

## Research Article

### High Frequency Character of Piezoelectric Pump Valve

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**Abstract:** In order to improve the performance of piezoelectric pump, research its check valve, find the interpretation of the incomplete closure of piezoelectric pump check valve in high frequency, analysis the characteristic of the pump in these conditions; give the judgment basis and theoretical demonstration of the existence for the phenomenon. Frequency response of the check valve in water is obtained from its dynamic model. Sufficient condition for the check valve incomplete closure was obtained which is amplitude amplification less than 0.25. Amplitude amplification factor in different frequency was calculated. The results showed that check valve can close completely operating at 80Hz, the incomplete closure phenomenon was observed at 140Hz. With further increasing of the frequency, amplitude amplification factor decreases, the phenomenon is more obvious under the condition of low amplitude amplification factor, the minimum clearance between the check valve and valve seat more than 30 $\mu$ m at 160Hz. The theoretical analysis results are verified, that the critical frequency can be used as the yardstick for working state of check valve in piezoelectric pump.

**Keywords:** Check valve, dynamic mode, kinetic pressure, piezoelectric pump, working principle

#### INTRODUCTION

Piezoelectric pump has received much attention in recent years due to its simple structure, high precision, low power consumption and small volume. Piezoelectric pump is a pump drive by the piezoelectric vibrator or stack. It has many possible uses in the instrument, chemical industry and MEMS (Kenji and Jayne, 2003; Cheng *et al.*, 2009; Dau *et al.*, 2009).

Traditionally, the research on piezoelectric pump included the valvular pump and valveless pump. Traditionally, the valvular piezoelectric pump is a concentrated direction in micro pump, because its high performance, suction and flexible structure design. The existing research on the valvular piezoelectric include the working mechanism on static (Zhang *et al.*, 2003) and dynamic mode (Kan *et al.*, 2005; Liu *et al.*, 2011), the theoretical model (He *et al.*, 2007) and the structure form (Zeng *et al.*, 2005; Yang *et al.*, 2007; Peng *et al.*, 2009). Valveless pump becoming the research hotspot because of the simple structure (Ma *et al.*, 2008; Zhang *et al.*, 2008; Koyama *et al.*, 2010), long life and easy of miniaturization and integration.

The valvular piezoelectric pump better than valveless one in performance. Due to the mechanical vibrations of the valve in the study, the valvular pump is worse than the valveless one in life and noise. In particular the valveless pump has better high-frequency characteristics. However, although the low-frequency characteristics were research several years, little

attention has been paid to the high-frequency character of valvular piezoelectric pump.

It has been found experimentally that the valve of the piezoelectric pump was incompletely closure in the high frequency. By this treasure, the valvular piezoelectric pump work in high frequency catch the advantages of valveless one in past, such as long life and low noise. The precision requirement is far lower than the existing low-frequency valvular pump when applied to field of high-precision. The output is more accurate than the low-frequency, because there are 3-5 cycles before these two kinds of piezoelectric pump reach the steady working.

The present study presets a theory method to explain the valve incompletely closure phenomenon of piezoelectric pump, furthermore describe the working mechanism of the piezoelectric pump in high frequency, when the valve incompletely close. Based on the hydrodynamic force on the valve plate, discussed the relationship between average open height and the instantaneous displacement through use the model of hydrodynamics and vibration mechanics. Furthermore, analysis the existence and formation conditions of the phenomenon. Verify the analytical results by the experiment. The research provides a theory to the design of piezoelectric pump, expand its application.

