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# Method for Calculating an Ultrasonic Scalpel with a $1\frac{1}{2}$ -Wave Acoustic Scheme and Enhanced Cavitation Surface

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Ultrasonic phacoemulsifiers and scalpels have transformed cataract surgery, enabling minimally invasive procedures through small incisions while minimizing trauma to ocular tissues. Despite its potential to clean the trabecular meshwork of the anterior chamber angle, restore its elasticity, and reduce intraocular pressure, applying ultrasonic cavitation in glaucoma surgery has not been fully implemented so far. A mathematical model of an ultrasonic scalpel for an ophthalmic phacoemulsifier used in glaucoma treatment has been developed in this study, based on a  $1\frac{1}{2}$ -wave vibrational drive for longitudinal displacements with a symmetric piezoelectric transducer. This model enabled the calculation of acoustic longitudinal dimensions and the simulation of its operation at the resonant frequency. The reciprocating-rotational oscillations of the scalpel needle are achieved by incorporating helical grooves on the surface of the larger-diameter stage of the first ultrasonic velocity transformer, which is in direct contact with the piezoceramic transducer. To enhance the convenience of surgical intervention and reduce the risk of damaging internal eye structures, the tip of the ultrasonic scalpel needle is angled at approximately  $15^\circ$ . The simulation results determined the resonant frequencies of the ultrasonic scalpel with a straight and angled tip, which were 48,373 Hz and 48,702 Hz, respectively. Additionally, the vibration mode of the angled needle tip was identified, exhibiting both longitudinal and bending components, confirming the proposed concept of using an angled tip to improve surgical convenience and reduce the risk of injury to internal eye structures. The implementation of the developed ultrasonic scalpel for glaucoma treatment addresses a significant scientific and applied challenge in modern ophthalmology and mechanical engineering.

**Keywords:** ultrasound; ultrasonic cavitation; sound-capillary effect; elasticity; scalpel; glaucoma; trabecula

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## Introduction

Despite the rapid development and widespread adoption of innovative technologies in diagnosing and treating glaucoma, this disease unfortunately remains the leading cause of disability and irreversible blindness worldwide, including in Ukraine [1, 2]. The introduction of advanced technologies in medicine has opened new opportunities for doctors. Using ultrasonic phacoemulsifiers and ultrasonic scalpels in surgical treatment of cataracts has ushered in a new era of performing minimally invasive eye surgeries, enabling interventions through incisions smaller than 1.2–1.3 mm without causing secondary traumatic damage to eye tissues [3].

However, using ultrasonic cavitation in the surgical treatment of glaucoma has not yet found its proper application. Nevertheless, preliminary studies suggest that applying an ultrasonic scalpel to clean the trabecular meshwork of the anterior chamber angle, due to the secondary effects accompanying the

phenomenon of ultrasonic cavitation, holds certain promise. Utilizing ultrasonic cavitation makes it possible, through the sound-capillary effect, to clear the pores of the trabecular meshwork, restore and preserve its elasticity, reduce resistance to aqueous humor outflow, and, as a result, lower intraocular pressure, thereby contributing to the successful treatment of glaucoma and preventing the progression of this disease [4–6].

The source of excitation of vibrations in the ultrasonic scalpel is an ultrasonic vibration drive, which creates reciprocating and reciprocating movements. This ultrasonic vibration drive includes an ultrasonic piezoelectric transducer and a vibration speed transformer with an end working surface, as well as a needle that is longitudinally tightly attached at one end to the end working surface of the vibration speed transformer, forming an additional vibration speed transformer. The other end of the needle features a ball-shaped working surface, which signi-

ificantly increases the area of the cavitating surface. The scalpel includes a sealed longitudinal channel that enables aspiration, which is the suction of fluid with fine contaminant particles from the surgical site.

It should be noted that in ophthalmology, a similar ultrasonic scalpel with an open tip, without a ball at the end of the needle, has recently been introduced for performing minimally invasive surgeries aimed at cataract removal. This type of scalpel, due to its high-frequency vibrations and the open sharp tip of the needle, allows the cloudy lens of the eye to be broken down for subsequent removal and replacement with an intraocular lens. However, using such a scalpel for cleaning the trabecular meshwork is not feasible, since the small surface area of the thin-walled needle tip does not allow for the formation of a sufficiently developed cavitation zone needed to induce the sound-capillary effect. Moreover, due to the pressure difference in the longitudinal aspiration channel, adjacent eye tissues –

including the surface of the trabecular meshwork – are drawn into the channel, and the sharp open needle tip causes significant trauma to these structures.

