Numerical simulation of the churning losses in vehicle rear axle hypoid gear

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Abstract. A simplified 3D flow field numerical model of rear axle including passive bevel gear and the differential housing is established, based on the VOF (Volume of Fluid) model and the RNG k-ε turbulence model. With the model, the transient oil flow distribution and the influence law of speed, viscosity and bolt structure on the velocity field and the power losses is obtained. In general, the churning power losses increases with the rotational speed and viscosity while the rotational speed has more impact than viscosity on the power losses. The fluid region and the flow velocity increases with the rotational speed and the bolt structure causes a high speed area with the larger velocity gradient in the backflow surface of the bolts, implying the bolts can generate additional churning torque.

1. Introduction

The sufficient dip lubrication method is usually adopted to meet the requirement for the lubrication and cooling of the hypoid gear pair and the bearing in the existing vehicle rear axle, while rotating parts such as the gears and the differential housing stir the lubricating oil constantly, resulting in unnecessarily high churning losses. Therefore, it is meaningful to study the churning losses mechanism.

In the last years, the numerical and experimental investigations, which can visualize the oil flow distribution inside the gearbox is widely applied by the domestic and foreign scholars. A three-dimensional flow field model of the spur gear and the spur gear pair building on C. Kodela et al. [1] is applied to investigates the influence of rotational speed, temperature and immersion depth on the churning power losses based on sliding grid technique. A finite volume CFD model and experimental investigate building on H. Liu et al. [2] is applied to investigates the influence law of circumferential speed, viscosity on the oil distribution and the churning losses.

The above literatures are less investigation the churning losses of the hypoid gears with complex structure. In this paper, a three-dimensional numerical flow field model of rear axle including passive bevel gear and the differential housing is established. With the model, the influence law of speed, temperature and bolt structure on the oil distribution, the velocity field and the churning losses is obtained.
2. Numerical method and models

2.1. VOF two-phase flow model

Generally, the governing equations of fluid mechanics can be applied only to single-phase problems, meaning the need of additional equations. The VOF two-phase flow model is widely used to solve the problem of oil-air two-phase flow by calculate the phase volume fraction in the unit. Therefore, a continuity equation for the volume fraction $\alpha_{oil}$ of lubricating oil is introduced [3, 4].

$$\frac{\partial}{\partial t}(\alpha_{oil}\rho_{oil}) + \mathbf{V} \cdot (\alpha_{oil}\rho_{oil}\mathbf{u}_{oil}) = S_\alpha + (m^+ - m^-)$$  \hspace{1cm} (1)

$$m^+ = C^+ \rho_{oil} (1 - \alpha_{oil}) \cdot \frac{\min[0, P_1 - P_V]}{0.5 \rho_{oil} U_{\infty}^2}$$ \hspace{1cm} (2)

$$m^- = C^- \rho_{oil} \alpha_{oil} (1 - \alpha_{oil})^2 / t_{\infty}$$ \hspace{1cm} (3)

The governing equation is solved considering the properties of the phases-mixture that are calculated as the properties weighted average of the two different phases of the fluid

$$\rho = \rho_{oil} \alpha_{oil} + \rho_{air} (1 - \alpha_{oil})$$ \hspace{1cm} (4)

$$\mu = \mu_{oil} \alpha_{oil} + \mu_{air} (1 - \alpha_{oil})$$ \hspace{1cm} (5)

Where $\rho_{oil}$ is density of oil, $\rho_{air}$ is density of air, $\alpha_{oil}$ is volume fraction of oil, $\mu_{air}$ is viscosity of air, $\mu_{oil}$ is viscosity of oil. $u_{oil}$ is velocity vector of oil, $S_\alpha$ is a source term, which defaults to 0, $m^+$ is the mass of oil vaporization, $m^-$ is the mass of oil condensation, $P_1$ is the filtered pressure, $P_V$ is the vaporization pressure, $C^+$ and $C^-$ is the empirical constants determining the phase transfer rate, $U_{\infty}$ and $t_{\infty}$ are the kunz coefficients.

