Stereo-PIV Study of Oil Flow Inside a Model Gearbox

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Abstract Gears inside the gearbox are cooled and lubricated by oil. If the amount of oil is too little, the lifetime of the gears is shorter due to insufficient heat dissipation, but if the amount of oil inside the gearbox is too much, it creates significant load for the gears when they are rotating, due to the shear of the oil. To find appropriate oil level inside a gearbox, understanding of the flow is needed. This study is to add understanding of the oil flow inside a gearbox and the data that has been generated will become a validation tool for numerical calculation. Two regions were chosen and measured. First region is below the gear. This region was chosen to understand the oil flow around the gear while the gear is immersed with the oil. And the second region is at the gear meshing. This region was chosen to study the squeezed oil when the gear is in contact. For measurement below the gear, five measurement planes with 5 mm apart were used to capture and measure 3D streamlines of the oil flow around the gear. Two pitch line velocity, 0.55 and 1.1 m/s, and oil temperature at 30 °C were used for both measurement regions. Oil level was at the centerline when measuring below the gear region and full box when measuring the meshing region. In this study, stereo-PIV was used to measure the oil flow velocity in all three directions. From flow visualization, the flow of the oil inside a gearbox is three-dimensional and consists of many recirculation regions. These recirculation regions have high shear stress and contribute to the higher viscous losses. At the meshing region, the oil enter the teeth exit the teeth in a gradual manner, meaning that the squeezing losses has lesser impact to the overall viscous losses compare to the losses due to shear.

1. Introduction

One third of the total losses in a vehicle are due to friction losses (Chu & Majumdar, 2012). The transmission unit contributes 15 % from the friction losses and 20 % of the losses inside the transmission unit are due to viscous losses, i.e. churning and shear of oil (Holmberg et.al., 2011). These viscous losses are significant especially in dip lubrication system and majority of vehicles nowadays use dip lubrication system.

Dip lubrication is a method of lubricating the gear by immersed them partially in oil. When the gear rotates, the gear will carry some of the oil with it, the attached oil on the gear teeth will act like a cushion when the gear tooth is in contact (meshing) with another gear tooth. After meshing, the temperature of the particular gear tooth will increase due to friction and this tooth will be cooled down by the oil when it dips into the oil bath. This means that for dip lubrication system, the correct amount of oil inside a gearbox is important. An excessive amount of oil will lead to high load-independent losses (viscous losses), but on the other hand, too little oil will not provide sufficient cooling for the gears (Höhn et.al., 2008). Since lowering the amount of oil in a dip lubrication system is not a simple task, due to the risk of overheating and wear of the gears, further studies on the oil flow inside the gearbox are needed to find a balance of low losses, good heat dissipation and lubrication.

Some attempts were made to predict the viscous losses with dimensional analysis, e.g. Changenet et al. (2008) and (2011). This approach is useful for determining the amount of oil which gives the lowest losses but it is not sufficient to answer the question about the cooling of the gears. It is because to cool the gear in dip lubrication system, the gear teeth have to be immersed in the oil in sufficient time. This means understanding the flow of the oil inside a gearbox in different rotational speed is essential for cooling. If the flow behaviour is known, the oil can be redirected to an area where it is needed. Hence smaller amount of oil inside the gearbox is needed due to efficient movement of the oil. Torque measurement data are available in the literature as well, but there are not many flow measurement data available about the flow field of oil inside the gearbox due to difficulty in the measurements.

The purpose of current study is to provide experimental data on velocity field in the gearbox which can be used for validation of numerical calculations. The importance of the correct flow velocity prediction is important for the heat prediction because the flow velocity has to be predicted correctly first in order to
predict the heat dissipation inside the gearbox. This paper is a continuation of the author’s previous work on gearbox flow measurement. The oil flow inside a model gearbox is further studied and measured with stereo-PIV in order to obtain more detailed information of the flow.

2. Experimental Setup

A new gearbox model (Chalmers gear test rig), based on a standardised FZG back to back test rig, and was specially built for flow study. The Chalmers gear test rig is particularly designed for optical measurements. Figure 1 shows the overview of the FZG test rig and the Chalmers gear test rig.

The optical requirement makes the test section wall and test gears have to be made from transparent material and in this case PMMA plastic was chosen. In order to get maximum optical access, severely hydrotreated process oil, Nytex 810, was used as test oil. This oil has refraction index close to the PMMA.

The walls of the test section are made from 10-mm PMMA plastic. The inner dimension of the test section is 270×180×56 mm³. The test gears are spur gears and made from PMMA plastic as well. We differentiate the name of the test gears by naming the bigger gear as test gear and the smaller gear as test pinion, as seen in figure 1. The outer diameter of the test gear is 118.36 mm and the outer diameter of the test pinion is 82.46 mm. The width of the teeth for the test gear and test pinion is 14 mm, and the distance between the gear axes is 91.5 mm. Number of teeth for the test gear is 24 and for the test pinion is 16, and both have the same module, 4.5 mm. Figure 2 shows the dimension of the test section, the gear and the pinion.
Two cameras (Imager X Pro 4M) with 105-mm f/2.8 Sigma lenses and low-pass filters (570 nm) were placed on the either side of the liquid prism with 45° angle. Nd-YAG laser equipped with the laser guiding arm and laser sheet optics was used for particle illumination. The test oil was seeded with spherical fluorescent Rhodamine B-based polymer particles with mean diameter of 10 µm. Figure 3 (a) shows the experimental setup.

As seen in figure 3 (b), in front of the test section there is a liquid prism. The liquid prism is a hollow thin walled prism that is filled with the same liquid as the test liquid (Prasad, 2000). In our case the liquid is the test oil. The purpose of the liquid prism is to reduce radial distortions that arise when imaging through a thick liquid layer, ensure paraxial recording, and maintain the orthogonal view with respect to the liquid-air-interface (Prasad, 2000). The dimension of the prism is 290×200×120 mm³, and it was made from 10-mm thick PMMA.

