Pressure Distribution in Gas Film in Traveling Wave Rotary Ultrasonic Motor

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Abstract: The current research on gas film is mainly in various precision instruments and machinery while the studies on gas film in ultrasonic motor is few. Based on original N-S equations, the mechanism of gas film action in traveling wave rotary ultrasonic motor (TRUM) is explored through physical explanations and analyzed through numerical simulation. Pressure distributions in the smooth gas film and the gas film considering stator teeth are analyzed. It is concluded that the squeeze number and the non-dimensional amplitude are the main factors that affect the pressure distribution. As the approximate region becomes smaller, the pressure peak of the smooth gas film is close to an atmosphere. The pressure on tooth region is the same as that on smooth model while the region between teeth affects weakly on the whole model.

Key words: gas film; ultrasonic motor; pressure distribution

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0 Introduction

With the advent of high-precision engineering and output stability, outfield environment on ultrasonic motor has received more and more attention from domestic and foreign scholars. Gas film in ultrasonic motor is generated in relative movement between stator and rotor and the hydrodynamic effect is produced in this process. A number of researchers have performed extensive studies on traveling wave rotary ultrasonic motor (TRUM). They built the motor model, analyzed the motion on contact interface and studied the output characteristics of motor structure. Zhu[1], Zhao[2] respectively established the dynamic model of ultrasonic motor, and Zhao[3] qualitatively discussed the stick-slip feature in contact area. Chen[4-6] proposed a three-dimensional contact model of TRUM, elaborating three-dimensional contact mechanism and analyzing the effect of radial slip on the output characteristic of TRUM. The current research on gas film is mainly in various precision instruments and machinery, such as medical apparatus and instruments, space inertial navigation system, magnetic memory devices and precision machine tools, etc[7]. While the studies on gas film in ultrasonic motor is not so much, among which the studies on radial lubricated film in ultrasonic motor are more than in TRUM. The aerodynamic characteristics of gas film are explored through calculating Reynolds equation by numerical method. It is very time-consuming to explore the characteristics of a complex form motion or geometry through programming. CFD simulates the phenomenon in the flow field by computer, predicting the flow field within a short time. FLUENT is one of the most comprehensive and the most widely useful CFD software[8]. Therefore, squeeze gas film model utilizing traveling waves is built based on FLUENT, and contact model between stator and rotor of TRUM is

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built under reasonable assumptions. Finally, dynamic characteristics of smooth gas film and gas film considering stator teeth are analyzed in this paper.

1 Theoretical Formulation

1.1 Principle of TRUM and mechanism of interface

The stator and rotor in TRUM are circular platein an axisymmetric structure and the stator is a structure with teeth. Fig. 1 shows the structure of the TRUM. The piezoelectric ceramic ring is driving component, and the rotor is pressed against the stator's teeth, spring piece and other assembled parts. The center of rotor fixed with axle is free to pivot around the axis. The spring piece is a kind of interference fit to ensure certain pre-load.

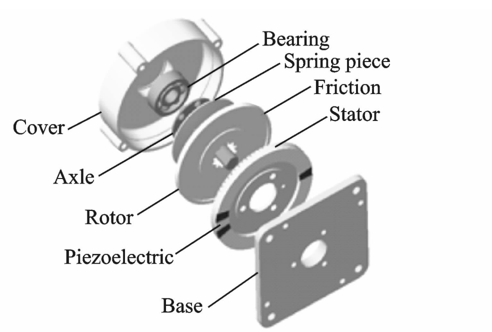

Fig. 1 Structure of TRUM

Structural vibration is named B_{0n}, where n represents the wave number of bending vibration (the number of node lines). The number of node lines is 9 in this paper. Two standing waves with the phase difference of $\pi/2$ both in time and in space and the same frequency and shape are excited on the stator, forming traveling wave by superposition[9-10]. The equation of the traveling wave is

