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A Novel Rotary Ultrasonic Motor Using the Longitudinal Vibration Mode

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ABSTRACT A novel rotary ultrasonic motor using only the longitudinal vibration mode was proposed in this paper, which avoided the frequency degeneration of multi-modal coupling ultrasonic motors. The structure of the ultrasonic motor was designed; the ultrasonic motor was mainly made up of two longitudinal transducers, a rotor, a basement and two mounting bases for adjusting the relative position between longitudinal transducers and the rotor. Two transducers were arranged symmetrically about the axis of the rotor, which drove the rotor under the frictional forces. The operating principle was discussed. The modal characteristics of the longitudinal transducer were investigated by the Finite Element Method (FEM). Two longitudinal transducers have the same structures and vibration modes, first order longitudinal vibration is used for drive; the ultrasonic motor is simple in structure and flexible in design, so it is suitable for industrial production. Furthermore, as the transducers' sizes and relative position between the transducers and the rotor are easy to vary, the mechanical characteristics of the proposed motor can be changed flexibly. The experimental rotary speed of the proposed ultrasonic motor at the voltage of 300 V_{p-p} is 350 revolutions; and the maximum torque is 186 N·mm.

INDEX TERMS Ultrasonic motor, longitudinal transducer, finite element method (FEM).

I. INTRODUCTION

Ultrasonic motors have merits of fast response, high power weight ratio, high resolution of displacement and a lack of electromagnetic radiation [1]–[5]. They have been widely used in systems, such as optical instrument, aerospace manipulator and biomedical science [6]–[10].

Travelling wave type ultrasonic motors have been industrialized in the field of digital camera autofocus. Nevertheless, ultrasonic motors with relatively high output power are still in demand. Comparing with the travelling wave type ultrasonic motors, the clamped type standing wave ones have advantages of high velocity, large stroke and large force [11]–[15]. Yamaguchi *et al*. studied the bolt-clamped Langevin-type ultrasonic motor used at ultralow temperature; the motor rotated at 65 rpm in helium gas, the rotation speed is 60 times that of previous motors of the same size [16]. Zhang *et al*. designed a frog shaped piezoelectric actuator using the clamped type longitudinal transducer, and a maximum speed and a thrust of 287 mm/s and 11.8 N were achieved [17].

Many multi-modal standing wave ultrasonic motors have been researched [18]–[22]. The desired motion trajectories, usually elliptical ones, are generated by composting two orthogonal vibration modes [23]–[25]. Frequency degeneracies of multi-modal are the necessary process of most standing wave ultrasonic motors, which make the change of sizes complicated. Yang *et al*. tuned of the resonance frequencies of the first longitudinal and fourth bending modes to be close at about 58 kHz [26]. Al-Budairi *et al*. proposed a mode degeneration method that converts the longitudinal response excited by the axially poled piezoceramic discs in the transducer into combined L–T vibration in the transducer front mass using geometric modifications of the wave path [27].

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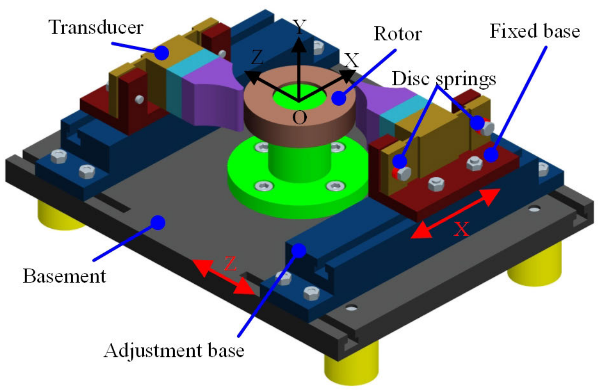


FIGURE 1. Structure of the proposed ultrasonic motor.

