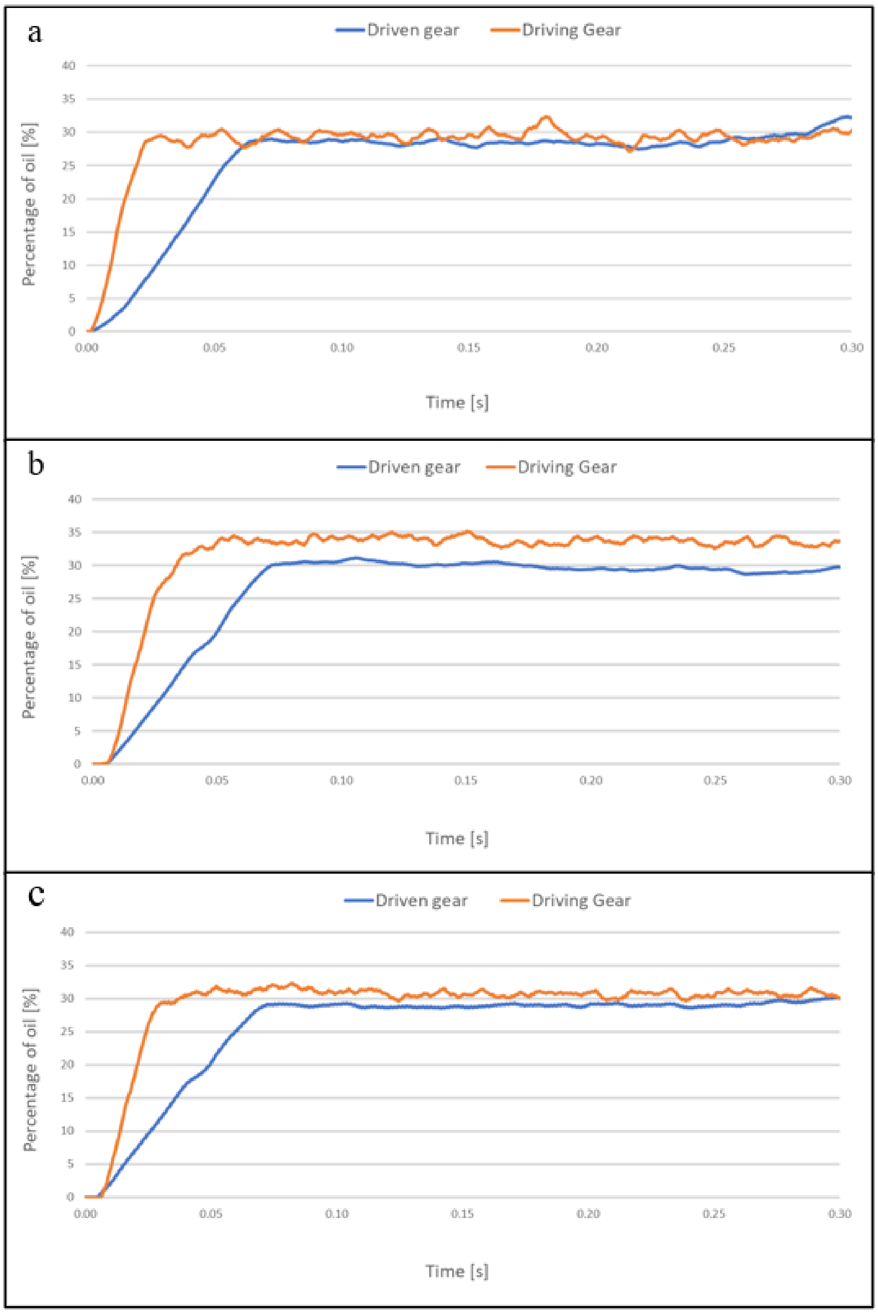

Figure 5. (a) Single nozzle; (b) Crossed nozzles; (c) Parallel nozzles

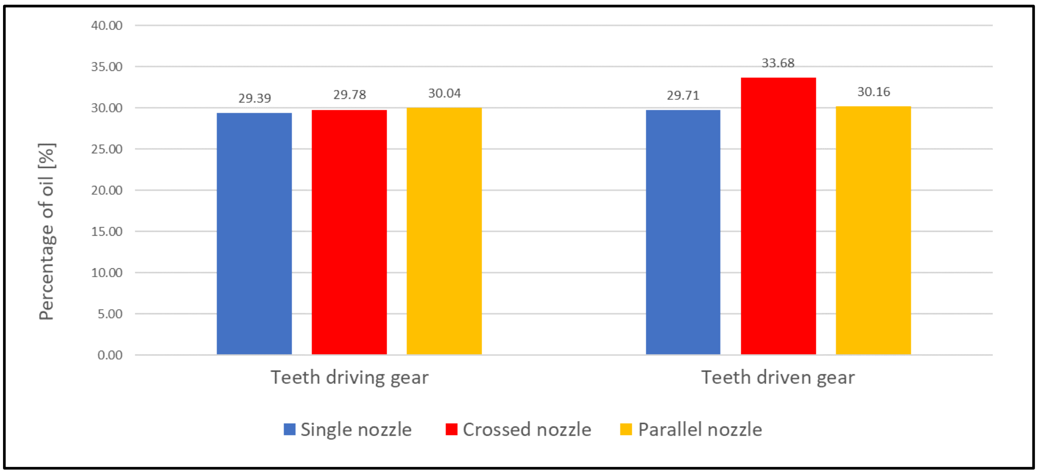

Figure 6. VOF percentage on teeth at 0.3 seconds instant

These plots showed very similar results for the driving gear, while a 3% increment of the volume of oil on the driven gear was found in Case #2 with respect to the other two configurations, thus suggesting a better lubrication of the component. Moreover, a faster lubrication of the driving gear was always observed. This is mainly due to the higher rotational speed along with the smaller outside diameter of the pinion.

Figure 6 shows a qualitative view of the oil distribution on the gears' surfaces in Case #2. The image refers to the final time step of the simulation.

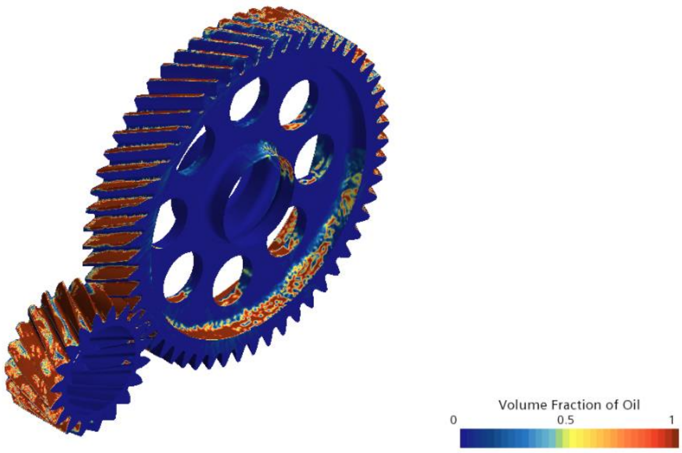

Figure 7. Oil distribution on the gears' surface

Finally, the resistive torques and the corresponding power losses were investigated to fully characterize the transmission from the hydraulic point of view. This analysis is part of a very actual topic for many automotive applications, namely the reduction of the system internal losses which leads to higher levels of the efficiency. In particular, the power losses are strongly influenced by the amount of oil on the gears surfaces as it inevitably generates friction, thus representing an obstacle to the shaft rotation. In Figure 7, the hydraulic passive torques from both gears are reported for the different nozzles' configurations. The curves were normalized with respect to measurements from Case #2 and they are presented here in percentage terms.