$$\omega(\theta,t)=W_0\sin(n\theta-\omega_n t) \tag{1}$$

where W_0 is vibration amplitude of the stator and ω_n is circular frequency. In order to reduce the number of grid and the computing memory, the length of a whole wave and the length of a tooth are respectively utilized in the smooth gas film model and the gas film model considering stator teeth, because the length is around four or five orders of magnitude of the thickness of the film. The analysis of locality can reflect the overall situation, because the structure of the motor is symmetrical. There is a layer of relatively flexible friction material between the stator and the rotor of the ultrasonic motor and the hardness of the stator and the rotor is large. Therefore, it is regarded that when the ultrasonic motor works, deformation is only generated on the friction layer while there is no contact deformation on the stator and the rotor. This deformation is in agreement with the contour of the stator surface. Fig. 2 shows the interface between stator and rotor in TRUM.

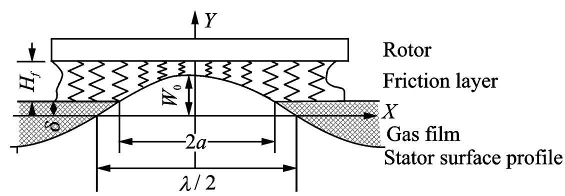

Fig. 2 Two-dimensional graph of interface between stator and rotor

Under different pressures, the deformation of the friction layer, the gap and the size of the contact area are different. The size of contact area is half of a wave when calculating. Fig. 3 shows the shape of the gas film changing with the wave traveling on the stator in a length of a wave, in which T is the vibration period.

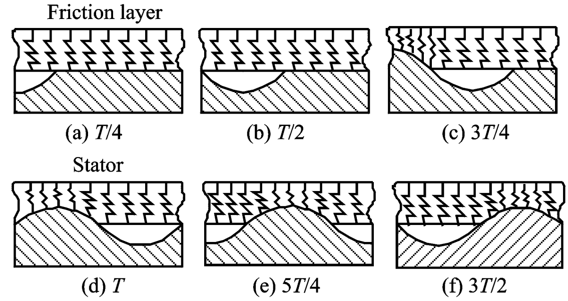

Fig. 3 Shape change of the gas film

In this model, gas dynamic viscosity is constant. The pressure gradient in the thickness direction is much smaller than in the plane direction, because the magnitude difference between the length and the thickness of the film is very large. So we can obtain that $\partial p/\partial z=0$. Reynolds number is very small because the longitudinal velocity of the particles is small and the magnitude of the thickness is the order of microns. So the gas flow is laminar. There is no external force on the film.

1.2 Reynolds equation

Reynolds equation is often utilized to solve problems about gas film lubrication. Fig. 4 shows the simplified lubrication model. Plate A is stationary while plate B is vibrating in form of traveling wave. They are separated by air.

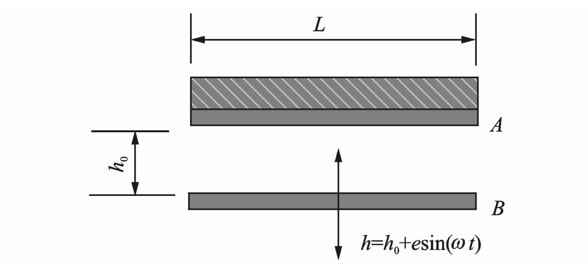

Fig. 4 Squeeze gas film between two plates

The Reynolds equation controlling pressure generation in the air gap is

$$\frac{\partial}{\partial x}\left(\frac{h^3\rho}{12\mu}\frac{\partial\rho}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{h^3\rho}{12\mu}\frac{\partial\rho}{\partial y}\right)=\frac{\partial(\rho h)}{\partial t} \tag{2}$$

Assuming sinusoidal vibration for plate B, that is

$$h=h_0+e\sin(\omega t) \tag{3}$$

where h_0 is the average film thickness and e is the amplitude. In non-dimensional form, that is

$$H=1+\varepsilon\sin(\tau) \tag{4}$$

Reynolds equation can be normalized into non-dimensional form

$$\frac{\partial}{\partial X}\left(H^3P\frac{\partial P}{\partial X}\right)+\frac{\partial}{\partial Y}\left(H^3P\frac{\partial P}{\partial Y}\right)=\sigma\frac{\partial(PH)}{\partial \iota} \tag{5}$$

