Axial piston pump mechanical vibration transmission path and the rear shell sensitivity analysis*

Lingxiao QUAN, Qiwei ZHANG, Zongxia JIAO, Jianwei LIU, Song Liu

Abstract—**The mechanical vibration transfer path model of the axial piston pump was established for aiming at the aviation hydraulic vibration that it has been more intense with the development trend of high speed and high pressure. In this paper, firstly, based on the first-order trajectory sensitivity method to solve the time-domain sensitivity function curves, the system parameters that have influence on the vibration response of the pump were determined. Secondly, two sensitivity measure indexes were defined to quantitative analysis of the effect that various parameters on the rear shell vibration displacement. We hope that the work in this paper can have some benefit for controlling the aircraft hydraulic system machinery vibration coming from the pump, optimizing the structure of aviation hydraulic pump and promoting the development of domestic large aircraft, providing theoretical and technical basis.**

I. INTRODUCTION

As the speed and pressure of the axial piston pump go on to raise, its vibration intensity and frequency range are increasing continuously. The research on axial piston pump vibration mechanism and vibration control has gotten more attention. The axial piston pump vibration can be divided into the fluid vibration and the mechanical vibration. The mechanical vibration is generated by eccentric rotator and uneven, the bearing vibration and the vibration of the swashplate-variable displacement mechanism [1]. Many scholars launched a lot of research on the mechanism of axial piston pump mechanical vibration at home and abroad. The axial piston pump shell vibration was studied and its structure was optimized by Germany Rexroth company and Andre Palmen of RWTH Aachen [2, 3]. Professor Landsberger of Texas University proved that the vibration of the axial piston pump was associated with the torque ripple of the shaft through the testing experiment [4]. Manring et al. of Columbia University studied the problem that the torque ripple of the transmission shaft of the tandem type axial piston pump theoretically [5]; Bing Xu of Zhejiang University proved that the main exciting vibration source of the plunger pump was the vibration of the swashplate-variable mechanism and the vibration caused by lateral flow and pressure impact of oil-trap area of the port plate through the vibration testing experiment [6, 7]. Lingxiao Quan of Yan Shan University analyzed the exciting vibration source of the bent axis axial piston pump, and pointed out that the ultimate receptor of the piston pump vibration is the shell [8].

The transfer path analysis (TPA) is a direct method to study the vibration transmission law of complex mechanical system, it comes from experimental techniques and has been widely applied to structural vibration control field [9]. The sensitivity analysis is a method to study the sensitivity that the state or output of a system or a model changes to their parameters or the surrounding conditions [10]. Based on the mathematical model of vibration transfer path, the quantitative analysis of the contributive degree of its parameters to the vibration transfer rate can be taken when the sensitivity analysis has been applied to the system parameters. The sensitivity analysis is widely used in the analysis of vibration mechanism and the vibration control of complex mechanical system [11]. Based on the basic theory of vibration, the general probabilistic perturbation and the structural reliability theory, in China, professor Yi min Zhang of Northeastern University obtained the time domain and frequency domain vibration transfer rate of one vibration transfer system [12]; and a method to assess the contributive degree of the parameters to the vibration transfer path was gotten with the technology of dynamic sensitivity [13]. To make the TPA can be used to the analysis of medium and high frequency segment, Professor Juha Plunt of Ingemansson Technology AB adopted the average 1/3 octave transfer function and obtained a better calculation method of the contributive degree of each transfer path [14].

In this paper, the mechanical vibration of the axial piston pump was studied, the method of lumped parameter was used to establish the vibration transfer path of the axial piston pump, and the sensitivity analysis of the parameters in the vibration transfer path had been done. And then, the axial piston pump mechanical vibration transfer law was explored, the anti-vibration design theory of the axial piston pump was provided.

