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Vibration Model and Characteristic Analysis of Hydraulic Piston Pump

Wei Wang

Xi'an Aeronautical University, Xi'an, China
WeiWang@126.com

Through the internal analysis of excitation vibration source and vibration transfer path of the piston pump, this paper puts forward that the final receptor of the plunger pump is the case, introduces the vibration harmonic response analysis, and derives the mathematical expression of the vibration harmonic response analysis. This study establishes a finite element model of the plunger pump, and makes modal analysis; according to the results of modal analysis, make vibration harmonic response analysis of the case, and determine the modal frequency that has the largest impact on pump shell structure dynamic performance; finally, finds out the region where the vibration is severe under the normal working state of axial piston pump. The research result provides a theoretical basis for the analysis and optimization of the axial piston pump's vibration test and analysis, and provides a new idea and method for the research on the vibration noise reduction technology of axial piston pump.

1. Introduction

In project practice, almost all equipment is in vibration environment, and keep their own unique vibration form, which not only hinders product function, but also damages the operator's physical and mental health and pollutes the environment. At the same time, with the development of science and technology, the product structure is becoming more and more complicated, and the performance requirements are increasingly high (Kumar and Bergada, 2013). In order to make the product work safely and reliably, it is necessary to ensure that the system has good dynamic characteristics. Therefore, it is necessary to carry out dynamic analysis and design of mechanical products and equipment, so as to meet the requirements of static and dynamic characteristics of mechanical structure and low vibration and low noise.
For a hydraulic system, the hydraulic pump is one of the most important noise sources. To control the noise of the hydraulic system, it is necessary to analyze and study the radiation noise of the surface of the hydraulic pump, while the noise of axial piston pump is more prominent than other hydraulic pumps (Quan et al., 2015). In order to ensure that the piston pump has sufficient strength and rigidity when working (Walmsley et al., 2017), make the deformation minimum, and vibration and radiation noise minimum, it is necessary to study the dynamic characteristics and improve its strength and stiffness by suppressing vibration and optimizing the structure.

2. Research content and method

(1) Introduction to pump body structure
The object of this study is the swash plate axial piston pump. In the right of the plunger pump end cover is the swash plate with angle of 14 DEG, 7 pistons are located in the pump core of the center of the pump body, and contact with through the slipper and swash plate end cover, and in the left of the pump core is the oil pan (Xu et al., 2016). The middle of the pump core is connected by spline and spindle, to realize spindle rotation, the pump core rotates, and the pump core drives 7 plungers to slide on the swash plate. Since that the axial piston displacement is continuously changing, the pressure oil is compressed into a high-pressure oil pump, a total length of 360mm, and the total weight of 15kg.
(2) Finite element method analysis

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The principle of modal analysis in this paper is based on the finite element method and linear vibration theory. The finite element model of piston pump is regarded as an elastic system with finite freedom degree, and its movement equation is described by virtual work principle as follows:

$$[\boldsymbol{M}]\{\ddot{\delta}\}+[\boldsymbol{C}]\{\dot{\delta}\}+[\boldsymbol{K}]\{\delta\}=\{\boldsymbol{R}_{(t)}\} \tag{1}$$

In (1), M is total mass matrix structure combined by concentrating each unit uniform mass in unit nodes in accordance with the finite element model; K is overall structure of assembled stiffness matrix based on tetrahedron solid element according to unit division. In order to obtain the natural frequency, the load vector is {R (T)} =0 (Wu and Yu, 2014); at the same time, because of the structural damping of piston pump is small, the influence on the natural frequency and mode of vibration can be neglected, then (1) becomes the free vibration equation without damping:

$$[\boldsymbol{M}]\{\ddot{\delta}\}+[\boldsymbol{K}]\{\delta\}=0 \tag{2}$$

Assuming that the solution for (2) is:

$$\{\delta\}=[\delta_M]\sin\omega t \tag{3}$$

In (3), {δM} is the modal column vector; t is time; ω is the natural frequency of vibration. Let ω2=λ, (3) is substituted into (2), then get the generalized eigenvalue equation:

$$([\boldsymbol{K}]-\lambda[\boldsymbol{M}])\{\delta_M\}=0$$

The eigenvalue value λ is corresponding to the natural frequency of the plunger pump, and the mode vector {δM} is corresponding to the vibration mode of the plunger pump at different frequencies.