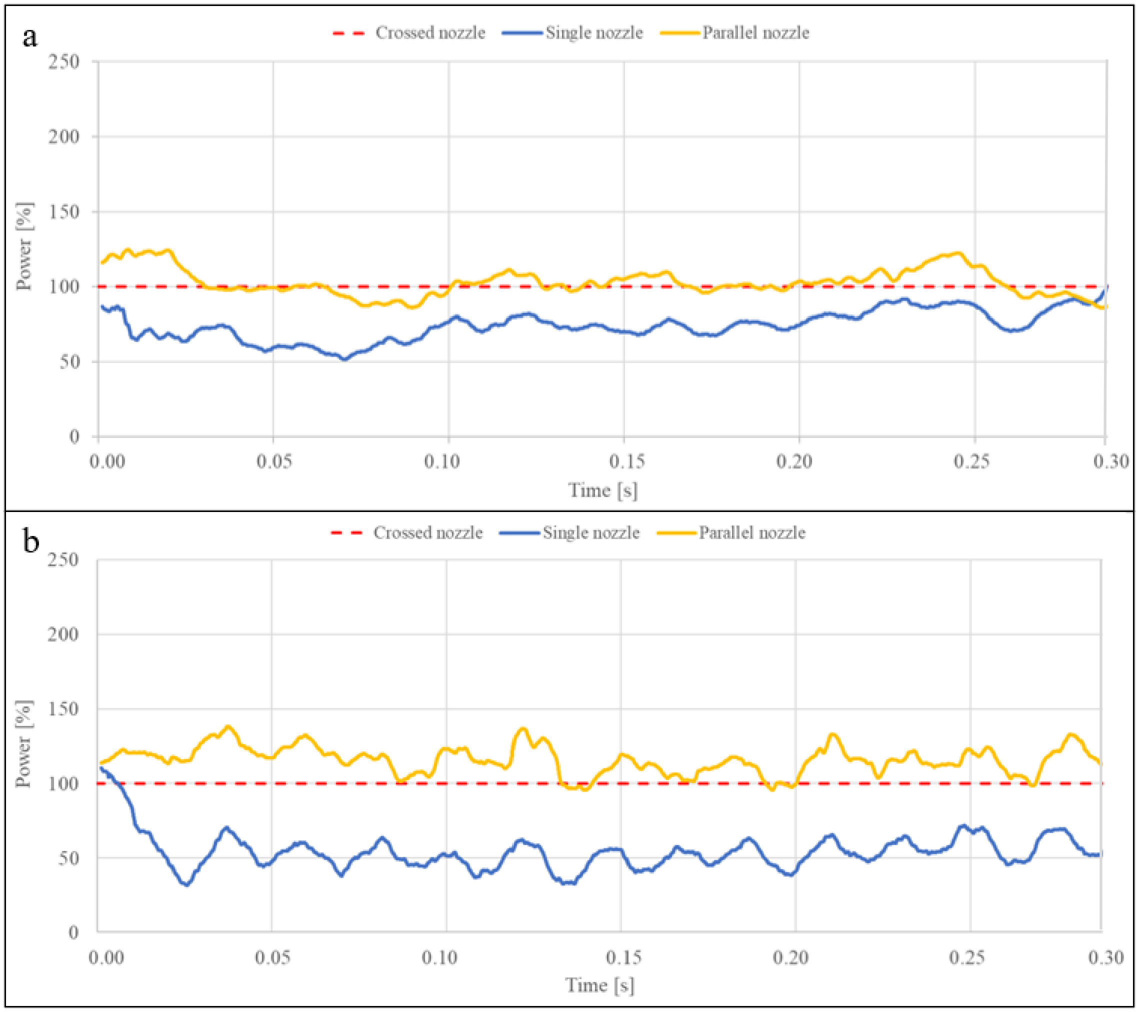

Figure 8. (a) Driven gear losses; (b) Driving gear losses

The relationship between passive torques and power losses is given by Eq. (1). For this reason, the previous percentage results stand for both powers and torques.

