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Abstract:

In order to take into account the high amplification factor of the stepped ultrasonic scalpel horn and the high fatigue strength at the abrupt section of the curve transition horn, an ultrasonic scalpel acoustic composite horn with the most fast curve transition section was proposed, and a series of experiments were carried out on the ultrasonic scalpel acoustic system. Firstly, the equivalent T-type circuit of the ultrasonic scalpel energy transducer was constructed based on the equivalent circuit method. The mathematical model of the transition curve structure was established. On this basis, the structure of energy transducer was designed, and the overall structure and initial size of the ultrasonic transducer was obtained. Secondly, using ANSYS to analyze the modal analysis, harmonic response analysis, transient dynamic analysis and feasibility analysis of the most fast curve of the energy transducer. The simulation results verify the rationality of the theoretical calculation. Finally, the performance of the energy transducer was tested and analyzed by experiments, and the effectiveness of the designed transducer is verified. The results show that the ultrasonic scalpel acoustic system meets the design requirements.

Keywords: ultrasonic scalpel acoustic system ; equivalent circuit method ; transition curve structure ; structural design

1 Introduction

As an advanced surgical instrument, ultrasonic scalpel can be used in various soft tissue anatomical operations [1-3]. Compared with traditional scalpels, ultrasonic scalpels have higher cutting accuracy, less release of toxic surgical smoke [4], and can reduce the probability of safety hazards such as implanted electronic device failures [5]. Therefore, relevant scholars have conducted a lot of research on ultrasonic scalpel.

During endoscopic surgery, Minoru HASHIMOTO [6] installed a super-elastic alloy ( SEA ) design at the end of the ultrasonic scalpel. The maximum bending degree of the elastic alloy scalpel head can reach 60 degrees, and ultrasound is successfully applied to make it vibrate, but the amplitude will be greatly weakened during bending, resulting in its inability to perform tissue
cutting. Khalaji\textsuperscript{(7)} et al. developed a multi-degree-of-freedom ultrasonic scalpel, which realizes the 180-degree steering of the scalpel head through a simple mechanical arm articulated transducer and the scalpel head. Kim\textsuperscript{(8)} designed a wireless ultrasonic scalpel with enhanced power and amplitude performance, and compared it with the traditional wireless ultrasonic scalpel. It was found that the developed wireless ultrasonic scalpel can reduce the power consumption by 12.3%. Guo\textsuperscript{(9)} designed a hemostatic enhanced ultrasonic scalpel by adding a spiral groove at the end of the ultrasonic guide, but the ultrasonic scalpel produces more heat as the ultrasonic amplitude increases.

In order to improve the working performance of ultrasonic scalpel, relevant scholars have explored the influencing factors of the working performance of ultrasonic scalpel. Jeffrey and Kosuke\textsuperscript{(10, 11)} studied the influence of vibration amplitude, resonance frequency and holding force on the cutting performance of ultrasonic scalpel. The results show that the vibration amplitude and holding force of the tool end have the greatest influence on the cutting performance of the ultrasonic knife, while the resonant frequency has little effect on the cutting and hemostatic performance of the ultrasonic knife. He\textsuperscript{(12)} studied the effect of ultrasonic scalpel and the load characteristics of different tissues from three aspects: working frequency, input admittance and reflection factor. Rahul and Suvranu\textsuperscript{(13)} analyzed the temperature field of ultrasonic scalpel in contact with soft tissue by finite element method, and studied the hemostatic mechanism of ultrasonic scalpel cutting from the thermodynamic aspect, which provided a demonstration for the theoretical model of ultrasonic scalpel cutting.

As a key actuator of ultrasonic scalpel, ultrasonic transducer plays a vital role in the operation of ultrasonic scalpel. In order to deal with different types or different scenarios of surgery, reduce the difficulty of surgery, and reduce the risk of postoperative complications, scholars have made corresponding improvements and innovations based on their structural and functional characteristics. Kurosawa et al.\textsuperscript{(14)} designed a flat miniature ultrasonic scalpel transducer based on the piezoelectric ceramic drive mode, which can be used in microsurgery with endoscope for precise and subtle operation. Wakako et al.\textsuperscript{(15)} designed an ultrasonic scalpel transducer that can change the direction of vibration propagation by using a super-elastic nickel-titanium alloy wire as a waveguide, which can be applied to more complex surgical scenarios. Li et al.\textsuperscript{(16)} designed a sandwich-type miniature ultrasonic scalpel transducer. The small volume makes it possible to place the snake-shaped joint in its supporting design to degree of freedom operation of the ultrasonic scalpel. Dong et al.\textsuperscript{(17)}
designed a hemostatic enhanced ultrasonic scalpel transducer by adding a spiral groove at the end of the ultrasonic guide. The above studies focus on the portability and functional diversity of the transducer, but in the actual surgical environment, the stable operation of the ultrasonic scalpel is often needed. If the working frequency of the transducer is not equal to the resonant frequency, most of the energy will be consumed in the internal heat, resulting in difficulty in cutting, tool temperature rise, and difficulty in surgery.