3. Vibration model and characteristic analysis

(1) Establishment of finite element model
Since that the plunger pump shell structure is complex, in order to facilitate the mesh division, save computing resources, and shorten the calculation time, on the premise of not great effect on the case whole vibration characteristic, it is necessary to simplify the case model. The specific simplification operation is as follows: (1) ignore the small holes that have small effect on the overall vibration characteristics; (2) ignore the thread feature that have small influence on dynamic characteristics but accounted for a larger memory (Choudhuri et al., 2014). According to the actual model, establish the three-dimensional solid model of pump case in the 3D software SolidWorks and import into ANSYS Work-bench. In this software platform, the grid case geometric model simplified is divided. In order to ensure good mesh division quality and high computational efficiency, use tetrahedral mesh division. For the stress concentration area with proper mesh in casting process, use properly encrypted grid, and finally, obtain the finite element model of the case, in which the division nodes are a total of 177545, and the total number of units is 105797 (Pelosi and Ivantysynova, 2013).
The analyzed axial piston pump is an inclined shaft type axial piston pump, whose model is A7V170, and the case material is ductile iron QT500-7. According to the "Mechanical design manual", it can be found that, the elastic modulus is E=1.5 * 1011Pa, Poisson's ratio is u=0.25, and the density is ρ =7.2 * 10^3kg/m^3.

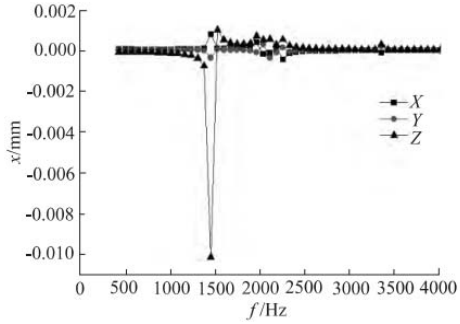
(2) Modal analysis
The axial plunger pump adopts the way in which the front flange bolt of the pump casing is installed, so the front flange bolt of the pump casing is provided with a fixed support constraint, and then the modal analysis is carried out. The natural frequencies of the first 10 modes are shown in Table 1.

Table 1: The natural frequencies of the first 10 modes

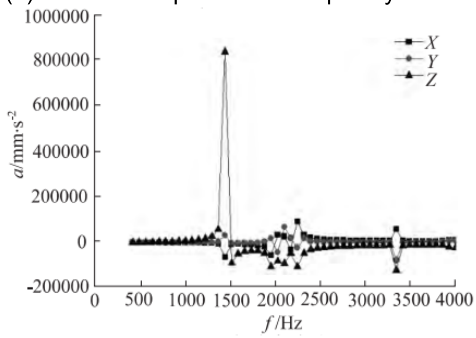
Order number	The natural frequency/Hz	Order number	The natural frequency/Hz
1	360.4	6	2085.1
2	362.79	7	2221.8
3	1177.1	8	2299.6
4	1451.3	9	3342.6
5	1990.1	10	3964.2

It is known from the vibration theory that what plays the major role in the process of structural vibration is the low order mode. The high order mode has little contribution to the response, and the attenuation is very fast, so it only needs to consider the lower order mode (Zhang and Guo, 2008). Next, the modal shapes of the first ten-order of the shell are listed, as shown in Figure 1, and the analysis is carried out. It can be seen that the larger regional deformation modes are mainly concentrated in the rear shell and the middle of the shell. The vibration of the shell surface and both sides in the middle of the shell have obvious deformation, so the structure stiffness of these parts is weak.

