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Simulation Analysis and Experimental Verification of Spiral-tube-type Valveless Piezoelectric Pump with Gyroscopic Effect

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Abstract: The current research of the valveless piezoelectric pump focuses on increasing the flow rate and pressure differential. Compared with the valve piezoelectric pump, the valveless one has excellent performances in simple structure, low cost, and easy miniaturization. So, their important development trend is the mitigation of their weakness, and the multi-function integration. The flow in a spiral tube element is sensitive to the element attitude caused by the Coriolis force, and that a valveless piezoelectric pump is designed by applying this phenomenon. The pump has gyroscopic effect, and has both the actuator function of fluid transfer and the sensor function, which can obtain the angular velocity when its attitude changes. First, the present paper analyzes the flow characteristics in the tube, obtains the calculation formula for the pump flow, and identifies the relationship between pump attitude and flow, which clarifies the impact of flow and driving voltage, frequency, spiral line type and element attitude, and verifies the gyroscopic effect of the pump. Then, the finite element simulation is used to verify the theory. Finally, a pump is fabricated for experimental testing of the relationship between pump attitude and pressure differential. Experimental results show that when Archimedes spiral θ=4π is selected for the tube design, and the rotation speed of the plate is 70 r/min, the pressure differential is 88.2 Pa, which is 1.5 times that of 0 r/min rotation speed. The spiral-tube-type valveless piezoelectric pump proposed can turn the element attitude into a form of pressure output, which is important for the multi-function integration of the valveless piezoelectric pump and for the development of civil gyroscope in the future.

Keywords: gyroscope, valveless piezoelectric pump, spiral tube

1 Introduction

Valveless piezoelectric pumps have the advantages of having a simple structure, low cost, and easy miniaturization, but have the deficiencies of low flow rate and low-pressure differential[1–6]. The key to effective application of these pumps is the mitigation of their weaknesses. Thus, some studies focused on the integration of pump functionalities[7–9]. Valveless piezoelectric pump, which combines periodic flow and attitude sensing in one operating element, has an important application prospect of utilizing low-cost and simplified gyroscopes.

Gyroscopes (attitude sensors) play an important role in many areas. However, the dual constraints of cost and technology hinder their wide application. Generally, high-precision and high-cost gyroscopes are used in the military field, whereas low-accuracy and low-cost gyroscopes are used in civil areas. The research and development of new principles, methods, and technology of gyroscopes to achieve lower cost and sufficient accuracy are urgently needed to reduce technical barriers[10–12].

Since 1905, people had studied the geophysical phenomena caused by the Earth's rotation[13]. ITO, et al[14], found that the direction of the Coriolis force caused by rotation is related to the direction of the rotational angular velocity. The systems transport phenomenon caught the attention of scientists after it was applied in the rotary mechanical engineering[15]. However, until the last century, the spiral tube operating characteristics of human knowledge emerged from experience. Therefore, to identify a greater role, Australian researcher STOKES[16] established a mathematical model of the spiral. Assuming the boundary conditions, he derived the N-S equation and the analytical solutions of the continuity equation to analyze the flow in the tube. U.S. researchers also established spiral geometry. The Law of Hydrology was used to analyze the flow in the tube to obtain the force in it[17]. Chinese Professor ZHANG, et al[18], studied flow and

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heat transfer in a rotary curve tube. The control volume method was used to examine the flow in a rotary pipe with a rectangular cross-section. He discovered that the greater the aspect ratio of a rectangular cross-section, the more stable the state of flow is. However, recent studies on rotary tubes have concentrated on propertied fluid in the rotating arc-shaped pipes, and only few focused on spiral devices[19]. In 2001, ZHANG[20] proposed a valveless piezoelectric pump by applying a spiral tube in a mechanical structure and explained the operation principle of the pump, which included two mutually linked and inverted stereo-spiral tubes under the work of the piezoelectric vibrator. The one-way mean flow characteristic of this pump is dependent on its position and attitude.