In order to solve the above problems, this paper designs an ultrasonic scalpel transducer with the fastest curve transition structure. Firstly, the overall structure and dimension of the ultrasonic scalpel transducer are determined by theoretical derivation and simulation optimization. Then, the performance of the ultrasonic scalpel was tested by experiments.

2 Theoretical design of ultrasonic scalpel transducer structure

As shown in Fig.1, the ultrasonic scalpel transducer consists of piezoelectric ceramic wafer, front cover plate, back cover plate, horn, tool head, metal electrode plate and prestressed bolt.

![Fig.1 Schematic structure of the ultrasonic scalpel](image)

In order to successfully complete a variety of complex and difficult human surgery, ultrasonic scalpel must meet the following requirements: Resonance occurs at an operating frequency of 55.5 KHz, and the vibration mode is one-dimensional longitudinal vibration, and the output amplitude of the tool end is guaranteed to be greater than 40.3μm \(^{[18, 19]}\). Based on this, the initial operating frequency of the ultrasonic surgical transducer is set to 55.5 KHz, and the output amplitude of the tool end is greater than 40.3μm.

2.1 Material selection of each part of ultrasonic scalpel transducer
According to the comparison of standard medical material parameters, the materials of each component were selected and summarized\(^{[20]}\), see table 1. In order to ensure sufficient contact between the components, a pre-tightening bolt is used to apply a certain uniform prestress to the gasket connected to the piezoelectric ceramic. This prestress can also suppress PZT hysteresis, thereby providing better output performance.

**Table 1** Material selection of each component of ultrasonic scalpel transducer

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Back panel</th>
<th>Piezoelectric ceramics</th>
<th>Front slab &amp; Horn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>304</td>
<td>PZT-8</td>
<td>7075</td>
</tr>
<tr>
<td>Density (\rho/(\text{kg} \cdot \text{m}^{-3}))</td>
<td>7850</td>
<td>7800</td>
<td>2810</td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>210</td>
<td>71</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(GPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.3</td>
<td>0.33</td>
<td></td>
</tr>
</tbody>
</table>

In order to improve the transmission efficiency of ultrasonic energy from piezoelectric ceramics to the end of the ultrasonic scalpel, the material selection of the ultrasonic scalpel needs to meet the following acoustic impedance rules\(^{[21]}\).

\[
Z_f < Z_p < Z_b
\]

\[
\begin{align*}
Z_p &= \sqrt{Z_b \cdot Z_f} \\
Z_p &= \rho_p c_p
\end{align*}
\]

There, \(Z_f\), \(Z_p\), and \(Z_b\) represent the characteristic acoustic impedance of the front slab, piezoelectric ceramic, and rear cover materials, respectively.

### 2.2 Ultrasonic scalpel transducer structure design

#### 2.2.1 Electro-acoustic equivalent circuit of transducer

In order to obtain the ultrasonic frequency required by the acoustic system, the equivalent circuit method is used to theoretically design and analyze the transducer horn. According to the simplified model of the transducer horn and the Mason equivalent circuit, the equivalent circuit is established, as shown in Fig.2.
There, $Z_b$ and $Z_f$ are the input and output load impedance of the transducer; $PC_o$ is the static capacitance of the piezoelectric ceramic stack of the transducer; $n$ is the acoustic-electric conversion coefficient. The input end of the transducer can be regarded as hollow load, that is, $Z_b = 0$. Because the output end is often connected to different loads such as tool head or horn, the value of $Z_f$ is difficult to determine. Therefore, the transducer output end is also considered as hollow load in design, that is, $Z_f = 0^{[22]}$.

