Analysis of flow characteristics of a cam rotor pump

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Abstract. Immersed solid model of CFX is a professional method to solve dynamic grid problems of small gaps. In this work, the flow characteristics of a cam pump were calculated by immersed solid model. Results show that the flow rate of the cam pump decreases with the discharge pressure, but increases with the rotor speed; radial force of the cam pump increases with the rotor speed, as well as the discharge pressure. Meanwhile, the values of various parameters present pulsations of different levels. Moreover, the flow pulsation increases with the discharge pressure, but decreases with the rotor speed. In addition, the dominant frequency of various parameters is mainly influenced by integer multiples of the blade passing frequency. This paper may play a certain role for the selection of main parameters, as well as the pulsation reduction of the cam pump.

1. Introduction
Cam pumps are mainly adopted to transport the residual liquid left in oil tanks. In general, good self-priming performance is a critical factor for cam pumps. Currently, the study of cam pumps has achieved some results at home and abroad, such as the theoretical study, which is relatively mature [1-3]. Researchers can forecast volumetric rate and other parameters of rotor pumps using theoretical calculations, but the gaps are not considered, including the gap between both rotors, as well as the radial and axial clearances between the rotor and the pump casing. Considering that gaps can cause reflux and largely affect the performance of cam pumps, this is an important issue that needs to be considered. Many researchers have started to be engaged in the leakages of the gap in theoretical calculations and several different leakage models [4-5] have been reported, but there are still some errors between the calculated value and actual value.

With the development of computer technologies, researchers begin to study flow properties of the rotor pump using numerical methods [6-7], such as the dynamic mesh method. Dynamic mesh computation proposes high requirements to technical personnel. Besides, dynamic mesh problems of small gaps add much difficulty to mesh generations and numerical calculations. There is another numerical method called immersed solid model. It simplifies calculations of small gap problems, such as gear pumps and screw pumps, saving computational resources significantly and getting a better result. This method is included by the computational fluid dynamics software CFX and shows moving entities without grid deformation. The solver employs momentum source method inside immersed solids, forcing the fluid to flow following the solid. When the immersed solid model is used, the fluid mesh should cover the fluid and solid regions. The overlapping solid grids show an initial position of rotating entities. Fluid mesh is used as a static underground and the solid regions rotate about it. Fluid domain nodes and solid grid nodes in the overlapping region have the same velocity, which can be
used to capture the effect of solid.

In this work, the flow of a cam pump is simulated using the immersed solid model of computational fluid dynamics software CFX. The structure of this paper is arranged as following: Firstly, the physical model and theoretical calculation are given in Section 2. Then, numerical model of a cam pump is provided in Section 3. Finally, results and discussion are reported in Section 4.

2. Physical model and theoretical calculation
The structure of a cam pump is shown in Figure 1. Its flow rate, speed, pressure are $Q_d=60m^3/h$, $n_d=730r/min$ and $P_d=0.4MPa$, respectively. The medium transported is the aviation kerosene with a density $\rho=780 \text{ kg/m}^3$, viscosity $\mu=2 \text{ mm}^2/s$ and specific heat $C_p=2.2 \text{ kJ/(kg } K)$. 

![Figure 1. Structure of a cam pump](image)

Theoretical flow of the cam pump can be obtained using Equations (1)-(3). Volumetric efficiency is not considered in theoretical calculation. In other words, the loss caused due to gaps and liquid compression is not considered.

$$\lambda = 1 - \frac{S}{\pi R_m^2} = 0.4561$$  (1)

$$q = 2\lambda \pi R_m^2 L'$$  (2)

$$Q = q n \times 10^{-9} \times 60$$  (3)

where, $\lambda$ is the area utilization factor of the rotor pump; $S$ is the cross-sectional area of the rotor (unit: mm$^2$), which can be calculated by the order of “area" in AUTOCAD; $R_m$ is the radius of the top circle of the rotor (unit: mm); $q$ is the displacement of the rotor pump (unit: mm$^3$/r); $L$ is the width of the rotor (unit: mm); $Q$ is the flow rate of the rotor pump (unit: m$^3$/h); $n$ is the rotor speed (unit: r/min).

