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An improved resonantly driven piezoelectric gas pump †

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Abstract

Piezoelectric pumps have the potential to be used in a variety of applications, such as in air circulation and compression. However, piezoelectric membrane pumps do not have enough driving capacity, and the heat induced during the direct contact between the driving part and the gas medium cannot be dissipated smoothly. When the gas is blocked, the piezoelectric vibrator generates heat quickly, which may eventually lead to damage. Resonantly driven piezoelectric stack pumps have high performance but no price advantage. In this situation, a novel, resonantly driven piezoelectric gas pump with annular bimorph as the driver is presented. In the study, the working principle of the novel pump was analyzed, the vibration mechanics model was determined, and the displacement amplified theory was studied. The outcome indicates that the displacement amplification factor is related with the original displacement provided by the piezoelectric bimorph. In addition, the displacement amplification effect is related to the stiffness of the spring lamination, adjustment spring, and piezoelectric vibrator, as well as to the systematic damping factor and the driving frequency. The experimental prototypes of the proposed pump were designed, and the displacement amplification effect and gas output performance were measured. At 70 V of sinusoidal AC driving voltage, the improved pump amplified the piezoelectric vibrator displacement by 4.2 times, the maximum gas output flow rate reached 1685 ml/min, and the temperature of the bimorph remained normal after 2000 hours of operation when the gas medium was blocked.

Keywords: Resonance; Gas pump; Piezoelectric pump; Displacement amplification; Bimorph

1. Introduction

At present, the research on piezoelectric pumps has undergone significant improvement, especially with regard to the output flow rate, pressure, precision, and so on [1, 2]. The working media include low viscosity compressed fluid, high viscosity liquid, granule fluid, and compressed gas. The application of the piezoelectric pump has extended to a variety of fields, including biomedicine, fine chemistry, MEMS, among others. Some piezoelectric pumps have also undergone series production [3-8].

A resonantly driven piezoelectric pump is a device that utilizes the system resonant principle to amplify and drive media flow. The Japanese applied for the first resonantly driven piezoelectric pump patent in 1993. This pump utilized centrifugal force to drive liquid flow in a single direction under resonance. Restricted by its structure, this pump produced extremely low output pressure and flow rate. In 1999, the precision and aptitude laboratory of the Japanese Tokyo Industry University developed a resonantly driven piezoelectric pump that was made of a piezoelectric stack, a pump chamber, bellows, and a cantilever check valve [9-11] and used water as medium. The maximal output flow rate of the piezoelectric stack pump was noted at 80 mm^3/s, and the maximal pump pressure was 0.32 MPa. In 2007, a new resonant membrane pump was developed successfully in Lyndon Johnson space center in Texas [12]. This pump was also driven by a piezoelectric stack. Under system resonance, the displacement of the piezoelectric stack was amplified by 50 times, and the cubage flow rate was increased greatly. In 2009, O'Neill [13] applied for an inventive patent of a resonantly driven piezoelectric pump that was also driven by a piezoelectric stack. Based on the literature, the resonantly driven piezoelectric pump is now driven by a piezoelectric stack. However, the piezoelectric stack manufacturing process is complicated and highly expensive. Moreover, the resonantly driven piezoelectric stack pump is not easy to distribute.

A piezoelectric pump with normal membrane is effective in delivering liquid but not in delivering gas, which can be explained by two reasons. One is that the piezoelectric membrane pump cannot provide enough compression for gas delivery, for which the deforming capacity is limited. Another problem is the heat generated by the piezoelectric vibrator. As

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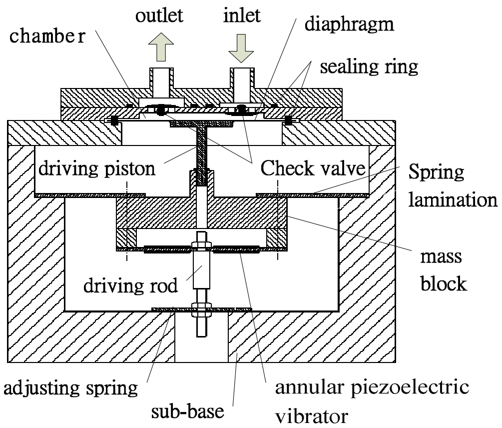


Fig. 1. Resonantly driven piezoelectric gas pump configuration.