**Piezoelectric pump:** Figure 1 shows the basic type of valve piezoelectric pump including body, outlet check valve, inlet check valve, piezoelectric vibrator etc. Outflow is formed by the effects of check valves and

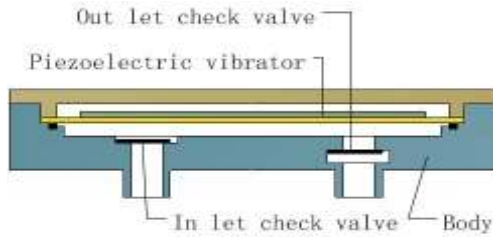


Fig. 1: Structure of piezoelectric pump

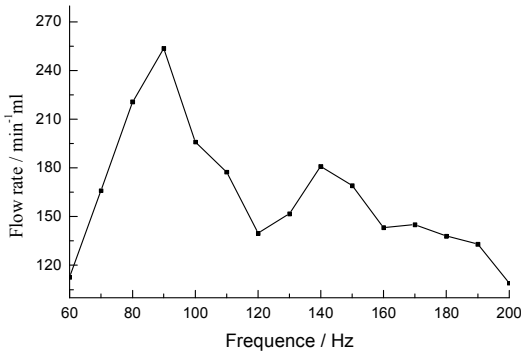


Fig. 2: Frequency characteristic of piezoelectric pump

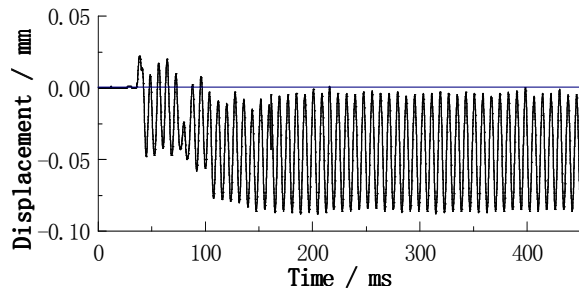


Fig. 3: Displacement curve of the check valve on 120Hz

volume variation of the pump chamber which produced by the both positive and negative bending deformation of piezoelectric vibrator under an alternative voltage.

The flow rate of the piezoelectric pump in line with driving voltage in the rated voltage interval of piezoelectric vibrator. The relationship between flow rate and driving frequency is relatively complicated. In Fig. 2, the flow rate was increased by the frequency in the low frequency region. The flow rate decreases sharply in the part of higher frequency. Local maximum velocity appeared after the increase of frequency.

**Valve incompletely closure:** The piezoelectric vibrator is 35 mm in diameter and 0.7 mm in thickness, its displacement had little different when driving in 60~300Hz, about 21 μm to 23μm. The displacement of pump valve was measured by laser micrometer in the frequency where has the second local maximum flow rate. The testing result shown in Fig. 3, the check valve never shut in the whole period when the pump in stability work.

In the conventional analysis for working principle of piezoelectric pump, the pumping include two processes: one is suction process, the vibrator may produce deformation, volume of chamber increase and pressure decreased in pump chamber, then inlet check valve open and outlet check valve close, the fluid flow into the chamber; the other one is removal process, the volume of chamber decreased with the deformation of vibrator, the pressure increase in the pump chamber, inlet check valve close and outlet check valve open, then the fluid was discharged. Flow rate of the pump in line with driving frequency. Previous study shown that the sharp drop of flow rate when driving frequency further increased. And it is because the phase lag between check valve displacement and the driver force of piezoelectric vibrator.

The working principle of piezoelectric pump in low frequency what had mentioned above cannot explain the pumping process when check valve incomplete closed, in that condition; the effect of check valve is base on the resistance difference of back-and-forth flow.

Divided the pump fluid into three categories to explain the working principle better when check valve incomplete closed:

- **Vibration fluid:** The fluid fill the volume difference when the vibrator is moving and there is no quality interchange between vibration fluid and the inlet-or-outlet fluid
- **Inlet fluid:** Quality of inlet fluid was taken an alternating motion between chamber and the inlet, no interchange to the outlet
- **Outlet fluid:** Moving between chamber and the outlet, never return to the inlet

The direction from inlet to outlet is defined as the positive direction. The motion of vibrator is divided into two phases: the phase of rising lead by the volume increase of chamber and the phase of falling lead by the volume decrease. In the rising phase, inlet fluid driving by the normal force, flow rate and dynamic pressure increase, opening size of valves, then the inlet flow rate further increased; Meanwhile, outlet fluid driving by the opposite force, flow rate and dynamic force decrease, opening size of valves decrease, flow resistance increase, flow rate further decreased, inlet flow rate greater than outlet, then the difference value of the fluid mass was stored in the chamber. In the falling phase, inlet fluid driving by the opposite force, flow rate and dynamic force decreases, opening size of the valve decreases, flow resistance increases, the flow rate further decreased; The outlet fluid driving by the normal force, flow rate and dynamic pressure increase, opening size of valve increase, flow resistance decreases, the flow rate further increase, the outlet flow rate greater than inlet, the difference value of the fluid was supplement with the deformation of vibrator.