And non-dimensional parameters are defined as follows

$$(x,y)=L(X,Y),p=p_0P,h=h_0H,\tau=\omega t \tag{6}$$

where p_0 is atmospheric pressure and ω is angular frequency. Eqs. (4), (5) indicate that the pressure in the squeeze film is determined by two parameters, that is σ and ε. Quantity σ is the squeeze number and ε is the non-dimensional amplitude, $0\leqslant\varepsilon\leqslant1$. They are normalized as

$$\sigma=\frac{12\mu\omega L^2}{p_0h_0^2},\quad \varepsilon=\frac{e}{h_0} \tag{7}$$

2 Squeeze Gas Film Utilizing Traveling Wave

2.1 Geometric model

The change of the gas film shape over time has been discussed. The shape of gas film is the same on any region of a wavelength when ultrasonic motor works. Fig. 5 is a geometric graph showing a whole traveling wave. The angle of both sides is very small. Negative volume occurs at dividing the grid, so Fig. 5 shows that the partial region of both sides is cut off.

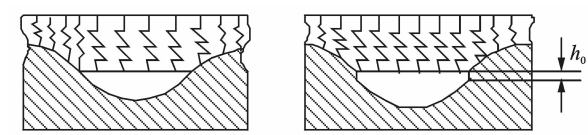

Fig. 5 Approximate model

2.2 Boundary condition setting

The model is meshed by ICEM. For the thickness is much smaller than width of the model, hexahedron mesh grids are generated to ensure quality of grid. There are 8—9 nodes on thickness direction, 660 nodes on length direction and 100 nodes on width direction. The compressible gas film is simulated using pressure-based laminar transient model. The upper and bottom walls of the film are the surface of the friction layer beneath the rotor and the stator surface, respectively. The upper wall is set to stationary wall. The particles on the bottom wall vibrate in a sinusoidal exciting motion to form a traveling wave. This vibration is achieved by dynamic mesh method. The deformation of boundary is programmed by UDF and achieved through linking UDF to FLUENT. The fore-and-aft face of gas film model contacts with the atmosphere, so symmetry condition is used. Cutting off partial region of both side results in the emergence of the left and right boundary faces which represent the contact area between stator and rotor. So they are set to wall boundary.

2.3 Smooth gas film and gas film considering stator teeth

The boundary conditions of gas film model considering stator teeth is similar to that of smooth gas model (Fig. 6). Film thickness on tooth area is very thin and the magnitude of thickness of tooth gap is equivalent to that of tooth width.

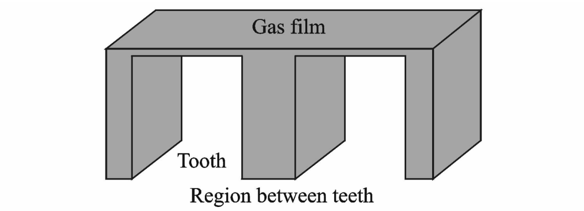

Fig. 6 Amplified gas film model considering stator teeth

3 Results

The pressure in gas film is calculated by solving Reynolds equation. The pressure in the squeeze film is determined by two parameters, that is the squeeze number and the non-dimensional amplitude. When $h_0 = 0.1$ μm and $\omega = 2\pi f = 80k\pi$, $\sigma = 2.13 \times 10^7 \gg 0$ can be obtained. Fig. 7 shows the curves of the variation of gas pressure versus time when $\varepsilon = 0.5$ or 0.8. In this figure, τ is non-dimensional time and P is non-dimensional pressure.

