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Study on the structure of spherical coronal microporous ultrasonic atomization

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Abstract

With the epidemic of the novel coronavirus pneumonia, aerosol inhalation drug delivery has been widely favored by people because of its advantages of direct access to the focus and small side effects. At present, among the popular medical atomizers in the market, the micro-pore piezoelectric ultrasonic atomization has the advantages of small particle size, low residue and no noise. In this study, the vibration principle of the atomizing plate was clarified, and a simplified axial displacement model was constructed. Based on the simulation results, the vibration and particle size detection platform was built, and the simulation and experiment were combined to verify the atomization effect of the resonant frequency. The experimental results show that the atomizing tablets can produce more droplets deposited in the lungs.

Keywords

Medical vaporizer, microporous atomization, resonant frequency, atomization effect.

1. Introduction

With reference to the structure of the musical instrument cymbal to make full use of its acoustic properties, a novel piezoelectric composite transducer, ball-crown cymbal transducer, is designed in this paper. The ball-crown transducer is composed of a thin piezoelectric ceramic disc polarized in the thickness direction and a ball-crown metal substrate bonded to its lower end face[1]. The structure is shown in Fig. 1.

Fig. 1 Physical picture of Musical Instruments and cymbals

When an electric field is applied at both ends of the piezoelectric ceramic, the piezoelectric ceramic will produce radial and axial displacement due to the inverse piezoelectric effect. In this process, the spherical coronal metal cap plays a role of mechanical amplification, which converts the small radial displacement of the thin plate into a large axial displacement perpendicular to the surface of the piezoelectric ceramic, so that the axial displacement of the spherical coronal plate can reach tens of times the axial displacement of the piezoelectric ceramic itself[2].

2. Theoretical analysis of spherical crown atomization structure

2.1. Displacement analysis of piezoelectric ceramics

When the piezoelectric crystal is excited by the external electric field, the piezoelectric ring here will produce radial and axial displacement. Fig. 2 shows that in the column coordinate system, the upper and lower sides of the piezoelectric ring are connected to the two poles of the battery respectively, that is, the polarization direction is the Z-axis direction[3].

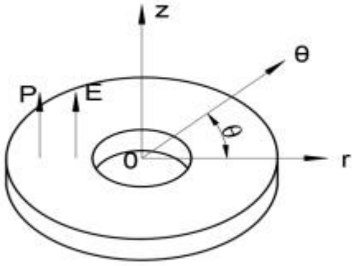


Fig. 2 Thickness direction polarization piezoelectric ring

The piezoelectric equation of this polarization direction is type d, and the equation is as follows:

$$\begin{cases} S_r = s_{11}^E T_r + s_{12}^E T_\theta + s_{13}^E T_z + d_{31} E_z \\ S_\theta = s_{12}^E T_r + s_{11}^E T_\theta + s_{13}^E T_z + d_{31} E_z \\ S_z = s_{13}^E T_r + s_{13}^E T_\theta + s_{33}^E T_z + d_{33} E_z \\ S_{\theta z} = s_{44}^E T_{\theta z} + d_{15} E_\theta \\ S_{rz} = s_{44}^E T_{rz} + d_{15} E_r \\ S_{r\theta} = 2\left(s_{11}^E - s_{12}^E\right) T_{r\theta} \end{cases} \tag{1}$$

Where, $S_r, S_\theta, S_z, S_{\theta z}, S_{rz}, S_{r\theta}$ is the strain component of the piezoelectric ceramics, T_r, T_θ, T_z, $T_{\theta z}$, T_{rz}, $T_{r\theta}$ is the stress component of the piezoelectric ceramics, s_{11}^E, s_{12}^E, s_{13}^E is the flexible constant component of the piezoelectric ceramics, d_{31}, d_{33}, d_{15} is the piezoelectric constant component of the piezoelectric ceramics, and, E_r , E_θ , E_z is the exciting electric field component.