The flow in a spiral tube element is sensitive to the element attitude caused by the Coriolis force, and a valveless piezoelectric pump with gyroscopic effect can be invented by applying this phenomenon. The angular velocity variation can be obtained when the pump attitude changes. Hence, the pump has a gyroscopic effect. Experimental results show that this pump has the pump characteristics of one-way mean flow, and that the pressure difference in the two vertical-pipes can notably reflect the change of the rotating table in the movement of the pump itself. So it has a gyroscopic effect.

2 Gyroscopic Effect Principle: Spiral-tube-type Valveless Piezoelectric Pump

The Coriolis acceleration is due to both circular and radial motions of the particle. It is the source of the Coriolis force. Newton's First and Second Laws do not apply to the rotating coordinate system, which is a non-inertial reference system. Hence, the Coriolis force is caused by the rotation of this reference system.

In the study of the flow in spiral tube, a rotating reference system is shown in Fig. 1. Assume that the fluid is inviscid, incompressible, homogeneous, and in a steady state. To make the analysis simple, only the average flow is considered, and the rotation is not impact of the viscosity.

2.1 Principle of piezoelectric pump

The current study considers the element of fluid M moving in the spiral tube, which is equivalent to the original inertial reference system (r_I, θ_I) rotating around an axis perpendicular to the plate where the spiral flow tube is. Thus, a rotating coordinate system (r_R, θ_R), which rotates in an angular velocity Ω, is involved. In Eq. (1) below, the subscript I indicates the parameter of the inertial reference system, and the subscript R indicates the parameter of the rotating coordinate system. Obviously, it has a quantitative relationship with the original inertial reference system (r_I, θ_I) at the counterclockwise direction of the rotation, as shown in Fig. 1(a):

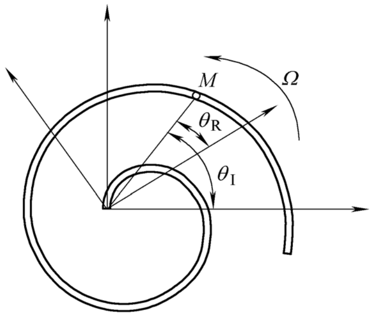
$$\begin{cases} r_\mathrm{R} = r_\mathrm{I} = r, \\ \theta_\mathrm{R} = \theta_\mathrm{I} - \Omega t_\mathrm{I}, \\ t_\mathrm{R} = t_\mathrm{I} = t, \end{cases} \tag{1}$$

where r is the radial coordinate, and θ is the tangential coordinate. Thus, the ideal fluid motion equation in the rotating frame is

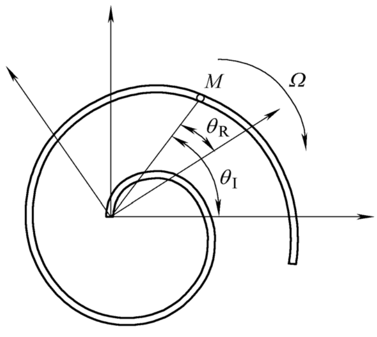
$$\begin{cases} \dfrac{\mathrm{d}u_\mathrm{R}}{\mathrm{d}t_\mathrm{R}} - \dfrac{v_\mathrm{R}^2}{r_\mathrm{R}} - 2\Omega v_\mathrm{R} - \Omega^2 r_\mathrm{R} = -\dfrac{\partial P}{\partial r_\mathrm{R}}, \\ \dfrac{\mathrm{d}v_\mathrm{R}}{\mathrm{d}t_\mathrm{R}} + \dfrac{u_\mathrm{R} v_\mathrm{R}}{r_\mathrm{R}} + 2\Omega u_\mathrm{R} = -\dfrac{1}{r_\mathrm{R}}\dfrac{\partial P}{\partial \theta_\mathrm{R}}, \end{cases} \tag{2}$$

where u_R and v_R are the two velocity components along the two axes of the rotating coordinate system (r_R, θ_R). The fluid is positive, and the pressure p is a function of the density ρ, which is expressed as