When the piezoelectric pump work on the condition of valve incomplete closure, its outflow capacity was due to the difference value of flow resistance which based on the distance change between the valves and the valve seat. The effect of the machining accuracy and the leakage of the valves on the flow properties was decreased, because of valve uncollided with the seat.

**Motion analysis of valve:** Hydrodynamic diameter is small in piezoelectric pump, the range of Re was 0.4-8, the force on the valve in water was affected by the pressure drag and the friction drag. The composite force is found to be Finnemore and Franzini (1989):

$$F_D = C_D \rho \frac{V^2}{2} A$$

where,

- A = The area of valve
- $\rho$  = The water density
- V = The equivalent velocity of the fluid
- CD = The total resistance coefficient

On the condition of Re less than 10, CD can calculate by the stokes formula:

$$C_D = \frac{24}{Re}$$

Which yields:

$$F_D = 12\rho \frac{V^2}{Re} A \tag{1}$$

To assume that the variation of chamber volume was homogeneous, due to amplitude of vibrator far less than its diameters. The flow rate drives by the vibrator expressed by VA, it's the average velocity in one period. While the valve can close and the phase difference between inlet valve and outlet valve was 90°, VA =  $\Delta v/T$ ; While the valve incompletely closed, VA <  $\Delta v/T$ , While the phase different between inlet valve and out valve was 0, the valve have no effect, VA =  $(\Delta v/2)/T$ , then we have:

$$\frac{\Delta v}{2T} < V_A < \frac{\Delta v}{T} \tag{2}$$

where, T =  $\omega/2\pi$

The average open altitude HA was:

$$H_A = \frac{F_{DA}}{k} \tag{3}$$

where, k was the equivalent stiffness.

By substitution of the results from Equality (1) and (2) into equality (3), we have:

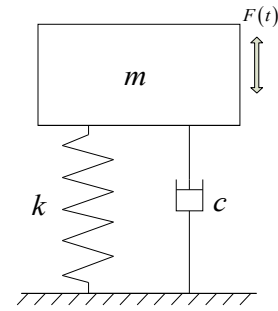


Fig. 4: Dynamic model of check valve in water

$$\frac{12\pi^2 \rho A \Delta V^2}{k\omega^2 Re} < H_A < \frac{48\pi^2 \rho A \Delta V^2}{k\omega^2 Re}$$

A dynamic model was built as Fig. 4 to calculate the displacement of the valve in the working pump. where, k was equivalent stiffness, c was the viscosity damping coefficient of moving valve, m was the quality of valve.

The motion of check valve is reciprocating vibration under the action of fluid, its driver is the piezoelectric vibrator. The excitation signal on vibrator is simple harmonic wave and then the exciting force of the valve was:

$$F(t) = F_0 \cos \omega t$$

The motion equation was:

$$m\ddot{x} + c\dot{x} + kx = F_0 \cos \omega t$$

The amplitude amplification factor of the valve was:

$$M = \frac{X}{\delta_{st}} = \frac{1}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}} \tag{4}$$

where,  $\delta_{st} = F_0/k$  was the valve displacement under the static force, then the motion of the valve can be expressed as:

$$X = \frac{F_0 M}{k} \tag{5}$$

F0 is the maximum force in a motion cycle as its definition. By substitution of the result from equality (1) and (2) into the equality (5), we have:

$$X < \frac{48\pi^2 \rho A \Delta V^2 M}{k\omega^2 Re}$$

The relationship of the H and X was shown in Fig. 5, when the minimum value of H bigger than the

