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FLUID FLOW MEASUREMENTS OF 5P4E BY PARTICLE TRRACKING VELOCIMETRY

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Abstract: *Lubricant flow in an elastohydrodynamic contact is investigated by new methodology based on particle tracking velocimetry. Measurement method provides positions of silver nanoparticles dissolved in the lubricant through several images captured by high speed camera. These are connected, in places of high probability of correct detection of identical particle on multiple images. Connected positions are linearly fitted to get average speed and after that statistically processed to obtain velocity profile. This method was applied on 5P4E base fluid, characterized by high viscosity and pressure sensitivity. Experimental results provide evidence about slide to roll ratio influence on the velocity profiles under piezoviscouse conditions. At low slide to roll ratios the profile shape match plug flow model with highly viscous core and slip on the solid-liquid interfaces. As the slide to roll ratio increases, corresponding velocity profile curvature is reduced.*

Keywords: Elastohydrodynamic Lubrication, Rheology, Fluid Flow, Particle Tracking Velocimetry.

1. Introduction

Elastohydrodynamic lubrication (EHL) taking place in many mechanical parts, where the geometry is highly non-conform (Fig. 1). In such regime, the film separating contact bodies usually reach up to 1 μm and is subjected to high pressures (up to 3 GPa), along with shear rates up to 10^8 s^{-1}. Conditions like these, usually lead to different behavior of lubricant from one under ambient conditions, given by pressure-viscosity, temperature-viscosity and shear rate-viscosity relationships.

Because of difficulties associated with predictions implementing all these relationships at once, a lot of studies are currently based on modified Reynolds equation, which is sufficient for film thickness. Film thickness is given by the processes ongoing in the inlet region, where the pressure is small enough. However, for those taking place in central region (friction, fluid flow), where the lubricant is exposed to high pressures, temperatures and shear rates, the Reynolds equation is inadequate. Phenomena such as limiting shear stress, wall slip or glassy transition are needed to be considered.

Estimation of lubricant behavior in Hertz area can be based on molecular dynamics phase diagram, like the one discussed by Martinie (2016). This diagram summarizes several proposed models of film behavior with respect to the pressure and shear rate, complemented by experimental data. For EHL are essential three of them. First one is solid like behavior of the lubricant caused by increase of the viscosity due to high pressures and low shear rates. Flow profile is expected to be linear. In higher shear rates one of two possible mechanism can occur. Wall slip respective plug flow model (Ehret, 1998), where the slip occurs on the solid- liquid interface and the core is solidified (Fig. 2) or last possible case derived from assumption of uneven temperature distribution along film thickness (Bair, 1994). The shear is presumed to be localized in plane of maximum temperature therefore lower viscosity (Fig. 2).

Only a little experimental evidence is available about fluid flow, most likely because an appropriate measuring method didn't exist. Lately, approach employing fluorescence microscopy (Reddyhoff, 2010) was used to study lubricant rheology inside point contact. This one was modified (Ponjavic, 2013) for using, in field of fluorescence specific technique, fluorescence recovery after photobleaching (FRAP), allowing to study through film thickness flow profile. This method is however limited by the diffusion of the fluorescence tracer to lubricants with high Péclet number. Flow profiles measured by this method for

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polybutene correspond to the Ehret plug flow model. Further investigations with 5P4E polyphenyl ether base fluid (Galmiche, 2016) clearly shows the importance of the pressure effect on the shape of velocity profile. At isoviscouse rigid conditions, the profile is almost linear as expected. However, as the pressure rises the shear banding starts to prevail.

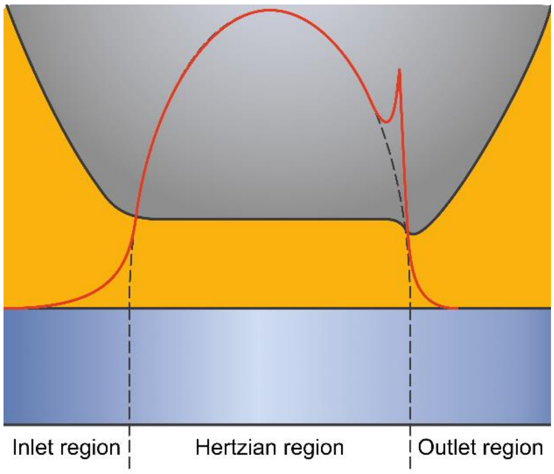

Fig. 1: EHL contact regions with pressure profile (red).