The piezoelectric ceramic has a small thickness to diameter ratio and free upper and lower electrode surfaces for axisymmetric vibration. Under constant stress, equation (1) is simplified as

$$\begin{cases} S_r = d_{31} E_z = d_{31} E \\ S_\theta = d_{31} E_z = d_{31} E \\ S_z = d_{33} E_z = d_{33} E \end{cases} \tag{2}$$

At this time, the axial displacement and radial displacement of the piezoelectric ceramic ring are respectively

$$\begin{cases} \Delta z = S_z t_p = d_{33} E t_p \\ \Delta r = -S_r \left(\frac{1}{2} D_p\right) = -\frac{d_{31} E D_p}{2} \end{cases} \tag{3}$$

Where, t_p is the thickness of the piezoelectric ceramic ring and D_p is the diameter of the piezoelectric ceramic ring.

2.2. Displacement model simplification.

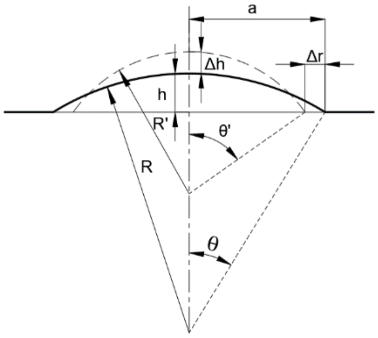


Fig. 3 Schematic diagram of vibration displacement of spherical coronal thin plate

It is assumed that the spherical coronal thin plate and the piezoelectric ceramic thin disc are ideally combined. There is no mechanical loss in the process of deformation. Under the action of electric field E, the spherical coronal thin plate is only subjected to simple geometric deformation, as shown in Fig. 3. The arc length of the busbar is unchanged, So $S = S'$ and it is an arc before and after deformation, and the end cap is only subject to elastic deformation. According to formula (3) and geometric relations, it can be obtained

$$\frac{a^2+h^2}{h}\arcsin\left(\frac{2ha}{a^2+h^2}\right)=\frac{(a-\Delta r)^2+(h+\Delta h)^2}{(h+\Delta h)}\arcsin\left[\frac{2(h+\Delta h)(a-\Delta r)}{(a-\Delta r)^2+(h+\Delta h)^2}\right] \tag{4}$$

In the above equation, given a and h, it is perfectly possible to solve for Δh. The total axial displacement of the spherical coronal thin plate consists of two parts: one is the axial elongation Δz of the piezoelectric ceramic thin plate under the action of electric field E; The other part is the radial contraction Δr of the piezoelectric ceramic thin disc under the action of electric field E, resulting in the axial displacement Δh of the metal crown, and the total axial vibration displacement is

$$d = \Delta h + \Delta z \tag{5}$$

3. Simulated Analysis

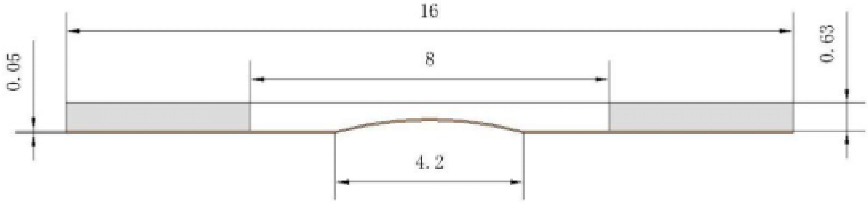


Fig. 4 Parameters of atomization structure model

Atomizing plate structure parameters, see Fig. 3. The atomizing plates are made of food-grade 316 stainless steel and PZT-4 piezoelectric ceramics, which are bonded with an epoxy silver adhesive layer, see Table 1.