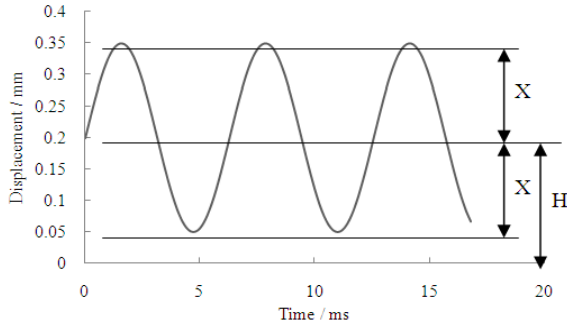


Fig. 5: Relationship between amplitude and balance position of check valve

maximum valve of X, the valve incomplete closure, we have:

$$\frac{12\pi^2 \rho A \Delta V^2}{k\omega^2 Re} - \frac{48\pi^2 \rho A \Delta V^2 M}{k\omega^2 Re} > 0$$

The equality can be simplified as:

$$M < 0.25$$

The mechanism of the incompletely closure phenomenon of check valve was explained by the above analysis. Main influence factor is amplitude amplification factor of the valve.

### RESULTS AND DISCUSSION

Flow the relationship in equality (4), the amplitude amplification factor affected by the damping ratio and frequency ratio. The calculation of  $\zeta$  (damping ratio of valve) is complicated and the calculation error is more than measurement. Then we used the method that calculated the parameters by the responding curve of the valve under the impact load (Singiresu, 2004).

The displacement and times free vibration curve of valve in piezoelectric pump was shown in Fig. 6.

The period of the damped vibration was 0.019s, the amplitude of the first cycle X1 was 0.150 mm and the amplitude of the second cycle X2 was 0.059 mm

The vibration of valves in water is equivalent to the damping vibration of the single degree of freedom system. The logarithmic decrement was:

$$\sigma = \ln \frac{x_1}{x_2} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$$

The damping ratio  $\zeta$  was:

$$\zeta = \frac{\sigma}{\sqrt{4\pi^2 + \sigma^2}}$$

The cycle of damped oscillation is equal to:

$$\tau_d = \frac{2\pi}{\omega_d} = \frac{2\pi}{\omega_n \sqrt{1-\zeta^2}}$$

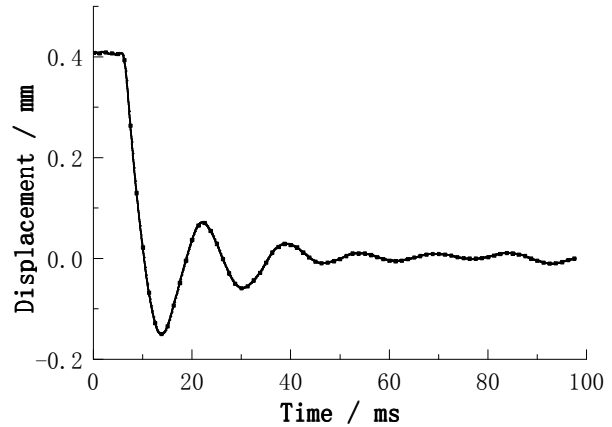


Fig. 6: Impulse response curve of check valve in water

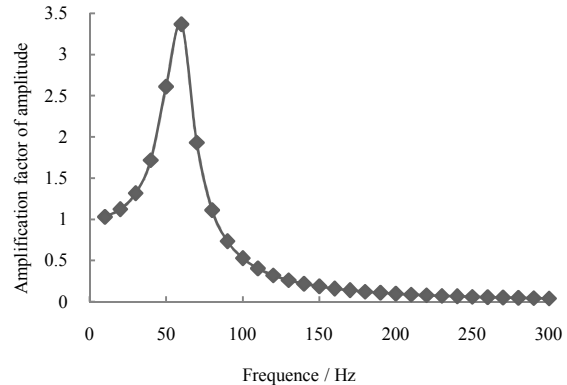


Fig. 7: Relationship between amplitude amplification factor M and frequency

The nature frequency then becomes:

$$\omega_n = \frac{2\pi}{\tau_d \sqrt{1-\zeta^2}}$$

As the measured data shown in Fig. 6, the damping factor  $\zeta = 0.147$ , then, the undamped natural frequency of the system of valve in radians per second is  $\omega_n = 317.6$  rad/s.

