Discussed on mechanism of production and improvement for Noise and Vibration of Hydraulic valve system

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Abstract. Based on mechanism of production for Noise and Vibration, in this paper, analysis model is established, and improvement measure is purposed through some factors, then is tested. The results are evaluated and shown: noise and vibration of hydraulic valve system are effectively reduced by enhancing design of cam profile, choosing appropriate lubrication oil and adjusting structure parameters.

1. Introduction
Automobile noise and vibration are two important indicators to measure vehicle ride comfort. NVH is combined by Noise, Vibration and Harshness. It is the study on vehicle performance, and also is a comprehensive technical index to measure vehicle design and manufacturing quality [1]. Hydraulic valve system is widely used in automobile, it can make up valve clearance caused by thermal effect in the operating between the camshaft and valve, so the valve mechanism durability is improved, and engine maintenance cost is reduced. However, valve timing is adjusted by controlling the action of hydraulic components (cam plunger, cam cylinder, valve plunger, valve cylinder). Therefore, hydraulic shock and cavitation are produced in this process to cause engine vibration and noise [2].

2. The structure and working principle of hydraulic valve system
Typical hydraulic valve system is shown in Fig. 1 [3].When the CAM base circle is contacted with tappet 1, oil pressure and return spring force below on the plunger 5 make tappet contact tightly with cam, there is no valve clearance between the CAM and a cylinder, the valve is closed. Crankshaft drives the CAM shaft, when CAM rotates to the rising period, tappet1 moves downward under the CAM pressure and makes oil pressure of high-pressure chamber9 risen, and then the oil column of high-pressure chamber transfers the force and movement [4]. When the sum force of the high-pressure chamber and return spring is greater than the valve spring force, hydraulic system composed of tappet, plunger and plunger sleeve becomes intermediates between the CAM and valve to transfer movement and force, at the moment, plunger sleeve and valve move downward with tappet. When the valve dropped back to valve seat, valve spring force is no longer on the plunger sleeve, high oil pressure and return spring forced plunger and plunger sleeve against CAM to move upward, lift of tappet is reduced to the zero. Hydraulic system returns to the initial stage, the valve clearance is automatically eliminated.
3. The mechanism analysis of hydraulic valve system noise and vibration

The noise caused by the hydraulic valve system vibration is one kind of engine inherent noise. The schematic diagram of hydraulic valve system is shown in Fig. 2, in which cam rotates as the CAM profile. CAM hydraulic system is composed of CAM cylinder and CAM plunger, yet valve hydraulic system includes valve cylinder and valve plunger. Valve cylinder is connected with CAM cylinder through pipes.

In order to further analyzing the leakage and hydraulic components of hydraulic system on the influence of noise and vibration, mathematical model was build up by parameters as cam profile, structure of the hydraulic system and engine oil performance.

3.1. The vibration and noise produced by matching between CAM profile and hydraulic system

CAM profile is the function curve of displacement (lift) and angle of CAM, which the CAM profile can be tested, equations of motion is got by function fitting, as followed:

$$\ddot{y} = c_0 + c_1 \frac{d^2 y}{dt^2} + c_2 \frac{d^3 y}{dt^3} + c_3 \frac{d^4 y}{dt^4} + c_4 \frac{d^5 y}{dt^5} + c_5 \frac{d^6 y}{dt^6} + c_6 \frac{d^7 y}{dt^7}$$

(1)
Which, $y_i$ is lift; $\theta$ is working half cornerite; $p\cdot q\cdot r\cdot s$ is power exponent, according to the ascending power arrangement, $c_0\cdot c_2\cdot c_p$ is unknown number.

According Ref.5 5, high power hepta polynomial cam profile was established, the boundary condition was determined by the single mass model, equidistant interpolation method in one known interval is used for solving and simulation. As results shown that, under the condition of same engine speed, leakage volume of valve cylinder firstly increases as the CAM lift risen, then gradually decreases.

Oil leakage occurs in the base circle section and return stoke, and ends in the lift stroke. CAM cylinder leaking makes overall rigidity of hydraulic valve weaken, lets maximum lift lessen, then causes noise and vibration.

3.2. The influence of structural parameters

(1) The influence of CAM cylinder and plunger

The oil leakage is associated with structural parameters of the hydraulic system. In hydraulic system comprised by CAM cylinder and plunger, $d_1$ is diameter of CAM cylinder, $q_i$ is oil leakage, $\delta_1$ is side sealing clearance between CAM plunger and cylinder, $p_i$ is CAM cylinder's transient pressure, $l_i$ is minimum matching length between plunger and cylinder, $\mu$ is oil viscosity.