$$P = \frac{p}{\rho}. \tag{3}$$



(a) Counterclockwise



(b) Clockwise

Fig. 1. Diagram of flow in the spiral tube in the rotating reference system

The mathematical model of the spiral flow tube is the Archimedes spiral $r = a\theta$, where a is a parameter. Meanwhile, considering the flow through the tube, the velocity component along the θ_R -axis or v_R is analyzed. By omitting the subscript R, the following equation is obtained:

$$v = -a\Omega^2 t \pm \sqrt{\frac{\partial P}{\partial t} t}. \tag{4}$$

Considering the speed values meaningful to take:

$$v=\sqrt{\frac{\partial P}{\partial t}t}-a\Omega^2 t. \tag{5}$$

Thus, at any given time t, the flow through the spiral tube is

$$Q_1=\left(\sqrt{\frac{\partial P}{\partial t}t}-a\Omega^2 t\right)S, \tag{6}$$

where S is the cross-sectional area of the spiral tube.

When the rotating coordinate system (r_R, θ_R) rotates clockwise, as shown in Fig. 1(b), then the equation is written as:

$$\begin{cases} r_R=r_I=r, \\ \theta_R'=\theta_I+\Omega t_I, \\ z_R=z_I=z, \\ t_R=t_I=t, \end{cases} \tag{7}$$

and further deduced that

$$v'=a\Omega^2 t\pm\sqrt{\frac{\partial P}{\partial t}t}. \tag{8}$$

Considering the speed values meaningful to take:

$$v'=\sqrt{\frac{\partial P}{\partial t}t}+a\Omega^2 t. \tag{9}$$

Thus, at any given time t, the flow through the spiral tube is

$$Q_2=\left(\sqrt{\frac{\partial P}{\partial t}t}+a\Omega^2 t\right)S. \tag{10}$$

Eqs. (6) and (10) show an additional parameter $\pm a\Omega^2$ in the fluid acceleration. This is the Coriolis acceleration. In the spiral tube, when the fluid flows clockwise or counterclockwise, the Coriolis force will alter the flow resistance. Thus, in the macro-phenomenon, the clockwise flow will be different from the counterclockwise flow and vice versa. When $\Omega=0$, the flow does not rotate in the spiral tube, the Coriolis force does not appear (ignore the effect of the Earth's rotation), and it will not generate the flow through the tube.

2.2 Principle of gyroscopic effect

As the plate of the pump is horizontal at the XOY plane (Fig. 2), the Earth spins component at an angular velocity $\omega_{ie}\sin L$, where ω_{ie} is the angular velocity of the Earth's spin 7 292 115.146 7×10^{-11} rad/s and L is the local latitude.

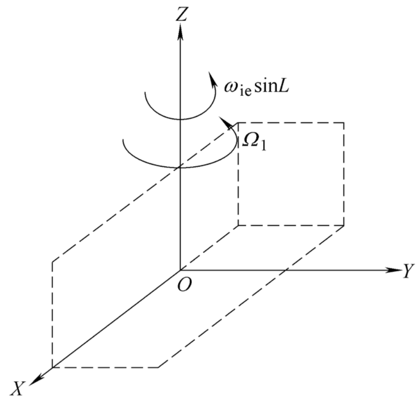


Fig. 2. Diagram of the earth spin angular component and pump attitude change

When the table, where the pump is fixed, rotates at an angular velocity Ω_1 (Fig. 2), the flow angular velocity of the element of fluid M moving in the spiral tube (Fig. 1(a)) becomes $\Omega+\Omega_1+\omega_{ie}\sin L$, whereas that of the element of fluid M moving in the spiral tube (Fig. 1(b)) is $\Omega-\Omega_1-\omega_{ie}\sin L$. When the piezoelectric vibrator moves upward, the chamber volume increases, and the flow through the spiral tube into the pump is

$$Q_{In}=\left[\sqrt{\frac{\partial P}{\partial t}t}+a(\Omega-\Omega_1-\omega_{ie}\sin L)^2 t\right]S. \tag{11}$$

