Study on Flow Characteristic of Gear Pumps by Gear Tooth Shapes

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Abstract

Oil pump models with different gear tooth shapes were established and the internal flow field simulation were conducted by utilizing Pumplinx. Then the characteristics of steady state flux and flow pulsation were analyzed. The research shows that: compared with straight gear pumps, the flow pulsation of other toothed gear pumps is much lower, although they have lower flow at low and medium speed. Especially the flow pulsation of dislocation gear pumps is much lower than straight gear pumps. It decreased by 27% at 1100 rpm and 35% at 2700 rpm, compared with straight gear pumps. Finally the straight gear pump flow is tested experimentally, and the experimental results match the simulation very well. This proves that the internal flow field models are correct and useful in technically supporting the oil pump development.

Key Words: Gear Pump, Gear Tooth Shape, Simulation Analysis, Flow, Flow Pulsation

1. Introduction

Oil pump is the main component of the automotive engine lubrication system. It sends oil to engine friction parts and renders the engine oil to recycle in the lubrication path so that the engine can be well lubricated. Oil pumps can be divided into gear and rotor types. Gear-type oil pumps can be of either in scribed gear type or circumscribed gear type, with the latter one usually called gear oil pumps. Basically a gear oil pump consists of one or more pairs of meshing gears sealed in a shell body. During gear meshing, in the side of exit the meshing, tooth cavity volume increases, partial vacuum forms, and oil under atmospheric pressure goes through the suction port into the oil absorption cavity and the formation of oil; in the side of entered the meshing, tooth cavity volume reduce, oil is squeezed out by the oil pressure and the formation of oil discharge [1]. With the constant rotation of the gear, the volume of oil suction chamber and pressure oil chamber has a periodic change, and the flow also has a periodic change, thus forming the flow pulsation of the oil. Gear oil pumps have been widely used due to its advantageous characteristics, such as simple structure, strong self-priming ability and insensitivity to oil. But its disadvantage is that it might significantly impact a gear oil pump’s service life and the system stability because large flow pulsation causes pressure pulsation, thus producing large noise and other issues such as gear oil pump heating and cavitation [2,3]. Therefore, the flow pulsation is a major factor that affects the further development of gear oil pumps.

The operational principle of gear oil pumps is as the same as general gear pumps and can be well analyzed. In order to solve the problem of flow pulsation, Wu et al. put forward a staggered gear pump [4]. Namely they divide the straight gear into two, three or more equal pieces along the tooth width, and the pieces form independent chambers because of the angle offset. Thereby the flow pulsation can be reduced. By utilizing the theory of staggered gear pump, Zhou et al. Studied helical gear pumps...
and proved that the flow pulsation of helical gear pumps is much smaller than straight gear pumps under the same circumstance [5–7]. Huang et al. studied the flow characteristic of multiple gear pumps, and drew the conclusion as follows: when the teeth number is odd and teeth dislocation is 180° offset, the flow pulsation amplitude reduces to 1/4 and its frequency increases to twice as the ordinary [8,9]. Shang et al. studied the structural characteristics of external meshing staggered gear pumps and helical gear pumps, and concluded that the flow pulsation of dislocation gear pumps is smaller than helical gear pumps [10]. Zhang et al. proposed and verified that gear pumps with staggered gears can effectively reduce the flow pulsation [11]. Ma et al. presented detailed introduction about the testing and analysis of performance measurement of gear oil pump [14].

The above researches discovered the relationship between the flow pulsation and the gear types of pumps, including staggered gear pumps, helical gear pumps and straight gear pumps. However, studies that involve experiments and simulations to verify the theory have been few. Based on the theory of staggered gear pumps, the paper analyzed the pump flow characteristics of several different gear tooth types, respectively, by utilizing the software Pumplinx which is powerful in fluid analysis. And finally we obtained the flow pulsation property of gear oil pumps.

2. The Theoretical Analysis on Flow Characteristics of Gear Oil Pumps

The tiled structure gear pump can be regarded as different numbers of straight gears that are turned over a certain angle. If tilted into two parts, the pump becomes a staggered gear pump; if tilted into countless parts, it forms a helical gear pump or a herringbone gear pump.

A herringbone gear pump on the stagger angle of direction differs from a helical gear pump. Because the flow pulsation of gear pumps can be considered as the result that multiple identical waveform with the same frequency staggers certain phase angles of the superposition. Therefore, the flow pulsation of dislocation gear pumps, helical gear pumps and herringbone gear pumps can be derived from the theoretical analysis.