The aim of this study is to develop a mathematical model of an ultrasonic scalpel for adapting known ophthalmic phacoemulsifiers for the treatment of glaucoma by using secondary effects that accompany the phenomenon of ultrasonic cavitation, which will allow performing minimally invasive surgical interventions. The advantages of this study are the calculation of the acoustic scheme of the ultrasonic scalpel of the ophthalmic phacoemulsifier for the treatment of glaucoma, the justification for the development of a mathematical model, finite element modeling of the vibration transducer, the calculation of the acoustic longitudinal dimensions of the ultrasonic scalpel and the modeling of its operation at the resonant frequency.

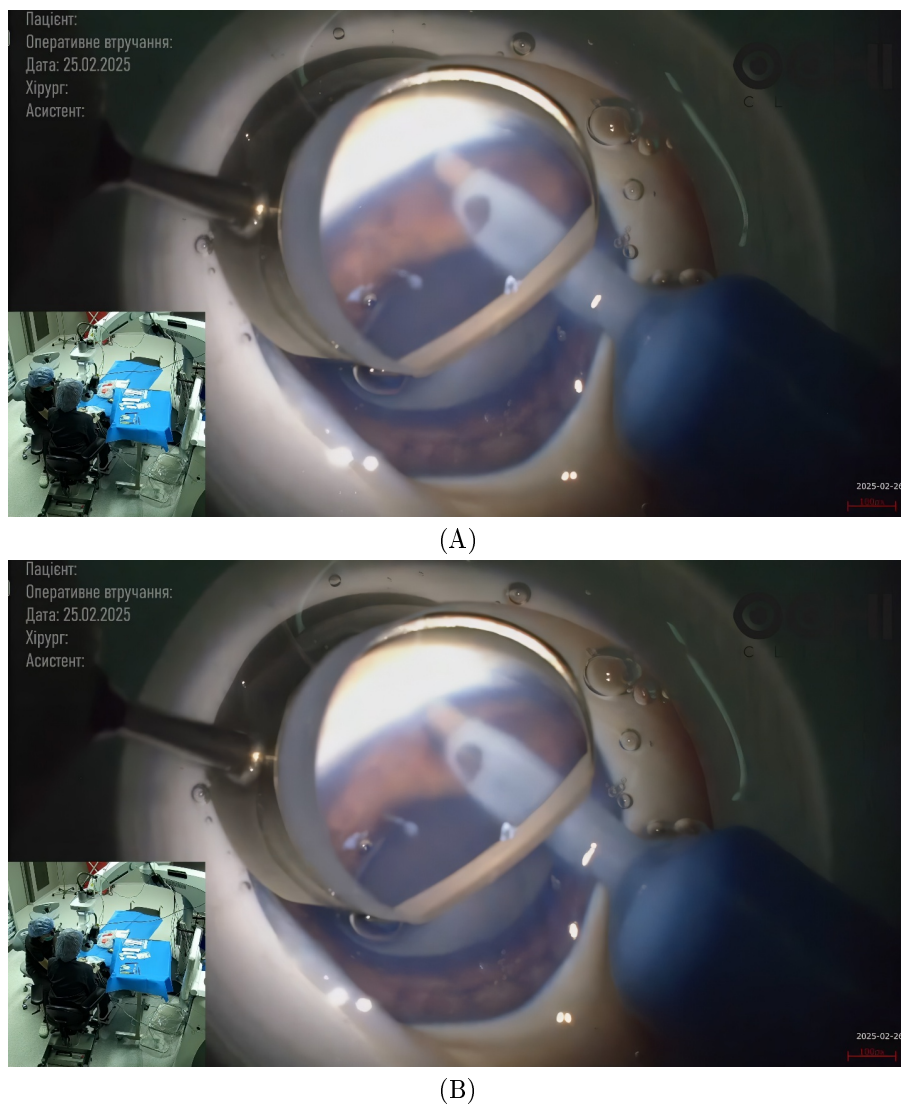


Fig. 1. Stages of trabecular cleaning with a scalpel with an open sharp end of the needle: A – no aspiration, B – suction of the trabecular meshwork into the open end of the scalpel during aspiration

By modeling in the experiment of a clinical situation to reproduce glaucoma in the experimental eye of an animal, the stages of trabecular cleaning were carried out using an open-ended scalpel, without a ball at the end of the needle. The stages of trabecular cleaning are shown in Fig. 1, A-B. The results demonstrate (Figure 1, B) that during aspiration, the trabecular meshwork is sucked into the open end of the scalpel. The open sharp end of the needle destroys the trabecular meshwork and surrounding eye tissues.