II. THE AXIAL PISTON PUMP MECHANICAL VIBRATION TRANSFER PATH MODELING

A. *The physical model of the axial piston pump mechanical vibration transfer path*

Taking PCY axial piston pump as the research object (As shown in Figure 1-a), the transfer path of the mechanical vibration that is caused by the eccentricity and imbalance of the pump rotor system should be modeled above all. There is an interference fit between the pump shaft and the cylinder

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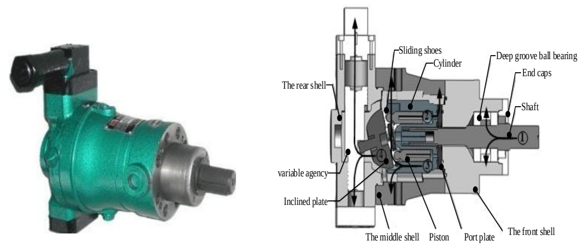
block, the component formed by piston and slipper is located in the piston chamber of the cylinder, so all the three can be viewed as a whole. Take the front, the middle and the rear shell of the pump as the final vibration receptors, when vibration generated, it will be transmitted to the surface of pump body by 4 paths, as shown in Figure 1-b.



a) The PCY Axial piston pump b)The mechanical vibration transfer path

Figure 1 Axial piston pump and the mechanical vibration transfer path diagram

Path 1: Shaft → Deep groove ball bearing → The front shell;

Path 2: Cylinder → Port plate → The middle shell;

Path 3: Cylinder → Cylindrical roller bearing → The middle shell;

Path 4: The component of piston and slipper → Swashplate → Variable displacement mechanism → The rear shell.

The main components of transfer path are coupling elements, such as the bearing, the bolt, and the variable displacement mechanism. The lumped parameter method was adopted to construct the axial piston pump mechanical vibration transfer path physical model, as shown in Figure 2. The model contains six vibration subjects, respectively as shaft-cylinder-the component formed by piston and slipper, the port plate, the swashplate, the front shell, the middle shell, the rear shell, they were abstracted in six mass block; the coupling elements such as the bearing were abstracted in spring and damper. In order to simplify the model, the quality of the coupling element was concentrated on the vibration subjects.

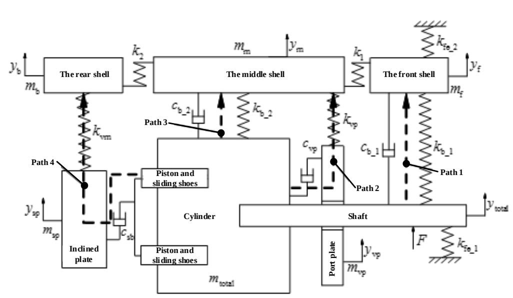


Figure 2 The physical model of axial piston pump mechanical vibration transfer path

It is observed that, the exciting force F was acting on the whole rotating body that formed by the shaft, the cylinder, the component of piston and slipper; y_{total}, y_v, y_f, y_m, y_b and y_{sp} were respectively as the vibration displacement along the radial of shaft-cylinder-the component formed by piston and slipper, the port plate, the front shell, the middle shell, the rear shell and the swashplate, when the exciting force F acting on; m_{total}, m_{vp}, m_f, m_m, m_b and m_{sp} were respectively as the lumped mass of shaft-cylinder-the component formed by piston and the slipper, the port plate, the front shell, the middle shell, the rear shell and the swashplate; k_{fe_1} was the radial stiffness between the shaft and the coupling; k_{fe_2} was the radial stiffness between the front shell and the fixed end; k_{b_1}, c_{b_1} were respectively as the radial stiffness and damp between the shaft and the front shell; k_{b_2}, c_{b_2} were respectively as the radial stiffness and damp between the cylinder and the cylindrical roller bearing of the middle shell; c_{vp} was the radial friction damp between the cylinder and the port plate; c_{sb} was the radial friction damp between the slipper and the swashplate; k_{vp} was the contact stiffness between the port plate and the middle shell; k_{vm} was the radial stiffness between the swashplate and the variable displacement mechanism; k_1 was the radial stiffness between the front shell and the bolt group of the middle shell; k_2 was the radial stiffness between the middle shell and the bolt group of the rear shell.