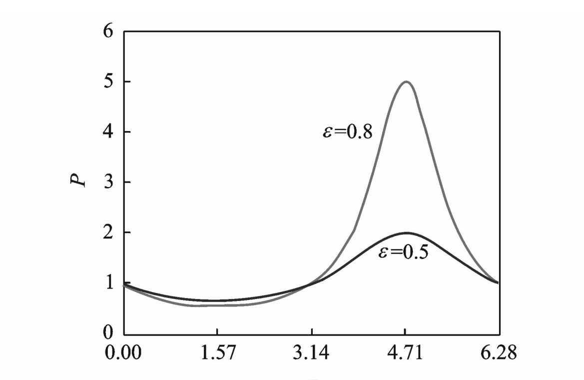

Fig. 7 Unsymmetrical pressure in a squeeze gas film for $\varepsilon = 0.5$ and $\varepsilon = 0.8$

The same observation was made in Refs. [11-12]. The motion between stator and rotor is not a sinusoidal exciting motion for the whole plate but a traveling wave deformation for the particles on the plate. Using the same parameters in the form of deformation, we can get the pressure contour and the curve of the variation of pressure versus time in Fig. 8.

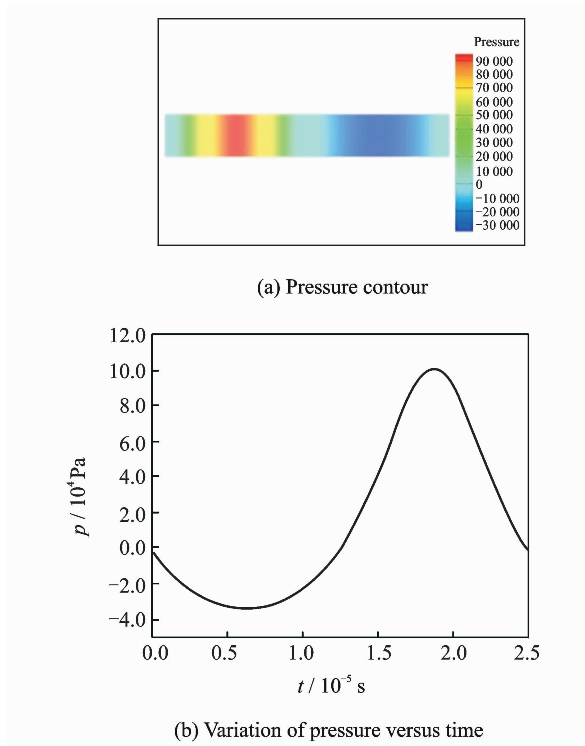

Fig. 8 Pressure contour and the variation of pressure versus time

The variation of pressure versus time is the same with Fig. 7. The difference is that all the particles on the wall is the same under sinusoidal exciting motion for the whole plate while the pressure of different particle is different under the squeeze motion utilizing traveling wave. Fig. 9 shows the relation between the pressure and the location of the middle line on the stator.

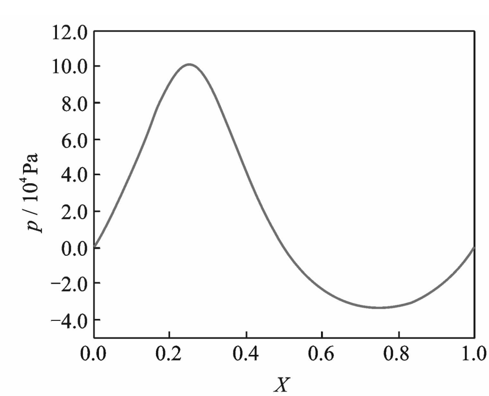

Fig. 9 Relation between pressure and location of the middle line on stator

When $\sigma\rightarrow\infty$, Reynolds equation (5) suggests that the term PH on the right-hand side tends to const. Using const=1 leads to

$$P=\frac{1}{1+\varepsilon\sin\tau} \tag{8}$$

In addition, Reynolds equation is based on the ideal gas law. Negative density is not permissible as $\rho=p/RT$. Therefore, $P>0$. but there is no upper limit. The pressure depends on two parameters, which is squeeze number σ and the non-dimensional amplitude ε. It means that high pressure is possible in theory.