Volumetric loss mainly includes leakage loss due to gaps and the elastic loss due to the liquid compression. For leakage loss due to gaps, the gaps are mainly divided into two different kinds. One is the radial clearance, which contains the gap ($\delta_1$) between the rotor and the pump casing and the gap ($\delta_2$) between two rotors. It can be seen as the flow through a thin-walled hole. The other is the end clearance ($\delta_3$), which can be seen as the flow through two parallel plates $^{[4]}$.

Therefore, the leakage rate is calculated by Equation (4).

$$\Delta q = 4\delta_c \sqrt{\frac{2}{\rho} \Delta p + \delta_c \sqrt{\frac{2}{\rho} \Delta p + 2}} \frac{\Delta p \delta_3^2}{12 \mu l}$$  (4)

where, $l$ is the width in direction of the leakage (unit: m); $\Delta p$ is the pressure difference between the suction and the discharge chamber (unit: Pa).

For elastic loss due to the liquid compression, it can be obtained using Equation (5).
\[ \Delta Q_t = 2 \frac{\Delta P V}{E} Zn \]

where, \( E \) is the bulk modulus of the liquid (unit: Pa); \( V \) is the sum of the dead volume of the blades and the effective volume of two adjacent vanes (unit: \( m^3 \)); \( Z \) is the blade number of a rotor.

3. Numerical model

3.1 Geometrical model

According to requirements of the immersed solid model in CFX, the fluid region includes the overlapping portions of the fluid region and the rotor when building the model of the cam pump. To compromise between improving the accuracy and reducing the computation effort, the physical model of the cam pump is simplified, in which fillets, chamfers and complex compensation devices of the rotor are omitted.

To make the flow of the inlet and outlet in a steady state, the inlet and outlet are extended to three times of the inlet and outlet diameter, respectively. To maintain the gap between the two rotors to be 0.1mm, the upper and lower rotors are inwardly out 0.05mm along the theoretical profile line. Meanwhile, the radial gap between the rotor and pump casing is 0.05mm and the axial clearance of the rotor and pump casing is 0.0025 mm.

3.2 Mesh model

For immersed solid model, a high quality of the fluid grid is needed. For the mesh quality of the solid region, it just needs to be able to identify the physical structure of the solid. However, the boundary layer of the solid area should be fine enough to distinguish between the solid and fluid regions. Thus, the fluid domain is discretized by the hexahedral structured grid with the grid quality larger than 0.5, while the solid portion is discretized using the tetrahedral mesh, with the boundary layer of 10 layers and the initial height of 0.001mm, shown in Figure 2. The element and node numbers of cells are shown in Table 1.

![Figure 2. Mesh of fluid and solid regions](image)

| Part          | Element number | Node number |
|---------------|----------------|-------------|
| Fluid         | 1120169        | 1090688     |
| Solid(s)      | 649280         | 169680      |

3.3 Boundary conditions and solution settings

Immersed solid is only valid when it is driven by pressure. So pressure inlet and pressure outlet are used as boundary conditions. The pressure of the inlet is set to the atmospheric pressure, and the pressure of outlet ranges from 0 to 0.4MPa. The rotor speed ranges from 300 to 730r/min. The turbulence parameters are specifically set to the hydraulic diameter of the turbulence intensity and inlet diameter. Momentum source scaling factor is set to 20.
Time step is an important factor in transient simulation. Every 0.5 degree the rotor rotated is treated as one time step. Besides, the time step should be set based on its rotor speed.

4. Results and discussion

4.1 Flow characteristics of cam pump

The relationships between flow rate and discharge pressure for theoretical and numerical calculations at rated speed are shown in Figure 3. Results indicate that the flow rate of the rotor pump decreases with the discharge pressure. This is because higher pressure can result in higher temperature of the medium and lower viscosity, which will lead to more leakage in the gap and decrease the actual flow rate and volumetric efficiency of the cam pump.