By contrast, when the piezoelectric vibrator moves downward, the chamber volume decreases, and the flow through the spiral tube out of the pump chamber is

$$Q_{0ut}=\left[\sqrt{\frac{\partial P}{\partial t}t}-a(\Omega+\Omega_1+\omega_{ie}\sin L)^2 t\right]S. \tag{12}$$

Hence, the piezoelectric vibrator moves one cycle, and the flow differential between the pump inlet and outlet is $2a(\Omega^2+\Omega_1^2+2\Omega_1\omega_{ie}\sin L+\omega_{ie}^2\sin^2 L)tS$.

The Earth spins angular component is small, so it can be ignored. The simple representation of the flow differential is

$$\Delta=2a(\Omega^2+\Omega_1^2)tS. \tag{13}$$

When the pump is stationary, the flow angular velocity Ω of thorough into or out of the spiral tube can be obtained. When the pump attitudes change, the value of the attitude angular velocity Ω_1 can be calculated using Eq. (13), and its direction can be determined by comparison to Ω. Therefore, the spiral-tube-type valveless piezoelectric pump acquires the function of measuring the attitude change and a gyroscopic effect.

2.3 Principle of the spiral-tube-type valveless piezoelectric pump with gyroscopic effect

The characteristics of the spiral tube determine the same angular velocity of the every point in the tube. During the half cycle of working, the spiral tube of the valveless piezoelectric pump sucks and discharges the flow is Q_1 and Q_2 respectively. If the pump senses the external counterclockwise rotation angular velocity Ω at the same time, the relationship of the flow sucked by any of the cross-section of the tube and the angle of the spiral linear θ' is

$$Q_1' = a\theta'\left(\frac{Q_1}{a\theta S}+\Omega\right)S = \frac{\theta'}{\theta}Q_1 + a\theta'\Omega S. \quad (14)$$

Similarly, the relationship of the flow discharged by any of the cross-section of the tube and the angle is

$$Q_2' = a\theta'\left(\frac{Q_2}{a\theta S}-\Omega\right)S = \frac{\theta'}{\theta}Q_2 - a\theta'\Omega S. \quad (15)$$

When the axisymmetric circular piezoelectric vibration vibrates under the sinusoidal voltage driving, the deformation surface approximated as a paraboloid of revolution, the center point has the maximum speed, and therefore the maximum amplitude appears in the center of the piezoelectric vibration. Assuming the amplitude in the center point is h_0, R is radius of the piezoelectric vibrator, so the change of volume of the pump chamber $\Delta V_{\max}$ in the movement of the piezoelectric vibrator from the equilibrium position to the highest point is

$$\Delta V_{\max} = 2\pi\int_0^R h_0\left(1-\frac{r^2}{R^2}\right)r\mathrm{d}r = \frac{\pi h_0 R^2}{2}. \quad (16)$$

At a certain frequency, the amplitude h of the piezoelectric vibrator is the function of the driving voltage V, that is $h(V)$. The result of the mass flow change by the change of the pump chamber is

$$\Delta m = \frac{\rho\pi R^2}{2}h(V). \quad (17)$$

When the vibration frequency is f, and the gyro senses the external counterclockwise rotation angular velocity in the unit time is Ω, the flow changes derived by the Eqs. (14) and (15) is

$$Q_1' - Q_2' = \frac{\theta'\rho\pi R^2 f}{\theta}h(V) + 4a\theta'\Omega S f. \quad (18)$$

As can be seen from the formula, the output flow of the gyro has the relationship with each section of the spiral tube, the input voltage, frequency, and the external angular velocity. When $|\Omega|>1$, the change of flow is larger by the impact of the angular velocity. When $|\Omega|<1$, the angular velocity impacts the flow smaller, but there is still affected.

