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Optimal design of the stator of a three-DOF ultrasonic motor

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Abstract

This paper introduces an optimization design method for a three-degree of freedom (three-DOF) ultrasonic motor stator using constrained variable metric algorithm (CVMA). It is a circular cylindrical stator with a spherical rotor attached at its end. A mathematical model of the stator is established with combining the finite element method (FEM) and the optimal analysis method. Based on the model, the authors code an optimal program, which is implemented with MATLAB. The object is to optimize the characteristic length L_1, and L_2 of the stator in order to satisfy its vibration and contained conditions. According the optimization results, the stator is manufactured and tested. The experiments show that the stator's mode frequencies and shapes agree well with those predicted by the program. The program is easy to operate, and that is time saving.

Keywords: Three-DOF ultrasonic motor; Piezoelectric ceramic; Stator; Optimum design

1. Introduction

Multi-DOF ultrasonic motor is a new type of the ultrasonic motor (USM). In recent years, many researchers have developed some three-degree of freedom (three-DOF) USM with single stator [1–3]. The USM provides three-DOF rotation around x, y and z-axes, which is implemented by two second-order bending modes with orthogonality and one first-order longitudinal mode of the stator. In designing the USM, a key and difficult problem is its stator's design because the stator's three modes must satisfy some conditions. In our previous research, in order to satisfy these conditions, a parameter fitting design method is used. However, it is an experiential design method with low efficiency and time consuming, sometimes it even cannot get a satisfactory solution. This paper puts forward an optimization design method for the stator. First, some design variables, such as characteristic lengths L_1 and L_2 of the stator, are defined by the dynamic sensitivity analysis. Second, a mathematical model for the stator is established with the combining finite element method (FEM) and the optimal analysis methods. Based on the model and the conditions, an objective function is established selecting L_1 and L_2 as the optimal parameters. Finally, the constrained variable metric algorithm (CVMA) is adopted for searching optimum parameters, and an optimal design program of the stator is developed by authors in MATLAB. Authors designed and implemented a new prototype of the three-DOF USM. Its stator is determined with the optimal design program, and the stator have been manufactured and tested with PSV-300F-B type Laser Doppler Vibrometer developed by Polytec Company. The experiments show that the stator's mode frequencies and shapes from the program are very close to the measured ones.

2. Construction and principles

The construction of the circular cylinder-sphere three-DOF USM designed by authors is shown in Fig. 1. It consists of a spherical rotor and a circular cylindrical stator with three groups A–C, and the every group consists of PZT ceramic elements and electrodes. Diameter, length, and mass of the stator are 20 mm, 57 mm, and 157 g, respectively. Basic driving principles of the three-DOF USM are described as

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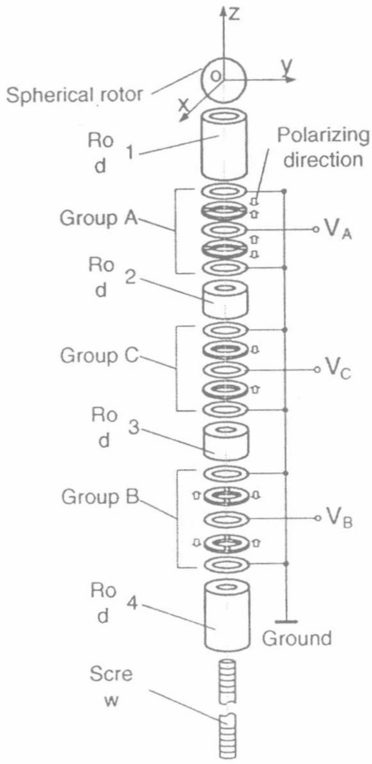

Fig. 1. Construction of the three-DOF ultrasonic motor.

follows. The rotor is rotated around z-axis by the rotor/stator frictional force when two-orthogonal second bending modes are excited applying two alternating voltages V_A and V_B with same frequency and a phase angle 90°, in time to the groups A and B, which have a phase difference 90° in space. The rotor is rotated around x (or y)-axis when the longitudinal mode and the bending mode are excited applying two alternating voltages V_C and V_A (or V_B) with same frequency and a phase angle 90°. Furthermore, the rotation around arbitrary axis is generated when the modes are appropriately combined.

3. Mathematical model of the stator

Two second-order bending modes with orthogonality and one first-order longitudinal mode of the stator are selected as the operating modes of the stator. In order to increase operating stability and efficiency of the motor, the three modes must satisfy following conditions: (1) The differences between the three mode frequencies are as small as possible; (2) The nodal plane of the first-order longitudinal mode shape (L_1 mode, see Fig. 2) coincides with the middle nodal plane of the second-order bending mode shape (B_2 mode, see Fig. 2); (3) The groups A and B for exciting two second-order bending modes with orthogonality are located on the wave peak and the valley of the bending modes [3]. On the other hand, the modes of the stator depend on its construction types, geometry parameters and the materials used for it. Our previous

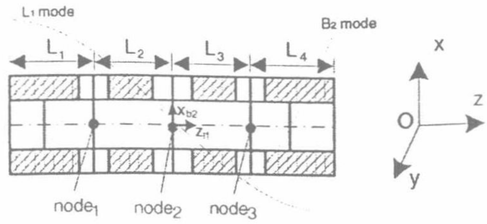

Fig. 2. Stator's section drawing for FEM.

researches have obtained following conclusion from dynamic sensitivity analysis for the stator: the modes depend mostly on the lengths L_1, L_2, L_3 and L_4 of the circular cylinder [3] when the materials and the outer diameter of the stator are defined, as the inside diameter of the circular cylinders have a little effect on the modes. Consequently, the lengths L_1 and L_2 shown in Fig. 2 are selected as optimization parameters of designing the stator, because the stator is symmetric with respect to its middle in z-direction, namely $L_1 = L_4$ and $L_2 = L_3$. A FEM model of the circular cylinder stator with symmetry with respect to z-axis is built-up by plan beam elements with shear deformation [4]. The net node point node$_1$, node$_2$ and node$_3$ must be located on the center plane of the piezoelectric ceramic groups A–C, respectively, making the net node points for the FEM, as shown in Fig. 2. A sum stiffness matrix **K** and a sum mass matrix **M** of the stator can be formed.