Taking the transducer part in Fig.2 as an example, the nodal plane is located between the front cover plates. $L_1 - L_3$ and $L_5 - L_9$ are 1/4 wavelengths respectively. When the transducer is in a resonant state, the transducer circuit has the largest current, the smallest impedance, and the highest acoustic-electric conversion efficiency. The static capacitance at the power supply is regarded as a path, the coil is regarded as an open circuit, and the displacement vibration velocity at the pitch surface is zero. Therefore, the left side of the equivalent circuit of the quarter-wavelength oscillator is also regarded as an open circuit, and the equivalent circuits on both sides of the pitch surface are transformed as shown in Fig.3.
According to Kirchhoff’s law, the total impedance in the equivalent circuit on both sides of the nodal plane and the equivalent impedance of each loop need to satisfy the following equations:

\[
\begin{align*}
Z_1 & = Z_{m1} + Z_{21} + Z_{23} \\
Z_{m1} & = Z_{11} Z_{13} / (Z_{11} + Z_{13}) + Z_{12} \\
Z_3 & = Z_{m3} + Z_{22} + Z_{23} \\
Z_{m3} & = (Z_{m4} + Z_{32}) Z_{33} / (Z_{m4} + Z_{32} + Z_{33}) + Z_{32} \\
Z_{m4} & = Z_{42} Z_{43} / (Z_{42} + Z_{43}) + Z_{41}
\end{align*}
\]

(3)

Among them, \( Z_L \) and \( Z_R \) are the total equivalent impedances of the equivalent circuits on the left and right sides of the nodal plane. \( Z_{mi} \) is the equivalent impedance of the \( i\)th loop in the equivalent circuit.

\[
\begin{align*}
Z_{i1} & = Z_{i2} = \frac{Z_i}{j \tan k_i l_i} - \frac{Z_i}{j \sin k_i l_i} \\
Z_{i3} & = \frac{Z_i}{j \sin k_i l_i}, \quad i = 1, 2, 3, 4
\end{align*}
\]

(4)

In the above equations, \( Z_i \) is the characteristic acoustic impedance of material \( i \): \( Z_i = \rho_i c_i s_i \), \( \rho_i \), \( c_i \), \( s_i \) are the density, longitudinal wave velocity and cross-sectional area of material \( i \), \( k_i = \frac{\omega}{c_i} \), \( k_i \) is the circular wave number of \( i \), \( \omega \) is the circular frequency, \( c_i = \frac{E_i}{2 \rho_i} \), \( E_i \) is the elastic modulus of \( i \).

The impedance values in Eq. (4) are brought into Eq. (3) \( Z_{m1} \), \( Z_{m3} \) and \( Z_{m4} \). When \( Z_i = 0 \), the frequency equation on the left side of the nodal plane is obtained:
\[
\frac{Z_1}{Z_2} \tan k_1 l_1 \tan \frac{k_1 l_2}{2} = 1 \quad (5)
\]

The total length of the piezoelectric ceramic stack is \( l_2 = 10mm \). The diameter of the back cover plate is the same as the outer diameter of the piezoelectric ceramic \( D_f = D_m = 16mm \).

Substituting it into Formula (3), the total axial length of the front cover plate is \( L_s = 9mm \), and the thickness of the bolt and the cover plate is 4.5mm respectively.

When \( Z_r = 0 \), the frequency equation on the right side of the nodal plane is obtained:

\[
\frac{Z_3}{Z_2} \tan \frac{k_3 l_3}{2} \tan k_3 l_3 + \frac{Z_4}{Z_2} \tan \frac{k_4 l_4}{2} \tan k_4 l_4 = 1 \quad (6)
\]

The diameter of the small end of the front cover plate \( D_2 = 12mm \) and the length of the large end \( L_s = 2mm \) are selected. The length of the small end \( L_s + L_s = 20.45mm \) can be obtained by substituting the parameters into formula (4).

Similarly, the frequency equation on both sides of the horn section is:

\[
\begin{align*}
\left\{ \begin{array}{l}
k_3 L_3 = \frac{\pi}{2} \\
k_4 L_4 = \frac{\pi}{2}
\end{array} \right.
\quad (7)
\]

The large end of the horn is connected with the front cover plate, so the diameter of the large end is \( D_2 = 12mm \), the diameter of the small end is \( D_3 = 6.4mm \), and the length of the large end is \( L_3 = 2mm \). The material parameters of the horn can be obtained by substituting the material parameters of the horn into the formula (4).

\[
L_6 + L_3 = L_8 + L_9 = \lambda / 4 = 22.75mm \quad (8)
\]

That is: \( L_6 = 20.75mm \).