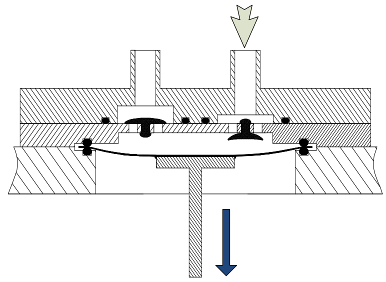
the vibrator functions, a small amount of heat is released, which in turn can depolarize and damage the vibrator after prolonged operation. Such damage can be attributed to a relatively closed pump chamber, low specific heat capacity of the gas, and poor heat distribution.

An improved piezoelectric resonant gas pump is therefore proposed. First, compared with that of the traditional piezoelectric resonant air pump, the driving part of the proposed pump is easily applicable for series production and adjustments. This improved pump also has a higher driving capacity compared with the traditional resonant pump because a circular piezoelectric vibrator is used for driving. A new displacement amplified mechanism is adopted in the pump to fit the large displacement and low output force features of the circular vibrator. Meanwhile, compared with the piezoelectric membrane air pump, the improved pump has a better temperature-resistant characteristic, as the gas is driven by an assisted framework. In this case, the compressed rate is increased greatly, and good heat distribution is ensured, making the improved pump convenient to use for gas and light fluid, which are sensitive to temperature change.

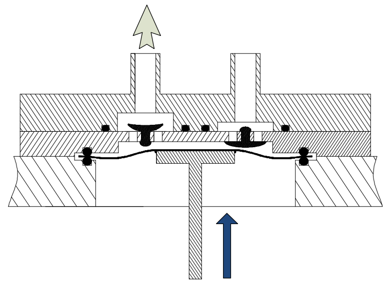
2. Composition and mechanical model

2.1 Composition of the piezoelectric gas pump

The framework of the improved resonantly driven piezoelectric gas pump is shown in Fig. 1. The framework includes two parts, namely, displacement amplification system and pump body. The displacement amplification system is composed of a sub-base, an annular piezoelectric vibrator, a mass block, a spring lamination, an adjusting spring, and a driving rod. The annular vibrator contains a metal sub-plate with holes and an annular bimorph adhered to both sides of the metal sub-plate. The pump body consists of sealing rings, a driving piston, a diaphragm, a pump chamber, check valves, an outlet, and an inlet. The working principle of the pump is described as follows. The annular piezoelectric vibrator features a micro amplitude vibration powered by AC voltage to excite the spring-mass system made up of spring lamination, adjusting spring, and mass block. When the excitation frequency reaches the system resonant frequency, resonance occurs in the displacement amplification system. Subsequently, the piezoelectric vibrator displacement, which is conducted by the driving piston working on the membrane, is amplified. As shown in Fig. 2, the membrane movement forces the chamber to undergo cubage change. With the cooperation of two check valves, the suction and discharge processes are initiated, and the fluid in the chamber flows in a single direction when the membrane continuously vibrates.



(a) Suction process



(b) Discharge process

Fig. 2. Operating principle of resonantly driven piezoelectric gas pump.