And the characteristic equation is established as follows

$$(\mathbf{K} - \omega^2\mathbf{M})\mathbf{X} = 0 \qquad (1)$$

From the Eq. (1), we can obtain mode frequency ω_i and corresponding mode shape $\mathbf{X}_i$, which is normalized with the maximum amplitude of this mode, and the mode shapes comprise optimization parameters L_1 and L_2. The L_1 mode and the B_2 mode can be identified from all modes obtained above by such characteristics: the L_1 mode shape value in z-direction is much larger than one in the direction x, while the B_2 mode shape value in z-direction is much less than one in the x-direction.

According to the first condition mentioned above, following frequency difference function can be established [3,5–7].

$$F_1'(L_1, L_2) = |f_{l1} - f_{b2}| \qquad (2)$$

where f_{l1} is the L_1 mode frequency f_{b2} is the B_2 mode frequency.

As for an optimal design of the stator, not only the first condition is requested, but also one requires that the nodal plane of the L_1 mode shape coincides with the nodal plane of the B_2 mode shape at node$_2$, which is the second condition. The coincidence can be described by a summation of absolute values of the two vectors $\mathbf{Z}_{l1}(\text{node}_2)$ and $\mathbf{X}_{b2}(\text{node}_2)$, as shown in Fig. 2, and the summation approaches zero. Then, we can make following the minimization function for the mode shape values

$$F_2(L_1, L_2) = |\mathbf{Z}_{l1}(\text{node}_2)| + |\mathbf{X}_{b2}(\text{node}_2)| \qquad (3)$$

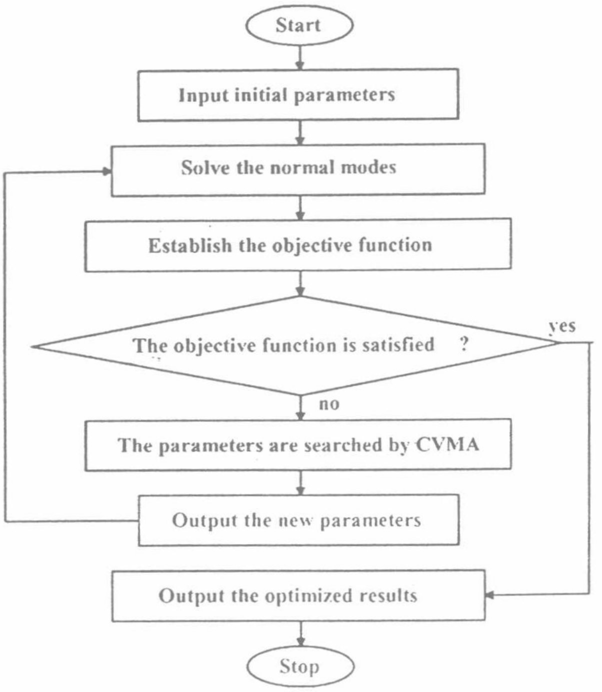

Fig. 3. Flow chart of the optimization program

Table 1
Performance parameters of PZT8

Parameters	Values
Coefficient of elasticity, E (GPa)	64
Poisson's ratio, μ	0.3
Modulus of elasticity in shear, G (GPa)	24.2
Mass density, ρ (kg/m^3)	7550
Piezoelectric coupling coefficient (c/m^2)	$e_{11} = 16$, $e_{12} = 36.8$
Permittivity coefficient (nN/V^2)	15.3

Table 2
Optimization results of the stator

Initial parameters (mm)	$L_1 = 18$, $L_2 = 5$
Constrained conditions (mm)	$18 \le L_1 \le 25$, $5 \le L_2 \le 12$
Optimization results of parameters (mm)	$L_1 = 20$, $L_2 = 8.5$

where $|Z_{11}$ (node$_2$)$|$ is the displacement (non-dimension) is normalized with the modal maximum displacement value. $|X_{b2}$ (node$_2$)$|$ is the displacement (non-dimension) is normalized with the modal maximum displacement value.

The third condition requires that the groups A and B are located on the wave peak and the valley of the B_2 mode. If the wave peak and the valley of the B_2 mode locate just on node$_1$ and node$_3$ then, the first derivative of the B_2 mode

Table 3
Mode frequencies of the stator

	Optimization	Experiment	Tolerance (%)
f_{11} (kHz)	32.07	30.65	4.4
f_{b2} (kHz)	31.10	28.03	9.9
Tolerance (%)	3.02	8.55	

shape function with respect to z at node$_1$ and node$_3$ equal zero. Namely

$$\left(\frac{dX_{b2}}{dz}\right) \text{node}_i \approx 0 \quad (i = 1, 3) \tag{4}$$

It can be expressed with the first derivative of the mode shape function with respect to z at node$_1$ and node$_3$. Then, we have the minimization function:

$$F_3(L_1, L_2) = 2|(dX_{b2}/dz)_{\text{node}_i}| \tag{5}$$

The frequency in formulation (2) is a very large value with frequency dimension. In order to reduce computational error, authors introduce a non-dimensional frequency and a weighing coefficient for F'as follows

$$F_1 = \frac{F_1'}{100000\,Hz} \tag{6}$$

Because F_1, F_2, and F_3 are dimensionless quantities, and possess same level of numerical value, then, they can be synthesized into an objective function

$$F(L_1, L_2) = F_1 + F_2 + F_3 \tag{7}$$

Therefore, the mathematical model for optimal design of the stator is a minimization problem with the constrained conditions, Namely

$$\text{MIN} \quad F(L_1, L_2) = F_1 + F_2 + F_3 \tag{8}$$

$$\text{S.T.} \quad L_{i\,\min} \le L_i \le L_{i\,\max} \quad (i = 1, 2)$$

where $L_{1\min} = 0.018$ m, $L_{1\max} = 0.025$ m and $L_{2\min} = 0.005$ m, $L_{2\max} = 0.012$ m.