2.2.2 Design of the fastest curve transition

In order to take into account the high amplification coefficient of the stepped horn and the high fatigue strength at the abrupt section of the curve transition horn, the fastest curve transition design
of the horn is carried out. In physics, the fastest curve can also be called the fastest descent line, the shortcut line, the roller line, etc., as shown in Fig.4. Its meaning is: the shortest path curve when a particle with zero initial velocity moves from point $A$ to point $B$ only by gravity\(^{[23]}\).

![Fig.4 The sketch of the fastest curve](image)

Studies have shown that the use of arc transition at the end of the horn can effectively reduce the stress concentration of the abrupt section and correct the actual resonance frequency\(^{[24]}\).

Therefore, this paper proposes a steepest curve as a transition curve, and applies the fastest curve to the step of the horn to achieve the purpose of correcting the resonance frequency and reducing the stress concentration of the abrupt pitch surface. The steepest curve horn is shown in Fig.5 below.

![Fig.5 The sketch of the fastest curve horn](image)

1. Motion trajectory of point $a$; 2. Motion direction of trajectory circle

From Figure 5, it can be seen that the curve contour is formed by a circle with radius $r_0$ rolling along the x-axis. A point $a$ on the circle moves forward a trajectory of $n\pi$ length along the x-axis
direction and when the motion length is \( r \pi \), \( y (x) \) reaches the maximum. Therefore, when the curve is used as the transition section, the value range of \( x \) should follow \( x \in [0, r \pi] \), and \( r_0 \) is the radius of the trajectory circle. The fastest curve is applied to the horn, and the Cartesian coordinate function expression is established according to the curve:

\[
x = r_0 \arccos\left(1 - \frac{y}{r_0}\right) - \sqrt{y(2r_0 - y)}
\]

(9)

According to the thin rod \( R, r \) at both ends of the step section, the radius of the moving circle can be obtained:

\[ r_y = (N - 1)/2r, \quad y \in [0, R - r] \]

(10)

In the formula, \( R \) and \( r \) are the radius of the end face of the horn, and the area coefficient of the horn is \( N = \frac{R}{r} \).

According to the diameter difference between the front slab and the end of the horn, the radius of the motion circle of the two parts is calculated: \( r_{b_1} = 2mm, \quad r_{b_2} = 2.8mm \).

Therefore, the axial lengths of the two transition sections are \( L_4 = 3.5mm, \quad L_5 = 16.95mm \), \( L_8 = 4.4mm, \quad L_9 = 18.35mm \), respectively.

According to the above analysis, the preliminary structure of the acoustic system of the ultrasonic scalpel is obtained, as shown in Figure 6, and the dimensions of each part are shown in Table 2.

![Fig.6 Initial structure of ultrasonic scalpel acoustic system](image)

**Table 2** Integral theoretical size of ultrasonic transducer
3 Design optimization of ultrasonic scalpel based on finite element simulation

The finite element model of the fastest curve ultrasonic scalpel is established by ANSYS. The modal analysis, harmonic response analysis, transient dynamic analysis and fatigue analysis of the ultrasonic scalpel transducer are carried out. The response surface method of the DOE module is used to optimize the axial size of the ultrasonic scalpel.

3.1 Establishment of finite element simulation model of transducer

According to the size parameters of each part of the transducer obtained in the previous section, SolidWorks software is used for parametric modeling, and Hypermesh is used for meshing. The meshing results are shown in Fig.7. The meshed model is imported into ANSYS for finite element analysis.
3.2 Modal analysis of transducer

The equipotential voltages of 1V and 0V are added to the positive and negative electrodes of each piezoelectric crystal. The modal extraction range is set to 45 ~ 65KHz, and the modal expansion order is set to 20. The modal analysis results of ultrasonic scalpel transducer are shown in Table 3. It can be seen from Table 3 that the longitudinal mode frequency is 55.5677 KHz, and the deviation from the design target value of 55.5KHz is 0.13%, which verifies the rationality of the theoretical calculation results.

<table>
<thead>
<tr>
<th>Number of mode</th>
<th>Modal vibration shape</th>
<th>Modal frequency (Hz)</th>
<th>Vibration type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>51305.3</td>
<td>Bending vibration</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>51600.6</td>
<td>Bending vibration</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>55104.9</td>
<td>Torsional vibration</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>55567.7</td>
<td>Longitudinal vibration</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>60346</td>
<td>Bending vibration</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>61099.7</td>
<td>Bending vibration</td>
</tr>
</tbody>
</table>

Fig.8 shows the vibration displacement distribution of the central axis when the vibration mode is extracted.