2.2 Analysis of mechanical model

According to the system resonance theory, the resonantly driven piezoelectric gas pump amplifies micro displacement from the piezoelectric vibrator and drives the gas flow through the diaphragm. This displacement amplification capability influences the pump output flow rate. As the base mass is larger than the other parts, the vibration displacement is close to zero. To simplify the analysis, take the spring lamination, adjusting spring, and the piezoelectric vibrator as ideal spring parts whose mass and vibration damp can be ignored. When the driving piston is moving, the gas in the pump is compressed or pulled to drive the check valve movement. When the check valve opens or closes, the driving piston is influenced by the gas, which is a process referred to as the coupling of solid-gas-solid. From the actual movement, the coupling effect is not obvious when the resonantly driven piezoelectric gas pump has no load because of low gas viscosity. In this condition, the interaction between the check valve and the

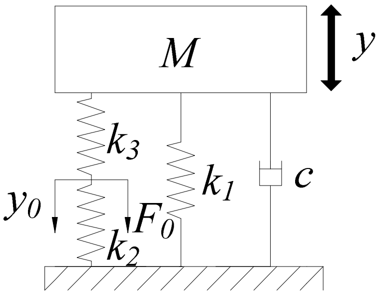


Fig. 3. Resonantly driven piezoelectric gas pump vibration model.

gas can be taken as a damper, which influences piston movement. The interaction can be defined as the system equivalent damp. As the mass of the connecting rod is much smaller than that of the mass block and its accessory, the mass of the connecting rod can then be ignored. The resonantly driven piezoelectric gas pump system is simplified (Fig. 3) in mechanical vibration mode, where M is the system equivalent mass for the connecting rod, the driving piston, and the mass block; k_1 is the spring lamination stiffness, k_2 is the adjusting spring stiffness, k_3 is the piezoelectric vibrator stiffness, and y_0 is the vibration displacement of the piezoelectric vibrator. Take $y_0 = A\cos\omega t$, where y_1 is the vibration displacement of the mass block, F_0 is the original excitation, $F_0 = k_3 y_0$, and c is the system equivalent damp.

The motion differential equation is

$$\begin{cases} M\ddot{y}+c\dot{y}+k_3(y-y_0)+k_1 y=0 \\ k_3(y-y_0)+F_0-k_2 y_0=0 \end{cases}. \quad (1)$$

Eq. (1) can be transformed to

$$M\ddot{y}+c\dot{y}+\frac{k_1k_2+k_1k_3+k_2k_3}{k_2+k_3}y=\frac{k_3}{k_2+k_3}F_0\,. \quad (2)$$

The general expression is

$$\ddot{y}+\frac{c}{M}\dot{y}+\frac{k_1k_2+k_1k_3+k_2k_3}{M(k_2+k_3)}y=\frac{k_3}{M(k_2+k_3)}F_0 \quad (3)$$

where ζ is the viscosity damping factor, $\zeta=\frac{c}{2M\omega_n}$, and ω_n is the system resonant frequency. Thus, Eq. (3) can be written as

$$\ddot{y}+2\zeta\omega_n\dot{y}+\omega_n^2 y=\frac{k_3^2}{k_1k_2+k_1k_3+k_2k_3}A\omega_n^2\cos\omega t\,. \quad (4)$$

The resonant frequency is

$$\omega_n=\sqrt{\frac{k_1k_2+k_1k_3+k_2k_3}{M(k_2+k_3)}}\,. \quad (5)$$

The system steady-state response is

$$y=\frac{k_3^2}{k_1k_2+k_1k_3+k_2k_3}\bullet\frac{A\cos\omega t}{[1-(\frac{\omega}{\omega_n})^2]^2+(2\zeta\frac{\omega}{\omega_n})^2}\,. \quad (6)$$

The vibration system displacement amplification time is

$$|H(\omega)|=\frac{Y}{A}=\frac{k_3^2/(k_1k_2+k_1k_3+k_2k_3)}{\sqrt{[1-(\frac{\omega}{\omega_n})^2]^2+(2\zeta\frac{\omega}{\omega_n})^2}}\,. \quad (7)$$

Based on Eq. (7), the displacement amplified times as well as the spring lamination stiffness k_1, adjusting spring stiffness k_2, piezoelectric vibrator stiffness k_3, and the viscosity damping factor ζ are related with the excitation frequency ω. When the excitation frequency $\omega = \omega_n$, the displacement amplified times reaches the maximum.