For CAM cylinder, flow equation of continuity is:

$$\frac{\pi d_1^2}{4} \frac{dy_i}{dt} - q_i - q_2 = 0 \quad (2)$$

Which, $q_2$ is leakage of valve cylinder.

Yet volume equation of continuity is:

$$q_i = \frac{\pi d_1 \delta_1 p_i}{12 \mu (l_i + y)} + \frac{\pi d_1 \delta_1 dy_i}{2} \quad (3)$$

In For.3, oil leakage volume of CAM cylinder is related to axial flow caused by differential pressure at the ends of the seal clearance, also related to relative motion between CAM plunger and cylinder. When cam is in return stage, movement direction of CAM plunger is in the same with cylinder leaks’, so the For.3 is plus (Similarly, in the lift stage, the For.3 is minus). Cylinder’s leakage is composed of differential pressure’s leakage and shearing flow caused by plunger movement. When in the CAM base circle, CAM plunger is static, and the seal ends face has differential pressure, the valve cylinder’s leakage is all differential pressure discharge. When in the lift stage, leakage is difference value between differential pressure’s leakage and shearing flow.

Because CAM plunger movement speed is high, shearing flow is much larger than differential pressure’s leakage, therefore, shearing flow can prevent the CAM cylinder’s leaking. The CAM cylinder’s leakage depends on the plunger’s movement speed, yet plunger’s speed depends on the engine speed. CAM cylinder’s volume leakage increases as engine speed risen, especially in return and base circle stage.

(2) The influence of valve cylinder and plunger

For valve hydraulic system, $p_2$ is valve cylinder's transient pressure, $d_2$ is diameter of valve plunger; $y_2$ is valve lift; $\delta_2$ is side sealing clearance between valve plunger and cylinder, $l_2$ is maximum matching length between plunger and cylinder. Volume equation of continuity from CAM cylinder to valve cylinder is:
\[ q_2 = \frac{\pi d^4 (p_i - p_f)}{128 \mu l} \]  
\[ \frac{\pi d^2 \cdot dy_2}{4} - \frac{q_1 - q_2}{dt} = 0 \]  
\[ q_3 = \frac{\pi d_2^2 \delta y_2^2 \mu}{12 \mu (l_2 - y_2)} - \frac{\pi d_2 \delta y_2}{2} \frac{dy_2}{dt} \]  

Which, \( d \) is pipe diameter connected CAM cylinder with valve cylinder, \( l \) is pipe length connected CAM cylinder with valve cylinder.

Flow equation of continuity is:

Valve cylinder’s leaks just has in lift and base circle stage, and ends in return stage. Shearing flow caused by the plug movement is the main reason for valve cylinder’s leaks, and increases with engine speed rising.

In For.(2) ~ (6), leakage increased as the engine speed risen in the return CAM and base circle phase, then caused more vibration and noise.

### 3.3. The influence of hydraulic transmission medium for noise and vibration

Hydraulic medium for the hydraulic valve is lubricating oil, the damping coefficient of hydraulic system is influenced largely by lubricating oil pressure, temperature, viscosity. Oil temperature is higher, damping coefficient is smaller; oil viscosity is larger, damping coefficient is greater.

Oil pressure of high pressure chamber and oil storage is respectively \( p_h \) and \( p_c \), \( A_h \) is sectional area of oil column for high pressure chamber, \( q_j \) is leakage of high pressure chamber per unit time. According to Ref. [6],

\[ c = \frac{(p_h - p_c) A_h^2}{q_j} \]  

In For.7, \( c \) is damping coefficient of hydraulic valve system. Damping coefficient depends on the leakage of high pressure chamber and lubricating oil pressure. The damping coefficient is smaller, tappet declining speed is faster, and the noise and vibration is greater.