Injuring the structures of the eye during surgical interventions in the treatment of glaucoma is unacceptable.

## 1 Ultrasonic Scalpel Acoustic Scheme Calculation

The equation of longitudinal vibrations of an ultrasonic piezoelectric composite transducer can be written in the general form as [7–14]

$$S \frac{\partial^2 U}{\partial t^2} = c^2 \frac{\partial}{\partial x} \left( S \frac{\partial U}{\partial x} \right), \quad (1)$$

where:  $U$  is longitudinal displacement;  $S$  is cross-sectional area of the transducer component;  $c$  is speed of sound in the material of the transducer component.

Since, in this case, it is assumed that the ultrasonic composite transducer has a certain natural frequency and performs harmonic oscillations, the solution to equation (1) can be expressed as

$$U(x, t) = U(x) (P \sin \omega t + Q \cos \omega t).$$

Then, for the end cap that reduces the frequency and the adjacent piezoceramic washer, the equations can be written as follows

$$U_1(x, t) = \left( A \cos \frac{\omega}{c_1} x + B \sin \frac{\omega}{c_1} x \right) \sin(\omega t + \phi) \quad (2)$$

and

$$U_2(x, t) = \left( C \cos \frac{\omega}{c_2} x + D \sin \frac{\omega}{c_2} x \right) \sin(\omega t + \phi), \quad (3)$$

where  $c_1$  and  $c_2$  denote the speed of sound in the material of the frequency-reducing cap and the piezoceramic washer, respectively.

According to the calculation scheme of the ultrasonic scalpel (Fig. 2), which represents the most convenient  $1\frac{1}{2}$ -wave oscillating system in ophthalmological practice, the boundary conditions for the oscillating system with the origin at point  $O_1$ , can be represented as

$$U_2 = 0 \quad \text{at} \quad x = 0; \quad (4)$$

$$\frac{\partial U_1}{\partial x} = 0 \quad \text{at} \quad x = a_1 + a_2; \quad (5)$$

$$\left. \begin{aligned} U_1 &= U_2 \\ E_1 S_1 \frac{\partial U_1}{\partial x} &= E_2 S_2 \frac{\partial U_2}{\partial x} \end{aligned} \right\} \quad \text{at} \quad x = a_2, \quad (6)$$

where  $a_1, E_1, S_1$  and  $a_2, E_2, S_2$  are the thickness, tensile modulus of elasticity, and end surface area of the frequency-reducing pad and the piezoceramic washer, respectively.

Under condition (4) from equation (3), we obtain:

$$C = 0. \quad (7)$$

Hence follows the expression:

$$U_2(x, t) = D \sin \frac{\omega}{c_2} x \sin(\omega t + \phi). \quad (8)$$

Condition (5) allows us to obtain the following equality from equation (2)

$$B \cos \frac{\omega}{c_1} (a_1 + a_2) = A \sin \frac{\omega}{c_1} (a_1 + a_2).$$

From which

$$B = A \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2). \quad (9)$$

Substituting equation (9) into equation (2), we get:

$$U_1(x, t) = A \left[ \cos \frac{\omega}{c_1} x + \sin \frac{\omega}{c_1} x \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) \right] \sin(\omega t + \phi). \quad (10)$$