B. *The mathematic model of the axial piston pump mechanical vibration transfer path*

The method of analytical mechanics was adopted to establish the mathematic model of the axial piston pump mechanical vibration transfer path. The relationship among the kinetic energy, the potential energy and the dissipated energy of each particle under the generalized coordinates was shown in Eq. (1) [15].

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial \boldsymbol{T}}{\partial \dot{q}}\right)-\frac{\partial \boldsymbol{T}}{\partial q}+\frac{\partial \boldsymbol{U}}{\partial q}+\frac{\partial \boldsymbol{D}}{\partial \dot{q}}=\boldsymbol{\Omega} \tag{1}$$

Whereby, q represents the generalized coordinate system, T represents the kinetic energy of the vibration subjects, U represents the potential energy between each vibration subject, D represents the dissipated energy between each vibration subject, Ω represents the force of the system, all the above parameters were under the generalized coordinates.

According to the parameters listed in Figure 2, the kinetic energy, the dissipation energy, the potential energy and the force of the system which under the generalized coordinates can be obtained. The parameters above were taken into Eq. (1), after then, the Lagrange differential equations of the axial piston pump mechanical vibration system can be established, as shown in Eq. (2).

$$\begin{cases} m_{total}\ddot{y}_{total}+c_{b\_1}(\dot{y}_{total}-\dot{y}_f)+c_{b\_2}(\dot{y}_{total}-\dot{y}_m)+c_{vp}(\dot{y}_{total}-\dot{y}_{vp})+c_{sb}(\dot{y}_{total}-\dot{y}_{sp}) \\ \qquad +k_{fe\_1}y_{total}+k_{b\_1}(y_{total}-y_f)+k_{b\_2}(y_{total}-y_m)=F_0\sin(2\pi n/60)t \\ m_{vp}\ddot{y}_{vp}-c_{vp}(\dot{y}_{total}-\dot{y}_{vp})+k_{vp}(y_{vp}-y_m)=0 \\ m_f\ddot{y}_f-c_{b\_1}(\dot{y}_{total}-\dot{y}_f)+k_{fe\_2}y_f-k_{b\_1}(y_{total}-y_f)+k_1(y_f-y_m)=0 \\ m_m\ddot{y}_m-c_{b\_2}(\dot{y}_{total}-\dot{y}_m)-k_{b\_2}(y_{total}-y_m)-k_{vp}(y_{vp}-y_m)-k_1(y_f-y_m)+k_2(y_m-y_b)=0 \\ m_b\ddot{y}_b-k_2(y_m-y_b)+k_{vm}(y_b-y_{sp})=0 \\ m_{sp}\ddot{y}_{sp}-c_{sb}(\dot{y}_{total}-\dot{y}_{sp})-k_{vm}(y_b-y_{sp})=0 \end{cases} \tag{2}$$

III. SENSITIVITY ANALYSIS OF THE MECHANICAL VIBRATION TRANSFER PATH OF THE AXIAL PISTON PUMP

The vibration characteristics of the mechanical vibration system depends largely on the mass, the stiffness and the damping values, but in general case, the sensitivity analysis is performed without taking the quality parameters into account as the quality parameters are hardly changed in a process. The static analysis was done in the finite element software ANSYS Workbench to get stiffness parameters. The theories of elastohydrodynamics and lubrication were used to calculate the bearing damping parameters. The friction and wear test experiment was done to determine the friction damp of pump.

A. *The first order trajectory sensitivity theory of the mechanical vibration system of the axial piston pump*

The expression that in state space for the mechanical vibration system of the axial piston pump was shown in Eq. (3):

$$\dot{\boldsymbol{y}} = \boldsymbol{f}(\boldsymbol{y},\boldsymbol{u},\boldsymbol{\alpha},t) \tag{3}$$

Whereby, y represents the m-dimensional state variables, α represents the p-dimensional parameter vector, u represents the r-dimensional input vector independent of α, t represents the time variable.