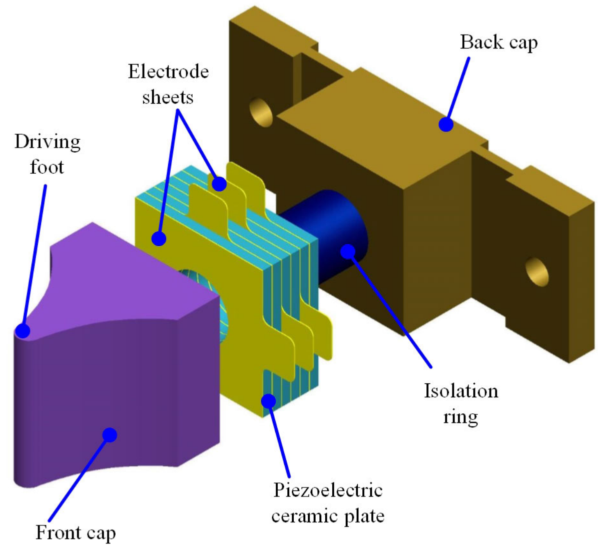
And the equal frequencies of vibration modes should be obtained. FEM analysis is a commonly used method to match the modal frequencies by parameter sensitivity analysis [28], [29]. Changing the sizes of these ultrasonic motors, design work will be repeated as the sensitivities of different vibration modes are various. In addition, with the wear and tear during the working process, the resonance working frequencies will vary, which may lead to the inconformity of the vibration frequencies. Finally, deterioration of the output characteristics will be occurred.

A rotary ultrasonic motor using two longitudinal transducers is proposed in this paper, the structures of the two transducers are identical, the longitudinal vibration mode is utilized for driving the rotor, and thus, only one excitation voltage is used. The two transducers are arranged symmetrically about the axis of the rotor, the rotor is driven under the frictional force. The contact positions between the transducers and the rotor can be adjusted flexibly, thus we can change the output characteristics easily. In addition, there is no need of modal degeneracy; therefore, the size of the longitudinal transducer can be adjusted easily, which is benefit for the industrialization. The design of the motor, the operating principle and experimental performances will be introduced in Part II, III and IV, respectively.

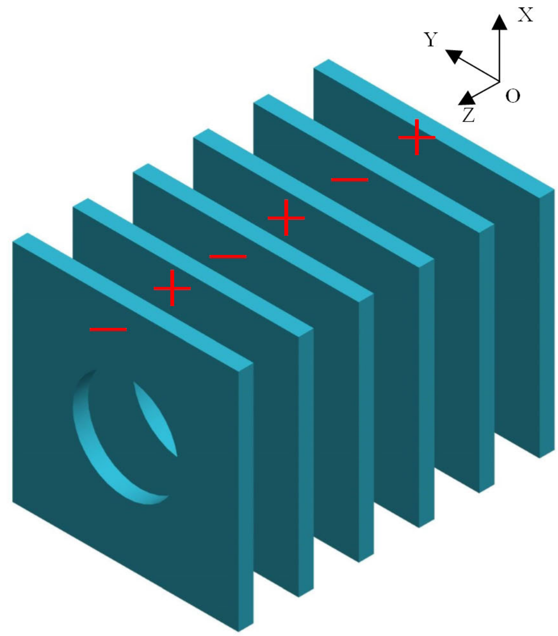
II. DESIGN OF THE ULTRASONIC MOTOR

The structure of the ultrasonic motor is shown in Fig.1, which is mainly composed of two longitudinal transducers, one rotor, two adjustment bases, two fixed bases and one basement. The relative position between the rotor and the transducer can be changed by the adjustment bases; the fixed base can move along the adjustment base to change the X direction displacement; the adjustment base can move along the basement to change the Z direction displacement. Therefore, in addition to change the amplitude, frequency and phase of the input voltage to change the output performances, we can also vary the output performances by changing the relative position between the rotor and the transducers. Disc springs are set between the transducer and the fixed base. Disc springs are utilized to adjust the preload between the driving foot of the transducer and the rotor by adjusting the screw tightening degree. Two longitudinal transducers are set rotational symmetrically to drive the rotor synchronously, which not only increases the thrust torque, but also avoids the bending deformation of the rotor under unilateral force. The rotor makes up of one deep groove ball bearing and one flange. The outer ring of the bearing contacts with the transducers, and the inner ring of the bearing is assembled with the shaft of the flange by interference fit.

Two transducers have the same structure; each transducer mainly consists of six pieces of piezoelectric ceramic plate, one front cap, one driving foot, one back cap, one isolation ring and six pieces of electrode sheets, as shown in Fig. 2(a). Six pieces of beryllium bronze electrode sheets



(a) Structure of the longitudinal transducer



(b) Polarization direction of the PZT ceramic plates

FIGURE 2. The longitudinal transducer.