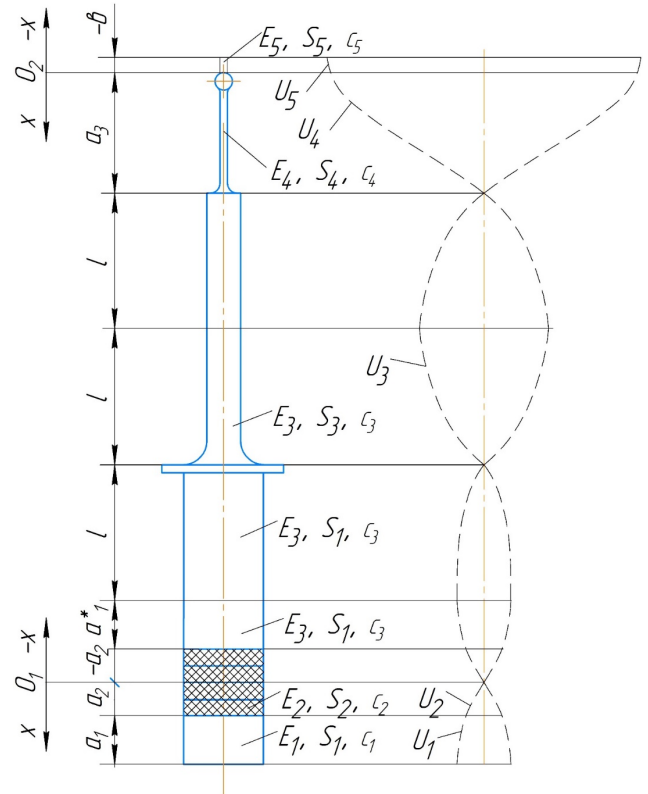


Fig. 2. Acoustic calculation scheme of the ophthalmic phacoemulsifier scalpel for glaucoma treatment based on a  $1\frac{1}{2}$ -wavelength vibration drive of longitudinal displacements with a symmetric piezoelectric transducer

The first half of the boundary conditions (6) allows, considering equations (8) and (10), to write

$$D \sin \frac{\omega}{c_2} a_2 = A \left[ \cos \frac{\omega}{c_1} a_2 + \sin \frac{\omega}{c_1} a_2 \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) \right].$$

From which we obtain the expression:

$$D = \frac{A}{\sin \frac{\omega}{c_2} a_2} \left[ \cos \frac{\omega}{c_1} a_2 + \sin \frac{\omega}{c_1} a_2 \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) \right]. \quad (11)$$

Considering the second half of the boundary conditions (6), after differentiating equations (8) and (10), we can write

$$\begin{aligned} E_1 S_1 \frac{A}{c_1} \left[ \cos \frac{\omega}{c_1} a_2 \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) - \sin \frac{\omega}{c_1} a_2 \right] = \\ = E_2 S_2 \frac{D}{c_2} \cos \frac{\omega}{c_2} a_2. \end{aligned} \quad (12)$$

After solving equations (11) and (12) together, we get:

$$\frac{E_1 S_1 c_2}{E_2 S_2 c_1} = \frac{\operatorname{ctg} \frac{\omega}{c_2} a_2 \left[ \cos \frac{\omega}{c_1} a_2 + \sin \frac{\omega}{c_1} a_2 \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) \right]}{\cos \frac{\omega}{c_1} a_2 \operatorname{tg} \frac{\omega}{c_1} (a_1 + a_2) - \sin \frac{\omega}{c_1} a_2}. \quad (13)$$

From which we can write:

$$a_1 = \frac{c_1}{\omega} \operatorname{arctg} \frac{E_2 S_2 c_1 \operatorname{ctg} \frac{\omega}{c_2} a_2 + E_1 S_1 c_2 \operatorname{tg} \frac{\omega}{c_1} a_2}{E_1 S_1 c_2 - E_2 S_2 c_1 \operatorname{ctg} \frac{\omega}{c_2} a_2 \operatorname{tg} \frac{\omega}{c_1} a_2} - a_2. \quad (14)$$

Considering that the angular frequency  $\omega = 2\pi f$ , where  $f$  is the excitation generator frequency, equation (14) allows calculating the thickness of the frequency-reducing cap, given the material parameters, as well as the selected size and material type of the piezoceramic washer. If, according to the acoustic calculation scheme (Figure 2), the design of the symmetric composite piezoelectric transducer is used, and the second frequency-reducing cap is made from the same material as the first, we can write:  $a_1 = a_1^*$  (Fig. 2).

Otherwise, to determine  $a_1^*$  it is necessary to use equation (14) again, replacing  $E_1, c_1$  with  $E_3, c_3$ , respectively. Typically, this second cap is made as an integral part of the first ultrasonic velocity transformer.

To calculate the second ultrasonic velocity transformer, which in the considered scheme is represented by a stepped concentrator with a load in the form of a spherical-ended ball on the end of the smaller-diameter step, we use the general form of the longitudinal vibration equation (1). Since in this case the assumption is also valid that the concentrator has a natural frequency and performs harmonic oscillations, the solution to equation (1) can be expressed as:

$$U_4(x, t) = \left( A \cos \frac{\omega}{c_4} x + B \sin \frac{\omega}{c_4} x \right) \sin(\omega t + \phi). \quad (15)$$

For simplicity, the larger-diameter section of the velocity transformer and the smaller-diameter section

(the needle) are assumed to be made of the same corrosion-resistant material.

Likewise, for a cylinder that is mass-equivalent to the structural element with a spherical surface, which, when vibrating, will ensure the formation of the cavitation region, the following expression can be written:

$$U_5(x, t) = \left( C \cos \frac{\omega}{c_5} x + D \sin \frac{\omega}{c_5} x \right) \sin(\omega t + \phi), \quad (16)$$

where  $c_5$  is the speed of sound in the material of the cylinder that is mass-equivalent to the element with a spherical surface.