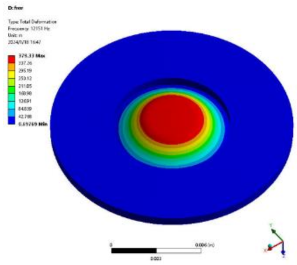
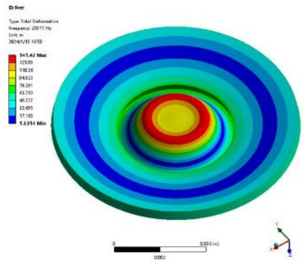
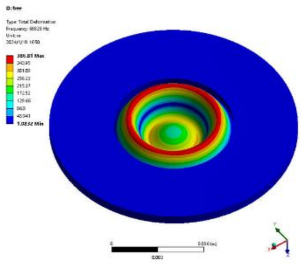
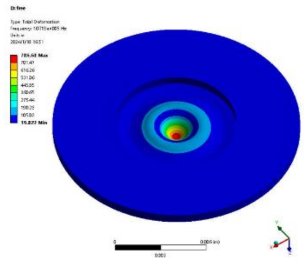
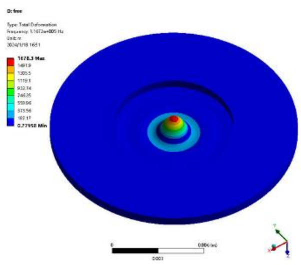
Table 1 Material parameters of atomizing structure

Material	Young's modulus (GPa)	Poisson ratio	density (kg/m3)
SUS316	193	0.29	7980
PZT-4	29	0.32	7500
bonding layer	10	0.38	1700

3.1. Dry modal analysis.

The number of pitch diameters and the number of pitch circles are represented by m and n, and the mode type (m,n) is defined to represent a certain mode mode. The maximum Z-displacement at the center of the structure is the non-pitch diameter mode (m=0), and the vibration is centrosymmetric[4]. The dry mode analysis mode is selected, as shown in Table 2. When the central area of the atomizing plate is arranged with multiple microholes, the film can generate continuous pressure under the state of vibration, so as to spray droplets.

Table 2 The dry mode represents the result

Inherent frequency (KHz)	Mode type (m,n)	Mode of vibration	Inherent frequency (KHz)	Mode type (m,n)	Mode of vibration
12.151	(0,1)		20.811	(0,2)	
68.828	(0,2)		107.19	(0,2)	
116.72	(0,2)				

When the natural frequency is 12.151kHz, there is a wave peak in the central region and the vibration is relatively severe, but the defect is that the frequency is low, it is not easy to achieve high-quality atomization, and it does not reach the ultrasonic range, there will be a certain noise, which can be eliminated. When the natural frequencies are 20.811kHz and 68.828kHz, the maximum Z-displacement is not in the central sphere crown region. When the natural frequency is 107.19kHz and 116.72kHz, there is a wave peak in the central spherical crown region and the vibration is relatively severe, and there is no obvious vibration in the rest, which conforms to the principle of mode selection.

3.2. Wet mode analysis.

The piezoelectric ceramic and microporous plate were set as the physical region, the liquid as the acoustic region, fluid density was 998.2kg/m3, the sound velocity was 1482m/s, the type of fluid-structure coupling solver was set as fully damped, and the contact surface of the liquid and the metal substrate was acoustically fluid-structure coupled to form a whole plane[5]. The crown part of the ball is in contact with the air, and the horizontal part of the microplate is in contact with the liquid. The model is more consistent with the actual working condition, see Fig. 4.

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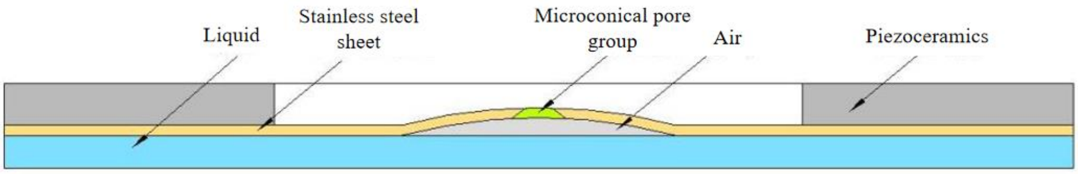
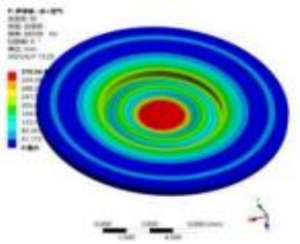
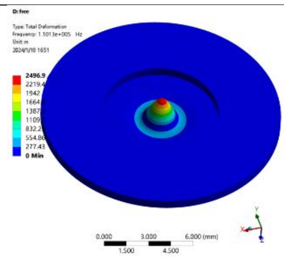


Fig. 5 Schematic diagram of the wet mode model

After analysis, the analysis results of two representative modes are selected, see Table 3. Compared with the results of dry mode analysis, the natural frequency of the same mode decreases.