$$|H(\omega_n)|=\frac{k_3^2}{2\zeta(k_1k_2+k_1k_3+k_2k_3)}\,. \quad (8)$$

Suppose that the efficient working area of the diaphragm is S under resonant working frequency, and that the cubage variable quantity from every working cycle is $\Delta V = y_0|H(\omega_n)|S$. Then, the maximal theoretical flow rate Q from the piezoelectric resonant pump is

$$Q=\frac{\Delta V\omega_n}{2\pi}=\frac{\omega_n|H(\omega_n)|SA\cos\omega_n t}{2\pi}\,. \quad (9)$$

As seen in Eq. (9), if the section area S is steady at a resonant frequency, the flow rate is directly proportional to the product of the displacement amplified times $H(\omega_n)$, resonant frequency ω_n, and amplitude A. Note that ω_n is the resonant frequency of the pump system and not of the piezoelectric vibrator. According to the actual testing result, the first-order resonant frequency of the piezoelectric vibrator in this paper is around 7 kHz, which is greater than the resonant frequency ω_n. With a frequency lower than 7 kHz, amplitude A increases with the increase of ω. When the displacement amplified times is the same, in the scope of the check valve response frequency, the bigger the system resonant frequency ω_n is, the bigger the output flow rate is.

3. Experiments and results

Prototypes were developed according to the structure shown in Fig. 2, and the experiments on working performances were carried out at 70 V of sinusoidal AC voltage. The bimorph had an outer diameter of 34 mm, an inner diameter of 10 mm, and a thickness of 0.6 mm. The piezoelectric vibrator plate had an outer diameter of 51 mm, an inner diameter of 6 mm, and a thickness of 0.8 mm. The mass block made of iron material

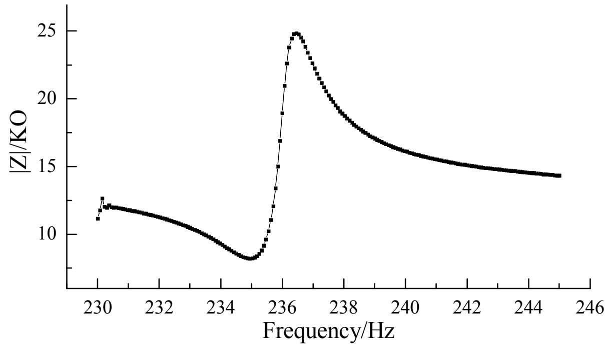


Fig. 4. Relationship between impedance and frequency.

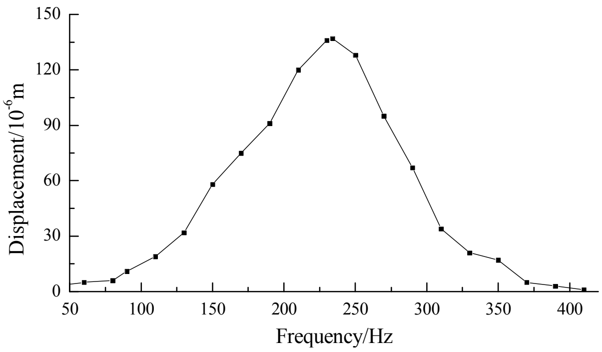


Fig. 5. Relationship between diaphragm displacement and frequency.

had a diameter of 76 mm and a thickness of 10 mm. The adjusting spring had a diameter of 8 mm and a thickness of 1 mm. The spring lamination had a length of 15.5 mm, a width of 10 mm, and a thickness of 0.4 mm. Both springs were made of spring steel. The diaphragm had a diameter of 50 mm and a thickness of 0.05 mm; the material was Be-bronze, and the diaphragm was glued to the driving piston using epoxy. The height of the chamber was 0.5 mm, and rubber check valves were used in the input and output. The main devices in the experiments included a precision impedance analyzer, a numeric piezoelectric frequency controller, and a laser displacement meter.