The solutions of the Eq. (3) can be expressed as:

$$\psi_n(t) = \boldsymbol{y}(t,\boldsymbol{\alpha})_n \tag{4}$$

Whereby, the subscript n =1, 2, … , 12, represents the n′ th state variable.

The first order trajectory sensitivity function of the state variable y to the parameter vector α was defined as Eq. (5):

$$\lambda_n^i = \left(\frac{\partial \boldsymbol{y}}{\partial \alpha_i}\right)_n \tag{5}$$

Whereby, λ_n^i represents a $m\times p$ matrix, the superscripty i =1, 2, … , p, represents the i′ th parameter vector.

The state variable y is a function that contains the parameter vector α and the input vector u, Eq. (6) can be obtained by taking partial derivative to parameter vector α at the both sides of the state space expression (3).

$$\left(\frac{\partial \dot{\boldsymbol{y}}}{\partial \alpha_i}\right)_n = \frac{\partial \boldsymbol{f}}{\partial \alpha_i} \tag{6}$$

The Eq. (7) was obtained by taking the Eq. (5) into the Eq. (6):

$$\dot{\boldsymbol{\lambda}}_n^i = \left(\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{y}}\right)_n \cdot \lambda_n^i + \left(\frac{\partial \boldsymbol{f}}{\partial \alpha_i}\right)_n \tag{7}$$

The Eq. (7) was the first order trajectory sensitivity equations, among the Eq. (7), $\left(\frac{\partial \boldsymbol{f}}{\partial \boldsymbol{y}}\right)_n$ and $\left(\frac{\partial \boldsymbol{f}}{\partial \alpha_i}\right)_n$ were respectively as the coefficient term matrix and the free term matrix of the first order trajectory sensitivity equations.

The coefficient term matrix (As shown in Eq. 8) can be obtained by taking partial derivative of the function to the state variable y.

$$\left(\frac{\partial f}{\partial y}\right)_n = \begin{bmatrix} \frac{\partial f}{\partial y_1} & \frac{\partial f}{\partial y_2} & \cdots & \frac{\partial f}{\partial y_n} & \cdots & \frac{\partial f}{\partial y_{12}} \end{bmatrix} = \begin{bmatrix} a_{1,1} & a_{1,2} & \cdots & a_{1,n} & \cdots & a_{1,12} \\ a_{2,1} & a_{2,2} & & & & \vdots \\ \vdots & & \ddots & & & \vdots \\ a_{n,1} & & & a_{n,n} & & \vdots \\ \vdots & & & & \ddots & \vdots \\ a_{12,1} & \cdots & \cdots & \cdots & \cdots & a_{12,12} \end{bmatrix} \tag{8}$$

The free term matrix (As shown in Eq. 9) can be obtained by taking partial derivative of the function $\boldsymbol{f}(\boldsymbol{y},\boldsymbol{u},\boldsymbol{\alpha},t)$ to the parameter vector α.

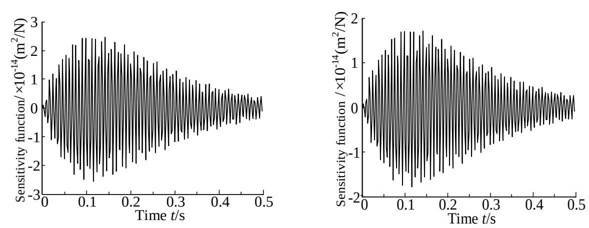
$$\left(\frac{\partial f}{\partial \alpha_i}\right)_n = \begin{bmatrix} \frac{\partial f}{\partial y_1} & \frac{\partial f}{\partial y_2} & \cdots & \frac{\partial f}{\partial y_i} & \cdots & \frac{\partial f}{\partial y_{12}} \end{bmatrix} = \begin{bmatrix} b_{1,1} & b_{1,2} & \cdots & b_{1,i} & \cdots & a_{1,12} \\ b_{2,1} & b_{2,2} & & & & \vdots \\ \vdots & & \ddots & & & \vdots \\ b_{n,1} & & & b_{n,i} & & \vdots \\ \vdots & & & & \ddots & \vdots \\ b_{12,1} & \cdots & \cdots & \cdots & \cdots & a_{12,12} \end{bmatrix} \tag{9}$$