In current study flow below the gear and in the meshing region were chosen to be studied. The region below the gear is measured for understanding the oil flow behaviour in the oil bath when the gear is rotating and the meshing region is measured to investigate the squeezing phenomena when two teeth engaged. Two sets of pitch line velocities, 0.5 and 1.1 m/s, and constant temperature, 30°C were used. The oil level was at centreline for measurement below the test gear and fully filled box for measurement at the meshing region was used. For measurement below the gear, scanning stereo-PIV was used. The scan consists of 5 different planes with 5 mm apart. The first plane located at 22 mm from the back wall. Cross flow measurement was done on the axis of the test gear and in the meshing region. Figure 4 shows the location of the measurement planes.

Fig 3. (a) The experimental setup and (b) the liquid prism

Fig 4. Location of measurement planes
Figure 5 (a) shows the gear from the front immerses in half full oil. It is seen that part of the gear that is immersed inside the oil is hardly seen. This is due to refraction index matching. Figure 5 (b) shows the raw image from Camera 1 in setup 3C. This figure shows the meshing region and the image is taken with the test gear located in front of the measurement plane on the optical path of the camera. Some minor optical distortion from the static gear hub can be seen in the left part of the image but other parts of the test gear do not introduce any noticeable optical distortion and is barely affecting the image due to refraction index matching.

3. Results and Discussion

PIV results are a phase-average from 100 images. The vector calculation is performed in multi-pass procedure with decreasing window size. Initial interrogation window size is 64×64 pixel² with 50 % overlap and square 1:1 weighing factor for the first 2 passes. Final 3 passes are performed with 32×32 pixel² window size, 50 % overlap and round 1:1 Gaussian weighing factor.

The splash pattern is investigated by performing flow visualization study. Figure 5 shows some of the instantaneous images. Visualizations at three different pitch line velocities ($V_t$) which are 0.88, 1.76 and 3.52 m/s are shown. The main purpose of the flow visualization is to provide information on the oil distribution inside the gearbox. One can clearly observe changes in the splash pattern and variation of the oil level which moves below the centreline as the pitch line velocity increases, due to oil splashing. The bubble that is created is more when the pitch line velocity is getting higher. This bubble limit the optical view hence reducing the signal to noise ratio.

Note that coloured gears were used during the visualization study in order to highlight the gears.
The streamlines of the flow at the mid-plane for two different pitch-line velocities are shown in Figure 6. In the mid-plane the velocity field is two-dimensional and was studied by 2C PIV. More extensive data on flow visualization and 2D PIV results is available in Hartono (2013).

![Streamlines of flow at mid-plane](image1)

**Fig 7.** Velocity field of oil flow at the mid-plane, with oil level at centreline.
(a) \( V_l = 0.55 \) m/s; (b) \( V_l = 1.1 \) m/s

As seen in Figure 7, several recirculation regions present in the mid-plane. Moreover additional recirculation regions are present outside of the mid-plane. Two additional recirculation regions are created at each side of the test gear and test pinion.

Figures 8 (a, c) show the streamlines of the flow around the test gear. The streamlines are obtained from scanning measurements at five different planes. Figures clearly reveal the three-dimensional flow structure inside the gearbox. Figures 8 (b, d) show the flow in the crossflow plane. These two figures also support the argument that the flow inside the gearbox is complex and three-dimensional. These recirculations are one of the sources of the load independent losses in the gearbox. Previous study by Changenet and Velex (2008) suggested that power losses can substantially be reduced by mounting flanges close to the lateral faces of the wheels. Presumably, this happens because of the reduced volume of the recirculation regions.
Figure 8. Velocity field of oil flow below the gear, with oil level at centreline; (a, c) $V_t = 0.55$ m/s; (b, d) $V_t = 1.1$ m/s

Figure 9 shows the velocity field in the crossflow plane at the meshing region for fully filled gearbox. This measurement was done to understand the oil squeezing phenomenon and its effect on the overall flow and the losses. Oil ejection velocities from the meshing region were measured. Figure 9 shows the crossflow velocity vectors coloured by z-component of velocity for two different pitch line velocities. It can be observed that the z-velocity component has magnitude of 0.4 m/s and 0.8 m/s correspondingly for pitch line velocity 0.5 m/s and 1.1 m/s. Although the velocity magnitude is large, the mass flow of the squeezed fluid is small and the effect on the overall flow is small. The velocity is not very large since the meshing of the gear teeth happens gradually. This gradual process makes the fluid, which is trapped in between the gear teeth, can escape. After the meshing is completed, the fluid is sucked back into the space between the teeth, which is seen in the bottom part in Figure 9.
Fig 9. Crossflow velocity field at the meshing region with fully filled box; (a) $Vt = 0.55$ m/s, (b) $Vt = 1.1$ m/s

4. Conclusion

Stereo-PIV measurement of oil flow inside the model gearbox has been done for two different pitch line velocities around the gear and in the meshing region. The measurements were successful due to specially developed setup with maximized optical access and the refraction index matching of the test oil and of the gears. This study also complements the previous study.

 Particularly, current work reveals the flow structure around the test gear and three-dimensional flow streamlines in the recirculation regions in the vicinity of the test gear as well as the shape of the three dimensional boundary layer. Measurements in the meshing region clearly showed the details of the squeezing flow and the effect of the squeezing flow on the overall flow inside the gearbox.

Current information provides solid background for future numerical studies of the flow inside the gearbox, which aim at optimizing the oil flow in order to decrease the viscous losses and optimize cooling.

5. References