TABLE 1. Main structural parameters of the transducer.

Parameters	Values (Unit: mm)
L_1	2
L_2	20
L_3	10
L_4	20
b	30
B	80
R	2.5

with thickness of 0.2 mm are set between the PZT ceramic plates to apply excitation voltage on the PZT ceramic plates. The PZT ceramic plates are polarized along OZ direction, the polarization directions are shown in Fig. 2(b). The polarization directions of two adjacent piezoelectric ceramics are opposite. With the sine signal, the PZT ceramic plates will shorten and elongate along the OZ direction. The type of the PZT ceramic plate is PZT4, the density, Poisson's ratio and modulus of elasticity of which are 7600 kg/m, 0.32 and 76.5 GPa, respectively. The materials of the front cap and the driving foot are set as duralumin with density of 2810 kg/m^3, Poisson's ratio of 0.33 and modulus of elasticity of 4.72 GPa. The materials of the back cap and the bolt are set as steel, the density, Poisson's ratio and modulus of elasticity of which are 7800 kg/m, 0.3 and 206 GPa, respectively. The piezoelectric matrix d, stiffness matrix c^{E}, and dielectric matrix ε^{T} of the PZT4 are as follows:

$$d = \begin{bmatrix} 0 & 0 & 0 & 0 & 5 & 0 \\ 0 & 0 & 0 & 5 & 0 & 0 \\ -1.6 & -1.6 & 3.3 & 0 & 0 & 0 \end{bmatrix} \times 10^{-10}\mathrm{C/N} \tag{1}$$

$$c^E = \begin{bmatrix} 15 & 8.4 & 6.8 & 0 & 0 & 0 \\ 8.4 & 15 & 6.8 & 0 & 0 & 0 \\ 6.8 & 6.8 & 12.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 2.8 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2.8 \end{bmatrix} \times 10^{10}\mathrm{N/m^2} \tag{2}$$

$$\varepsilon^T = \begin{bmatrix} 8.1 & 0 & 0 \\ 0 & 8.1 & 0\ 0 \\ 0 & 0 & 6.7 \end{bmatrix} \times 10^{-9}\mathrm{F/m} \tag{3}$$

The first order longitudinal vibration mode is selected as the working mode. The sizes of the transducer are designed by the finite element and parameter sensitivity analysis methods. The transducer is composed of six pieces of PZT ceramic plates with $30 \times 30 \times 2$ mm^3; the radius of the driving foot is 2.5 mm; the length of the front cap is 30 mm. In this way, the total length of the longitudinal transducer is 65.7 mm. The specific structure sizes of the transducer are shown in Table I.

The finite element model of longitudinal transducer is established in ANSYS. Fixed boundaries are applied on the holes of the back cap. The element type of the model is set as SOLID227. Modal extraction method of Block Lanczos is used in this design process. Flexible hinges are used to fix

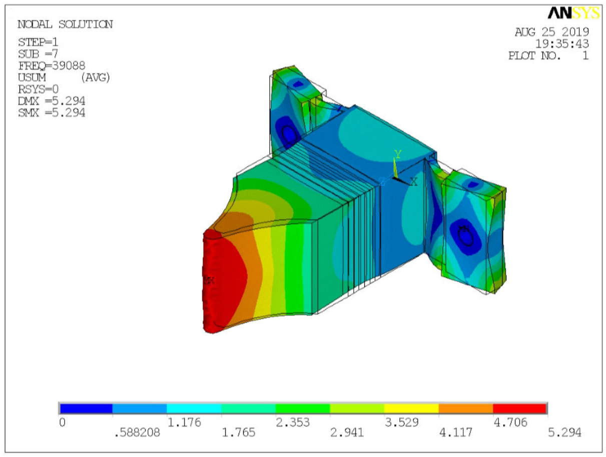


FIGURE 3. The first order longitudinal vibration mode of the transducer.

