Effect of Cam Angular Velocity on Working Efficiency of Fuel Engine

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Abstract. The intermittent working process of fuel entry and injection will cause the pressure in the high-pressure fuel pipe to change, causing deviations in the amount of injected fuel, which will affect the engine's operating efficiency. Taking a high pressure oil pump system as an example, the feasibility of using constant pressure to improve the working efficiency of the high pressure fuel system is studied. First, a series of simplified assumptions are made for the model. Secondly, use MATLAB software to make cam mechanism diagram. A cam angular velocity model based on pressure stability was established using the fuel quality of one injection of the injector and the fuel quality of one cam rotation. Calculate the number of times the cam needs to rotate to get the time that the cam needs to rotate once, so as to determine the high stability of the cam. The angular velocity required for tubing pressure was obtained.

Keywords: Pressure Control, MATLAB Software, Cam Angular Velocity

1. Introduction  
As the most widely used thermal power conversion device, the working efficiency of fuel engines directly affects all aspects of production and life [¹]. The high-pressure fuel pipe is an important part of the engine fuel system, and its main role is to provide fuel for the engine [²]. The intermittent working process of fuel entry and injection will cause the pressure in the high-pressure fuel pipe to change, affecting the working efficiency of the engine. Therefore, it is extremely important to study how to stabilize the pressure in the high-pressure oil pipe and improve the working efficiency of the engine. Aiming at the problem of high-pressure oil pipe pressure control, a lot of research and analysis work has been done by domestic and foreign scientific research institutions. Wang Jiaju made a comparative analysis of the TBD234V12 diesel fuel injection system. An improved scheme of the injection system was obtained [³]. Gu Lichang analyzed the injection system of the diesel engine and proposed a scheme for attenuating pressure waves [⁴]. Bai Shuzhan and Li Guoxiang proposed to change the connection between the fuel injection pump and the drive gear to flange connection. Effectively solved the vibration problem of high pressure oil pipe [⁵].
Synthesizing the above research conclusions, this article takes the high-pressure tubing in the "High Education Cup" National University Students Mathematical Modeling Contest A in 2019 as an example. Analyze the problem. By establishing relevant mathematical models, the angular velocity of the plunger cavity cam is controlled. The internal pressure of the high-pressure fuel pipe is kept stable, thereby improving the working efficiency of the fuel engine.

2. Introduction of High Pressure Oil Pipe
The high-pressure fuel pipe is an important part of the diesel fuel system. One end is connected to the fuel injection pump or common rail, and the other end is connected to the injector [6]. The length of the inner cavity of a high pressure oil pipe is 500mm, the inner diameter is 10 mm, and the diameter of the small hole at the oil supply inlet A is 1.4 mm. The oil supply time is controlled by the one-way valve switch, and the one-way valve will be closed for 10ms every time it is opened. The injector works 10 times per second, and the injection time is 2.4ms. The initial pressure in the high pressure oil pipe is 100 MPa.

3. Introduction of Working Process
The working principle of a high pressure fuel system is shown in Figure 1. The fuel enters the high-pressure fuel pipe from a through the high-pressure oil pump, and then ejects from nozzle B. The intermittent working process of fuel entering and ejecting will lead to the change of pressure in the high-pressure oil pipe, which makes the quantity of fuel ejected deviate and affects the working efficiency of the engine.

![Figure 1. Schematic diagram of high pressure oil pipe](image1)

4. Questions Raised
It is known that the oil pressure process of the plunger of the high-pressure oil pump is shown in Fig. 2, and the nozzle structure of the injector is shown in Fig. 3. When the angular velocity of the cam is about 100 MPa, the pressure in the high-pressure oil pipe can be stabilized as much as possible.

![Figure 2. Schematic diagram of actual working process of high pressure oil pipe](image2)

![Figure 3. Schematic diagram of enlarged injector nozzle](image3)
5. Problem Analysis
The problem requires that the angular velocity of the cam be calculated so that the pressure in the high-pressure oil pipe is as stable as possible at about 100MPa. To determine the angular speed of the cam, it is necessary to determine the time required for the cam to rotate for one turn. In this paper, the number of times that the cam needs to rotate is calculated by using the mass of fuel injected by the injector once and the mass of fuel provided by the cam once. Then calculate the time required for the cam to rotate once, and then calculate the angular speed of the cam to rotate.

6. Assumptions of the Model
This model is based on the following assumptions:
(1) The pressure in the high-pressure oil pipe is uniform at all times.
(2) The change of temperature with pressure and time is ignored.
(3) The friction resistance of needle valve shall not be considered.
(4) The flow loss of high-pressure oil pipe at both ends of high-pressure oil pump and fuel injection nozzle is not considered.
(5) The influence of variable cross-section and concentrated volume of oil pipe at the high-pressure oil pipe interface on fuel injection is ignored.
(6) At a certain time, the pressure in the plunger cavity of the high-pressure pump does not fluctuate.
(7) System leakage caused by oil supply process of high-pressure oil pump shall not be considered.
(8) The flow velocity of fuel in the plunger pressure chamber and the needle valve chamber is very low, so it is considered that the static compression in each chamber can achieve the balance in the moment of state change.
(9) When the cam rotates, the angular velocity changes uniformly.

