Numerical Analysis and Experimental Study on High Frequency Piezoelectric Feeding Device of Block Materials

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Abstract. According to the needs of ultrasonic vibration feeding, we developed an ultrasonic piezoelectric feeding device. The device with unrestricted length and width and the feeding speed is uniform. We analyzed feeding the boundary conditions and calculated the expression of the average feeding speed. Using ANSYS to analyze the relevant parameters of feeding vibrator, we made the piezoelectric feeding vibrator and carried out a series of experiments to test the feeding effect by using Laser Doppler vibrometry. The results showed that the amplitude of the first order longitudinal vibration is maximum when the excitation frequency is 34.7kHz; When the feeding device is at the excitation frequency and the driving voltage is 130V, the feeding effect of the heavy material with smooth surface is very good (M10×30 bolts, M20 nuts); Materials with rough surface and lighter than 0.5g have almost no feeding capacity (tablets and grains), and the feeding device has certain selectivity for materials; When the mass of material is 72g, the feeding speed can reach 60.45mm/s. The study provides a reference for the research of ultrasonic feeding device.

1. Introduce
At present, the ultrasonic motor technology has matured and achieved fruitful research results[1-3]. Many scholars are expanding the application of ultrasonic motor technology and conducting in-depth researches in the field of material precisely feeding[4,5], which has paved the way for the researches of ultrasonic material feeding devices. Unlike traditional vibration transport, ultrasonic material feeding possesses the follow features: fast response, small noise, not affected by magnetic field, miniaturized structure and so on[6,8]. In 2004, S.B. Choi and D.H. Lee of Inha University in Korea developed a spiral piezoelectric ceramic drive feeder[9]. The feeding speed is 51mm/s for the individual weight of 2.16g of the object. In 2005, M.Racek and J.Allaschek et al from Paderborn University in Germany designed and studied the ultrasonic powder feeding device[10]. The working frequency of the device is 39.3k Hz and the feeding section length is 150mm, which can realize the precise feeding of ultrafine powder. In 2017, German scholars P. Dunst and P. Bornmann et al studied the ultrasonic powder-feeding device[11]. In 2020, Su Jiang, Tong Jie et al developed a new piezoelectric linear vibrating feeder. When the driving frequency is 209.5~214.5Hz, the piezoelectric feeder is capable of feeding substance[12].

The vibration contact and interaction forms between the conveyed material and the elastomer vibrator are diversified and complicated. It is found that the effect of the material feeding system is affected by the driving frequency, amplitude, coefficient of dynamic friction and the type of materials...
transported[14]. Although some preliminary results have been achieved in ultrasonic feeding[15], most of them focused on pre-pressure and the friction between the joint surfaces of the stator and the rotor. The structure of the principle prototype designing is complicated and there are certain differences in precisely ultrasonic transportation. It can be seen from the reference documents that the existing ultrasonic feeding devices use piezoelectric ceramics as the excitation source and thin pipe as the feeding body to realize powder material feeding. The lossy traveling-wave on thin pipes which has large energy loss coefficients, results in uneven distribution of the feeding speed in the length and width on the feeding pipeline. Another way of material feeding is indirectly driving the hopper. The complicated relationship between the hopper and the excitation source has a significant influence on the performance of the material feeding system. This study overcame the uneven speed of the existing feeding device, proposed a new type of piezoelectric feeding vibrator with uniform feeding speed and unlimited feeding length and width. The paper studies the dynamic model of the feeding system under the action of longitudinal exciting force, analyzes the movement of materials, carries out dynamic design of the piezoelectric vibrator with finite element analysis ANSYS, checked its feeding capacity by Laser Doppler vibrometry, which provides data support for the practical application research of the ultrasonic material precision feeding device.