We take 0.02 as terminative tolerance for computing F.

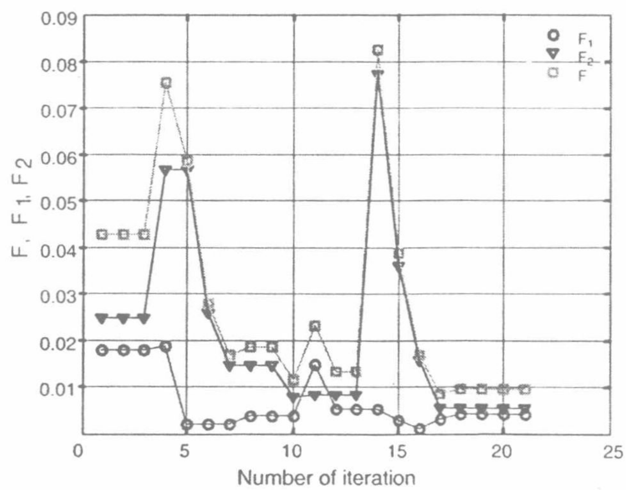

Fig. 4. Iteration processes of F, F_1 and F_2.

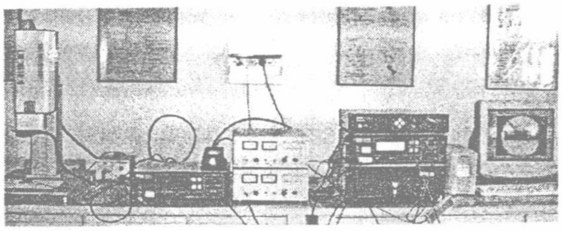

Fig. 5. Modal test device with Laser Doppler Measurement System (PSV-300FB).

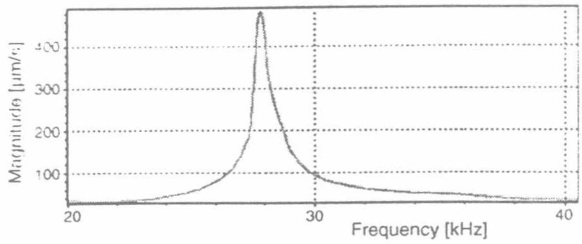

Fig. 7. Response curve to excitation with the groups A and B.

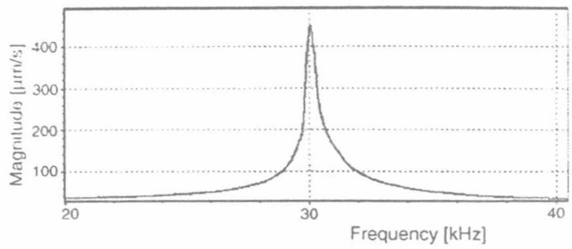

Fig. 8. Response curve to excitation with the group C.

4. Algorithm and results

A constrained variable metric algorithm is used to resolve the Eq. (8). This algorithm possesses fast convergence, well reliability and wide utility [8,9]. A computing program is developed by the authors in MATLAB, and its flow chart is shown in Fig. 3. The outer diameter and inside diameter of the stator is 20 mm and 10 mm, respectively. The material of the stator is stainless steel. The piezoelectric ceramic is PZT8 whose performance parameters are listed in Table 1.

The optimization results of the characteristic lengths L_1 and L_2 of the stator are listed in Table 2. The mode frequencies and mode shapes are shown in Table 3 and Figs. 9–10, respectively. The iteration processes of the objective function F and the function F_1 and F_2 are show in Fig. 4. It is seen that value of the objective function is very approach to the taken objective value (< 0.02). Authors tried different initial values for (L_1, L_2), the solutions always converge to that of Table 2 so long as (L_1, L_2) satisfy $0.018\,\text{m} \leq L_1 \leq 0.025\,\text{m}$ and $0.005\,\text{m} \leq L_2 \leq 0.012\,\text{m}$.

5. Modal test of the stator

The stator of a new prototype of the three-DOF ultrasonic motor is designed and fabricated using optimized parameters. The operating modes of the stator are measured with Laser Doppler Measurement System (PSV-300F), as shown in Fig. 5. Its block diagram is shown in Fig. 6. First, the frequency responses of the stator are obtained by frequency scanning from 20 kHz to 40 kHz. The mode frequencies that are listed in Table 3 are taken from the frequency response curves shown in Fig. 7 and Fig. 8. The B_2 mode is excited with group A or B at frequency 28.03 kHz, and the normal mode shape displays automatically on computer screen, as shown in Fig. 9. The L_1 mode is excited with the group C at frequency 30.65 kHz, and the normal mode shape displays automatically on computer screen, as shown in Fig. 10.