3 Structure of the Spiral-tube-type Valveless Piezoelectric Pump

The basic structure of the spiral-tube-type valveless piezoelectric pump is illustrated in Fig. 3. The pump consists of the pump body, spiral flow tube, linear flow tube, vertical pipe, piezoelectric vibrator, pump chamber, and other parts. The spiral and linear flow tubes are connected through the vertical pipe. As shown in Fig. 4, the piezoelectric film in the vertical pipe is used as a sensor to measure the pressure differential caused by the pump flow changes in the tubes. The presence of the flow or pressure differential will cause the piezoelectric film to sense the pressure change and deform. The deformation of the film will generate voltage under the direct piezoelectric effect.

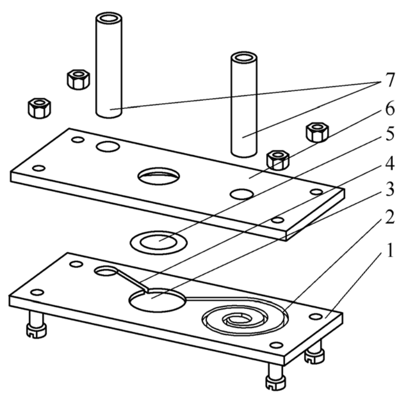


Fig. 3. Structure diagram of the spiral-tube-type valveless piezoelectric pump

1. Lower part of the pump body, 2. Spiral flow tube, 3. Pump chamber, 4. Linear flow tube, 5. Piezoelectric vibrator, 6. Upper part of the pump body, 7. Vertical-pipe

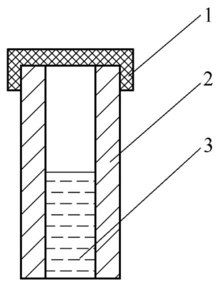


Fig. 4. Structure diagram of generating the pressure differential

1. Piezoelectric film, 2. Vertical-pipe, 3. Fluid

Applying AC voltage to the two poles of the piezoelectric ceramic will result in the piezoelectric vibrator bending periodically along its axis. When the piezoelectric vibrator moves upward, the volume of the pump chamber increases, and the pump is in the suction cycle where the fluid flows into the pump chamber through the spiral and linear tubes. On the other hand, when the piezoelectric vibrator moves downward, the volume of the pump chamber declines, and the pump is in the discharging cycle where the fluid flows out of the pump chamber through the spiral and linear tubes. As a result of the Coriolis acceleration derived in section 2, a one-way mean flow occurs, which facilitates the flow into the pump chamber from the linear tube and out of chamber from the spiral tube.

A test pump (Fig. 3) is horizontally fixed on a rotating table. A piezoelectric film is used as a sensor to measure the pressure differential caused by the pump flow changes in the tubes. Considering the combination of the angular velocity caused by the flow in the spiral tube and the angular velocity caused by the rotating plate, the effect of the Coriolis force is amplified, and the gyroscopic effect emerges.

4 Simulation

Using the Fluent software to simulate, and using Gambit2.4.6 modeling and meshing. The geometry parameters of the spiral-tube-type valveless piezoelectric pump are as follows: Base circle radius is 10 mm; the pitch of the spiral is 20 mm, it contains 0.75 circles, and the cross section is square of 2 mm×2 mm; the linear flow tube is 20 mm long, and its cross section is square of 2 mm×2 mm too; the radius of pump chamber is 17.5 mm. The fluid selected is water, its density is $\rho = 998.2\ \mathrm{kg/m^3}$, and its dynamic viscosity coefficient is $0.001\,003\ \mathrm{kg/(m\cdot s)}$.

In the case of the spiral-flow-tube valveless piezoelectric pump not sensing the angular velocity, the tangential velocity of the orifice of the spiral tube is shown in Fig. 5. When the piezoelectric vibrator reaches the equilibrium state, the flow velocity is small, but due to the influent of the inertial effect, there is still a slight current. When the piezoelectric vibrator moves upward (shown by the coordinate axis of the Fig. 5), the gyro is in the suck cycle, and shown by the velocity is negative. When the piezoelectric vibrator moves downward, the gyro is in the discharge cycle, and shown by the velocity is positive.

