Oil splashing, Lubrication and Churning losses prediction by moving Particle Simulation

Lubrication, churning losses and heat dissipation are fundamental aspects in the design of gear boxes and transmission systems. These three aspects affect the functionality, life and efficiency of the device, but, in spite of their importance, the use of simulation to study these phenomena and support the design of transmission systems is very limited. The reason is that traditional mesh-based CFD methods can handle simulation of gear boxes and similar systems only with complex meshing methods and with long transient simulations, that do not fit in the design process. This paper shows how particle based methods like the Moving Particle Simulation (MPS) can simulate lubrication and oil splashing by completely eliminating mesh generation from the CFD process and by drastically reducing the simulation time, thanks to the semi-implicit scheme used by MPS for time integration. In particular the article shows the results of the MPS method on a two speed reduction gear box, that is part of the rotor drive transmission change for a forage harvester machine. The gearbox has to work in a very wide range of rotational speed and torque and a good lubrication for all rotating components is mandatory to avoid failures and overheating issues.

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Introduction

The design of gear boxes and transmissions systems has to maximize the power transmission efficiency, guarantee lubrication and heat dissipation. One of the components of the transmission losses is the churning losses, that is the loss of power due to the resistance exerted by oil on gears. Churning losses have to be minimized, while lubrication issues and overheating affect the functionality of the system and must be avoided. For this reason, after the first design phase of a gear box, a prototype is tested to verify lubrication and heat dissipation. In these tests, lubrication can only be "measured" in a qualitative way by visually looking at the oil distribution on the gear box external walls. Quantitative measurements, like oil flow rate to the bearings, cannot be acquired and oil distribution in the internal volumes cannot be even visualized. When the tests give negative feedbacks, due to insufficient lubrication or due to overheating, a new design and prototyping iteration has to be done, usually in a trail-and-error manner, until targets are reached. This process takes time and resources and finding the right solution is usually based on experience. In order to make this process faster and more efficient Comer Industries, an Italian manufacturer of transmissions systems, decided to test a new design process, that integrates fluid-dynamic simulation in the early stages of the design.

The aim of this methodology test is not only to verify the feasibility and accuracy of the simulations, but also to understand if the simulation process could fit in the design phase of a real gear box. This phase lasts between 2 and 3 weeks, its aim is to produce

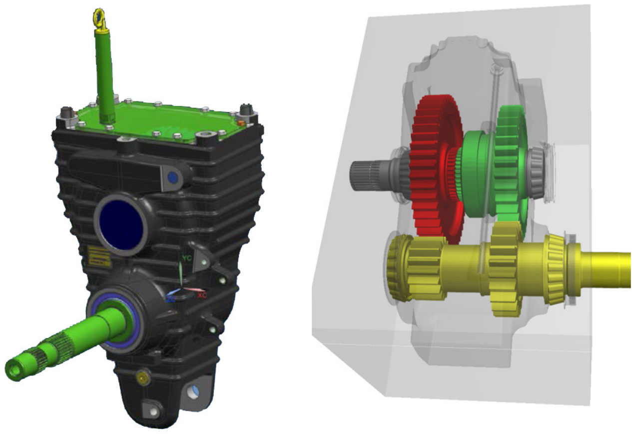

Figure 1 - Speed reduction gear box, part of the rotor drive transmission change for a forage harvester machine.

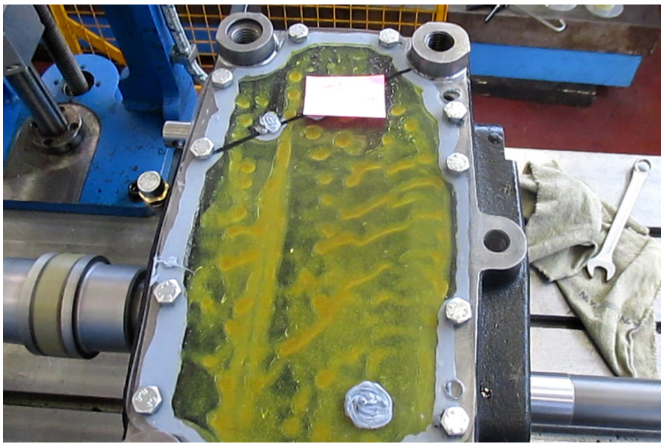

Figure 3 - Oil distribution on the upper cover of the gear box during a lab test at Comer Industries.

Figure 4 - Oil distribution in the gear box, comparison of the original design (left) and new design of the housing (right). Oil reaches the upper cover and drops down on the gears

the first design of the gear box and in this phase fluid-dynamic modelling is expected to simulate and compare the performances of at least 3 designs, in order to select the best one for physical prototyping and testing.