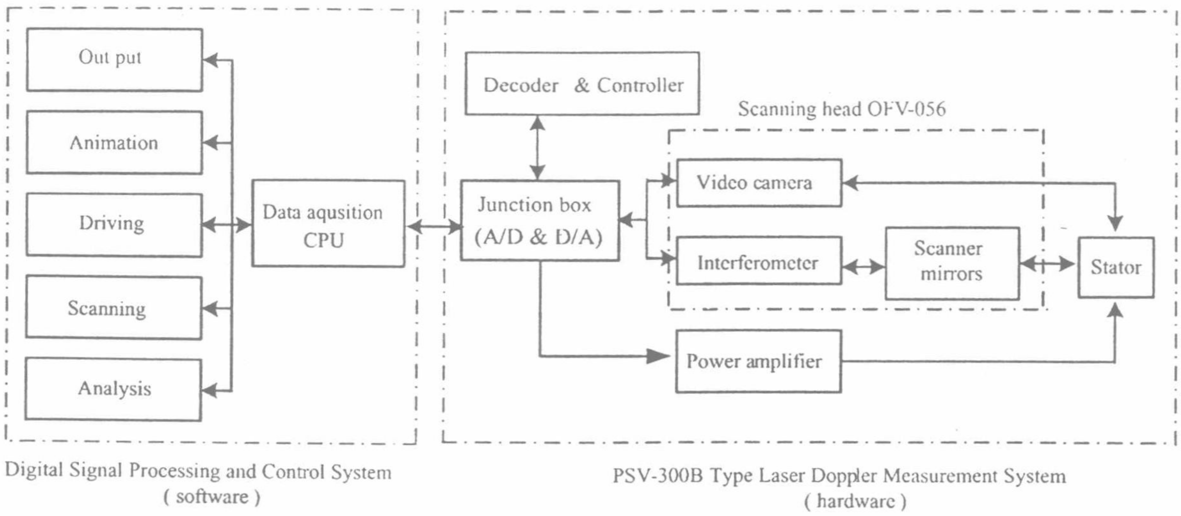

Fig. 6. Block diagram of the modal test device with Laser Doppler Vibrometer (PSV-300F).

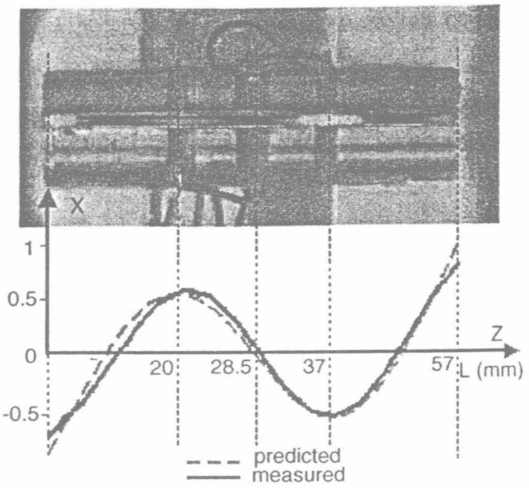

Fig. 9. The second-order bending mode shapes of the stator.

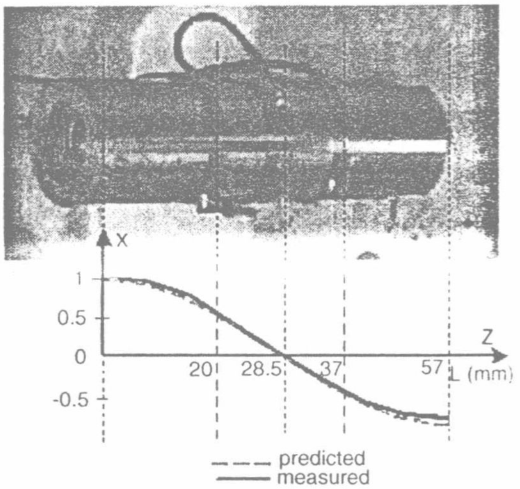

Fig. 10. The first-order longitudinal mode shapes of the stator.

6. Conclusion

In this paper, a new design method is developed for determining the stator's construction parameters of the three-DOF ultrasonic motor. It can be seen from Table 3 that the consistency of the mode frequencies is satisfied basically. Fig. 9 shows that the groups A and B are really located at the wave peak and the valley of the B_2 mode shape, respectively. Fig. 9 and Fig. 10 indicates that the group C is indeed located at the nodal plane of the L_1 mode shape and the middle nodal plane of the B_2 mode shape.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.sna.2005.03.010.

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Biographies

Chunsheng Zhao is a professor at Nanjing University of Aeronautics and Astronautics (NUAA) in China. He received the Doctor of Engineering from the "Ecole Nationale Superieure d'Art et Métiers-Paris", France, in 1984. He was a visiting professor at the Massachusetts Institute of Technology (MIT) from December 1992 to September 1994, where he has begun to research on ultrasonic motor techniques. He founded the first Research Center of Ultrasonic Motors (RCUM). In China in 1997, and since he has been the director of the RCUM. At the same time, He also is the Vice-president of the University Association of Mechanical Engineering Measurement Technologies and the chief editor of the Journal of Vibration, Measurement & Diagnosis. He has written a book "Identification of Mechanical Vibration Parameters and its Applications" in 1989. Now his research interests are in the USM techniques and their applications. He has published more than 100 papers and obtained 15 Chinese patents about USM.

Zhirong Li is a graduate student for PhD at Nanjing University of Aeronautics and Astronautics in China. He studies on the ultrasonic motor with multi-degree of freedom, worked at mechanical vibration, measure and test techniques in mechanical engineering, vibration monitoring and fault diagnosis techniques, machine design and manufacturing, etc.

Weiqing Huang is an associate professor at Nanjing University of Aeronautics and Astronauticsin China. He received the Bachelor degree and the Master degree of Engineering from the NUAA in 1987 and 1990, respectively. He received the PhD from Hong Kong University of Science and Technology in 1999. At present, he is the Vice-director of RCUM. He also is an editor for the Journal of Vibration, Measurement and Diagnosis. He has published more than 20 papers. Now his research interest is in USM techniques.