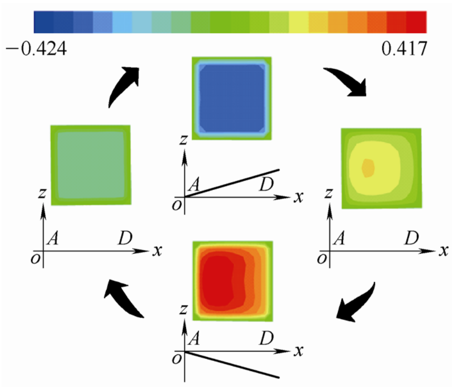


Fig. 5. Tangential velocity cycle variation diagram of the orifice of the spiral tube when the rotation angular velocity $\Omega = 0$ (m/s)

When the spiral-tube-type valveless piezoelectric pump senses the angular velocity $\Omega = 3$, the movement of the fluid in the tube is changed, as shown in Fig. 6. The tangential velocity of the orifice of the spiral tube relative to no external velocity interference has changed. When the pump senses the angular velocity $\Omega = 4$, as shown in Fig. 7, the suction of the flow is strengthened, and the discharge of the flow is weakened.

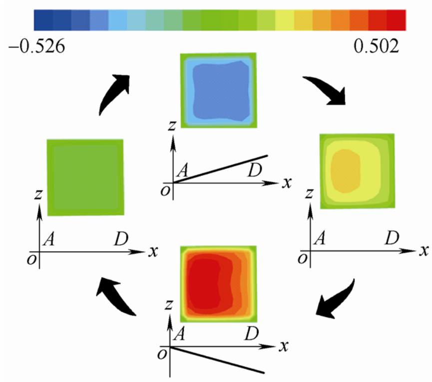


Fig. 6. Tangential velocity cycle variation diagram of the orifice of the spiral tube when the rotation angular velocity $\Omega = 3$ (m/s)

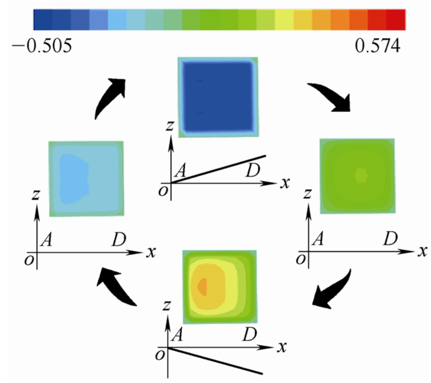


Fig. 7. Tangential velocity cycle variation diagram of the orifice of the spiral tube when the rotation angular velocity $\Omega = 4$ (m/s)

These are the changes of the flow in the spiral-tube-type piezoelectric pump in a cycle. Apply the AC voltage to the piezoelectric vibrator, it will vibrate in natural frequency and the frequency is faster. Affected by the angular velocity within a certain time, the pump shows good gyroscopic effect.

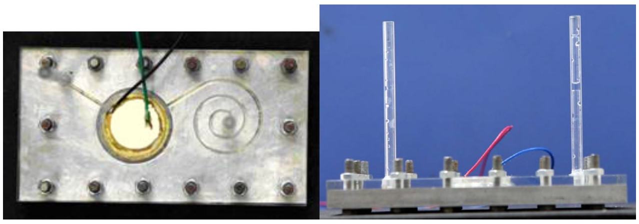
5 Experiments and Results

A pump was fabricated to verify the validity of the theoretical analysis. The design parameters of the pump chamber and the spiral flow tube are shown in Table 1. The photos of the fabricated spiral-tube-type valveless piezoelectric pump are shown in Fig. 8, where Figs. 8(a), 8(b) and 8(c) are the top views of the spiral tube $\theta = 1.5\pi$, $\theta = 2\pi$ and $\theta = 4\pi$ respectively. The front view of the pump is shown in Fig. 8(d).