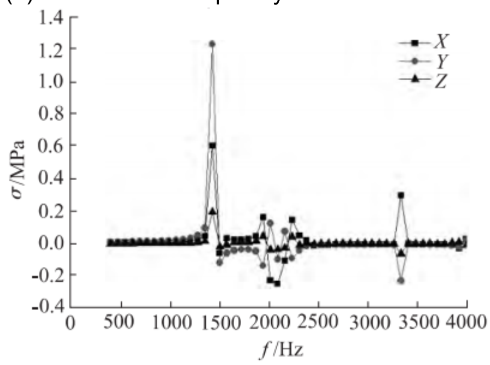
(3) Vibration harmonic response analysis



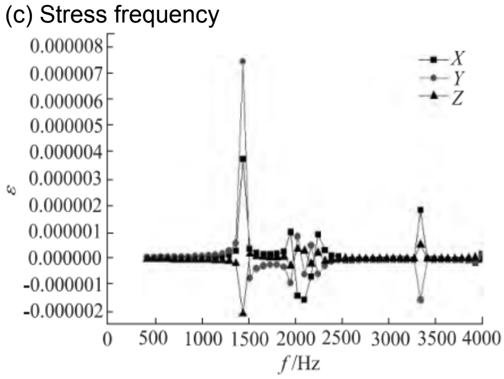
(a) Vibration displacement frequency



(b) Acceleration frequency



(c) Stress frequency



(d) Strain frequency

Figure 1: The curves of vibration displacement, acceleration, stress, and strain frequency

As a result, in the analysis of harmonic vibration response described below, focus on the displacement, acceleration, and the relationship between stress and strain and the input excitation frequency of these places in the external excitation, to establish the basis for structure optimization and test analysis.
Respectively choose the axial piston pump rear shell and the middle of the shell to carry out vibration harmonic response analysis. Combined with the above contents, focus on the analysis of vibration harmonic response when the shell bearing is under forced excitation. It is assumed that the amplitude of the excitation is 1×10^3N, the frequency range is 3×10^2~4×10^3Hz (Alaswad et al., 2011). The response curves of displacement, acceleration, and the response curve between the stress, strain and excitation frequency are obtained by means of vibration harmonic response analysis.

1) Vibration harmonic response analysis of the rear shell
The surface A of the axial piston pump rear shell is taken as the research surface for the vibration harmonic response analysis, to establish the three-dimensional coordinate system, X, Y, Z three directions respectively represent two mutually orthogonal radials and axial of spindle axial piston pump. Choose X, Y, Z three directions vibration displacement, acceleration, and response curve between stress and strain and the excitation frequency, as shown in Figure 1.
It can be seen that, with the increase of the excitation frequency, vibration displacement, acceleration, stress and strain will generate the peak at the corresponding resonant frequency, but at the fourth order natural frequency (about 1445Hz), the peak is the largest. Table 2 gives the maximum vibration displacement, acceleration, stress and strain peak value.

Table 2: Rear shell largest value corresponding frequency

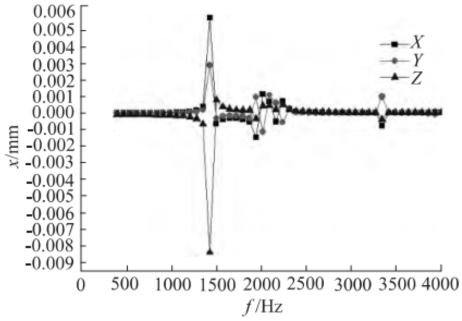
	Peak/valley value	Frequency/Hz
Vibration displacement	-1.013×10^{-3}mm	1445
Acceleration	8.351×10^5mm/s^2	1445
Stress	1.223MPa	1445
Strain	7.39×10^{-6}	1445

2) Vibration harmonic response analysis of the middle part of shell
(1) Sweep frequency analysis in the middle of the shell
The middle D surface of the shell of axial piston pump is taken as the research surface for the study of vibration harmonic response analysis, to establish the three-dimensional coordinate system, choose the response curves of X, Y, Z three directions respectively representing vibration displacement, acceleration, stress and strain and excitation frequency, as shown in Figure 2.
Similarly, it can be seen that, in the fourth order natural frequency (about 1445Hz), the peak generated in the middle of the shell of the axial piston pump is the largest.
Table 3 shows the largest vibration displacement, acceleration, stress and strain peak.