The deformation of friction layer and the width of contact interface are different under different pre-load when the ultrasonic motor works. Half of a wave of the contact interface is simulated. It was mentioned that there is an approximation for the gas film model. In order to analyze the influence for the results under this approximation, the size of the approximate region needs to change. That means changing σ and ε at the same time. As Fig. 10 revealed, with the approximate region becoming smaller, the central region is becoming larger and tends to horizontal while the place on both sides is becoming smaller. Fig. 11 shows the variation of pressure peak versus ε.

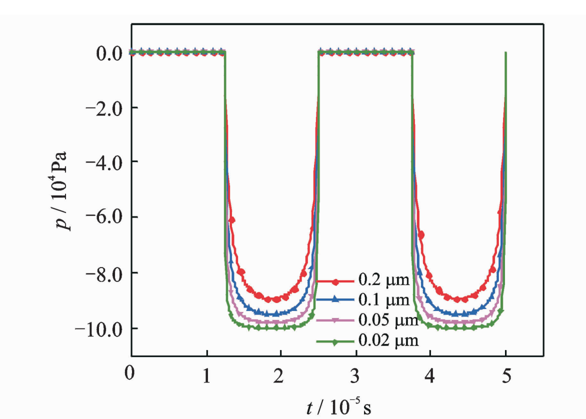

Fig. 10 Variation of the pressure versus time under different size of approximate region

As the width of the approximate region becoming smaller, the non-dimensional amplitude approaches infinity and squeeze number is much larger than 0. And the pressure peak tends to an atmosphere pressure.

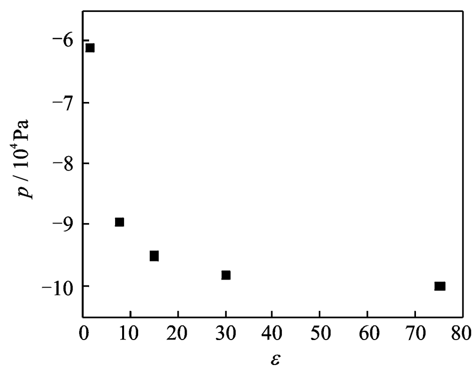

Fig. 11 Relation between ε and pressure

The gas film considering stator teeth is calculated by the same method. The magnitude of the thickness of tooth gap is close to the width of tooth. The pressure in this region is very small because the amplitude of traveling wave is much smaller than the thickness of the gas film. The variation of the pressure in the tooth region is the same as the result of smooth model. Fig. 12 compares the pressure of tooth gap and gas film on the tooth region. It suggests that the influence of tooth gap is very weak for the whole model.

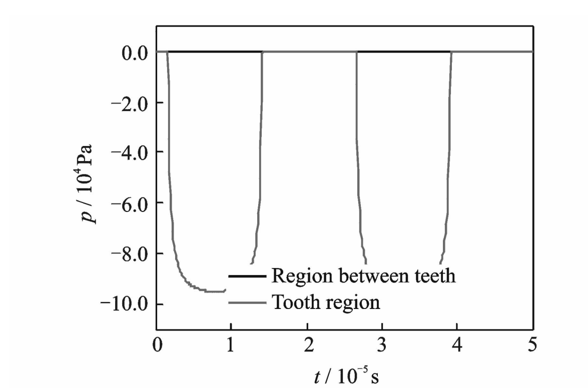

Fig. 12 Comparison between pressure of tooth gap and gas film on tooth region

4 Conclusions

In this paper, a gas film model under traveling wave squeeze on TRUM is built and analyzed. It is concluded that squeeze number and non-dimensional amplitude are the main factors that affect the pressure distribution. The squeeze model is simulated at the finite non-dimensional amplitude, and the result has a good agreement with the existing literature, which proves the method in this paper to some degree. Owing to the restriction on the grid, the model needs to be approximated. The pressure peak is close to an atmosphere with the width of the approximate region becoming smaller. The width of contact interface is half of a wave, and the relative pressure is negative under the expansion and contraction motion. In addition, the gas film considering stator tooth is simulated. Results show that the pressure of the gas film on tooth is the same as that of smooth gas film model, and the pressure on tooth gap affects weakly on the whole model. These results provide the basis for the subsequent development of ultrasonic motor and the exploration of the external environment.

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