Table 1. Performance and geometrical parameters of the pump

Parameter		Value
Pump size V/mm^3		180×50×10
Spiral tube cross-section A_s/mm^2		2×2
Linear tube cross-section A_L/mm^2		2×2
Vertical-pipe	Inner diameter D_I/mm	4
	Outer diameter D_o/mm	6
	Length l/mm	80
Pump chamber	Diameter D/mm	28
	Depth h_b/mm	1
Piezoelectric ceramic	Diameter d/mm	25
	Thickness h_y/mm	0.23
	Piezoelectric strain costant d_{33}/PC/N	425
	Mechanical quality factor Q_m	100

(a) Top view of $\theta = 1.5\pi$ (b) Top view of $\theta = 2\pi$

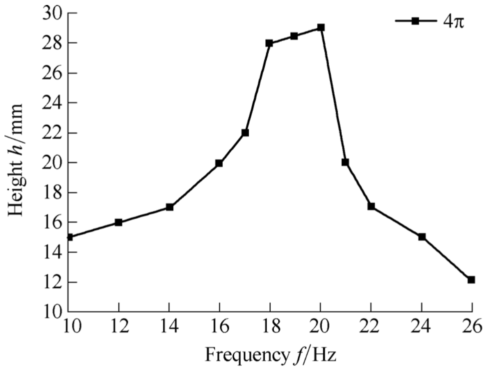


(c) Top view of $\theta = 4\pi$ (d) Front view

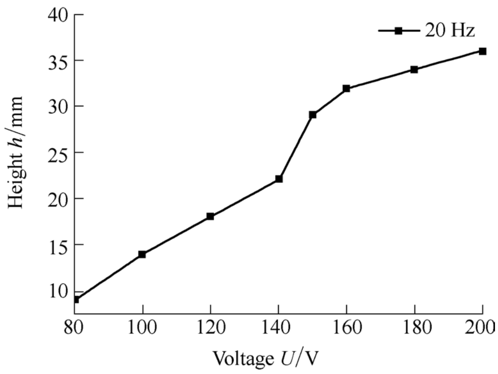
Fig. 8. Photos of the fabricated spiral-tube-type valveless piezoelectric pump

The pump measurement result is shown in Fig. 9. In the case of Archimedes spiral containing two circles ($\theta = 4\pi$), with the frequency of the spiral-tube-type valveless piezoelectric pump vibrator increases, the pressure differential in the vertical-pipe reaches a peak and then falls. Meanwhile, with the increase of the driving voltage of the vibrator, the pressure differential in the vertical-pipe becomes larger, but constrained by the performance of the piezoelectric ceramic, the pressure differential reaches a certain value and then slows down. In the case of $\theta = 4\pi$, this experiment ideal driving voltage of the piezoelectric vibrator is 150 V, the driving frequency is 20 Hz, and the pressure differential is 284.2 Pa.

When the Archimedes spiral angle changes (Fig. 10) at θ=1.5π, 2π, 3π, 4π, 5π, 6π with increasing piezoelectric vibrator driving voltage, the pressure differential between the pump inlet and outlet increases and reflects the characteristics of the pump. In a small number of circles, such as $\theta = 1.5\pi$, the Coriolis force sensed by the fluid is limited, and the pump pressure differential is very small because of insufficient rotation of flow tube. When $\theta = 2\pi$ and 3π, the flow tube can rotate over one full circle, and the fluid can be fully sensitive to the Coriolis force caused by the rotation. Thus, the pump pressure differential significantly increases. Meanwhile, when $\theta = 5\pi$ and 6π, the pump pressure differential drops significantly. This result can be attributed to the ideal fluid assumption in theoretical analysis. In an actual experiment, the flow resistance may increase, and the flow velocity is uneven during the rotation of more than two circles. Therefore, it is reasonable to select $\theta = 3\pi$ or 4π of the spiral based on the efficiency of the spiral-tube-type valveless piezoelectric pump.