The boundary conditions for the oscillatory system with the origin of coordinates at point  $O_2$  can be written as follows:

$$U_4 = 0 \quad \text{at } x = a_3; \quad (17)$$

$$\left. \begin{aligned} U_4 &= U_5 \\ E_4 S_4 \frac{\partial U_4}{\partial x} &= E_5 S_5 \frac{\partial U_5}{\partial x} \end{aligned} \right\} \quad \text{at } x = 0; \quad (18)$$

$$\frac{\partial U_5}{\partial x} = 0 \quad \text{at } x = -b, \quad (19)$$

where  $E_5$  is the Young's modulus of the material of the spherical ball;  $S_4$  and  $S_5$  are the cross-sectional areas of the smaller-diameter step of the velocity transformer and the equivalent cylinder, respectively;  $a_3$  is the length of the smaller-diameter step of the transformer;  $b$  is the height of the equivalent cylinder.

With regard to condition (17), equation (15) can be written as follows:

$$\begin{aligned} A \cos \frac{\omega}{c_4} a_3 &= -B \sin \frac{\omega}{c_4} a_3; \\ B &= -\frac{A}{\operatorname{tg} \frac{\omega}{c_4} a_3}. \end{aligned} \quad (20)$$

Considering the first part of condition (18), equations (15) and (16) give:

$$A = C. \quad (21)$$

The second part of condition (18) can be transformed into the following form:

$$E_4 S_4 c_4 B = E_5 S_5 c_5 D. \quad (22)$$

Condition (19) allows us to obtain from equation (16):

$$-C \sin \left[ \frac{\omega}{c_5} (-b) \right] + D \cos \left[ \frac{\omega}{c_5} (-b) \right] = 0.$$

From which we have:

$$D = -C \operatorname{tg} \frac{\omega}{c_5} b. \quad (23)$$

Then, taking into account (22), it can be written as:

$$\frac{A}{\operatorname{tg} \frac{\omega}{c_4} a_3} E_4 S_4 c_4 = C E_5 S_5 c_5 \operatorname{tg} \frac{\omega}{c_5} b$$

or, considering equation (21), we obtain:

$$\operatorname{tg} \frac{\omega}{c_4} a_3 \operatorname{tg} \frac{\omega}{c_5} b = \frac{E_4 S_4 c_4}{E_5 S_5 c_5}. \quad (24)$$

Then, it can be written as:

$$a_3 = \frac{c_4}{\omega} \operatorname{arctg} \frac{E_4 S_4 c_4}{E_5 S_5 c_5 \operatorname{tg} \frac{\omega}{c_5} b}. \quad (25)$$

The length of the larger-diameter step of the second velocity transformer will be determined from expression (25), considering that, in the absence of a load at the end of the smaller-diameter step of the stepped transformer,  $b = 0$  and  $a_3 = l$ :

$$l = \frac{c_3}{\omega} \frac{(2n-1)\pi}{2}, \quad (26)$$

where  $n$  is the order of oscillations.

In the case when  $n=1$ , that is, when the length of the step is equal to  $\frac{1}{4}$  of the longitudinal deformation wavelength, we obtain:

$$l = \frac{c_3}{\omega} \frac{\pi}{2},$$

that is

$$l = \frac{c_3}{4f}. \quad (27)$$

The volume of the structural element with a spherical surface (Fig. 3) at the end of the scalpel needle can be expressed by the following equation

$$V = V_{\text{sph}} - V_{\text{asp.channels}}, \quad (28)$$

where  $V_{\text{sph}}$  and  $V_{\text{asp.channels}}$  denote the volume of the spherical bead and the aspiration channels, respectively.

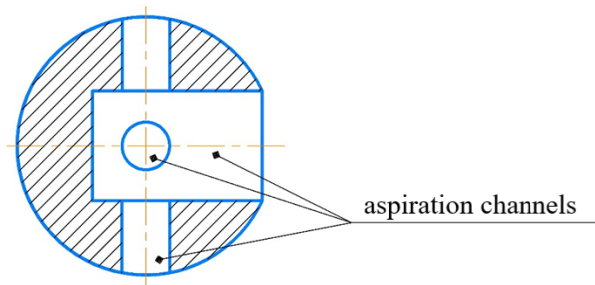


Fig. 3. Constructive element with a spherical surface at the end of the ultrasonic scalpel needle