The governing equations are correlated with the continuity equation (1) of the oil volume fraction through equations (4) and equations (5).

2.2. Geometrical model and boundary conditions

A simplified computation domain model of rear axle is established using UG 8.0(Figure 1). The whole computation domain has been discretized with unstructured tetrahedral mesh (Figure 2). The meshes of the differential housing, gear and bolts rotates in the computation domain at the predefined rotational speed. A pressure-outlet boundary condition is prescribed at computational domain ends.

![Figure 1. Computation domain model.](image1)

![Figure 2. Grid model of the computational domain](image2)

Table 1 shows the specific simulation parameters, where different oil viscosities correspond to different temperatures(120 mm$^2$/s (90°C), 33 mm$^2$/s (60°C), 15 mm$^2$/s (30°C)).

| Parameters      | Specific value  |
|-----------------|-----------------|
| Viscosity       | 120             | 33  | 15  |
| Speed(rpm)      | 444 888 1065    | 444 888 1065 | 284 444 621 888 1065 |

Table 1. Simulation Parameters.
3. Results and discussion

Figure 3 shows contours of volume fraction for the oil distribution at different moments. It’s clear that part of the oil sticks to the surface of the gear and was carried to the top of the rear axle, and then flows back to the oil tank under the action of gravity, after a few turns and then the flow is repeated stably.

Figure 4 shows the sectional velocity distribution for bolts of gear at different speeds. The fluid region driven by bolts increases with the increase of the rotational speed, so does the flow velocity. A high speed area with the larger velocity gradient is generated in the backflow surface of the bolts even forming vortex with the speed increases, implying the bolts can generate additional churning torque.

**Figure 3.** Contours of volume fraction for the oil phase at different moments when the rotational speed is 284 rpm

(a) 284 rpm, 2.69 m/s (b) 621 rpm, 5.46 m/s (c) 888 rpm, 7.59 m/s (d) 1065 rpm, 9.27 m/s

**Figure 4.** Sectional velocity distribution for bolts of gear at different speeds

**Figure 5.** The effect of the viscosity on the churning power losses at the different speeds
Figure 5 shows the effect of the viscosity and speed on the churning power. Increasing the viscosity from $15 \text{mm}^2/\text{s}$ to $120 \text{mm}^2/\text{s}$, the churning power increases slowly under the same speed, which increase about only 30watts at 1065rpm, meaning the relation between the viscosity and the churning power is weak. While the churning power increases sharply with the rotational speed, which increases from 21watts to 254watts at a viscosity of $120 \text{mm}^2/\text{s}$ when the speed increases from 444rpm to 1065rpm, meaning the rotational speed has impact than viscosity on the churning power.

4. Conclusion
A simplified three-dimensional flow field numerical model of rear axle including passive bevel gear and the differential housing is established, based on the VOF model and the RNG k-ε turbulence model. With the model, the transient oil flow distribution and the influence law of speed, viscosity and bolt structure on the velocity field and the power losses is obtained. The fluid region and the flow velocity increase with the rotational speed and the bolt structure causes a high speed area with the larger velocity gradient in the backflow surface of the bolts, implying the bolts can generate additional churning torque. The churning power losses increases with the increase of the rotational speed and the viscosity while the rotational speed has more impact than viscosity on the power losses. Increasing the viscosity from $15 \text{mm}^2/\text{s}$ to $120 \text{mm}^2/\text{s}$, the churning power increases about only 30watts at 1065rpm. While the churning power increases from 21watts to 254watts at a viscosity of $120 \text{mm}^2/\text{s}$ when the speed increases from 444rpm to 1065rpm, meaning the rotational speed has impact than viscosity on the churning power. The impact of geometry parameters like the connection bolts and flange diameter on the churning power losses will be investigated in further numerical and experimental research.

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