7. Establishment and Solution of the Model
According to fluid mechanics, fluids are compressible. When the pressure of the fluid changes, the volume also changes \(^6\). This article assumes that the pressure of the high-pressure tubing is uniform throughout the process, and simplifies the model. Assuming that the mass of the oil ejected from the nozzle every 100 ms is the mass of the oil that is pressed into the high-pressure oil pump, the formula in the note is used to solve the mass of oil ejected from the nozzle. Then, according to the working principle of the cam and the change in pressure, the injection quality of the high-pressure oil pump is calculated. Through two comparisons, the number of times the high-pressure oil pump needs to be pressurized is obtained. Get the time required for each fuel supply, that is, the time that the cam rotates once, and then use the formula:

\[
W = \frac{2 \times \pi}{T}
\]

Find the angular velocity. The result is:

\[
w = 0.027 rad / ms
\]

7.1 Preparation before modeling

7.1.1 Understanding of nouns
Modulus of elasticity: "Elastic modulus" is generally defined as the stress in a unidirectional stress state divided by the strain in that direction. The fuel is short in the injection process, while the high-pressure fuel has a certain compressibility, and the high-pressure fuel pipe also has some elasticity \(^8\).
We have defined the following concepts and made a reasonable mathematical explanation.
In this paper, the elastic modulus refers to the physical parameters of the fuel and is used to describe the elasticity of the fuel.
Flow coefficient: The flow coefficient refers to the constant pressure maintained by the pipeline
under the test conditions, and the volume flow of the pipeline medium through the valve per unit time. The larger the value of the flow coefficient, the smaller the pressure loss of the fluid flowing through the valve. The flow coefficient in this article refers to the volume flow of fuel through the high-pressure fuel pipe check valve.

### 7.1.2 Data preprocessing

Descriptive statistics of known data:

**Table 1** Descriptive statistics of polar angle and polar diameter of cam edge curve

| index     | Polar angle | Polar diameter |
|-----------|-------------|----------------|
| Average   | 3.135       | 4.824777       |
| Standard error | 0.072399 | 0.068124       |
| Median    | 3.135       | 4.82405        |
| Standard deviation | 1.814323 | 1.707176       |
| Variance  | 3.291767    | 2.914449       |
| Kurtosis  | -1.2        | -1.50214       |
| Deflection | -2.6E-16  | 0.000719       |
| Area      | 6.27        | 4.826          |
| Min.      | 0           | 2.413          |
| Max.      | 6.27        | 7.239          |
| Summation | 1968.78     | 3029.96        |
| Number of observations | 628  | 628            |

**Table 2** Descriptive statistics of pressure and modulus of elasticity data

| index     | pressure  | Modulus of elasticity |
|-----------|-----------|-----------------------|
| Average   | 100       | 2265.43741            |
| Standard error | 2.893959226 | 26.0222606          |
| Median    | 100       | 2171.4                |
| Standard deviation | 57.95148833 | 521.095363         |
| Variance  | 3358.375  | 271540.378            |
| Kurtosis  | -1.2      | -0.924553             |
| Deflection | -2.23158E-18 | 0.46557655      |
| Area      | 200       | 1855                  |
| Min       | 0         | 1538.4                |
| Max.      | 200       | 3393.4                |
| Summation | 40100     | 908440.4              |
| Number of observations | 401  | 401                  |

In Table 1, it can be concluded that the total observations of polar angle and polar diameter are 628, and the average value of polar angle is 3.135, the median value is 3.135. It changes within the range [0, 6.27]. The mean value of polar diameter is 4.824777, the median value is 4.82405, and the range of variation is [2.413, 7.239].

In Table 2, it can be concluded that the total observation data of pressure and modulus of elasticity are 401. The average value of pressure is 100MPa, the median value is 100, and the variation range is [0, 200]. The average value of elastic modulus is 2265.43741mpa and the median value is 2171.4. It changes within the range [1538.4, 3393.4].
7.1.3 Making cam diagram with MATLAB

The polar angle is converted to the angle under the rectangular coordinate system, and the formula is used: 

\[ \text{1 rad} = \frac{180^\circ}{\pi} \]

Convert the polar angle value in the attachment to the angle value in the rectangular coordinate system, take the polar diameter as the \( x \)-axis and the converted angle value as the \( y \)-axis, and use MATLAB software to make the image of polar diameter value and angle value, that is, the cam diagram, as shown in Figure 4.