Then the mass of this structural element is defined as:

$$m_k = \frac{E_4}{c_4^2} V. \quad (29)$$

For a cylinder equivalent in mass to the structural element with a spherical surface, the following expression can be written:

$$m' = \frac{E_5}{c_5^2} S_5 b. \quad (30)$$

By comparing expressions (29) and (30), we obtain:

$$b = \frac{E_4 V c_5^2}{c_4^2 E_5 S_5}. \quad (31)$$

If the structural element with a spherical surface is made of the same material as the scalpel needle, one can write:

$$a_3 = l - b. \quad (32)$$

The reciprocating rotational oscillations of the scalpel needle are ensured by the helical grooves made on the surface of the larger-diameter section of the first ultrasonic vibration velocity transformer, which is in direct contact with the piezoceramic transducer.

## 2 Justification for the Mathematical Model of the Ultrasonic Scalpel

To determine the resonant frequency of the ultrasonic scalpel, a finite element model of the vibration transducer was created. The transducer consists of a stepped concentrator made of 12Kh18N9T stainless steel, four piezoelectric rings made of APC-841 piezoceramic, and a frequency-lowering plate also made of 12Kh18N9T stainless steel (Table 1).

Acoustic contact exists between all components of the transducer, ensuring the propagation of the ultrasonic wave along the entire length of the transducer, achieved by compressing all components into a package using a stud and a nut. In the modeling, the stud and nut were not included in the calculations. In modeling, a bond simulating acoustic contact was specified between all contacting components of the transducer.

Table 1 Finite element model of the vibration transducer

| Component                  | Concentrator      | Step-down horn    | Piezoceramic     |
|----------------------------|-------------------|-------------------|------------------|
| Material                   | 12X18H10T         | 12X18H10T         | PCM-41           |
| Young's modulus, MPa       | $1,95 \cdot 10^5$ | $1,95 \cdot 10^5$ | $6,3 \cdot 10^4$ |
| Poisson's ratio            | 0,3               | 0,3               | 0,3              |
| Density, kg/m <sup>3</sup> | 7900              | 7900              | 7600             |

When modeling ultrasonic systems, the natural frequencies, vibration modes and their harmonics, locations of stress nodes and antinodes, selection of waveguide mounting points in the housing, and even the amplitude values of working surface vibrations are determined (in this work, calculation of concentrator vibration amplitudes was not performed).

The calculation consists of frequency analysis, which allows determining the natural

frequencies, modes, and harmonics of the transducer vibrations. The modeling frequency range was 42–58 kHz. A 4-node tetrahedron C3D4 was selected as the finite element type for the components.

The presented mathematical model made it possible to calculate the acoustic longitudinal dimensions of the ultrasonic scalpel of the ophthalmic phacoemulsifier for glaucoma treatment (Figs. 4–5) and to simulate its operation at the resonance frequency (Figs. 6–9).