As shown in Fig.9, according to the amplitude coordinate parameters on the extraction path, the specific coordinates of the two nodes located on the x-axis are obtained. The nodes x1 and x2
are 13.94 mm and 62.94 mm, respectively, which are basically consistent with the positions of the nodes $x_1 = 14 mm$ and $x_2 = 62.93 mm$ obtained by theoretical design, and meet the design requirements of the minimum amplitude at these two positions, which verifies the rationality of the theoretical design again.

**3.3 Feasibility analysis of the fastest curve**

In order to compare the different characteristics of the designed fastest transition curve with other common transition curves, the finite element analysis of the performance parameters of various types of composite horns is carried out. The analysis results are shown in Table 4.

<table>
<thead>
<tr>
<th>Type</th>
<th>Pattern</th>
<th>Size parameter /mm</th>
<th>Resonance frequency /Hz</th>
<th>$M_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$l_1$ $l_2$ $l_3$</td>
<td>$N$</td>
<td>Theoretical value</td>
</tr>
<tr>
<td>The fastest curve</td>
<td>63</td>
<td>5.03 57.97 1.25</td>
<td>20000</td>
<td>19909</td>
</tr>
<tr>
<td>Best arc transition</td>
<td>63</td>
<td>8.37 54.63 1.5</td>
<td>20000</td>
<td>20007</td>
</tr>
<tr>
<td>Catenary transition</td>
<td>63</td>
<td>5.16 57.84 1.25</td>
<td>20000</td>
<td>19926</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>7.33 55.67 1.5</td>
<td>20000</td>
<td>19959</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>7.82 55.18 1.75</td>
<td>20000</td>
<td>20009</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>5.03 58.74 1.25</td>
<td>20000</td>
<td>19791</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>8.04 56.60 1.5</td>
<td>20000</td>
<td>19655</td>
</tr>
<tr>
<td></td>
<td>63</td>
<td>10.77 55.45 1.75</td>
<td>20000</td>
<td>19588</td>
</tr>
</tbody>
</table>

From the results of the finite element analysis in Table 4, it can be seen that the frequency correction effect of the fastest curve horn is equivalent to the best transition arc and obviously better
than the catenary transition when $N \in 1.25 - 1.75$; there is no difference between the vibration velocity amplification coefficient and the two, and it can be applied to the transducer designed in this paper.

### 3.4 Harmonic response analysis

A sinusoidal alternating voltage of $U = 30V$ is applied in the polarization direction of the piezoelectric ceramic, and $U = 0V$ is set in the opposite direction, and the structural damping coefficient is 0.001. The law of the displacement of the output end of the ultrasonic transducer with the frequency is extracted. The results are shown in Figure 10. The peak output amplitude of the designed ultrasonic transducer reaches 14μm at 55.486 Hz, which meets the requirements of 10 ~ 20μm.

![Fig.10 Displacement frequency response curve of transducer](image)

### 4 Test verification and analysis

#### 4.1 Acoustic performance test

Based on the results of theoretical design and simulation analysis, the pre-stressed bolts, front slab-horn and rear cover are processed and assembled, as shown in Fig.11. The impedance characteristic analyzer (JY-J301) is used to test the acoustic parameters of the transducer. The test frequency range is 55 ~ 56 kHz, and the test results are shown in Fig.12.
It can be seen from Fig. 12 that the resonant frequency of the transducer is 55.505 kHz, and the equivalent impedance is 8 at this frequency. This is 0.11 % different from the modal analysis result (55.5677 kHz), which is basically consistent with the design operating frequency (55.5 kHz) and meets the expected requirements.

At the output end of the transducer, a tool rod with an amplitude magnification of about 3.5 is connected by bolts, and the connection effect is shown in Fig. 13. The laser vibration measurement platform was built, and the LV-FS01 fiber-optic infrared laser vibrometer using Sunny OIT was tested. The sampling frequency was set to 120 kHz, and the measurement displacement accuracy was 0.01 μm. The position of the transducer flange is clamped by a fixture to make the transducer-tool bar fixed as a whole. The sensor laser is focused on the output surface of the end of the tool rod, and the amplitude is measured.