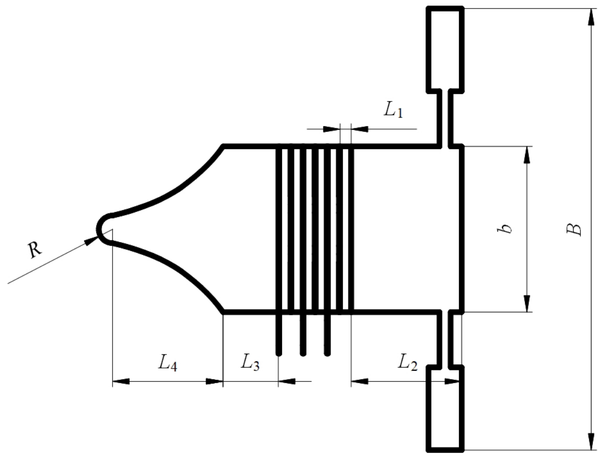


FIGURE 4. The main structural parameters of the transducer.

transducers to minimize the impact on longitudinal vibration mode. The first order longitudinal vibration mode of the transducer is shown in Fig. 3. The maximum displacement occurs at the driving foot, which is used for driving.

As the first order longitudinal vibration mode of the transducer is easy to find out, the workload of the finite element analysis has been reduced greatly. The frequency of the designed longitudinal transducer is calculated to be 39088 Hz. The longitudinal transducer has a simple structure and the relative position between the transducer and the rotor is easy to adjust, which ensures the proposed ultrasonic motor convenient for manufacture, suitable for industrial production and easy to vary the output performances.

III. OPERATING PRINCIPLE

When sine signal is applied to the designed ultrasonic motor, the first order longitudinal vibration mode of the transducer will be excited; displacement along the OZ direction will be produced. Figure 4 shows the operating principle of the proposed ultrasonic motor. The output displacements and forces of two transducers are the same, which are

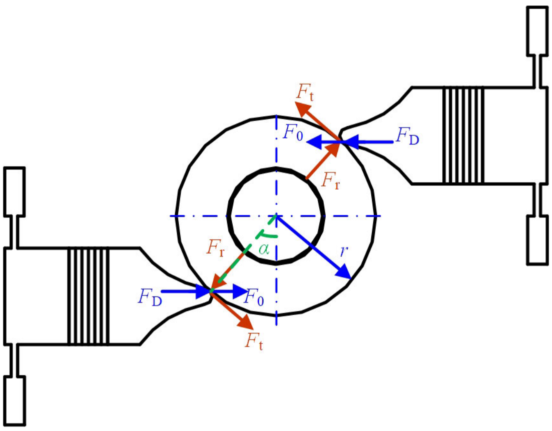


FIGURE 5. Operating principle of the proposed rotary ultrasonic motor.

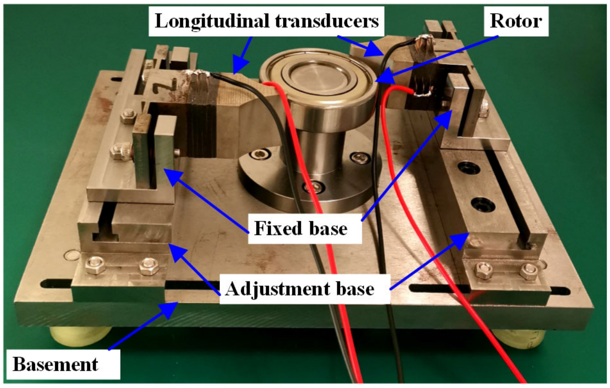


FIGURE 6. Photograph of the proposed rotary ultrasonic motor.

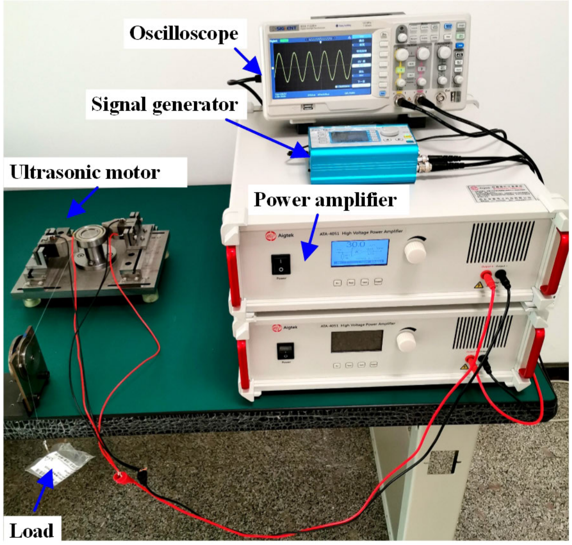


FIGURE 7. Experimental setup of the proposed rotary ultrasonic motor.