The relationship between amplification factor of amplitude M and the working frequency of valve was shown in Fig. 7. If  $f > 140$ Hz, the amplification factor of amplitude reduced to  $M < 0.25$ . So that the valves of piezoelectric pump working in incompletely closer mode as the result of above analysis.

The displacement curve of valve shown in Fig. 8B, it was measured by the laser measuring equipment LK-HD500 which is product of KEYENCE. The result shown that valve working in incompletely closer mode when the working frequency  $f = 140$ Hz.

In addition, as shown in Fig. 3, the valve working in the incompletely closer state too at 120Hz. This frequency is smaller than the result of analysis, because the equilibrium position was the minimum of valve

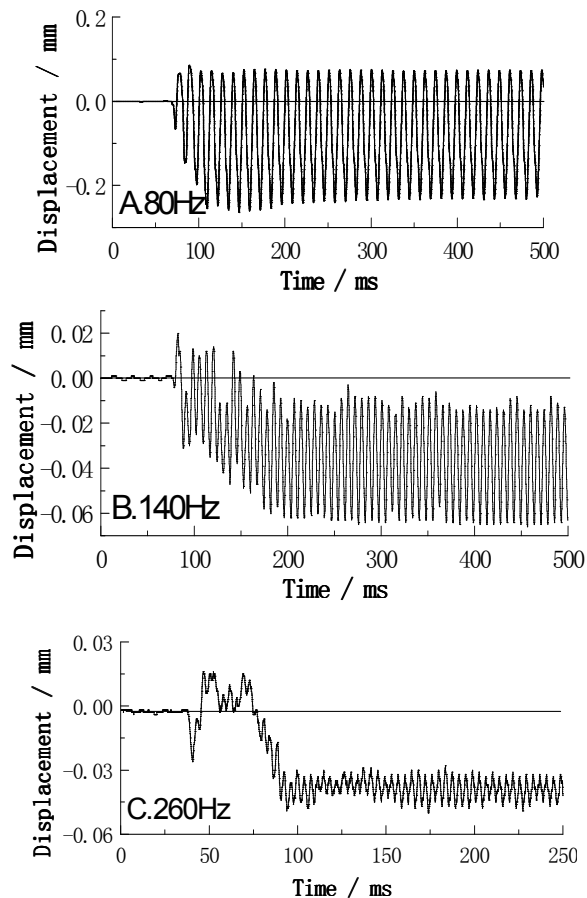


Fig. 8: Displacement curve of check valve on different frequency

fetch in analysis and the calculated value bigger than the critical frequency in actual. The valve working in the completely close state at 80Hz and working in the incompletely closer state at 260Hz, as shown in Fig. 8. The comparison of different frequency shows that the valve incompletely closer phenomenon is more obvious with the increase of frequency.

### CONCLUSION

- A new phenomenon, the valve incompletely close in piezoelectric pump, was discovered in the frequency character test. The analysis shown the characteristics when the valve working in incompletely closer state, such as low noises, low wear rate, long life and high manufacturability.
- Existence of valve incompletely closer in piezoelectric pump was proved in theory. The result of theory analysis shown that the amplitude amplification factor  $M < 0.25$  was the sufficient condition for the valve incompletely closer phenomenon.
- When the piezoelectric pump work in the condition of normal flow at the frequency which bigger than

critical frequency, the valve incompletely closer phenomenon is more obvious as the increase of frequency. The distance between the valve and its seat bigger than  $30\mu\text{m}$  at 260Hz.

Through the research about the valve incompletely closer phenomenon in piezoelectric pump, provided a theory to the research and optimize for the piezoelectric pump at high frequency.

### ACKNOWLEDGMENT

This study is financially supported by the National Natural Science Foundation of China under Grant No. 51175213.

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