CFD modelling of a gear box using Moving Particle Simulation (MPS)

The object of the modelling and simulation activity is a two speed reduction gear box, that is part of the rotor drive transmission change for a forage harvester machine. The gearbox has to work in a very wide range of rotational speeds and torque and a good lubrication for all rotating components is mandatory to avoid failures and overheating issues. The aim of the design and simulation process is to change and adapt the external housing of an existing gear box to the new requirements of the final customer of Comer Industries. The lubrication of the new design has to be at least as good as the one of the previous design of the housing. The modelling and simulation activity is defined in two phases, the first one aims at a qualitative comparison of the lubrication performances of the old and new designs of the housing, the second phase aims at investigating the effect of design changes or operating conditions changes on lubrication.

Figure 2 - MPS model of the speed reduction gear box with the initial oil volume at the bottom.

Figure 1 shows the two speed reduction gear box with the input and output axis and the four gears. The CFD model is set-up using the software Particleworks that is based on the Moving Particle Simulation method. This is a mesh-less CFD method, that allows the simulation of incompressible single-phase and multi-phase flows. In the MPS method fluids are represented by particles. Governing equations are expressed by conservation laws of mass and momentum. The Navier-Stokes equations are discretized by particle interaction models and solved with the Lagrangian methodology. The mesh-less nature of the CFD solver allows to easily account for the effect of moving walls or bodies on the fluid flow, without the complexity and effort of managing mesh movements, deformation or overset, and without even involving the mesh generation for complex geometries like in the case of a gear box. A semi-implicit algorithm is employed in the MPS method [4]. When solving a free surface flow the MPS method accounts for the effect of surface tension, calculates free-surface fragmentation, droplets break-up and coalescence.

Comparison of lubrication efficiency for two designs of the housing

The first step of the simulation process is to compare the original and new designs of the housing in terms of oil distribution. The key factor when evaluating oil distribution and lubrication is the fact that oil, initially located at the bottom of the gear box (Figure 2) has to be lifted up by the lower gears to the upper ones. The upper gears will then lift up again the oil to the upper cover of the housing. Oil will then move on the cover wall driven by the rotational effect of the gears and it will drop down from the cover, thus lubricating gears and bearings through dedicated channels that collect oil by gravity. This process and the lubrication efficiency was verified experimentally for the original design of the housing by Comer Industries. Figure 3 shows the top view of the original gear box with a Plexiglas wall that replaces the upper part of the prototype. Figure 3 shows the Plexiglas wall covered with oil. This means that the action of the gears is capable of lifting up the oil to the upper wall and demonstrates that the lubrication is acceptable. The Moving Particle Simulation (left side of Figure 4) shows the same behaviour and the same oil distribution on the cover wall of the original design of the housing. This is a first qualitative validation of the CFD model. The same type of simulation is carried out on the new design of the housing. Figure 4 shows that the new and original designs of the gear box have the same oil behaviour. The results of the two simulations show oil on the upper cover of the housing and oil droplets falling on the gears and entering the channels that lubricate the bearings. The conclusion of this first simulation phase is that the new design gives the same level of lubrication of the original one and that no macroscopic modifications has to be applied to the new housing.

The simulation process of the Comer Industries gear box with the MPS method takes less than one week to simulate 5[s] of physical time. The time needed to let the flow develop and to evaluate lubrication is between 3 and 5 [s]. The simulation time on 4 cores is 7.9 [days] using the software Particleworks version 5.2.0 (Table 1). The use of parallel calculation on 8 cores allows to halve the simulation time, 4.1 [days], while the use of GPU reduces the simulation time to 27 [hours].

Table 1: simulation time using CPU-4 cores and GPU K40

	Simulation time [days] using Particleworks 5.2.0 Simulated physical time = 5.0 [s]	
Particle Size	CPU - 4 cores and 8 cores Intel Core i5-2400 - 3.10GHz	GPU NVIDIA Tesla K40 Intel Core i7 - 5930K - 3.50GHz
1.2 mm	7.9 [days] on 4 cores 4.1 [days] on 8 cores	1.1 [days]

The time needed to set-up the MPS model starting from the CAD geometry is less than 1 hour. This is the time needed to import the CAD geometry, set-up the rotational axis and speed of the gears, set-up oil properties and level and select the proper numerical models. This aspect together with the simulation time shown in Table 1 allowed Comer Industries to understand that the simulation process could fit in their normal design process and could allow to compare the performances of at least 3 different designs in 2 weeks.

Investigation of the effect of design changes and operating conditions changes on lubrication

After the qualitative validation of the MPS model and the comparison of the original and new housing, the focus of the study moves to the effect of design changes of the lubrication holes located on the gears and on the effect of the initial oil level. In some cases Comer Industries uses inclined holes on the gears instead of radial ones. Holes are inclined according to the rotational direction, so that, in theory, they should increase lubrication with respect to radial holes by enhancing the capture of oil during gears rotation. This phenomenon cannot be verified on real prototypes, because it is impossible to measure the oil flow rate through these holes.