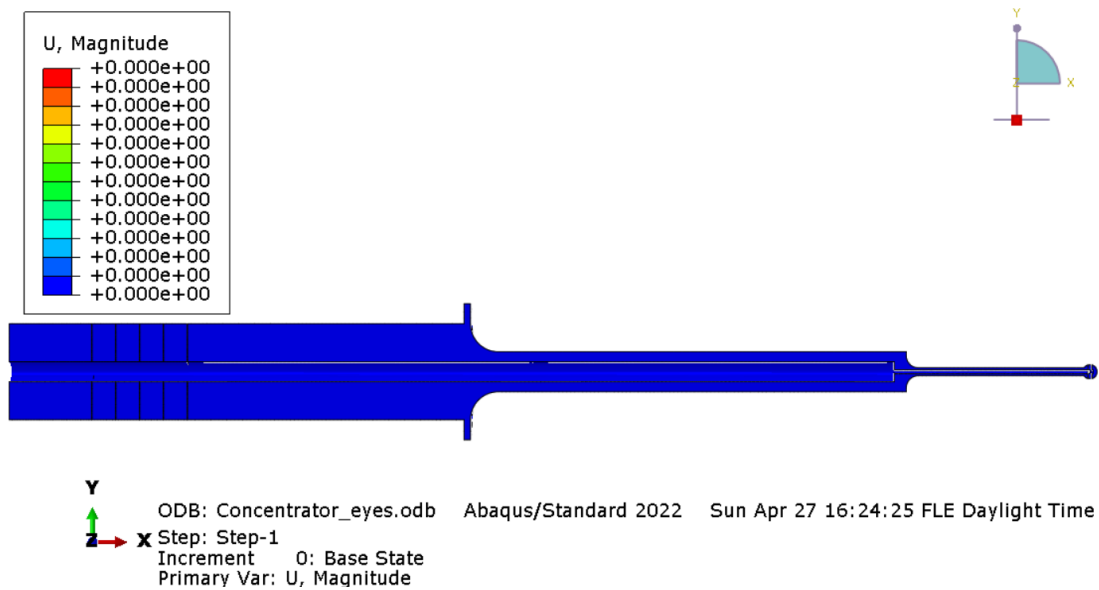


Fig. 4. Computational model of the ultrasonic scalpel of the ophthalmic phacoemulsifier for glaucoma treatment based on a  $1\frac{1}{2}$ -wavelength longitudinal vibration actuator with a symmetrical piezoelectric transducer

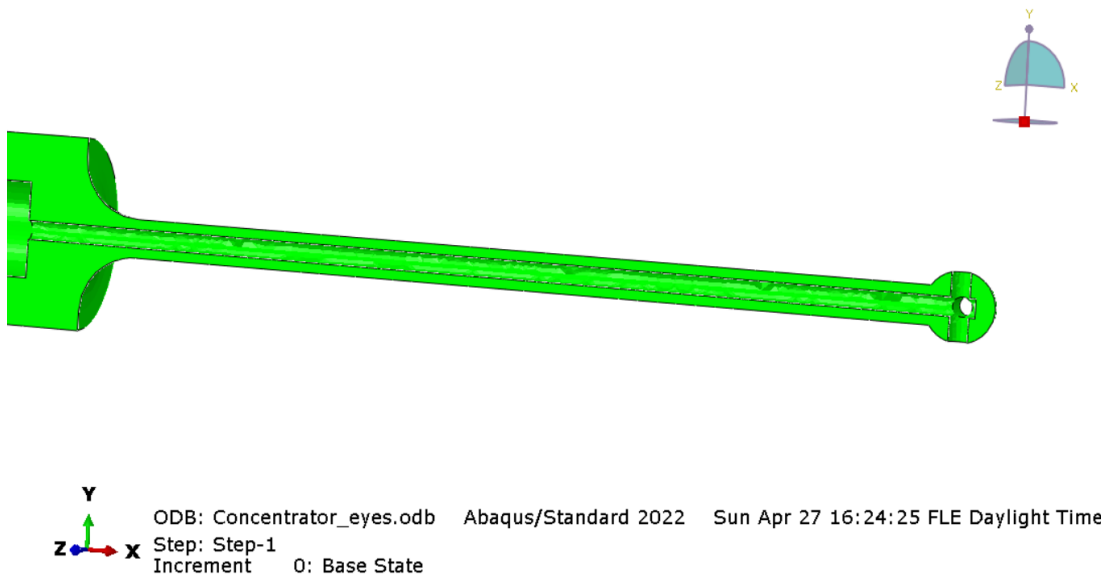


Fig. 5. 3D model of the straight needle of the ultrasonic scalpel with a spherical tip

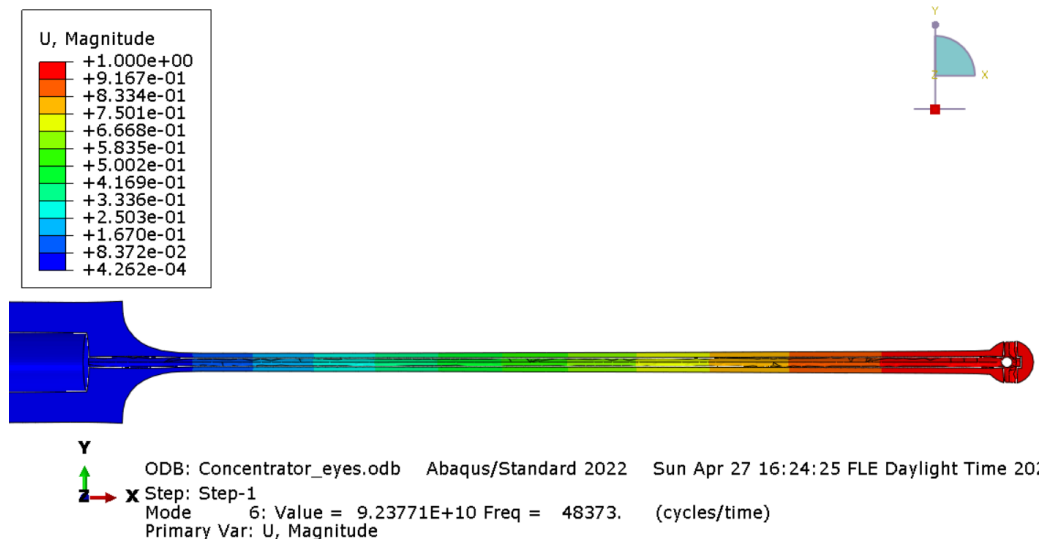


Fig. 6. Simulation of the excitation of the ultrasonic scalpel at the resonance frequency