Table 2 The wet mode represents the result

Inherent frequency (KHz)	Mode type (m,n)	Mode of vibration	Inherent frequency (KHz)	Mode type (m,n)	Mode of vibration
68.59	(0,4)		110.1	(0,2)	

The natural frequency of the mode in the left figure is 68.589khz, and a central wave peak appears. However, the vibration of the inner ring part of the piezoelectric ceramics is obvious, which is easy to cause damage to the ceramics, and the mode is unreasonable. The natural frequency of the mode in the figure on the right is 110.13khz, the wave peak appears in the center, and the vibration of the piezoelectric ceramic part is close to zero. The mode conforms to the selection principle.

3.3. harmonic response analysis.

The plug-in PiezoAndMEMS was extended to the workbench, and a fixed constraint was imposed on the edge of the hole plate. An exciting voltage of 0V and 5V was applied to the upper and lower surfaces of the piezoelectric ceramic, respectively. The piezoelectric ceramic was set as a piezoelectric body, and the piezoelectric stress constant matrix and relative dielectric constant matrix were input. The sweep frequency range is set to 10kHz-120kHz, the solution interval is set to 220, and the solution method is complete. Five resonant frequencies, 12.5kHz, 20.5kHz, 70kHz, 102.5kHz and 116.5kHz, are found in the analysis results, which are close to the modal analysis results. The response amplitude of 102.5kHz and 116.5kHz is obviously larger than other frequencies, which is the best resonant frequency, see Fig. 5.

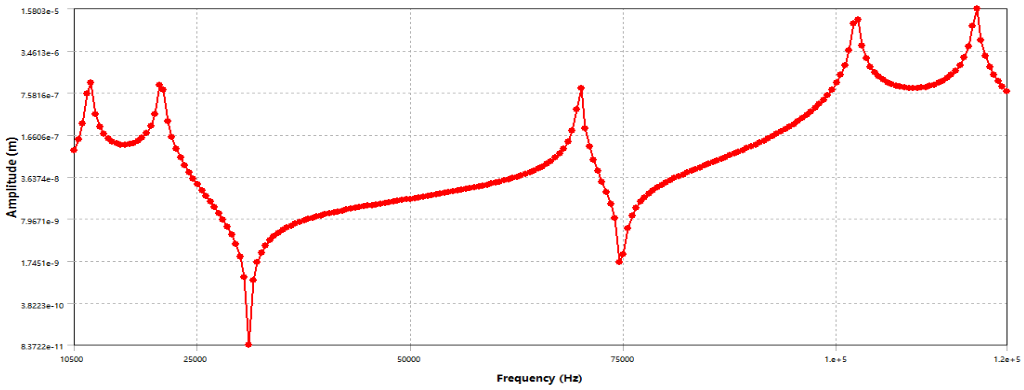


Fig. 6 Harmonic response curve at the center point of the free boundary

During the harmonic response analysis, the MAPDL db file was saved and the calculated results were imported into ANSYS classic. The impedance analysis was carried out under the condition

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of free microplate boundary. The resonant frequencies were 106.8KHz and 117.3KHz, and the real and imaginary values of the two resonant frequencies had a large difference, see Fig. 7.