Research on Ultrasonic Motors in NUAA

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1. Introduction

Research on ultrasonic motors began in 1995 at Nanjing University of Aeronautics and Astronautics (NUAA). A Research Center of Ultrasonic Motors (RCUM) of NUAA was founded by the author in 1997. It is the first and only one special institution to research the ultrasonic motors in China. The goal of RCUM is to develop actively the ultrasonic motor techniques, explore new types of ultrasonic motor and bring up researchers for ultrasonic motor techniques. The RCUM has developed 16 new types of ultrasonic motors and their corresponding drivers. Especially, it has formed two series of traveling wave ultrasonic motors: disk-type and bar-type. It has been awarded with 22 invention patents in China and published more than 170 papers.

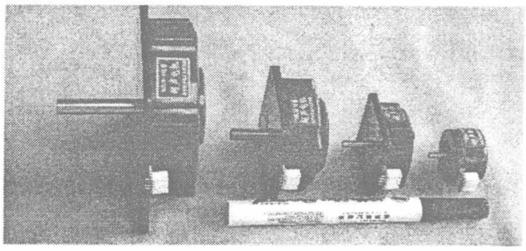
The First Workshop on Ultrasonic Motor techniques (CWUMT) in China was held in NUAA in 1999. The author presided over the meeting sponsored by the National Nature Science Foundation of China (NSFC). About30 organizations and 70 scientists and engineers attended the meeting, as shown in Fig.1, and more than 30 papers were presented at the meeting. This meeting has sparkled and promoted interests in research on the ultrasonic motor techniques in China [1].

Fig. 1 Participants of 1st CWUMT on May, 1999

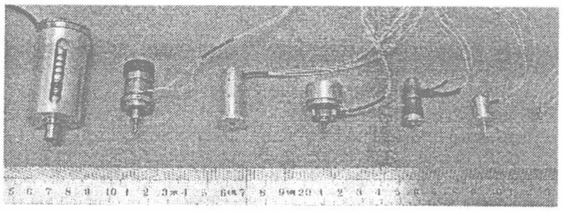
This paper presents in detail some key techniques during the researches on USM, including theoretic progress, experimental technologies, exploration of various new-type motors and their applications in practical engineering. Finally, the author introduces some projects on USMs in NUAA and main problems that challenge us today.

2. Solution of some key techniques

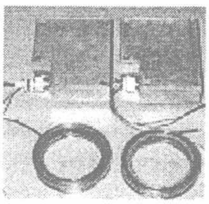
More than 16 kinds of new type ultrasonic motors and

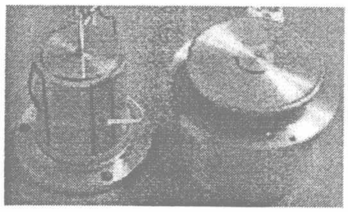


(a) A disk-type TRUM series of rotary traveling wave USM (Φ100~30 mm)

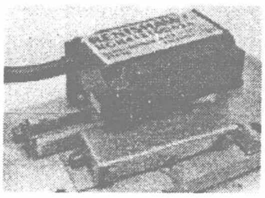


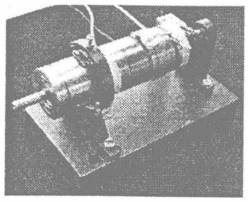
(b) A bar-type BTRUM series of rotary traveling wave USM (Φ20~2 mm)





(c) A ring type of USM (d) Non-contact types USM





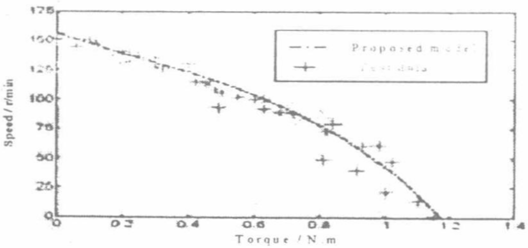
(e) Micro-type Linear USM (f) L-T hybrid type USM

Fig. 2 A part of new types of USM developed by RCUM their corresponding drivers have been developed by RCUM. Fig. 2 shows a part of them.

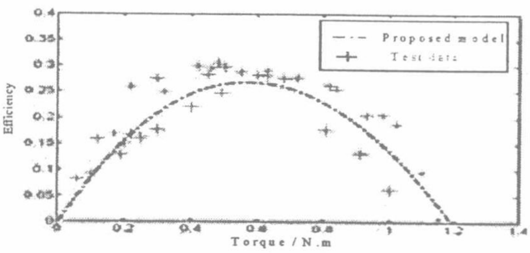
During exploring these motors, we have solved many key technical problems, the paper will briefly summarize some of them due to the page limitations.

2.1. A more complete and precise dynamic model for traveling wave type rotary ultrasonic motor

Based on the modeling of N.W. Hagood[2], considering the dynamic effect of gears and channels of stator, the contact condition with three dimensions between stator/rotor and the flexibility of rotor, first, we established independent stator, rotor and contact interface models respectively. Second, integrating them, one obtained a more complete and precise dynamic model for traveling wave type rotary ultrasonic motor. This model can predict precisely mechanical characteristics under different condition of pre-pressures, amplitudes and frictional material [3], as shown in Fig.3 and 4. Based on the model, we propose design methods to optimize the parameters of the USM [4-7], and program the optimal design software.