The flow of tiled structure gear pump can be obtained by a pair of identical size of infinitely thin straight gear meshed from the Datum arbitrary x emitted flux integral. According to [6], the instantaneous flow rate of a pair of infinite thin straight gears meshed is:

\[
\frac{dv}{d\theta_i} = \frac{dx}{2} \left[ (R_{a_i}^2 - R_i^2) + u(R_{a_i}^2 - R_i^2) - (1 + u)R_i^2 \left( \theta_i + \frac{x \tan \beta}{R_i} \right) \right]
\]

(1)

where \(\theta_i\) is the drive wheel rotation angle, \(x\) is the distance from gear piece to the datum plane, \((0 \leq x \leq b)\), \(b\) is tooth width, \(R_{a_i}\) is the addendum circle radius of drive wheel; \(R_1\) is the pitch circle radius of drive wheel, \(R_{a_i}\) is base circle radius of drive wheel; \(u\) is the gear ratio; \(R_{a_i}\) is the addendum circle radius of follower wheel; \(R_2\) is the pitch circle radius of follower wheel, and \(\beta\) is the helical angle of pitch circle.

Usually, the parameters of the drive gear and follower gear are the same, namely: \(R_1 = R_2 = R\), \(R_{a_i} = R_{a_i} = R_{a_i} = R_{a_i}\), \(\theta_1 = \theta_2 = 0\). So equations (1) can be expressed as:

\[
\frac{dv}{d\theta} = dx \left[ (R_1^2 - R_i^2) - R_i^2 \left( \theta + \frac{x \tan \beta}{R^2} \right) \right]
\]

(2)

Based on equation (2), a series of periodic curves can be drawn. Stacking all the curves we can obtain the displacement of a helical gear pump. Since the equation (2) is a continuous periodic function (period: \(2 \pi n/\tau\), \(n\): tooth number), studying one period is enough to get the characteristics of output flow pulsation. According to references [5], the flow pulsation of the helical gear pump decrease relative to the pulsation of the straight gear pump, which can be expressed as:

\[
\Delta P = R_h^2 b^2 \pi \tan \beta / (2 \pi R)
\]

(3)

The tiled structure study verifies that a helical gear pump has lower flow pulsation than a straight gear pump. A helical gear oil pump can also reduce the flow pulsation just like a helical gear pump because they have the same structure. Similarly, herringbone gear oil pumps and staggered gear oil pumps can also decrease the flow pulsation.
3. Flow Characteristics Simulation of Gear Oil Pumps with Different Gear Tooth Shape

Figure 1 shows the model of a straight gear oil pump. The flow field of the gear oil pump is analyzed by utilizing the fluid simulation software Pumplinx. Based on a UG model of an ordinary gear oil pump, the fluid models of the inlet and outlet of the gear oil pump and the gear wheel are obtained respectively. As Figure 2 shows, they can be saved as STL format.

The above models are imported into Pumplinx respectively and, according to their functions, divided into three parts as inlet, gear and outlet part. Then the interfaces with flow, including inlet-inlet, drive-gear, slave-gear, outlet-outlet interfaces, were acquired respectively. By simulating in Pumplinx, the gear part can generate structured moving grid and the inlet and outlet parts can generate Cartesian grids. The parameters were set as follows: the end clearance of the gear is 0.1 mm, the radial clearance is 0.15 mm, the rotating shaft is Z axis, and the driving wheel rotates clockwise, as shown in Figure 3.

According to the fluid flow, the interface was established and the parameters were set as follows: inlet pressure was -0.8 kPa, outlet pressure was 100 kPa, the oil temperature is 80 °C, oil type was 15W40 and its viscos-
ity was 0.00808 Pa.s, the density was 808 kg/m³. Finally we executed the test and recorded the simulation results. Under different rotating speeds, the outlet flows of the straight gear oil pump were obtained as shown in Table 1.

According to the parameters of the gear oil pump, the simulation analysis of the gear with different gear tooth shape (straight tooth, helical tooth, herringbone tooth, dislocation tooth) was carried out respectively, as shown in Figure 4. Except their different gear tooth shape, the other parameters remain the same.

The output flow and flow pulsation of the gear oil pump with different gear tooth shape can be obtained respectively, through CFD simulation analysis. The simulations of four kinds of pumps are shown in Figure 5 and Figure 6.

As Figure 5 and Figure 6 show, the outlet flow pulsations under different speeds of a helical gear oil pump, herringbone gear oil pump and dislocation gear oil pump can be described as follows:

1. The flow pulsations reduce significantly at the low and medium speed within 1100~2700 rpm. Especially the dislocation gear oil pump reduced greatly, 27% in 1100 rpm and 35% in 2700 rpm.