At the initial moment we assumed that the value of the vibration velocity and the displacement of each vibration subject belongs to the axial piston pump were zero, that means y_0=0, so the initial value of the first order trajectory sensitivity function was that:

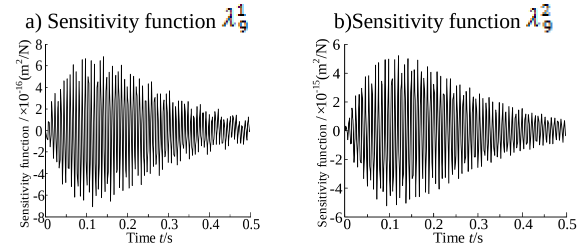
$$\boldsymbol{\lambda}_{n0}^i = \boldsymbol{0}_{m\times p} \tag{10}$$

B. *The first order trajectory sensitivity analysis of mechanical vibration system of the axial piston pump*

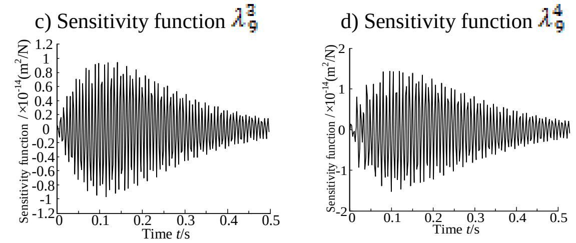
In order to obtain the time domain curves of the first order trajectory sensitivity function without any load which can be used to determine the contribution of system parameters to the vibration response, the four order Runge-Kutta method was used to solve the Eq. (3), the Eq. (7), the Eq. (8) and the Eq. (9). The curves about the vibration displacement y_9 of the rear shell to the parameter α_i was as shown in Figure 3, among the figures, the parameter α_1~α_{12} were respectively as the parameter k_{fe_1}, k_{fe_2}, k_{b_1}, k_{b_2}, k_1, k_2, k_{vp}, k_{vm}, c_{vp}, c_{b_1}, c_{b_2} and c_{sb}.



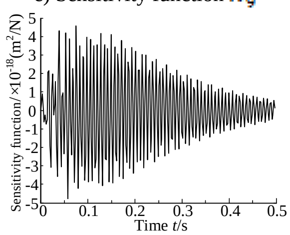
a) Sensitivity function λ_9^1 b)Sensitivity function λ_9^2



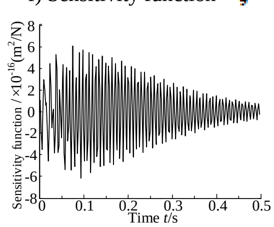
c) Sensitivity function λ_9^3 d) Sensitivity function λ_9^4



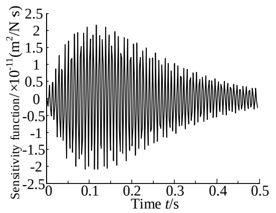
e) Sensitivity function λ_9^5



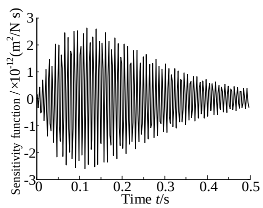
f) Sensitivity function λ_9^6



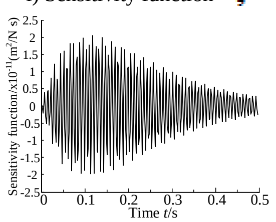
g) Sensitivity function λ_9^7



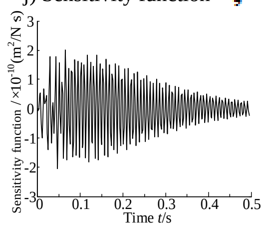
h) Sensitivity function λ_9^8



i) Sensitivity function λ_9^9



j) Sensitivity function λ_9^{10}



k) Sensitivity function λ_9^{11} l) Sensitivity function λ_9^{12}

Figure 3 The time domain curve of first order trajectory sensitivity function to y_9