2. Driving Principle of Feeding Vibrator

Ultrasonic feeding is a new technology trend in the field of ultrasonic motors. It is based on the inverse piezoelectric effect of the piezoelectric ceramics, The micro vibration of piezoelectric feeding vibrator is excited, it is driven by the friction between the solid surface and the feeding material. According to the references[16], the waist of the vibrator is shaped like a dumbbell, when the axial size of the vibrator is small, the excitation frequency will be lower and the output force will increase significantly. This discovery provides a basis for its design of structure and size. The structure design of this piezoelectric feeding vibrator is shown in Fig.1. It adopts a structure with thin middle and thick ends, similar to a dumbbell. The upper and lower vibrator bodies are approximately symmetrical. The piezoelectric ceramic sheet is bonded to the waist of the metal elastomer vibrator by adhesive. It is shown that the thickness of the adhesive has little effect on vibration mode, so we ignored the influence of thickness of the adhesive in the analysis. In order to make the feeding surface as large as possible, the feeding surface adopts the inclined rectangular surface. The study suggests that it is appropriate to adopt the longitudinal vibration mode in order to generate a larger amplitude of the piezoelectric vibrator in the same direction. The electromechanical coupling coefficient of the PZT is the largest under its longitudinal vibration excitation, the effect of using stretching vibration along the polarization direction is the best[16]. Under vibration excitation of the PZT, the first-order longitudinal vibration is selected for the analysis of the operational mode of the feeding vibrator, and the force pushing the material forward are from horizontal and vertical components of the excitation force generated by the longitudinal vibration. We could arrange multiple feeding vibrators in vertical or parallel to the transportation direction to meet the feeding distance requirements.

Figure1. feeding vibrator
3. Movement Analysis of feeding Materials

3.1 Material feeding Distance
The movement of the material has a certain influence on the design of the feeding device in the piezoelectric ultrasonic material conveyor system, so it is of great necessity to analyze the movement of material. The system can be approximated as a single degree of freedom system.

Where:
- $s$: displacement, $A$: vibration amplitude, $\beta$: angular frequency, $\omega$: angular frequency, $v$: velocity of material
- $a$: acceleration of material, $m$: the mass of material, $F_1$: excitation force, $F_f$: friction, $F_N$: positive pressure

$A_0$: The critical vibration range when the material is separated from the feeding surface;
$A_1$: Critical vibration range of feeding surface when material is sliding;

$$S = \frac{1}{2} A \sin \varphi = \frac{1}{2} A \sin \omega t$$
$$v = \frac{1}{2} A \cos \omega t$$
$$a = \frac{1}{2} \omega^2 A \sin \omega t$$

The force analysis of the system is shown in fig. 2

$$F_1 = \frac{1}{2} m \omega^2 A \sin \omega t$$

$$F_x = F_1 \cos \alpha = \frac{1}{2} m \omega^2 A \sin \omega t \cos \alpha$$

$$F_y = F_1 \sin \alpha = \frac{1}{2} m \omega^2 A \sin \omega t \sin \alpha$$

$F_N = mg \cos \beta - F_y = mg \cos \beta - \frac{1}{2} m \omega^2 A \sin \omega t \sin \alpha$

$$F_f = \mu F_N = \mu (mg \cos \beta - \frac{1}{2} m \omega^2 A \sin \omega t \sin \alpha)$$

$$ma = m \ddot{x} = -mg \sin \beta + (ma) \cos \alpha - F_f$$

$$\ddot{x} = \frac{1}{2} A \omega^2 \sin \omega t (\cos \alpha + \mu \sin \alpha) - g (\sin \beta + \mu \cos \beta)$$

$$S = v_0 t + \frac{1}{2} \ddot{x} t^2 = \frac{1}{4} A \omega^2 \sin \omega t (\cos \alpha + \mu \sin \alpha) - g (\sin \beta + \mu \cos \beta) t^2$$

It can be seen from the expression, the distance of material feeding is related to amplitude and roughness of contact surface.