D and F_D, respectively. F_0 is the preload between the driving foot and the rotor. F_t and F_r are the frictional force and the radial force of the rotor, respectively; and the rotor is driven by two transducers with torque T.

$$T = 2F_t r = J\frac{d\omega}{dt} = J\frac{d^2\theta}{dt^2} \tag{4}$$

where F_t is the frictional force, r and J are the radius and moment of inertia of the rotor, respectively, ω and θ are the angular velocity and angular displacement of the rotor, respectively.

$$F_t = \mu F_r = \mu\sqrt{\frac{1}{1+\mu^2}}(F_D + F_0) \tag{5}$$

where μ is the frictional coefficient between the transducer and the rotor.

$$F_D = kD \tag{6}$$

where k is the stiffness of the front cap. D is the output longitudinal displacement of the transducer, which can be calculated by the finite element method.

The rotor will rotate in one direction when the voltage signal with designed resonance frequency is applied to the proposed ultrasonic motor. Usually, we change the amplitude of the input voltage to vary the output speed of the ultrasonic motor; the phase of the input voltage is used to change the rotating direction of the rotor. In addition, we can change the position of the two transducers to change the output performances of the ultrasonic motor.

IV. EXPERIMENTAL STUDY

Prototypes are manufactured to verify the feasibility and to measure the output performances of the proposed ultrasonic motor. The photograph of the proposed ultrasonic motor is shown in Fig. 5. The size of the basement is $60 \times 5 \times 3.5$ mm^3. The measured first order longitudinal vibration mode frequency of the transducer by the ultrasound impedance analyzer (ZX80A, Xuji Electric Co., China) is approximately 39230 Hz; the deviation of which with the simulation one is approximately 0.4 %.

The experimental setup, as shown in Fig. 7, composed of the designed ultrasonic motor, a signal generator, a power amplifier (ATA-4051, Agitek, China), an oscilloscope and the load. The bearing of the rotor is a deep groove ball bearing (6206, NSK). Sine signal is generated by a signal generator, and then amplified by a power amplifier; the output sine signal with 300 V_{p-p} and frequency of 39230 Hz is applied to the proposed ultrasonic motor.

Figure 8 shows the relationship between the rotary speed and the torque. With increasing of the output torque, the rotary speed decreased. The maximum torque is 186 N·mm.

Figure 9 shows the relationship between the rotary speed and voltage, the voltage ranges from 100 V_{p-p} to 300 V_{p-p}. It indicates that the ultrasonic motor cannot work with the lower voltage as the driving force cannot overcome the friction. Then, with increasing of the input voltage amplitude, the rotary speed increases. The maximum rotary speed is 350 r/min with the voltage of 300 V_{p-p}.

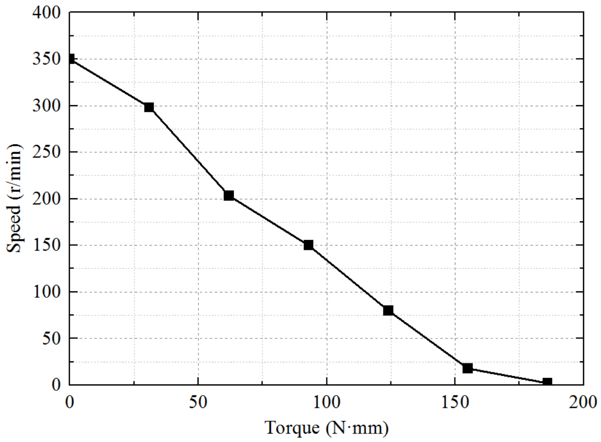


FIGURE 8. Relationship between the rotary speed and the torque.