![Figure 3. Relationships between flow rate and discharge pressure for theoretical and numerical calculations at rated speed.](image)

The relationships between flow rate and rotor speed for theoretical and numerical calculations at discharge pressure of 0.2MPa are shown in Figure 4. It can be observed that the flow rate increases linearly with the rotor speed. However, rotor speed should not be too high. Because higher speed will result in higher centrifugal force and the medium cannot fill with the cavity of the cam pump fully, which leads to the decrease of the flow rate. Moreover, low flow rate can cause cavitation and reduce the efficiency of the rotor pump.

![Figure 4. Relationships between flow rate and rotor speed for theoretical and numerical calculations at discharge pressure of 0.2MPa.](image)

4.2 Radial force of rotor pump

The radial force acting on the rotor is composed of two parts. One part is caused by fluid pressure along the rotor circumference direction $F_p$, and the other is caused by the rotor engagement. However, there is a gap between both rotors and they are not in contact with each other. Thus, the cam rotor is only subjected to radial force $F_p$.

Result shows that radial forces stood by both rotors are identical. The relationship between the flow rate and rotor speed, as well as the relationship between the radial force and discharge pressure, are shown in Figures 5-6. It can be seen that the radial force increases with the rotor speed, as well as the discharge pressure. This is because only the radial force caused by fluid pressure exits. Therefore, when the discharge pressure increases, the pressure difference between the inlet and outlet, as well as the hydraulic pressure, increases. When the rotor speed increases, the flow rate and hydraulic pressure increase. As a result, the radial force of the cam pump increases.
4.3 Pulsation characteristics of rotor pump

Pulsation, noise and efficiency are three major indicators when evaluating pump performances. In following, only the pulsation of the rotor pump is considered. As the engaging point of both continuously rotating rotors changes, the volume of the oil chamber changes accordingly and the instantaneous flow discharged from the oil chamber changes, which can cause a periodic flow pulsation. Pulsation can cause vibration of the system, which may result in unsteady flow and reduce the stability of the rotor pump.

Pulsation of the flow rate is usually represented by relative flow pulsation amplitude \( \delta \), which is solved by Equation (6). The relationship between flow pulsation rate and discharge pressure, as well as the relationship between flow pulsation rate and rotor speed, is shown in Figures 7-8. It can be seen that the flow pulsation rate increases with the discharge pressure, as well as the rotor speed.

\[
\delta = \frac{2(Q_{\text{max}} - Q_{\text{min}})}{(Q_{\text{max}} + Q_{\text{min}})}
\]  

(6)

To clearly see the relationship between the flow pulsation and radial force, Fast Fourier Transformation (FFT) is used to transform time domain signals into frequency domain signals. The spectrums of flow rate and radial force at rated speed are shown in Figures 9-10. It can be seen that three main frequencies can be clearly identified, which are related to the rotor speed and are independent on discharge pressure. Take the flow spectrum at rated speed as an example. The first frequency \( f_1 \) is the dominant frequency, 98.38Hz, equal to \( 8f_n = 2Zf_n \) (\( f_n \) is the rotation frequency of the rotor, 12.167Hz). This frequency is also defined as the blade passing frequency, mainly caused by the external excitation. The second frequency \( f_2 \) and third frequency \( f_3 \) are harmonic components, wherein \( f_2 = 16f_n = 2f_1 \), \( f_3 = 24f_n = 3f_1 \). When the radial force is considered, three main frequencies are the same as
that of the flow rate, but it should be noted that the second frequency $f_2$ is the dominant frequency.

![Figure 9. Spectrum of flow rate of cam pump](image)

![Figure 10. Spectrum of radial force of cam rotor](image)

5. Conclusions
In this work, flow characteristics of a cam pump have been calculated and the following conclusions are obtained:
1) The flow rate of the cam pump decreases with the discharge pressure, but increases with the speed of the cam rotor.
2) The radial force of the cam pump increases with the rotor speed, as well as the discharge pressure.
3) Values of various parameters present pulsations of different levels. Moreover, the flow pulsation increases with the discharge pressure, but decreases with the rotor speed.
4) The dominant frequency of various parameters is mainly influenced by integer multiples of the blade passing frequency.
5) This paper may play a certain role for the selection of main parameters, as well as the pulsation reduction of the cam pump.

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