3.1 Displacement amplification effect tests

The prototype resistance characteristic was obtained from the precise resistance analysis instrument, as seen in Fig. 4, which shows that the first resonant frequency (|Z| is the bottom location) is 234.8 Hz. The diaphragm output displacement was tested by the laser micrometer, and the result is shown in Fig. 5. When the driving frequency departed from the resonant frequency, the diaphragm displacement decreased dramatically. When the driving frequency remained the same as the resonant frequency, the diaphragm displacement reached a maximum of 137 μm. In the same supporting condition, i.e., when supported by the outer supporting, the maximal displacement that the piezoelectric vibrator achieved is 33 μm.

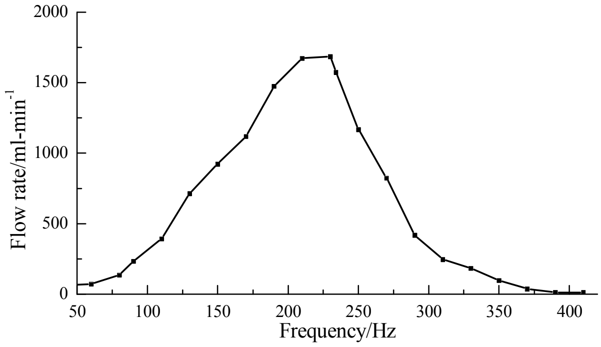


Fig. 6. Relationship between output flow rate and frequency.

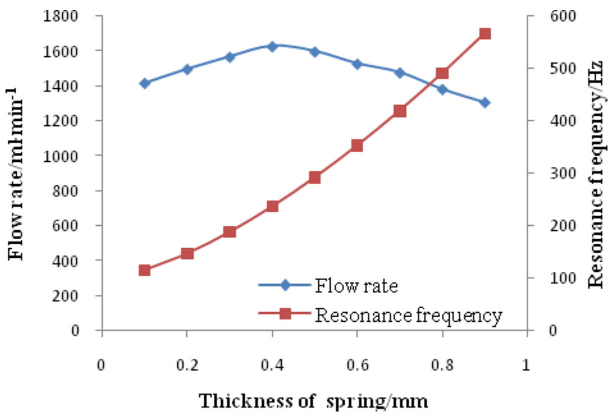


Fig. 7. Influence curve of adjusting string thickness to the flow rate and resonant frequency.

Therefore, under resonance, the piezoelectric vibrator displacement is enlarged by at least 4.2 times.

3.2 Flow rate frequency characteristic

The relationship between flow rate and frequency of the resonantly driven piezoelectric gas pump was determined through the drainage method (Fig. 6). Similar to the frequency characteristic of the displacement amplification system, the gas flow rate changed according to the change of the frequency characteristic (Fig. 6). Under resonance, the flow rate reached the maximum value of 1685 ml/min.

3.3 The stiffness test

The relationship among k_1, resonant frequency, and flow rate is shown in Fig. 7. As evident in this figure, the parameter is adjusted through the spring thickness. Moreover, the resonant frequency increases, but the flow rate decreases as k_1 increases.

The relationship among k_3, resonant frequency, and flow rate is shown in Fig. 8. Here, the parameter valve is adjusted through the spring thickness. As k_3 increases, the resonant frequency increases, and the flow rate decreases after the in-

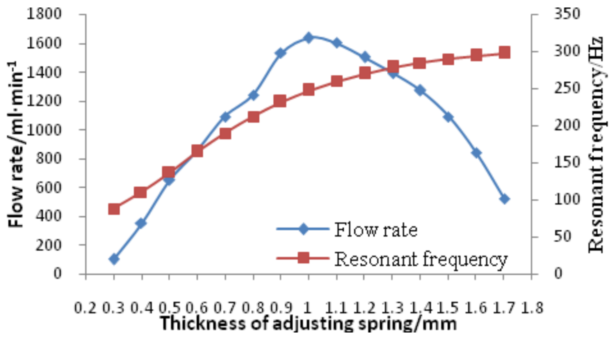


Fig. 8. Influence curve of adjusting string thickness to the flow rate and resonant frequency.