When the input working voltage is 30 V, the vibration amplitude of the front end of the cutter rod is shown in Fig. 14, and the peak amplitude is 53.30 μm. After calculation, the peak amplitude of the transducer end is about 15.23 μm, which meets the requirements of 10 ~ 20 μm. Fig. 14 is the amplitude of the tool end.
4.2 Ultrasonic scalpel performance test

The impedance and amplitude measurement methods are used to compare and analyze the ultrasonic scalpel designed in this paper and a mature ultrasonic scalpel on the market. Impedance tests were performed on two ultrasonic scalpels, and the key performance parameters of both are shown in Table 5. It is not difficult to see that the frequency of the two ultrasonic knives is less deviated from the working frequency of 55500Hz. In terms of quality factor, electromechanical coupling coefficient and other performance indicators, the self-developed ultrasonic scalpel is superior to a certain ultrasonic scalpel in the market, indicating that the ultrasonic scalpel designed in this paper has better performance.

Table 5 Comparison of measurement parameters of self-developed and market mature transducers

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Numerical value</th>
<th>Self-developed</th>
<th>A type of the market</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonance frequency (Hz)</td>
<td>55555</td>
<td>55650</td>
<td></td>
</tr>
<tr>
<td>Quality factor</td>
<td>1026.9</td>
<td>910.4</td>
<td></td>
</tr>
<tr>
<td>Electromechanical coupling coefficient</td>
<td>0.0790</td>
<td>0.0589</td>
<td></td>
</tr>
<tr>
<td>Dynamic inductance</td>
<td>425.69</td>
<td>645.39</td>
<td></td>
</tr>
<tr>
<td>Dynamic capacity</td>
<td>3.325</td>
<td>3.179</td>
<td></td>
</tr>
<tr>
<td>Equivalent impedance (Ω)</td>
<td>144.71</td>
<td>351.64</td>
<td></td>
</tr>
</tbody>
</table>
The amplitude of the ultrasonic scalpel is measured, and the vibration amplitude of the two scalpels under the same output power is compared. Different input powers are used to measure the amplitude of the ultrasonic scalpel, and the ultrasonic amplitude is compared when the tool bar is installed. According to the amplitude-power curve as shown in Fig. 15. From Fig. 15, with the increase of output power, the amplitude of the cutter head also increases, showing a certain linear relationship. In addition, when the tool bar is installed, when the input power is greater than or equal to 8W, the amplitude is greater than 40.3μm, which meets the design requirements.

![Amplitude-power curve](image)

**Fig.15 Amplitude-power curve**

### 4.3 Temperature characteristic analysis of piezoelectric crystal stack

Fig. 16 shows the temperature-amplitude relationship curve drawn based on the experimental data. Under the output power of 10 W, the temperature of the piezoelectric stack increases in 0 ~ 120 s and tends to be stable in 120 ~ 180 s. During the same period, the amplitude trend first decreased and then gradually stabilized. The amplitude value at 180 s was 48 μm. Compared with the amplitude value of 44.2 μm at 0 s, the deviation was only 3.8 μm, and the temperature increased by 21 °C. Under the output power of 15 W, the temperature of the piezoelectric crystal stack increases before 140 s, and tends to be stable around 140 s. The amplitude change is the same as above. The amplitude deviation from the beginning to the end is only 6.2μm, and the temperature is increased by 27.5 °C.

Obviously, at high power, the temperature climbs faster, the slope of the amplitude change curve becomes steeper, and the amplitude attenuates faster. In addition, during the experiment, there
There was no matching failure between the ultrasonic scalpel and the ultrasonic power supply, and the amplitude was less affected by the temperature rise, which verified the reliability of the ultrasonic scalpel design.

![Graphs showing temperature and amplitude over time](image)

**(a)** 10W output power excitation 180s  
**(b)** 15W output power excitation 180s

Fig. 16 Temperature-excitation time curve of ultrasonic scalpel

### 5 Conclusion

In this paper, the theoretical design, structural optimization, dynamic analysis and experimental test of the acoustic system of ultrasonic scalpel are carried out. Firstly, the equivalent circuit and frequency equation of the acoustic system of the ultrasonic scalpel are established based on the acoustic-electric analogy method, and the design of the transducer structure size is completed through the frequency equation. In order to verify the rationality of the calculation of the structural size of the transducer, the acoustic performance of the transducer is analyzed by finite element software. The multi-type transition curve horn is compared and analyzed to verify the feasibility of the transition curve application. Finally, the performance of the ultrasonic scalpel transducer was tested through experiments: it was found that the ultrasonic scalpel had excellent performance parameters.

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Data availability All data generated or analyzed during this study are included in the present article.

Declarations

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