![Cam diagram](image)

Figure 4. Cam diagram

7.1.4 Calculation of orifice area

\[ s_1 = \pi \times r_1^2 = 3.14 \times \left( \frac{1.4}{2} \right)^2 = 1.5386 \text{mm}^2 \]

(3)

Among them, \( s_1 \) is the area of orifice; \( r_1 \) is the radius of orifice.

7.1.5 Calculation of the circle area formed by needle valve:

Height of initial needle valve from cone tip:

\[ h_2 = \frac{r_2}{\tan 9^\circ} \]

(4)

\[ R = (h_2 + h_3) \times \tan 9^\circ \]

(5)

\[ s_2 = \pi R^2 - \pi r_2^2 \]

(6)

\( r_2 \) is the radius of needle valve; \( h_3 \) is the height of rising.

7.1.6 Volume of oil ejected by the fuel injector \( V_1 \) per second

The volume of oil ejected by the nozzle every 0.01s and a every 0.01s are changing. Therefore, the flow rate \( Q \) in each second is different, so the volume \( V_1 \) in each second is different:

\[ V_1 = Q \times t = C \times \sqrt{\frac{\Delta p}{\rho}} \times A \]

(7)

\( \Delta p \): Assuming that the atmospheric pressure outside the nozzle is a standard atmospheric pressure of 0.1MPa, the pressure difference between the high-pressure oil pipe and the atmospheric pressure.
7.1.7 Flow rate of oil in and out of the orifice every 0.01s

\[ Q_i = C \times S \times \sqrt{\frac{2 \times \Delta p}{\rho}} \]  

(8)

The area of the circle formed by the needle valve increases first, then remains unchanged, and finally decreases, and the area of the orifice remains constant. The area of the circle formed by the needle valve is compared with the area of the orifice. The smaller the area restricts the amount of oil entering, and the smaller area is selected as the value.

\[ S = \begin{cases} s_1, & s_1 \leq s_2 \\ s_2, & s_2 \leq s_1 \end{cases} \]  

(9)

7.2 Establishment of cam angular velocity model based on pressure stability

\( m_1 \) is the quality of the oil that is added to the cam once.

\[ m_1 = \rho_1 V_2 = \rho_1 \times (V_3 + V_4) \]  

(10)

\[ V_4 = s_1 \times h_1 = \pi \times r_2^2 \times h_1 \]  

(11)

\( m_2 \) is the quality of oil ejected by the injector at one time:

\[ m_2 = \rho_1 \times V_5 \]  

\( V_5 \) is the volume of oil ejected by the injector at one time.

The volume of fuel injected by the injector is \( v \) per 0.01ms:

\[ v = Q_i \times T_0 \]  

\( Q_i \) is the rate at which fuel enters and exits the injector orifice.

Time interval of \( T_0 \) is 0.01s. The volume of fuel injected for every 0.01ms injector is \( v \). Sum to get \( V_5 \):

\[ V_5 = \sum_{i=0}^{37} v_i (i = 0, 0.01, 0.02 \cdots) \]  

(12)

The number of times that the cams need to rotate once for injector operation:

\[ a = \frac{m_2}{m_1} \]  

(13)

One operation of the fuel injector is the time required for the cam to rotate once in 100ms:

\[ T = \frac{100}{a} \]  

(14)

Angular velocity of cam:

\[ w = \frac{2\pi}{T} = 2\frac{a\pi}{100} \]  

(15)
Establishment of cam angular velocity model:
The model of cam angular velocity can be established after comprehensive arrangement.

\[
w = \frac{2 \times \pi \times \rho_1 \times \sum_{i=0}^{247} v_i}{\rho_1 \times (V_3 + \pi \times r_2^2 \times h)}
\]  

(15)

7.3 Model solution

\[
w = \frac{2 \times \pi \times \rho_1 \times \sum_{i=0}^{247} v_i}{\rho_1 \times (V_3 + \pi \times r_2^2 \times h)}
\]  

By substituting the data into the model and using Excel to calculate the angular velocity of the cam:

\[w = 0.027 \text{ rad} / \text{ms}\]  

(17)

Therefore, the angular velocity of the cam:

\[w = 0.027 \text{ rad} / \text{ms}\]  

(18)

8. Conclusion
The intermittent working process of fuel entering and ejecting high-pressure fuel pipe will lead to the change of pressure in the high-pressure fuel pipe, which will lead to the deviation of fuel quantity ejected from the high-pressure fuel pipe and affect the working efficiency of the engine. In order to make the injector spray the same amount of fuel every time, it is necessary to control the pressure of the high-pressure oil pipe to keep stable. In this paper, by controlling the angular velocity of the plunger cavity cam, the internal pressure of the high-pressure oil pipe is kept unchanged and the working efficiency of the engine is improved. This solution is universal and has certain guiding significance for solving other similar problems.

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