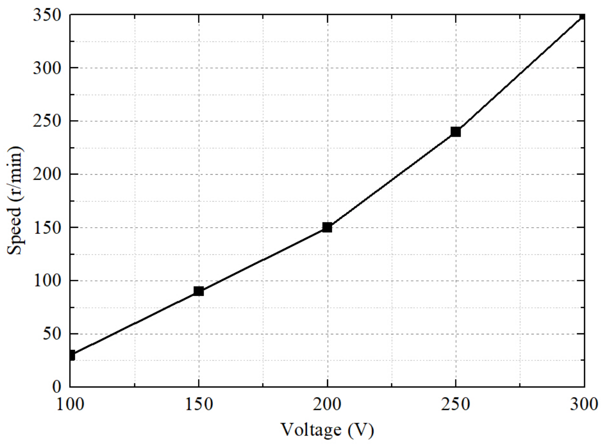


FIGURE 9. Relationship between the rotary speed and voltage.

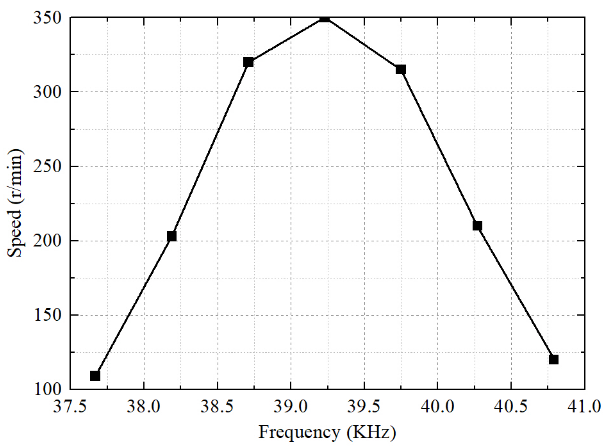


FIGURE 10. Relationship between the rotary speed and frequency.

The above results are measured with α is 45°; α represents the relative position between the piezoelectric transducer and the rotor (as shown in Fig. 5). At last, we adjust the position of the transducer relative to the rotor to measure the output mechanical performances; set α equal to 60°, the measured

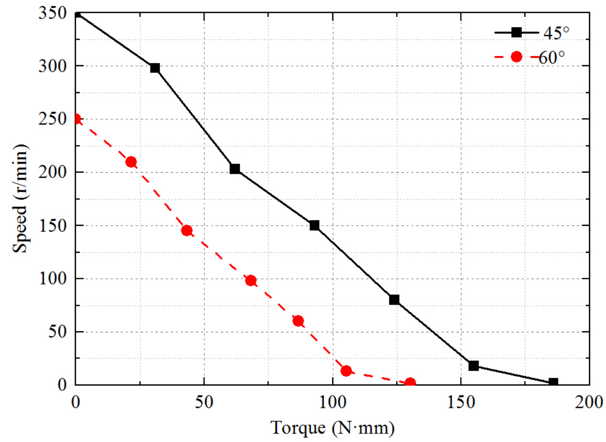


FIGURE 11. The output performances under different conditions.

results are shown in Fig. 11. It indicates that the proposed ultrasonic motor can vary the output performances not only by changing the input voltage, but also by modifying the relative position between the transducer and the rotor; and the adjust method is flexible.

V. CONCLUSION

A novel rotary ultrasonic motor with two longitudinal transducers is proposed in this paper. Only first order longitudinal vibration mode is used in the ultrasonic motor, which avoids the frequency degeneration of modal coupling ultrasonic motors. The relative position between the two transducers and the rotor can be varied easily, which provides additional method for changing the output mechanical performances. Besides, we can also change the output mechanical performances by the frequency, phase and amplitude of the input voltage. The experimental results indicate that the frequency deviation between the measured first order longitudinal vibration of the piezoelectric transducer and the theoretical one is approximately 0.4 %. Mechanical performances show that the motor can obtain rotary speed of 350 r/min under the voltage of 300 V_{p-p}, and the maximum torque is 186 N·mm. The proposed ultrasonic motor has the advantages of simple structure, easy to design and manufacture and convenient for the industrial production.

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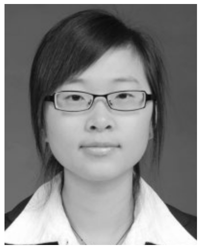

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