With the unit value of parameters increased, the larger the value of sensitivity function was, the greater the response became, simultaneously, the greater the contribution of parameters to response became too. As can be seen from the Figure 3, the variation law of the first order trajectory sensitivity functions were similar to each parameter throughout the whole sampling period: firstly, the sensitivity function was gradually increased to the maximum value from the initial state with the time, then the sensitivity function was gradually converged to zero. The sensitivity functions were sorted according to the magnitude as follow: $\lambda_9^7<\lambda_9^8<\lambda_9^3<\lambda_9^4<\lambda_9^5<\lambda_9^6<\lambda_9^2<\lambda_9^1<\lambda_9^{10}<\lambda_9^{11}<\lambda_9^9<\lambda_9^{12}$. It can be seen that the unit damping coefficient has much larger sensitivity than the unit stiffness coefficient to the vibration displacement response of the rear shell. So the damping parameters should be taken adequate consideration in modifying the structural parameters or replacing parts of the axial piston pump.

C. *The measure indexes of the first order trajectory sensitivity*

The influence of different parameters on the vibration displacement of the rear shell was measured by the percentage about the change of vibration displacement and the maximum value of vibration displacement:

$$\frac{|\Delta y|}{y_{\max}}\times 100\% = \frac{|\lambda_n^i|\cdot\Delta\alpha_i}{y_{\max}}\times 100\% \tag{11}$$

Whereby, the corner mark $i = 1, 2, \dots, 12$, represents the number of parameters; the subscript $n = 9$ represents the 9th state variables: the vibration displacement of the rear shell, and the percentage above was changing over time. The first sensitivity measure index (denoted as S_1) was defined as the max value of the percentage:

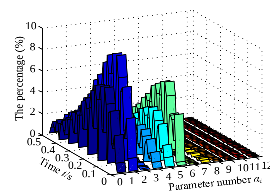
$$S_1 = \left.\frac{|\Delta y|}{y_{\max}}\right|_{\max}\times 100\% = \left.\frac{|\lambda_n^i|\cdot\Delta\alpha_i}{y_{\max}}\right|_{\max}\times 100\% \tag{12}$$

In order to measure how much the effect of each various parameters on the $\triangle y$ was, we defined the second sensitivity measure index (denoted as S_2) as the integration of $|\lambda_n^i|\cdot\Delta\alpha_i$ to sampling time:

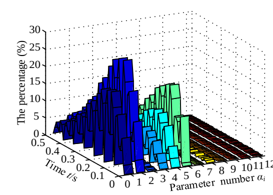
$$S_2 = \int_0^t |\lambda_n^i|\cdot\Delta\alpha_i \mathrm{d}t \tag{13}$$

The effect of each various parameters on the vibration displacement of the rear shell were clearly compared by using the two kinds of measure indexes defined above to the quantitative analysis of each parameters.

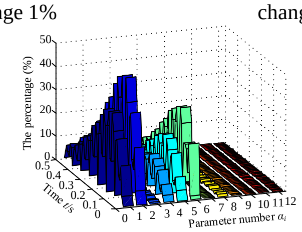
When each parameters were changed about 1%, 3% and 5%, the maximum vibration displacement of the rear case (denoted as y_{max}) was 1μm, according to the Eq. (11). The time-history curves of the percentage about the change of the rear shell vibration displacement caused by each various parameters were shown in the Figure 4:



a)The parameters change 1%



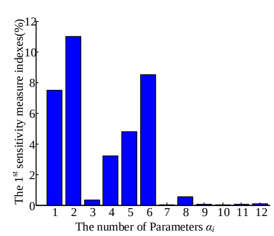
b) The parameters change 3%



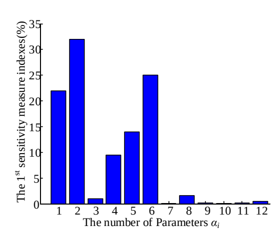
c) The parameters change 5%

Figure 4 The time-history curves of the percentage about rear shell vibration displacement caused by each various parameters