Alternative approach to study fluid flow (Šperka, 2014), employed in this study, is the particle tracking velocimetry (Fig. 3). Methods using particles have certain limitation in direct determination of particle position along film thickness, commonly requiring modification of an experimental rig (Kikuchi, 2015; Byeon, 2016). This could be overcome by statistical processing of the data set. The aim of present study is to investigate response of flow profile on different slide to roll ratios under piezoviscous conditions. The lubricant used in this study is 5P4E for it's high viscosity and for which the flow behavior under high pressures has been shown.

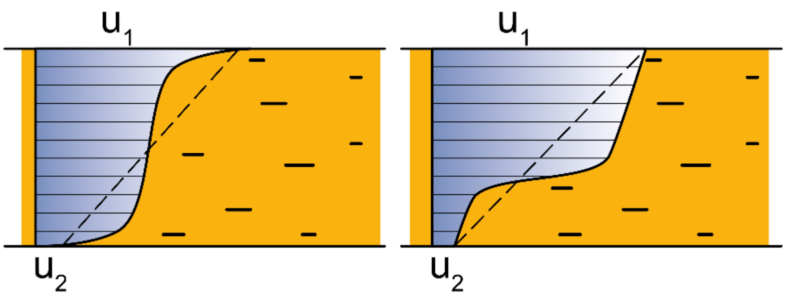

Fig. 2: Plug flow and shear banding. U_1 and U_2 are speeds of contacting surfaces.

2. Methods

The lubricant flow profile measurements were conducted on ball-on-disc optical tribometer, capable of precision thickness measurement. EHL contact is formed between 25.4 mm bearing steel ball and borosilicate BK7 glass disc. Applied load is 15 N through the liver, giving a maximum pressure around 401 MPa falling under piezoviscous regime. The slide to roll ratio (SRR) is defined as $2(u_1\text{-}u_2)/(u_1+u_2)$ and varies between 100 % and -100 %. Contact is captured by the CMOS camera at 6000 fps along with 120 µs exposition time. The lens has magnification 50×.

For a flow analysis, the silver nanoflakes with diameter up to 10 µm (Sigma Aldrich) and thickness in nanometers were added to the 5P4E with a viscosity around 2.63 Pa s at 25 °C. Amount of nanoparticles dispersed in the lubricant was increased until in the central region were approximately 10 of them during experiment. Solution was mixed in ultrasonic cleaner, then mechanically using spatula. Before experiments, layer of lubricant was applied on disc, followed by loading the contact and putting it's into pure rolling for 5 minutes to ensure better dispersion of particles. From every experiment 400 images were captured. When needed, a median filter with radius 2 pix were applied to reduce outliers and noise.

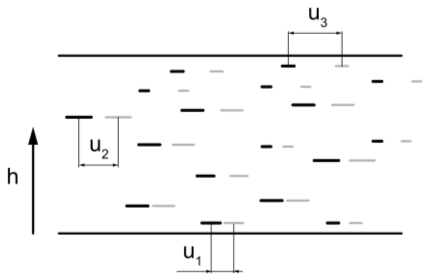

Fig. 3: Particle tracking: black lines – particles, grey lines – particles captured on subsequent image. U_x are speeds of particles at different heights of film

The actual particle tracking consists of three steps. First one is the particle detection, which was done by multiscale detection algorithm (Olivo-Marin, 2002) in Hertzian region. Second step is joining individual detections together (Chenouard, 2013), so the average velocity could be calculated from the change of position between subsequent images by linear fit. Number of created connections between spots is limited by uncertainty, which increases with tracking distance. Third step (Fig. 4) consists of velocity profile evaluation from tracked displacements of particles. This is done under certain assumption that the through film distribution of particles is uniform. Then the cumulative histogram of measured speeds should describe the flow profile. Velocities lying outside the interval 15-45 mm s^{-1} could be caused by insensitivity of the technique.

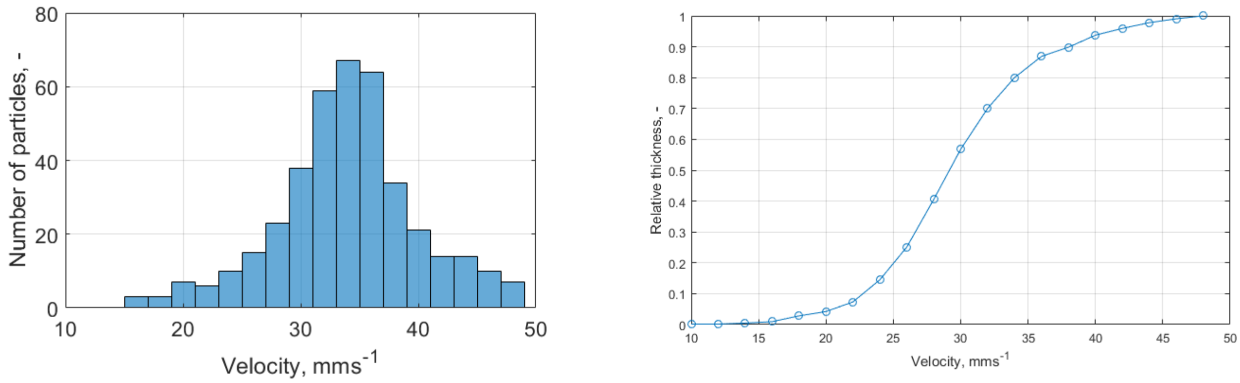

Fig. 4: Speed profile evaluation fort SRR -100 %.