(a) Speed vs. torque

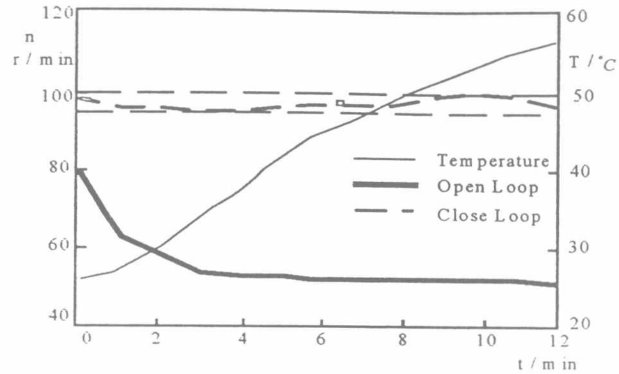


(b) Speed vs. torque

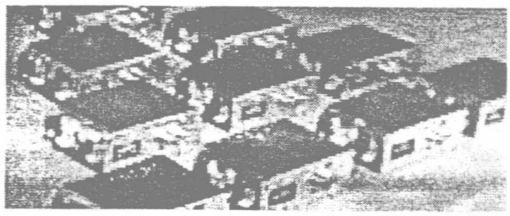
Fig.3 Mechanical characteristics of one of TRUM series USM developed by RCUM

2.2. Putting forward an effective frequency automatically tracking control techniques

When an USM is operating, the temperature of the USM increases with time due to energy losses of piezoelectric ceramic (PZT) element, loss of adhesive layer between stator and PZT element, frictional loss of between stator and rotor, damping loss of stator vibration, the rotary speed of the USM sharply drop with the raise of the temperature. To solve this problem, we put forward an effective frequency automatically tracking control techniques (FATCT)[8], which can limit the instability of the motor's rotate speed to 5%, as shown in Fig. 4 (a), and developed the corresponding drivers with two phases and FATCT, as shown in Fig.4 (b).



(a) Experimental curves of speed vs. time



(b) Drivers with two phases and FATCT

Fig.4 Freq. automatically tracking control techniques

2.3 Putting forward a new electrode arrangement for on PZT element, and developing corresponding drivers with 4 phases.

As one knows that a current (old) electrode arrangement on PZT element with ring-type is shown in the right coroner of Fig.5, which needs a driver with two phases (A and B). Because it is a asymmetrical type excitation. Applying A or B Phase voltage to the element, one obtains the frequency response curve as in Fig.5. It is difficult to excite requested a "pure" mode (standing wave) and a "pure" traveling wave (rotary mode) of the stator at some resonance frequency. Usually, a mixture of standing and traveling waves is formed. In order to obtain these "pure"ones , we put forward a new electrode arrangement on PZT element with ring-type, which is shown in the right corner of Fig.6, and needs a driver with four phases (A, B, C and B). Because it is a symmetrical type excitation. Applying A and C Phases

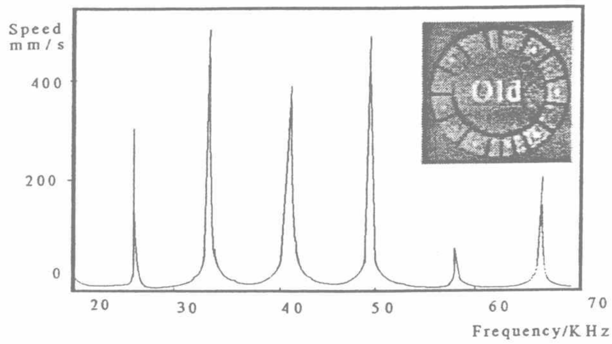


Fig.5 An old electrode arrangement for PZT element and frequency response curve

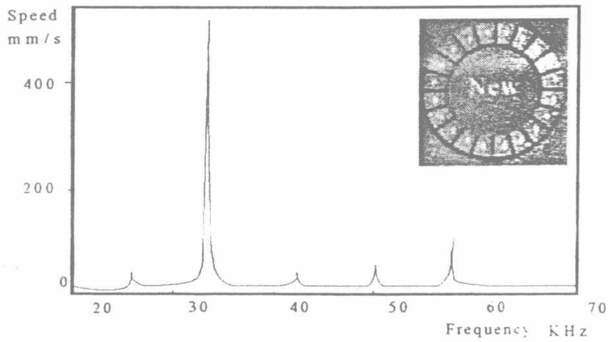


Fig.6 A new electrode arrangement. for PZT element and frequency response curve

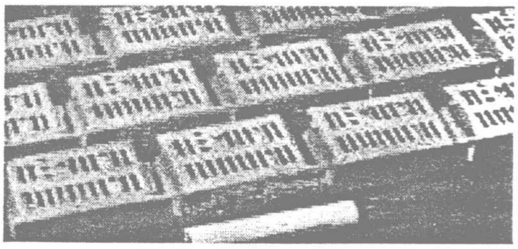


Fig.7 Drivers with 4 phases and with FATCT

voltages to the element, one obtains the frequency response curve, as shown in Fig.6. It is easy to excite requested "pure" mode of the stator at some resonance frequency. Then, the "pure" travel wave can be formed. That is effective to improve stability of rotary speed and raise efficiency of the motor. Else, it also simplifies poling process. In order to match this new electrode arrangement, we also developed the corresponding drivers with 4 phases and FACT [9], as shown in Fig.7.

2.4 Putting a method for adjusting the two modal frequencies of traveling wave motor into the same one and removing non-working mode of stator

As one known that the stator's two working modes with orthogonality possess same frequency in theory, but we discovered in modal test of the stator that due to non-uniformity of material and error of stator's manufacture, their frequencies are usually different, as shown in Fig.8, which makes the stator's traveling wave instable, and the motor's rotary speed instable and lower efficiency. In order to improve the case, combining the