The CFD modelling allows instead the calculation and comparison of oil flow rates for different inclinations of the holes. The simulation of different geometries shows that the hole inclination can increase the oil flow and lubrication of the system as visible in Figure 6, that compares the average oil flow rate in the lubrication holes when their direction is radial or inclined. The inclined holes in some locations increase the flow rate by more than 100% with respect to the radial holes.

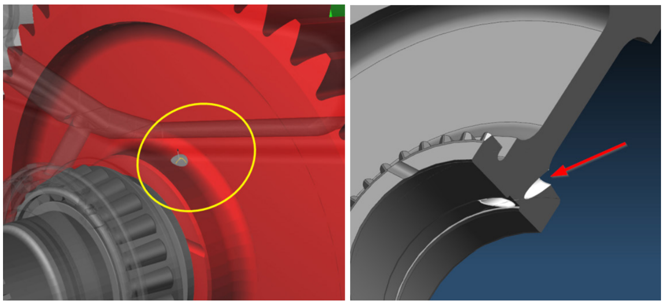

Figure 5 - Lubrication hole on one of the gears, the inclination of these holes according to the rotational direction can increase the gear lubrication.

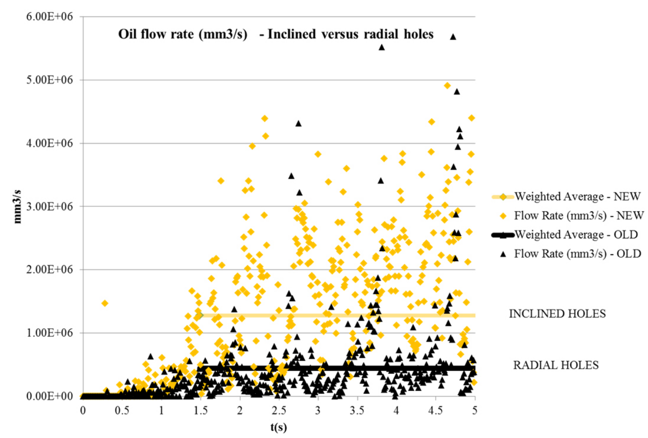

Figure 6 - Oil flow rate through the holes located on the gears, comparison between inclined and radial holes.

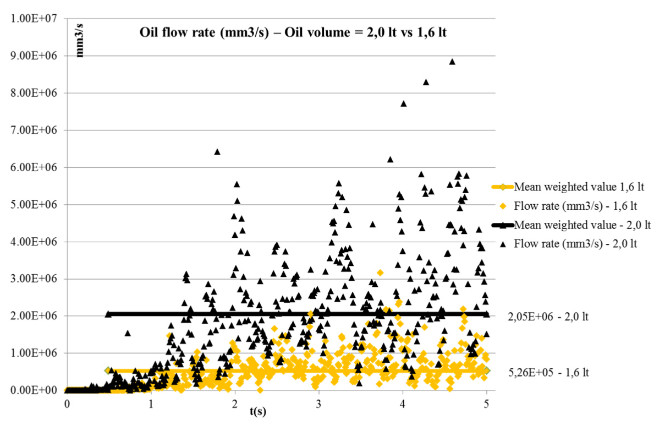

Figure 7 - Oil flow rate through the holes located on the gears, comparison between oil volume 2 litres and 1.6 litres.

Another factor affecting lubrication is the oil volume in the gear box. Reducing the oil volume can reduce the churning losses and increase the transmission efficiency, but it could negatively affect lubrication. For this reason Comer Industries decided to simulate the effect of a 20% reduction in oil volume, from 2.0 litres to 1.6 litres. Figure 7 shows that the 20% reduction in oil volume produces a 74% reduction in oil flow rate at the lubrication holes located on the gears. Hence the oil level cannot be reduced below a certain threshold without changing the oil pattern in the system and without affecting lubrication.

Validation of churning losses

The churning loss is the torque exerted by the fluid on the gears and, like the oil flow rate, it cannot be measured during experimental tests, but it can be calculated by the MPS simulation. Figure 8 shows the churning losses calculated on the 1st speed output gear. The average value calculated by the CFD model after the initial transient period is in line with Comer Industries estimations. In order to fully validate the churning losses calculated by the MPS method, after the study of the two speed reduction gear box, a new and simpler geometry with one single gear is simulated, and the calculated churning losses are compared to the experimental data, that are available for this simpler geometry. The gear box with the single gear and the oil pattern at 500 rpm are shown in Figure 9. Figure 10 shows the total torque acting on the single gear and the torque components due to oil viscosity and pressure. The