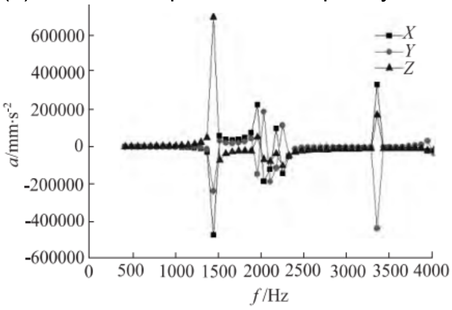
Table 3: The middle of the shell largest value corresponding frequency

	Peak/valley value	Frequency/Hz
Vibration displacement	-8.368×10^{-3}mm	1445
Acceleration	6.898×10^5mm/s^2	1445
Stress	6.481MPa	1445
Strain	3.596×10^{-6}	1445

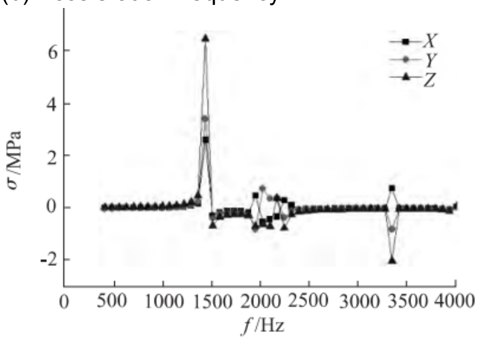
(2) The middle shell structural response analysis under the fourth order natural frequency
Respectively analyze the vibration displacement, stress and strain in the middle of the shell, and find out the response sensitive area of the middle surface of the shell under the excitation frequency of 1445Hz. It can be drawn that, the area that the largest value the vibration displacement in the middle shell corresponds to is on the lower right side, while the stress and strain the maximum corresponding area is on the lower left side. These analyses can be used as the basis for vibration sensor installation in the vibration data detection of the middle shell part of the axial piston pump.
Comparing the modal analysis and harmonic response analysis results, we can see that, the fourth order natural frequency is slightly different from the maximum peak frequency. The main reason is that if the vibration frequency resolution of the input excitation is set small in the harmonic response analysis, the computation will be very large, affecting the calculation speed. However, if the two frequencies are close, and the error is about 1.8%, it will have little effect on the results of the study.



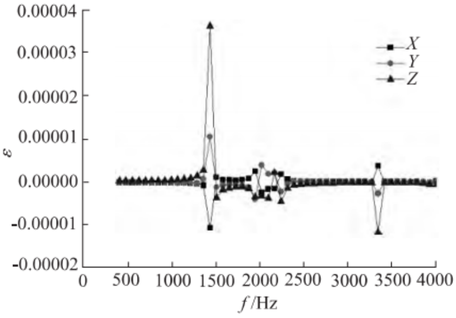
(a) Vibration displacement frequency



(b) Acceleration frequency



(c) Stress frequency



(d) Strain frequency

Figure 2: The curves of vibration displacement, acceleration, stress and strain frequency

4. Conclusion

The conclusion can be drawn as follows through the above research results: (1) The vibration severe region is concentrated in the rear shell and the middle of the shell in analyzing the axial piston pump. When the input excitation frequency that the axial piston pump bears is 1445Hz, namely in the fourth order natural frequency, the vibration is the most severe. (2) When the rear shell and the middle of the shell of the axial piston pump vibrate at the same frequency, vibration displacement, stress and strain sensitive areas will be different. In consequence, to detect the vibration data of the rear shell and the middle of the shell, if make use of vibration sensors in different types, they are supposed to be installed in the corresponding sensitive areas.

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