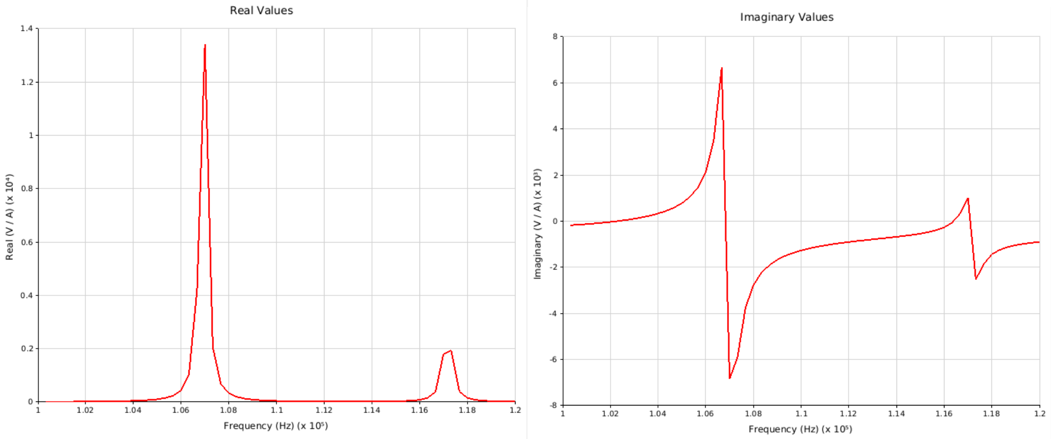

Fig. 7 Impedance analysis results under free boundary

Combined with the figure above, it can be concluded from equation (6) that the minimum value of the impedance is the best resonant frequency, that is, 117.3KHz. Where, $|Z|$ is the impedance mode, R is the real part, X is the imaginary part.

$$|Z| = \sqrt{R^2 + X^2} \tag{6}$$

4. Experimental verification

4.1. Atomizing sheet

Fig. 8 Physical picture of atomizing sheet

As shown in Fig. 8, wires are welded on the bonding surface between the metal substrate and the piezoelectric ceramic and on the upper surface of the piezoelectric ceramic, which are used to connect the external AC driving voltage. The liquid is directly in contact with the liquid under the atomizing plate, and the liquid is atomized through the cone hole of the atomizing plate to form a tiny liquid drop, which is then sprayed to achieve atomization. Conical hole plays a very important role in atomization, and its size is also a parameter of concern. The observation results of the size of microconical hole under scanning electron microscope are shown in Fig. 9.

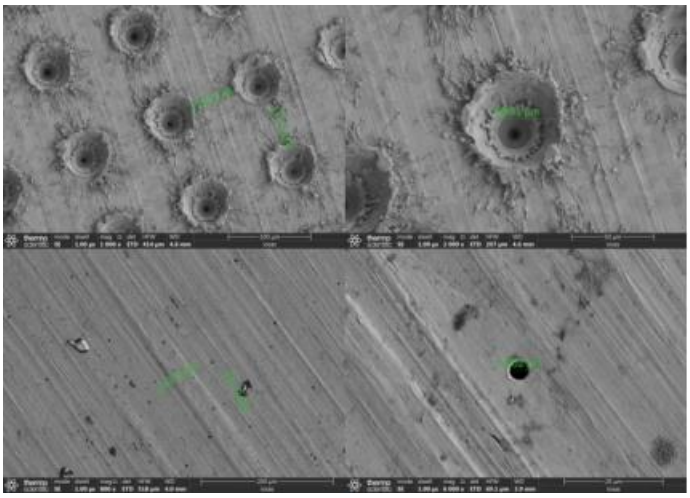

Fig. 9 SEM images of the front and back sides of the microcone holes

From the data in the figure above, the Angle of the microcone hole is calculated.

$$\varphi = 2\arctan\frac{(49.91-4)}{2\times 50} = 49.32^{\circ} \tag{7}$$

4.2. Laser vibration detection

The vibration and particle size test bench was built, and the KV series multi-channel laser vibration measurement system was used, as shown in Fig. 10, for sweep frequency and fixed frequency vibration measurement analysis[6].

Fig. 10 KV series multi-channel laser vibration measurement system

The vibration measurement results are shown in Fig. 11. In the range of 50kHz-120kHz, there are roughly three resonance frequency points, which are 76.3KHz, 97.8KHz and 115.2KHz, respectively, which are similar to the results of harmonic response analysis of 70kHz, 102.5KHz and 116.5KHz, and can correspond one-to-one. At 115.2KHz, The vibration amplitude is the largest, and the following fixed-frequency analysis focuses on this resonant frequency.