3.2 Conditions for Material Transportation
The piezoelectric feeding vibrator generates first-order longitudinal vibration effected by excitation source. The material is momentarily separated from the feeding surface due to the excitation force.

$$F_N = mg \cos \beta - F_y = mg \cos \beta - \frac{1}{2} m \omega^2 A \sin \omega t \sin \alpha$$
If $F_N \leq 0$, the material begins to leave the feeding surface

\[ A = \frac{2g}{\omega^2} \frac{\cos \beta}{\sin \omega t \sin a} \rightarrow A_0 = \frac{2g}{\omega^2} \frac{\cos \beta}{\sin \omega t} \quad \text{when} \ A \geq A_0 \]

\[ \ddot{x} = \frac{1}{2} A \omega^2 \sin \omega \left( \cos a + \mu \sin a \right) - g(\sin \beta + \mu \cos \beta) = 0 \]

\[ A = \frac{2g}{\omega^2} \frac{\sin \beta + \mu \cos \beta}{\sin \omega (\cos a + \mu \sin a)} \]

\[ A_1 = \frac{2g}{\omega^2} \frac{\sin \beta + \mu \cos \beta}{\cos a + \mu \sin a} = A_0 \frac{\mu + \tan \beta}{\mu + \cot a} \]

When $a + \beta = 90^\circ$ when the first-order longitudinal vibration excitation force excited by the feeding vibrator is in the vertical direction. $A = A_1 = A_0 = \frac{2g}{\omega^2}$

As long as the amplitude of the feeding surface is greater than $A_0$, the material can be transported.

### 3.3 Speed of Material Transportation

Supposed that the material starts move at $t_2$

\[ v = \int_{t_2}^{t_1} \dot{x} \, dt = -\frac{1}{2} A \omega (\cos a + \mu \sin a) \cdot \cos \omega t (t_1 - t_2) - g(\sin \beta + \mu \sin a)(t_1 - t_2) \]

When $t_1 = t_2$, material transfer is over. $v = 0$

\[ -\frac{A \omega}{2g} (\cos a + \mu \sin a) \cdot \cos \omega t (t_1 - t_2) = g(\sin \beta + \mu \sin a)(t_1 - t_2) \]

The material starts to move at $t_2$, stop at $t_3$. Average speed of material movement is $\bar{v}$.

\[ \bar{v} = \frac{1}{t_2} \int_{t_2}^{t_3} v \, dt = \frac{\omega}{2\pi} \int_{t_2}^{t_3} \left[ -\frac{1}{2} A \omega (\cos a + \mu \sin a) \cdot \cos \omega t (t_1 - t_2) - g(\sin \beta + \mu \sin a)(t_1 - t_2) \right] \, dt \]

\[ = -\frac{A \omega}{4\pi} (\cos a + \mu \sin a) \left[ (t_3 - t_2) \sin \omega t_3 + \frac{1}{\omega} (\cos \omega t_3 - \cos \omega t_2) \right] \]

\[ -\frac{A \omega}{2\pi} g(\sin \beta + \mu \sin a) \left( \frac{(t_3 - t_2)^2}{2} \right) \]

It can be seen that the average speed of the material is related to the excitation frequency and amplitude of the feeding vibrator, the inclination angle of the feeding surface, and the friction coefficient between the material and the feeding surface.

### 4. Vibrator Finite Element Analysis

#### 4.1 Influence of Vibrator on Parameters on Modes

In the following, analyzed the piezoelectric feeding vibrator by using finite element ansys. Set the initial frequency to 20KHz, aluminum, brass and stainless steel as the research objects. An appropriate model of the vibration was built using finite-element-simulation in ansys, see figure3. The vibrator was meshed using a number of each 0.05 elements. Table 1 shows the data of the key displacement nodes, which indicates that the transverse relative displacement ratio of duralumin key nodes was 16.6%, while that of brass and stainless steel was 2.92% and 1.96% respectively. Finally, stainless steel is chosen as the material of vibrator. Material parameters for the stainless steel vibrator were taken from literature (modulus of elasticity 200GPa, Poisson's ratio 0.3, density 7900 kg/m$^3$)

Figure3. Vibrator finite element mesh
Table 1. Analysis of different materials

| Materials         | brass | stainless steel | aluminum |
|-------------------|-------|-----------------|----------|
| frequency/Hz      | 25491 | 35177           | 36306    |
| Relative Longitudinal displacement of key nodes | 1.9063 | 1.9648 | 3.6857 |
| Lateral relative displacement of key nodes    | 0.0556 | 0.0386 | 0.6125 |