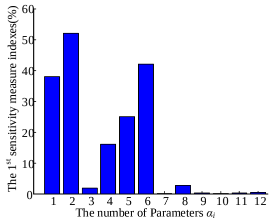
The histograms of the two kinds sensitivity measure indexes were obtained (shown as Figure 5 and Figure 6).



a)The parameters change 1%

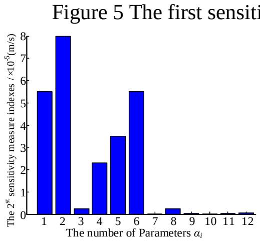


b) The parameters change 3%

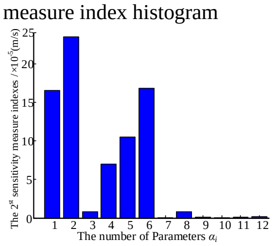


c) The parameters change 5%

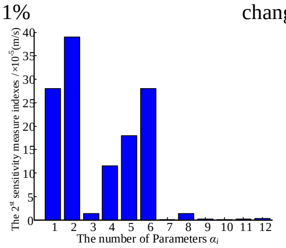
Figure 5 The first sensitivity measure index histogram



a)The parameters change 1%



b) The parameters change 3%



c) The parameters change 5%

Figure 6 The second sensitivity measure index histogram

As can be seen, when the parameters were changing by different percentages, the two kinds of sensitivity measure indexes substantially changed linearly. Moreover, the parameter α_3, α_7, α_8, α_9, α_{10}, α_{11} and α_{12} took little proportion of the longitudinal axis in histogram. It can be concluded from the size and the proportion of the two kinds of sensitivity measure indexes that the parameters above have little impact on vibration displacement of the rear shell (denoted as y_9), among them the parameter α_7, α_9, α_{10}, α_{11} and α_{12} have the least impact.

Simultaneously, the parameter α_1, α_2, α_4, α_5 and α_6 took major proportion of the longitudinal axis in histogram. Among them the parameter α_2 took the greatest proportion, the value of the first sensitivity measure index respectively as 10%, 30% and 50%; the value of the second sensitivity measure index respectively as 0.02μm、0.058μm、0.096μm with the parameters changed by 1%, 3% and 5%. Moreover, the parameter α_1 and α_6 took basically same proportion of the longitudinal axis in histogram, second only to the stiffness coefficient α_2. It can be concluded from the size and proportion of the two kinds of sensitivity measure indexes that the parameters above have major impact on vibration displacement of the rear shell (denoted as y_9), they are the main influencing parameters, among them the supporting parameters have the greatest impact.

IV. THE CONCLUSION

In this paper, the transfer path method was used to establish the vibration transfer model of the PCY axial piston pump, and a series of studies were carried out by taking advantage of the first order trajectory sensitivity theory. The conclusions are as follows:

(1) Vibration transfer path method is a direct and effective method to study the mechanical vibration transfer law of the axial piston pump, the vibration transfer model of the PCY axial piston pump was established in this paper which can reflect the mechanical vibration characteristics of the pump integrallty.

(2) The first order trajectory sensitivity of the 12 parameters to the vibration displacement of the axial piston pump rear shell were analysed. We find that the damp coefficient has much larger sensitivity to the response of vibration displacement of the axial piston pump rear shell than stiffness coefficient.

Therefore, the damp coefficient should be taken into fully consideration in modifying the structural parameters of the axial piston pump or replacing the parts.

(3) The two kinds of sensitivity measure indexes were defined, which had been applied to quantitative analysis of each parameter extracted from the vibration transfer path. It is founded that the parameter α_1, α_2, α_4, α_5 and α_6 are the main influencing parameters. Therefore, when the axial piston pump is optimized to reducing vibration with the aim of minimize the vibration displacement of the shell, the optimization should be mainly aimed at the stiffness coefficient α_1, α_2, α_4, α_5 and α_6.

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