$$P = T_{passive} * \omega_{shaft} \tag{1}$$

These trends highlighted a significant reduction of the power losses in Case #1 with respect to the other two configurations, while very similar values were obtained for both Case #2 and Case #3. This result was mainly linked with an evident oil accumulation near the teeth meshing region of the double-nozzle architectures. Indeed, the slightly different volume fractions of oil measured on the teeth surfaces in the proposed configurations could not explain such a high discrepancy between passive torques. The previous analysis assesses the oil fraction on the overall teeth surface, but it cannot precisely estimate any oil accumulations within the system, especially in the teeth meshing zone, which certainly represent the major source for power losses, since a higher friction coefficient in that zone is more relevant than in any other part of the system. For this reason, three-dimensional images of the entire fluid domain were exploited to detect areas with larger quantities of oil. In Figure 8, a threshold representation of the volume fraction associated with the liquid phase shows the final oil distribution within the transmission for each nozzles arrangement.

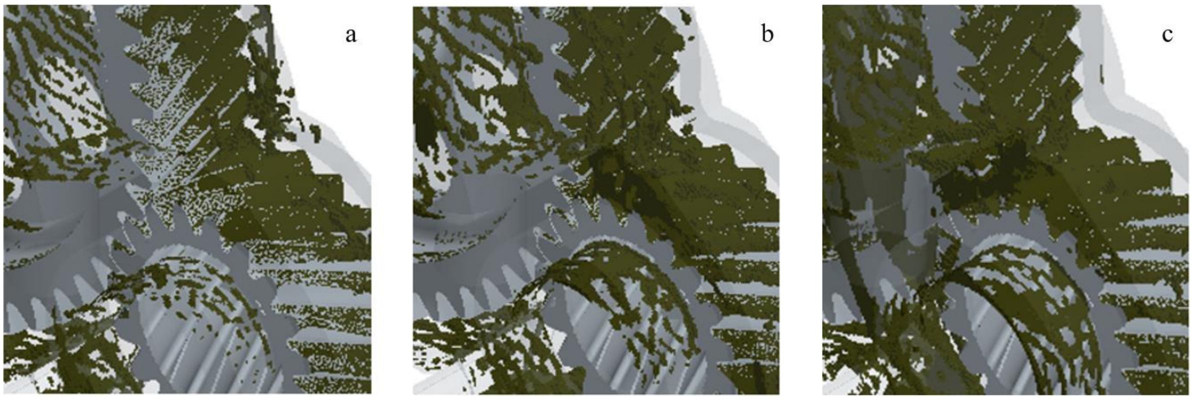

Figure 9. Oil distribution of: (a) Single nozzle; (b) Crossed nozzles; (c) Parallel nozzles

The images pointed out a lower amount of oil in the gears meshing area for the single-nozzle architecture, thus suggesting the importance of a proper lubrication layout and nozzle positioning.

4. Conclusions

This manuscript proposes a specific lubrication analysis of a helical gear transmission. The study focused on the very first transient of the lubrication stage to evaluate the prompt response of the system in terms of both oil distribution and passive torques. A lumped parameter model of the full hydraulic schematic provided the boundary conditions for a three-dimensional CFD model, and the effects of different nozzles configurations on the overall performance were investigated. In details, a single-nozzle layout and two double-nozzle architectures with different nozzles orientations were simulated.

Each configuration highlighted a 30% oil on the teeth surfaces of both the driving gear and the driven gear, except for the crossed nozzles arrangement where a 33% oil was measured on the driven gear teeth, thus suggesting a better lubrication of the component. However, these results ensured a quick and balanced lubrication of the moving parts.

The power losses were subsequently investigated and a significant difference between the simulated cases was observed. Indeed, the single-nozzle layout produced lower passive torques with respect to both the double-nozzle designs. Quantitatively, 50% and 25% reductions were noted on the driving gear and on the driven gear respectively. This result was mainly supported by a qualitative 3D view of the oil distribution within the computational domain, which pointed out a larger oil accumulation near the meshing region in double-jet configurations.

In conclusion, this paper proves the influence of the lubrication architecture on the hydraulic efficiency of the transmission. In fact, a double-nozzle layout with crossed oil jets slightly improved the system lubrication, while a significant reduction in power losses was reached with a single-nozzle design. According to the authors, these results would help in further improving the efficiency of modern transmissions in the automotive field.

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