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Numerical simulation and experimental research of the flow force and forced vibration in the nozzle-flapper valve

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ABSTRACT

In the pilot stage of nozzle-flapper servo valve, the flow force on the flapper is the key reason that leads to forced vibration of the armature assembly, which may result in the fatigue of the flexure tube in torque motor. To master the principles and features of the flow force and the source of the forced vibration of the armature assembly, mathematical models of flow force and the forced vibration are deduced in this paper. For validating the model, a three-dimensional model is built and a finite element analysis of the flow force with different inlet pressure and deflections is presented and an innovative and experimental rig for measuring the steady and dynamic frequency of flow force is also designed. The characteristic of the main flow force, minor flow force and total flow force are analyzed contrastively, and the experimental results agree well with the CFD results and mathematical model analysis. To find the source of forced vibration of the armature assembly, a knocking method is proposed to measure the natural frequency of armature assembly. By comparing the spectrum of the pressure and vibration movement through experiments, a conclusion can be drawn that the inlet pressure fluctuation near the natural frequency of armature assembly and the asymmetric structure of pilot stage are the necessary and sufficient conditions to make the armature assembly yield forced vibration. In the end, some suggestions have been made to decrease the intensity of forced vibration of the pilot stage according to the findings.

1. Introduction

The nozzle-flapper value plays as a pilot stage in a nozzle-flapper value, converting mechanical displacement to hydraulic energy. It has been widely applied in electro-hydraulic control system for its characteristics of high sensitivity, broad bandwidth and accuracy. Flow force on the flapper in the nozzle-flapper valve strongly leads to the forced vibration, intense hauling and even instability in some cases [1]. The flow moment produced by the flow force resists the input torque acting on the flapper. Consequently, the flow force on the flapper directly influences the deflection of the flapper and the hydraulic output of the nozzle-flapper valve. To summarize, Finding the law of flow force on the flapper and the source of the forced vibration of the armature assembly are of reference value to increase the reliability, performance and service life of the whole servo valve, bringing about benefits to design and manufacture of the nozzle-flapper valve.

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Flow force of the spool has been adequately studied in relevant researches [2–6]. However, to the author's knowledge, there are not many published papers about the research on the flow force on the flapper in a nozzle-flapper servo valve. Zhang [7] utilized dynamic mesh strategy to simulate flow field characteristics in the pilot valve with the flapper under working conditions. A finite element method proven in good agreement with experiments had been used to study the flow force on the flapper at different oil pressure and distances between the nozzle and flapper by Han [8]. Most importantly, he proposed that the flow force on the flapper is comprised of main flow force and vortex flow force, which both becomes larger as the oil pressure increases. However, owing to the limitations of his visualized experimental equipment, his research had failed to consider the actual structure, materials and working pressure in servo valve. The momentum principle method and the differential pressure method had been designed to calculate the steady-state flow force on the pilot stage of jet deflector servo valve instead of the flapper-nozzle servo valve by Yan [9]. Wang [10] proposed the determination of the flow force on the flapper using an experimental approach and the effectiveness of it was verified by comparing experimental and simulated results. While finding the causes of the forced vibration and the hysteresis of stability limit, Li [11] showed the flow field distribution, variation of the vortex and pressure oscillations inside the jet flow field with the increase of inlet velocity in her work, which provided reference for the control of self-excited noise in a hydraulic servo-valve and better design of the flapper-nozzle pilot stage. The possible causes of the self-excited high frequency oscillations and noise are predicted according to the analysis result by Li [12]. Based on the results, suggestions were given to reduce the pressure oscillations and noise in hydraulic servo-valves. Hidetoshi [13] pointed that the jet force strongly contributes to the self-excited of the valve theoretically and experimentally. Later momentum theory was applied to estimate the flow force acting on the flapper by Urata [14] in water hydraulic servo valve. Finally he also discussed the flow force and its influence on the flapper-nozzle system, and experimental verification of his theory was also presented. Similarly, the influence of flow force was also developed in pneumatic servo valve. Due to the fact that the flow force more easily changes the flapper displacement in the pneumatic nozzle. Zhang [15] proposed a simplified model of flow force on the flapper. The influences of flow jet force on flappers have been experimentally measured by frequency response tests, which proves the model is practical. The harmonic response of the armature assembly was conducted through numerical and experimental method in Pengs work [16]. The resonance peak occured at 533.66 Hz and 1111.52 Hz in his modal analysis. He also guessed that the pressure fluctuation excitation signals was a critical source to induce the resonance in the flow filed. Zhang[17] and Aung [18] both conducted a comparative study of flow forces acting on the two different flapper shapes aiming to reduce these undesired lateral forces on the flapper.

However, in virtue of the stumbling block of the limitations of the experimental equipment, little effort toward the research of the law of flow force under normal operating pressure in a real nozzle-flapper servo valve instead of simplified model is found up to now. In order to investigate the law of the flow force on the flapper more precisely and to find the source of the forced vibration of the armature assembly, the numerical simulation of flow in the nozzle-flapper coupled with cavitation is performed using finite element method. Besides, a kind of new experimental design is also presented for verification in this work.

2. Mathematical model

2.1. Profile of the pilot stage in nozzle-flapper servo valve

A complete nozzle-flapper servo valve with two stages is illustrated schematically in Fig. 1. The nozzle-flapper value as pilot stage in servo valve is featured with high control precision, fast dynamic response and good linearity. Under the rated working pressure, the flapper stays in the very middle of the double nozzles without current excitation exerted on the coils. Hydraulic oil flows through the oil supply port, filter and fixed orifice finally dashing against the two surfaces of the flapper. To increase the return pressure and reduce cavitation in pilot stage chamber, there installs a return fixed orifice before oil goes back to the power station [19].

When the coils are excited with input current, rotating torque is generated under the unbalanced magnetic field. The flappers bonded with the armature deflects around the center of rotation within a macro displacement. Consequently, the pressure balance in the two nozzles is thrown off by the asymmetric structure change, which drives the spool valve to move. Under the comprehensive feedback action of the magnetic torque, flexure tube, flow force and the feedback rob, the flapper gets the trend to return to the null position until the pressure in the two control chambers recovers its new equilibrium. Because of the symmetrical structure, only half of the schematic is seen in Fig. 2, the flow action on the flapper can be divided into two processes. Firstly, the velocity of the fluid changes from the axial direction to the radial direction when the fluid is ejected from the nozzle and then impacts on the flapper. Afterwards, flow from annular orifice is squirted out in powerful jets along the wall of the flapper. Assuming that there is a rectangular control volume at the outlet of the nozzle shown in Fig. 2. According to the momentum theory, flow force on the two side of flappers can be obtained below [20] in both two control chambers.

$$\begin{cases} F_1 = p_{c1}A_N\left[1 - \frac{16C_{df}^2(x_{f0}-\Delta x_f)^2}{D_N^2}\right] \\ F_2 = p_{c2}A_N\left[1 - \frac{16C_{df}^2(x_{f0}+\Delta x_f)^2}{D_N^2}\right] \end{cases} \tag{1}$$