(a) Curve of the frequency and driving voltage



(b) Curve of the driving and pressure differential

Fig. 9. Curve of the piezoelectric vibrator frequency, driving voltage and the pump pressure differential

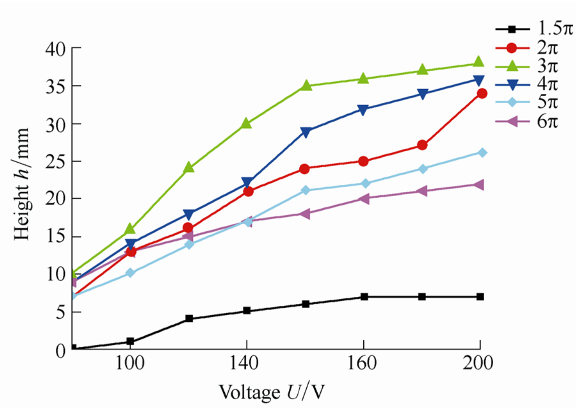


Fig. 10. Curve of the voltage and the pressure differential under different θ

To verify the gyroscopic effect of the pump, the pump was placed on a test rig that can rotate in a horizontal plate.

The spiral contains two circles ($\theta = 4\pi$), and the operating conditions are 100 V driving voltage at 24 Hz. One curve of solid dots and another of hollow dots are shown in Fig. 11. The solid dots curve indicates that the pressure differential between the pump inlet and outlet increases with increasing rotary speed of the plate. This indication proves that the pump exhibits a gyroscopic effect when an angular velocity is added. When the rotary speed is 0, the pressure differential is 58.8 Pa induced by the simple pump motion driven by the piezoelectric vibrator. When no voltage is applied onto the piezoelectric vibrator, the pump does not work, and the pressure differential is very small even if the plate is rotating at high speed, as shown in the hollow dots curve. Thus, the Coriolis force caused only by plate rotation is difficult to measure. With the pump working and the combination of the angular velocity caused by the flow in the spiral tube and the angular velocity caused by the rotating plate, the effect of the Coriolis force is amplified. The pump can drive the flow in the spiral tube to induce the Coriolis force and subsequently shows the gyroscopic effect. For example, when the rotary speed is 70 r/min, the pump pressure differential is 88.2 Pa, which is 50% larger than that when the rotary speed is 0. This result exactly reflects that the spiral flow tube-type valveless piezoelectric pump has a gyroscopic function that is more suitable for measuring large-spin speed.

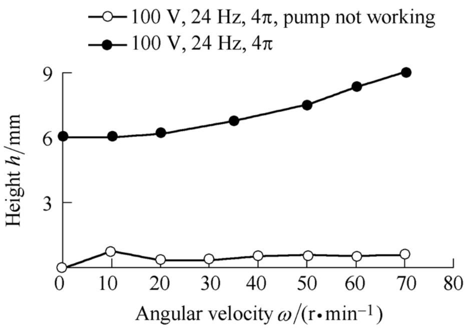


Fig. 11. Curve of the pump attitude and the pressure differential

6 Conclusions

(1) A spiral-tube-type valveless piezoelectric pump was proposed to have integrated functions of an actuator to driving flow and a gyroscope to sense the element attitude change that may bring the integration application of the valveless piezoelectric pump into a new field.

(2) The present paper revealed a phenomenon that the flow in a spiral tube element is sensitive to the element position. The flow characteristics in the pump and the flow tube were analyzed, and the calculation formulation of the pump flow is established.

(3) Pump flow characteristics were sensitive to its attitude. The calculation formulation between the pump attitude and flow was established. Illustrate the influence of the flow and the driving voltage, frequency, the spiral lines and the element attitude; prove the gyroscopic effect of the spiral-tube-type valveless piezoelectric pump was proven theoretically.

(4) Based on the finite element method, simulate the flow state in the spiral-tube-type valveless piezoelectric pump, and verify the pump has a gyroscopic effect.

(5) The relationship between the pump attitude and pressure differential was experimentally investigated. The experimental results showed that the pump can change the element attitude into a form of pressure output. This new gyroscope may have important application prospects in smart cars, robots, and home and health care devices because of its low cost and simplicity.

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