Fig. 4 shows the first-order longitudinal vibration mode changes of finite element analysis when the axial dimension changes from 50mm to 70mm, the step length is adjusted to 2mm, and other parameters are unchanged. It can be learned from the Fig. 5 that within the selected range, the shorter the axial dimension, the greater the lateral deformation ratio when the longitudinal mode is generated, and the more uneven the relative longitudinal displacement of the nodes on the feeding surface. The frequency of the first-order longitudinal vibration mode of the vibrator decreases linearly as the axial size increases. The feeding surface is made into an oblique rectangular surface to make its length as long as possible. Adjust the step length to 1mm and make the oblique angle varying from 13° to 22° to analyze the effect of the oblique angle on the first-order longitudinal mode. We found that the vibration frequency of the first-order longitudinal mode of the vibrator decreases linearly with the angle of the feeding surface. Choose the vibrators with square cross-section of 14mm~34mm, and adjust the step length to 2mm. We found that the lateral deformation of the first-order longitudinal vibration mode is larger and increases linearly with the angle of the feeding surface.

![Figure 4. Influence of Vibrator Size](image)

The driving force of the ultrasonic material feeding system comes from the excitation source. It can be seen that the excitation source is the core component of the ultrasonic material feeding system and directly affects the performance of the material feeding. The excitation source uses piezoelectric ceramics, then analyze its related parameters. Fig. 5 showed that vibration frequency of the first-order longitudinal mode decreases linearly with the axial dimension of the piezoelectric ceramic, as well as the width dimension. But the vibration frequency of the first-order longitudinal mode increases linearly with the length dimension. It is demonstrated that the dimension parameter of piezoelectric ceramic sheet in the excitation source has a great influence on the vibration frequency of the piezoelectric feeding vibrator.

![Figure 5. Influence of piezoelectric Size](image)
4.2 Harmonic Response Analysis of feeding Vibrator

The harmonic response of 35.176kHz~35.178kHz including the harmonic frequency 35.177kHz was analyzed using the Full solution method. Calculate the amplitude distribution of the nodes of the feeding surface at different frequencies in this interval. The harmonic response curve when the electrical load between the two poles of the excitation source is 150 V and amplitude-frequency characteristic curve under concentrated load on the feeding surface are shown in Fig.6. It can be seen from the fig.6 that the amplitude of the piezoelectric feeding vibrator changes linearly around the resonant frequency under the effect of electric load, but the amplitude reaches the maximum at the resonant frequency. When the feeding surface of the piezoelectric vibrator is subjected to concentrated load, the amplitude of the feeding vibrator is the largest at the resonant frequency.

![Figure 6. Amplitude-frequency characteristic curve of load](image)

5. Tests of Feeding Vibrator

In order to verify the theoretical analysis, the piezoelectric feeding vibrator is made as shown in figure.1. Doppler laser vibrometry was used to study the feeding performance of the vibrator. The experimental equipments are shown in figure.7, TektronixAFG320, Power Amplifier Type 2713, OFV-505/5000 Vibrometer and Tektronix TDS1002,etc. Calculate the amplitude according to y.

\[ y = \frac{k_v \cdot V_{p-p}}{4\pi f} \]

- \( k_v \) —Coefficient of laser vibrometer (25mm/s/V);
- \( V_{p-p} \) —Voltage(V), \( f \) —Excitation frequency(kHz),
- \( y \) —Amplitude(\( \mu \)m);

![Figure 7. experimental test apparatus](image)

5.1 Tests of Excitation Frequency And Amplitude Distribution

The amplitude and uniformity of the distribution surface of the vibrator have a great influence on the performance of the entire feeding system. The feeding surface of the vibrator uses a rectangular surface with an oblique angle. The axial dimensions and height of both sides of the feeding surface are different. The side with the larger size is used as the higher feeding surface and the small side is used as the low feeding surface. Start the tests from the larger side. Adjust the step length of the test point to 2.5mm. Then we test the amplitude distribution by moving the test bench evenly along the feeding
It can be seen from figure 8 that there is a tiny deviation in the amplitude distribution of the high and low feeding surfaces, mainly due to the unequal axial dimensions of the feeding vibrator. Adjust the step length of the test point to 2.5mm in the width direction of the feeding surface, test the amplitude distribution of the high and low feeding surfaces in the width direction. It can be drawn from the curve: the amplitude distribution of the piezoelectric feeding vibrator on the width feeding surface is rather uniform, and the amplitude difference between the high and low feeding surfaces is 0.05um.