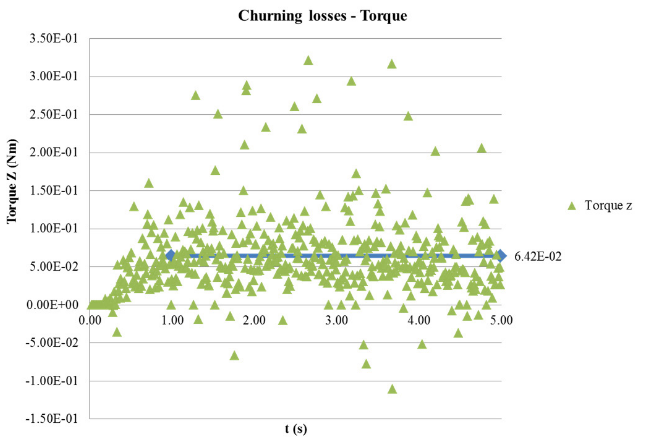

Figure 7 - Oil flow rate through the holes located on the gears, comparison between oil volume 2 litres and 1.6 litres.

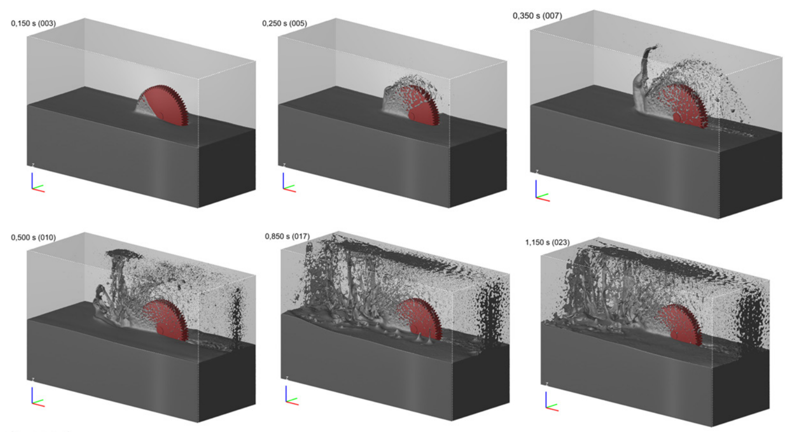

Figure 9 - Test case for churning losses validation, single gear in a squared gear box

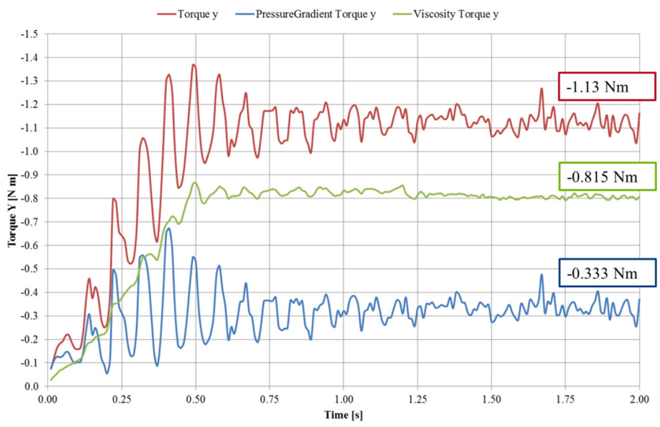

Figure 10 - Test case with single gear ina squared gear box: total torque (red line), viscous torque (green) and pressure torque (blue).

delta between the total torque calculated with the MPS method and the experimental churning losses is 10%. This last quantitative comparison allowed to complete the validation of the MPS method.

Conclusions

The prediction of oil splashing phenomena, lubrication and churning losses during the early stages of the design of transmission systems brings benefits in terms of optimization of transmission performances, reduction in number of design reviews and prototypes. While the benefits are clear to all the industrial players in this sector, feasibility of fluid-dynamics modelling has been the main limiting factor to the adoption of simulation. For this kind of applications the feasibility of CFD simulation is mainly associated to the geometrical complexity of the transmission systems, to the management of the mesh and to the solution methods adopted by traditional mesh-based solvers. The bottlenecks due to the geometrical complexity and due to the management of the computational grid are removed by the mesh-less particle based methods, like the Moving Particle Simulation. The application of this methodology allows to reduce the time needed to set-up the CFD model from 2-3 weeks of a mesh-based software to 2-3 hours or less. Moreover, the semi-implicit scheme applied by MPS for time integration reduces the computational time and resources needed to run the simulations, also thanks to the exploitation of GPU calculation. For the Comer Industries case, this means that the simulation process based on the Moving Particle Simulation fits in the standard design process and allows to select the best design of the system by comparing at least 3 configurations in about 2 weeks. The benefit is that most likely the solution selected for prototyping will have no lubrication or overheating issues, with a positive impact on development cost and time to market.

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