**Table 1. Simulation results under different rotating speeds**

<table>
<thead>
<tr>
<th>Rotational speed /rpm</th>
<th>Pump pressure /kPa</th>
<th>CFD flow analysis / (L·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>100</td>
<td>12.191</td>
</tr>
<tr>
<td>2000</td>
<td>100</td>
<td>22.956</td>
</tr>
<tr>
<td>2700</td>
<td>100</td>
<td>31.113</td>
</tr>
<tr>
<td>4000</td>
<td>100</td>
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<tr>
<td>5400</td>
<td>100</td>
<td>59.803</td>
</tr>
<tr>
<td>6000</td>
<td>100</td>
<td>66.472</td>
</tr>
</tbody>
</table>

**Figure 4.** Different models of gear tooth.

**Figure 5.** Flow simulation results under different speeds.

**Figure 6.** Pressure pulsation comparison of different tooth types at different speeds.
(2) At medium and high speed within 4000~5400 rpm, the outlet flow of the helical gear oil pump and herringbone gear oil pump are basically consistent with that of the straight gear oil pump, and the flow of dislocation gear oil pump is lower. However, the flow pulsation of the dislocation gear oil pump is equal to that of the straight gear oil pump, and the pulse amplitude is smaller than that of other tooth shapes of gear oil pump.

4. Experimental Research on Gear Oil Pump

The experiment was carried out in Hunan Oil Pump Co. Ltd, which has a national advanced oil pump noise laboratory. Since only straight tooth gear pumps are in mass production, it was taken as the test object. And the test results can verify the CFD analysis from the side.

The test-bed uses an industrial computer as the main control unit, and develops a testing system which can monitor the testing process in real time. With testing parameters including speed of oil pump, number of teeth, oil temperature and oil pump pressure being set, the system can automatically collect test data such as the actual speed of the oil pump, oil supply, oil pump inlet and outlet pressure, inlet and outlet temperature, volumetric efficiency and total efficiency. After acquiring the data, we executed the signal analysis process, and the test curve was drawn according to the demand of users. The test-bed is shown in Figure 7. The flow rate of different speed was obtained by experiments, as shown in Table 2 and Figure 8.

According to the results shown in Table 2 and Figure 8, the error between the experimental flow and CFD simulated flow was within 5%, and the experimental flow matches well the simulation flow. Thus the results show that the oil pump analysis, by utilizing Pumplinx, can obtain valuable data and technically support the oil pump development.

5. Conclusions

Through the CFD analysis of gear pumps with different tooth profile and the experiment of straight gear oil pumps, the following conclusions can be drawn:

(1) Comparing with straight gear oil pumps, the outlet flow of other types of gear oil pumps is a little lower at speed of 1100~2700 rpm. At medium and high speed of 4000~5400 rpm, the flow of four types is very close, except that the flow of dislocation oil gear pumps is lower.

(2) The error between the experimental flow and the CFD simulation flow is within 5%, which shows the CFD simulation can simulate the practical working

Table 2. The flow value of experiment and simulation

<table>
<thead>
<tr>
<th>Rotational speed /rpm</th>
<th>Pump pressure /kPa</th>
<th>Experimental flow /(L/min)</th>
<th>CFD analyzed flow /(L/min)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>1100</td>
<td>100</td>
<td>12.798</td>
<td>12.19149</td>
<td>-4.97%</td>
</tr>
<tr>
<td>2000</td>
<td>100</td>
<td>23.598</td>
<td>22.95603</td>
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<tr>
<td>2700</td>
<td>100</td>
<td>32.298</td>
<td>31.1127</td>
<td>-3.81%</td>
</tr>
<tr>
<td>4000</td>
<td>100</td>
<td>46.552</td>
<td>45.4957</td>
<td>-2.32%</td>
</tr>
<tr>
<td>5400</td>
<td>100</td>
<td>58.254</td>
<td>59.803</td>
<td>2.59%</td>
</tr>
<tr>
<td>6000</td>
<td>100</td>
<td>63.264</td>
<td>66.47217</td>
<td>4.83%</td>
</tr>
</tbody>
</table>

Figure 7. Experiment of the oil pump.

Figure 8. Flow curves of experiment and simulation.
condition of the oil pump and technically support the development of the oil pump.

(3) The dislocation gear oil pump can effectively reduce the flow pulsation. The reduction is 27% in 1100 rpm and 35% in 2700 rpm. But at the high speed of 5400 rpm, its pulsation is almost the same as the straight gear oil pump. Therefore, dislocation oil gear pumps could reduce flow pulsation greatly in low and medium speeds.

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