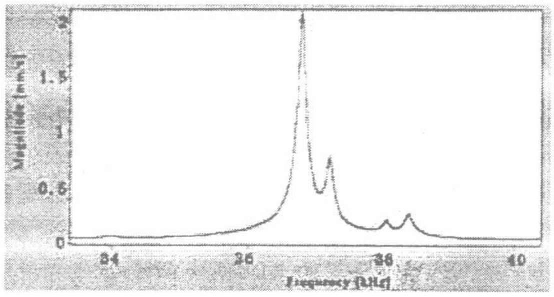
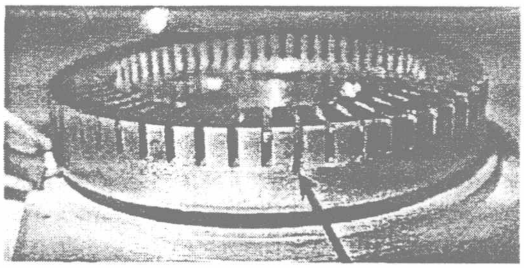
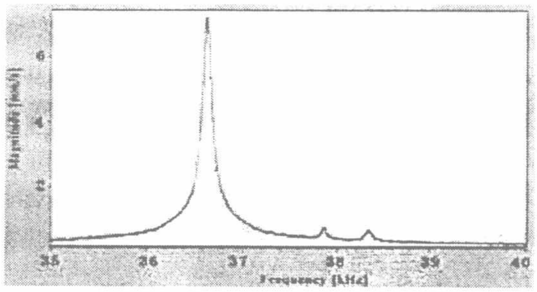


Fig.8 Experimental frequency response of an USM's stator before modifying



(a) Deepening the channel 0.4mm on location Pointed out by the arrow



(b) Experimental frequency response curve of the USM's stator after modifying

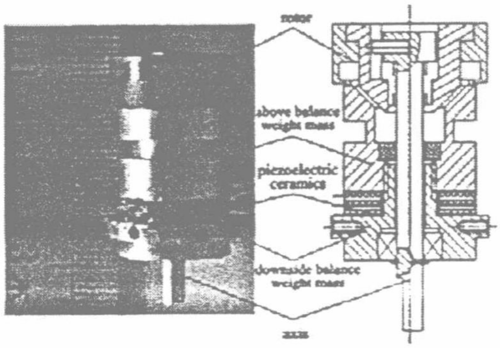
Fig.9 Adjusting the two modal frequencies into the same one

structural sensitivity analysis and dynamic modifying techniques, we put forward a method, which can adjust the two modal frequency into the same one [10], as long as cutting a little mass from the channel located on the trough of the requested mode with lower frequency, as shown in Fig.9 (a). Then, we get a new frequency response curve with a largest crest, as shown in Fig.9 (b), which describes that the two modal frequencies have been adjusted into the same one. Similarly, we can also remove the interference modes that appear near working frequency of stator [11-12].

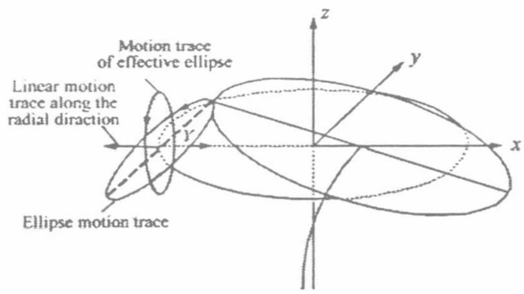
2.5 Deducing the elliptical motion trace equation and the contact angle, and putting forward the concepts about the optimal contact angle and the effective elliptical motion

Based on vibration and wave theory, we deeply investigated the motion mechanism of the bar-type traveling wave ultrasonic motor, and deduced the displacement equation of a particle P on its stator's end surface [13]

$$W_{pz} = -r\beta_0 \sin(\omega_1 t + \theta)$$



(a)



(b)

Fig. 10 Construction of bar-type USM (a) and elliptical motion trace view of point P on stator's surface

From this equation we can see that there is a traveling wave on the end surface of the bar in direction Z. Based on the equation, we deduced that the traveling wave exist in the radius direction and in the circumferential direction. Their wave number is one, and wavelength is $2\pi r$, where r is the radius of the end of the bar. And we deduced yet and the elliptical motion trace equation of a particle P on the stator's end surface [13] and contact angle γ between the stator and rotor

$$\frac{x_p^2}{w_0^2} + \frac{y_p^2}{(\gamma\gamma_0)^2 + w_0^2} = 1 \qquad tg\gamma = \frac{r\beta_0}{w_0}$$

Based on the trace equation and γ, we put forward the concepts about the optimal contact angle[14] and the effective elliptical motion trace [15] as shown in Fig.10 (b), which offered theory basis for designing the bar-type ultrasonic motor with high efficiency. From this theory, we developed a BRTUM series of bar-type traveling wave ultrasonic motor. The construction of BRTUM-15 type USM is shown in Fig.10 (a).

2.6 Developing frictional materials, Increasing life of USM

To increase life of USM is very important task for our researchers for USM. Key of increasing life of USM is to improve the wearability of frictional material. We have cooperated with Harbin Institute of Technology [16] testing and manufacturing many frictional materials, as shown in Fig.11 and table 1. These frictional materials are glued to rotor with adhesive. In order to check the life of the USM, we explored a life test system, as shown

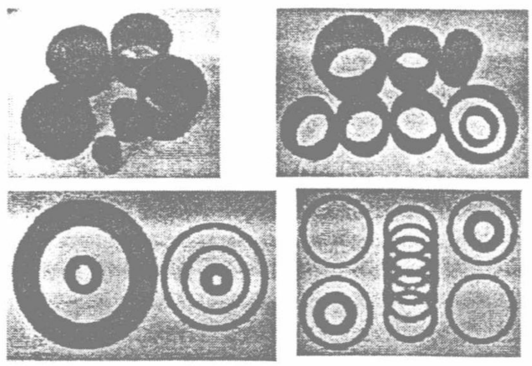


Fig.11 Samples of friction materials
(below: nano friction materials)

Table 1. Performances of the friction materials

Basic material	Friction coefficient	Hardness (HRM)	Comp.elastic Modules (MPa)
Phenoweld	0.4~0.5	90～95	3800～4000
Fluon	0.2~0.3	85～90	1500～2000

in Fig.12 .The test carried out under the two conditions: load torque no and half load toque (equal to half of rated torque) The test results show that the life of TRUM series USM is more than 1500 hours under half load torque. At present, we are testing a new nano-friction material which will be glued to stator. It will be possible to make USM's life to extend to more than 3000 hours.