3. Results and discussion

Experiments were conducted at mean speed 30 mm s^{-1} for a range of SRR from -100 % to 100. Speed of ball respectively disc varies from 15 to 45 mm s^{-1}. Velocity profile was evaluated from limited number of particles inside relatively flat central region. Film thickness is estimated by Homrock&Dowson prediction to 745 nm. Experiments are conducted under piezoviscous conditions in the region of plug flow or shear banding (Martinie 2016). Therefore, shape of the velocity profiles should correspond to plug flow model for low shear rates and for higher one the shear banding should occur.

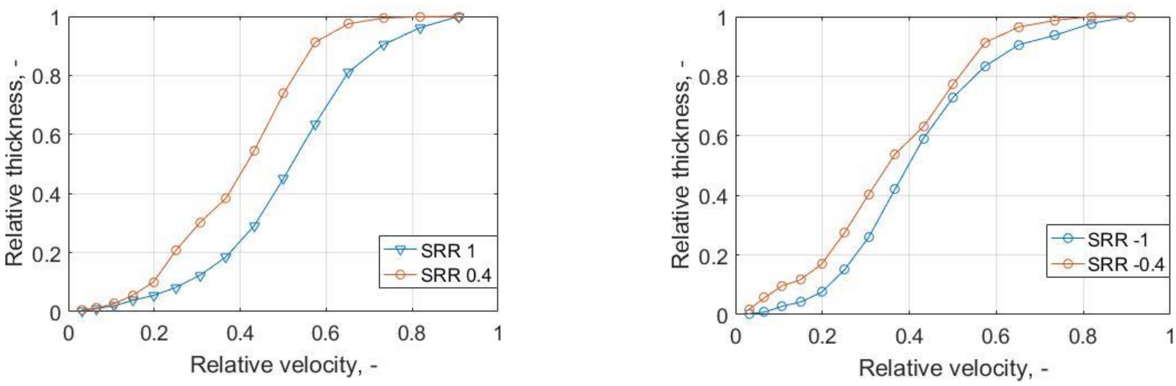

Fig. 5: Speed profile evaluation.

As can be seen from Fig. 5, velocity profiles for both positive and negative SRRs have shape of the S curve divided into three regions. Two regions where major shear take a place are near the surfaces of contact bodies. They're thicknesses are around 10 % of film thickness. These two are separated with thick core, where the speed changes only a little. This description corresponds to the plug flow model.

With increasing the SRR, the boundary regions getting thicker and the transition between central and boundary regions are smoother. Near the slower surface, it seems, that the transition to the plug is longer, especially for positive SRRs. This may be related to temperature gradient, since the surface with lower speed remains in contact longer thus, it's temperature should be higher. Similar temperature distribution was concluded by (Galmiche, 2016), for the shear banding, where the layer with localized shear was approximately at height of 20 % of film thickness. Profiles however do not show any signs of shear banding as it was in the previous study. Central part of profile doesn't seem to change. The tilt remains constant.

Changes in profile shape are more likely caused by viscosity changes inside the lubricant. Viscosity variations could be caused be pressure or temperature change. Since the applied load is constant, and thus the pressure should be as well. It suggests that the viscosity is influenced by the temperature. Temperature increase could lower the viscosity of the core of lubricant. At a higher slide to roll ratios, profile could become even more linear. However, at some value of SRR, approaching to the linear profile should stop accompanied by transition to shear banding regime caused by temperature gradient.

4. Conclusion

Particle tracking velocimetry method was used to study nanometer thick fluid film inside EHL contact. Velocity profiles of 5P4E for several values of SRR were measured. With higher SRR the profiles become smoother and the curvature is slightly reduced. Shape changes were attributed to viscosity decrease caused by temperature gradient through film thickness. Although velocity profiles were obtained for a range of SRRs, it would be great benefit to be able to investigate fluid flow at higher shear rates, where is the shear banding transition likely to occur. Further work will focus on the estimation of fluid flow under such conditions.

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