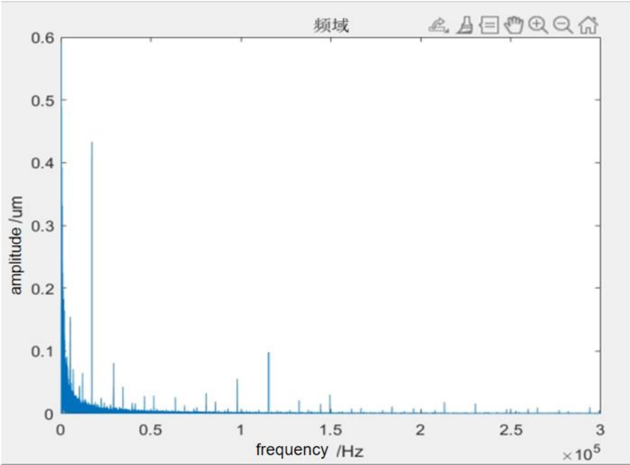

Fig. 11 Result of scanning frequency analysis

4.3. Atomized particle size detection


Fig. 12 Laser diffraction particle size analyzer

The particle size distribution and measurement of atomized particles were carried out using the laser diffraction particle size analyzer, as shown in Fig. 12, to detect the particle size of droplets when the resonant frequency was operating.

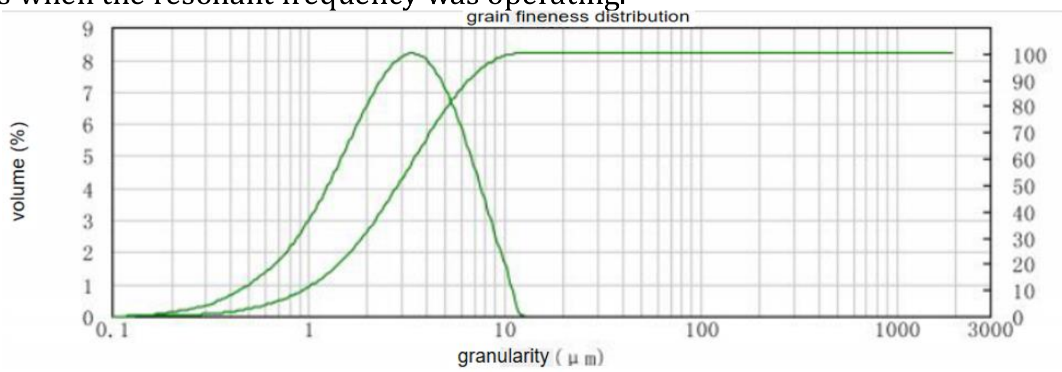

Fig. 13 Particle size test results

The analysis results of atomized particle size at 115.2kHz excitation frequency show that when the cumulative distribution of atomized droplets reaches 90%, the particle size is 6.67μm. At this time, the total volume of droplets smaller than this particle size exactly accounts for 90% of all droplets, and the proportion of droplets between 1 ~ 5μm is 67.5%, see Fig. 13.

5. Conclusion

In this paper, the vibration characteristics of a spherical coronal microporous atomizing plate are studied. The vibration characteristics and atomizing performance of the structure are studied in detail. The main conclusions can be drawn as follows:

1) The mathematical expressions of vibration deformation of piezoelectric ceramic plates and spherical coronal thin plates are established. It is shown that the axial and radial displacements of the ceramic plate can be generated under excitation, and the axial displacements of the spherical coronal plate can reach tens of times of the axial displacements of the piezoelectric ceramics themselves.

2) According to the simulation analysis results, the optimal resonant frequency of the atomizing plate is around 117.3kHz. Due to the addition of fluid, the natural frequency of the same mode as the dry mode decreases.

3) The experimental results show that the optimal resonance frequency is similar to the simulation results. At this frequency, the atomized particle size between 1 and 5 microns accounts for 67.5%, and the effective particle size of pulmonary deposition increases.

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