![Amplitude Test](image)

Figure 8. Amplitude Test

The feeding speed of piezoelectric vibrator is determined by the amplitude of feeding surface. On the sides of the resonant frequency, the amplitude changes linearly increasing and decreasing respectively. The experimental test accords closely with the finite element analysis. see figure 9.

![Amplitude-frequency curve](image)

Figure 9. Amplitude-frequency curve

5.2 Performance Test of Ultrasonic Feeding System

The feeding rate of material feeding system is an important index to measure the feeding capacity of material. Several feeding vibrators were made and placed along the length direction to meet the requirements of feeding length, as shown in Fig. 10. Test the influence of the main factors such as the type of feeding material, driving voltage and excitation frequency on the feeding performance. Materials selected for the test: stainless steel blocks, screw nuts, bearings, bolts, screws, pills, grains, etc.

Testing the effect of driving voltage: the excitation frequency is 34.70kHz, the test material is a single material hexagonal bolt (M10×30), the driving voltage is set to 60V~200V, then we obtained the relationships between the feeding speed and the driving voltage, the driving voltage and the amplitude, and the amplitude and the feeding speed and their curve are shown in Figure 11.
It can be seen that under the same test conditions, the feeding speed increases approximately linearly with the increase of the driving voltage. When the driving voltage is less than 50V, the material feeding speed is pretty low, the material can hardly be conveyed. Adopt Doppler laser vibrometer to test the amplitude of the feeding vibrator. The results show that the driving frequency is constant and the amplitude increases with the increase of driving voltage. If driving voltage of the system is excessively high, the piezoelectric ceramic plate in the excitation source will have hyperpyrexia due to temperature rising and shorten service life. Working under high voltage for a long time will cause the operating frequency point to drift, and the actual driving voltage shouldn’t be too high. It is known from Fig.12 that when the system operating frequency is in the range of 34.64kHz~34.78kHz, the piezoelectric vibrator has a better feeding performance, and the best frequency is 34.70kHz, because the amplitude reaches maximum.

Setting the working voltage to 130V, the working frequency to the resonance point frequency and keeping other conditions unchanged, we selected various materials to test. It is shown that the feeding system has a certain selectivity for feeding materials. The heavy materials with smooth surface have higher feeding speed, such as nuts (M14, M8), bolts (M10×25, M10×30) and bearings (M10, M8), etc; the materials with smooth surface but light weight have lower feeding speed, such as nut (M5), bearing (604), stainless steel cylinder (15×5×2)/mm, etc; For materials with rough surface and light weight, transport capacity is particularly poor, which are almost unable to convey, such as tablets and grains. Select the bolts (M10×30) with different weight as the feeding object. figure.13 is a graph of the change in feeding speed plotted by our experimental test data, which shows that keeping excitation frequency and voltage unchanged the feeding speed increases with the increase of bolt’s weight, and the feeding speed reaches 60.45mm/s when the bolt’s weight is 72g.
6. Conclusion
A new piezoelectric feeding vibrator was developed to solve the millimeter-scale material feeding problem, which has the characteristics of simple structure, unlimited feeding length and width, and high feeding speed. At the beginning of the study we established the dynamic model of piezoelectric vibrator and analyzed the material motion by numerical method. Then we used the finite element method to dynamically design the feeding vibrator and analyzed the influence of the parameters of the excitation source and feeding vibrator on the material feeding performance we fabricated the piezoelectric vibrator, and verified the theoretical study by using the Doppler laser vibrometry. The results show that the feeding system has selectivity to the materials. Materials with smooth surface and large mass have good conveyance performance; materials with rough surface and small mass (0.5g tablets, grains, etc.) cannot be conveyed. Taking the bolt as an example, the feeding rate reaches 60.45mm/s when the bolt’s weight is 72g. This study paved the way for the practical application of ultrasonic material feeding devices.

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