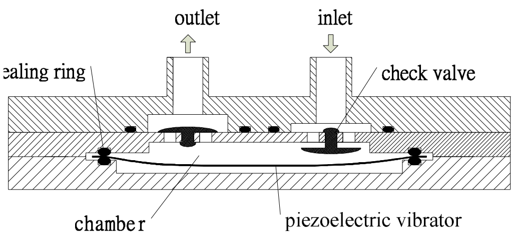


Fig. 9. Piezoelectric membrane gas pump configuration.

crease. The influence of k_3 is greater than that of k_1.

The changing tendency of k1 and k3 is identical with the models shown in Eqs. (5) and (7). k2 and k3 have similar functions, but no further analysis is carried out in the next step.

3.4 Piezoelectric vibrator working temperature test

The traditional piezoelectric membrane gas pump is shown in Fig. 9. The driving element is part of the pump chamber, which is sealed in the chamber, and the cooling medium is mainly the pumped gas. The improved piezoelectric resonant gas pump is shown in Fig. 1, wherein the driving element is in the amplified mechanism. As the chamber does not have good ventilation, no pumped gas is needed for cooling.

To test the increasing temperature of the piezoelectric vibrator during prolonged operation, a temperature micro probe sensor was mounted on the metal sub-plate, with the input and output of the resonantly driven piezoelectric gas pump blocked simultaneously. The temperature of the piezoelectric vibrator rose to just 0.5 °C after ten hours of continuous operation. The temperature then became the same with the ambient temperature after 2000 hours of continuous operation. However, when the pipe for the piezoelectric membrane pump was blocked, the piezoelectric vibrator became damaged within five minutes because of the rapid temperature increase. Therefore, compared with the piezoelectric membrane pump, the improved resonantly driven piezoelectric gas pump is able to solve the temperature problem of the piezoelectric vibrator.

4. Conclusions

In this paper, prototypes of the resonantly driven piezoelectric gas pump were designed, and the displacement amplified effect and output performance were tested at a sinusoidal AC voltage of 70 V. The following conclusions can be drawn from the experiment results:

(1) Based on the theoretical analysis, the displacement amplification effect of the resonantly driven piezoelectric gas pump is related with spring lamination stiffness k_1, adjusting spring stiffness k_2, piezoelectric vibrator stiffness k_3, viscosity damping factor ζ, and excitation frequency ω.

(2) The micro displacement of the piezoelectric vibrator can be amplified dynamically by system resonance. The frequency characteristic is the same with the general resonant system. The structure in the paper can amplify the displacement by at least 4.2 times under a resonant frequency of 234.8 Hz.

(3) The piezoelectric pump that was improved based on resonance can deliver gas, and the frequency characteristic of the gas flow rate is basically the same with the displacement amplification. The maximum flow rate reaches 1685 ml/min, as tested by the drainage method when the driving frequency is 230 Hz.

(4) When the outlet and inlet are blocked, the gas cannot flow, which in turn increases the temperature of the piezoelectric membrane pump rapidly, resulting in damage. As for the improved resonantly driven piezoelectric gas pump, after 2000 hours of continuous operation, the improved pump can still operate under normal conditions.

Acknowledgment

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Nomenclature

k_1	: Spring lamination stiffness
k_2	: Adjusting spring stiffness
k_3	: Piezoelectric vibrator stiffness
y_0	: Piezoelectric vibrator displacement
y_1	: Mass block vibration displacement
F_0	: Original excitation
c	: System equivalent damp
ζ	: Viscosity damping factor
ω_n	: System resonant frequency
ω	: Excitation frequency
S	: Efficient working area of diaphragm
Q	: Flow rate
A	: Amplitude

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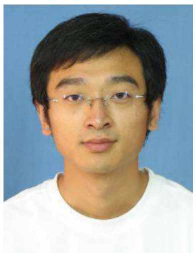

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