### 4. discussed on measures for reducing the vibration and noise of hydraulic valve system

#### 4.1. Improve the design of CAM profile, and optimize dynamics model of the valve driving system

Cam runout and lift bounce are main reasons for noise and vibration, they are improved best at the design stage. Because cam profile can let the total rigidity of hydraulic valve system cut down, high pressure chamber leaks can make the maximum lift reduced, then the correction of acceleration for CAM profile can inhibit the maximum lift decreased. In rising transition section, plunger lift should be able to make oil pressure of high pressure chamber go up to equal the valve springs pre-tightening force, and able to compensate valve body deformation under the valve spring pre-tightening force and camshaft runout. In falling transition section, CAM lift loss caused by high pressure chamber leaks should be considered, it also can be improved through CAM profile changing, or used compound cycloidal [8], or dynamic correction.
4.2. Reasonably determine the scope of design parameters, and optimize the design of the hydraulic system

The value, such as CAM cylinder, CAM plunger, valve cylinder, valve plunger etc., will directly affect the vibration and noise of hydraulic valve system. Influence parameters are compared by two optimization design factors, they are "dry clearance" and "leakdown". In a completed engine hydraulic valve system, when CAM base circle is in alignment with a tappet, the tappet plunger is pressed into the bottom, the gap between the matching parts is dry clearance [9]. When high pressure chamber is filled with specified lubricating oil and a certain load is put on both ends of the hydraulic valve, leakdown is measured time [10] which plunger passed specified distance. The time can reflect the size of the fitting clearance between plunger and plunger sleeve, and also reflect how much leakage during the period of the valve opening and closing. The clearance and the fitting length have greater influence for leakdown, for example, wears between plunger and plunger sleeve, cavitation of the hydraulic system, they can shorten leakdown. If leakdown is serious, when valve had dropped on the seat in engine warming-up condition to cause vibration and noise easily.

In order to restrain noise and vibration in hydraulic valve system, fitting surface between plunger and plunger sleeve should be in wear resistance and corrosion resistance. Low pressure oil cavity should be larger volume, and maintain to interlink with oil exports of the guide hole, so that oil can be added in the high pressure chamber, the air cannot enter into the chamber, the larger vibration and noise also can be avoided after restart vehicle. The right fitting clearance is selected, the necessary sealing length is kept, and then the leakage of the low pressure chamber is lower.

4.3. Correctly select the engine lubricating oil

Oil temperature largely effect oil leakage of hydraulic valve system, Ref.[10] shows that two curves are shown between the leakage and body force under different oil temperature. The curve indicated the temperature is higher, leakage is more. Because oil temperature is higher, the general rigidity of the valve system is lower.

In engine lubricating oil selecting, in addition to attention to brand and grade, still specially the kinematic viscosity. The viscosity should be $(70 \pm 4) \text{ mm}^2 / \text{s}$. The viscosity is greater, the liquidity of lubricating oil drops, then will lead to the change of leakdown.

![Figure 3. The influence of oil temperature to hydraulic valve leakage](image)

5. Test verification

5.1. In this test, target noise value original design is compared with the value after optimization to verify whether improvement approach is available.

Testing comparison of engine parameters is shown in Tab.1. Test procedure is indicated in Fig.4.
Table 1. Testing comparison of engine parameters

| Comparison items | Before optimization | After optimization |
|------------------|---------------------|--------------------|
|                  | Intake CAM          | Exhaust CAM        | Intake CAM | Exhaust CAM |
| CAM profile      | High order polynomial | Compound cycloidal polynomial |
| Contact stress (N) | 471 472 | 456 604         |
| Lift (mm)        | 7.7 8.51 | 7.61 8.491       |
| Height of surge section (mm) | 0.16 0.17 | 0.32 0.35 | 0.32 0.36 | 0.45 0.47 |
| Rate of surge section (m/s²) | 1.10 1.10 | 1.10 1.10 | 1.01 0.88 | 1 0.79 |
| Lubricating oil  | General brand oil   | Matched oil        |

Figure 4. Test procedure

Vibration software and hardware of Germany Head Company is used in this test. Vibration signals is picked up by a three-way acceleration sensor, noise signals is collected through earphone and microphone. Hardware of signal collection is portable four-channel front terminal, software is Head Recorder. Artem post-processing software is used for signal analysis, and software interface is shown in Fig.5.

Figure 5. Software interface

In Fig.6, when engine speed is 1000r/min, the optimized engine noise is significantly lower than the value before optimization. So improvement approach can effectively control the noise and vibration.
6. Conclusion

A. CAM profile has a certain influence on NVH of hydraulic valve system, especially in return and base circle stage.
B. The influence parameters of NVH is formed by gap leakage of cam and valve hydraulic system.
C. The relationship between NVH regularity and the structural parameters need be further discussed.

Acknowledgments

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