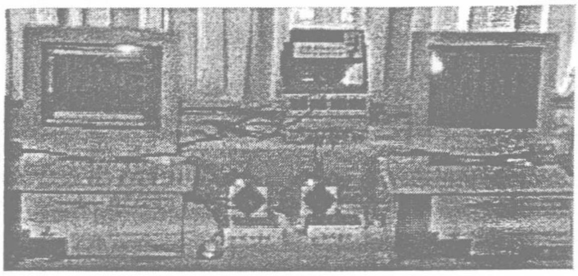
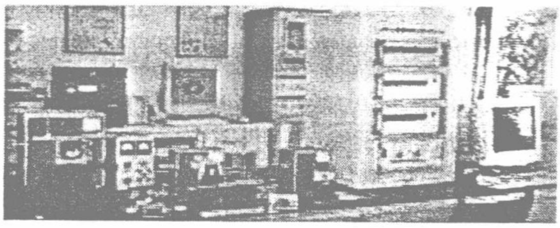


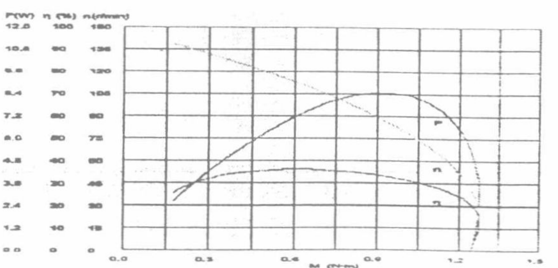
Fig 12 Life testing system of USM with half load torque

2.7 Putting some test methods and developing correspond test devices for USM

It is well know that the test researches on ultrasonic motors are very important. Consequently, we put forward some test methods and established a series of test devices [17-18] during the devolvement of the ultrasonic motors, besides a PSV-300F-B type laser Doppler vibration measurement system imported from Polytec Company, (cooperation in home), as shown in Fig.13, a transient characteristics test system, from which an experimental results shows in Fig.14 (you can see that starting -up other all devices were explored by RCUM, including a mechanical characteristics measurement system response is 29.01 ms and stopping response time is 0.93 ms) and an automatically measuring and modifying pre-pressure system. These devices not only were used to RCUM,



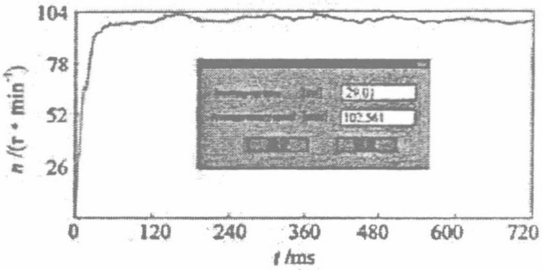
(a) Mechanical characteristic measurement system



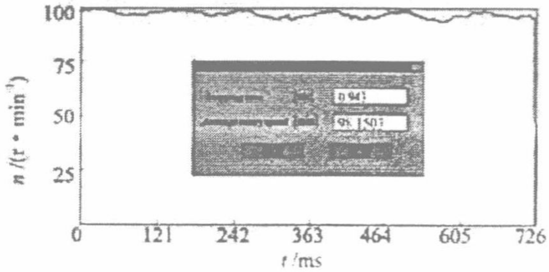
(b) Load characteristics of TRUM-60 using the system

Fig.13 Load characteristic measurement system and measuring results

also can be used to all researchers in China.



(a) Starting-up

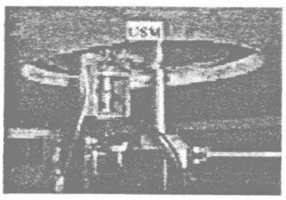


(b) Stopping

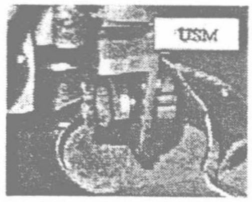
Fig.14 An USM's starting-up and stopping response characteristics tested by transient characteristics test system

2.8 Application researches on USMs in engineering's

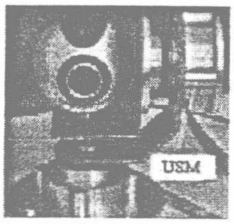
Our object of the research on USM is for applying them in engineering's. Here, we met some difficulties: one doesn't know USM, and how do use USM? Then, we must carry out application researches. Usually, we investigated an engineering system combined engineering device and our USM, as shown Fig.15.



(a) TRUM-30 type used in flutter test of a wing



(b) TRUM-60 type used in Cutting machine



(c) TRUM-45A type used in monitor

(d) TRUM-45 type used in small generator

Fig.15 Some examples of applying researches

3. Primary Projects in ultrasonic motor field at present and some problems in NUAA

The following projects in ultrasonic motor field are studied in NUAA at present:

- Mechanism of new type ultrasonic motor, Dynamic modeling and optimal design;
- Micro-type and integrated ultrasonic motor, Linear ultrasonic motor, Surface acoustic wave USM;
- Ultrasonic motor with high efficiency;
- New friction materials and piezoelectric materials;
- Non-linear characteristics of the ultrasonic motor;
- Drive and control techniques of the USM;
- Applications in engineering.

The main problems that challenge us today:

- Increasing life of USM to 10000 hours;
- Enlarging efficiency to 40 % or more;
- Decrease cost of production.

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