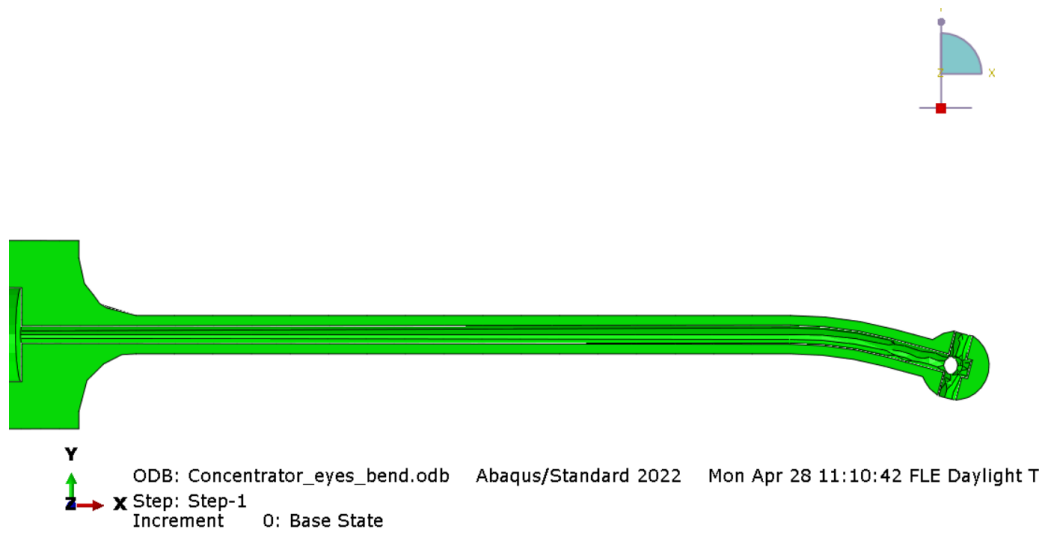


Fig. 7. Needle with an inclined tip

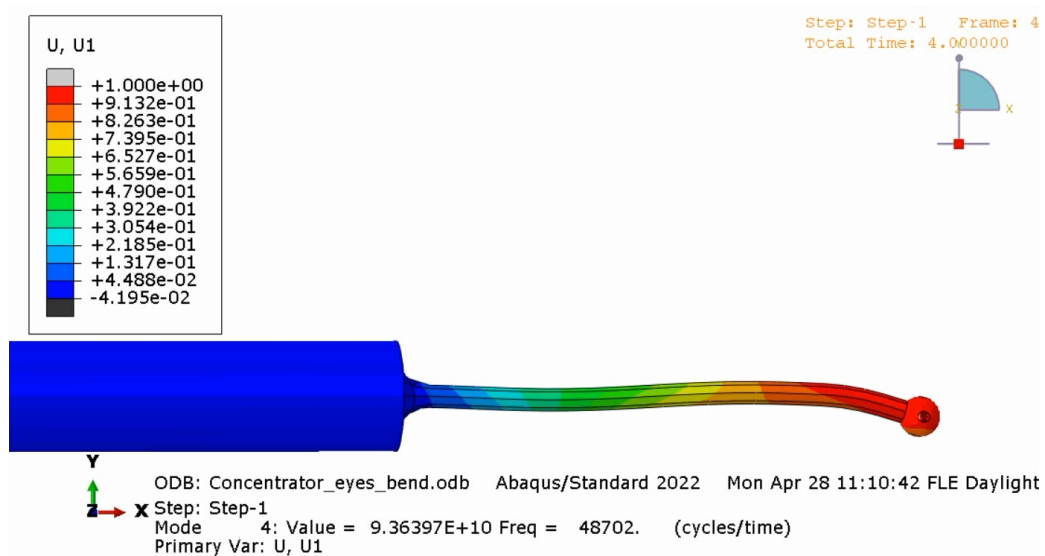


Fig. 8. Simulation of the excitation of the ultrasonic scalpel at the resonance frequency in the case of an inclined needle tip with a spherical tip

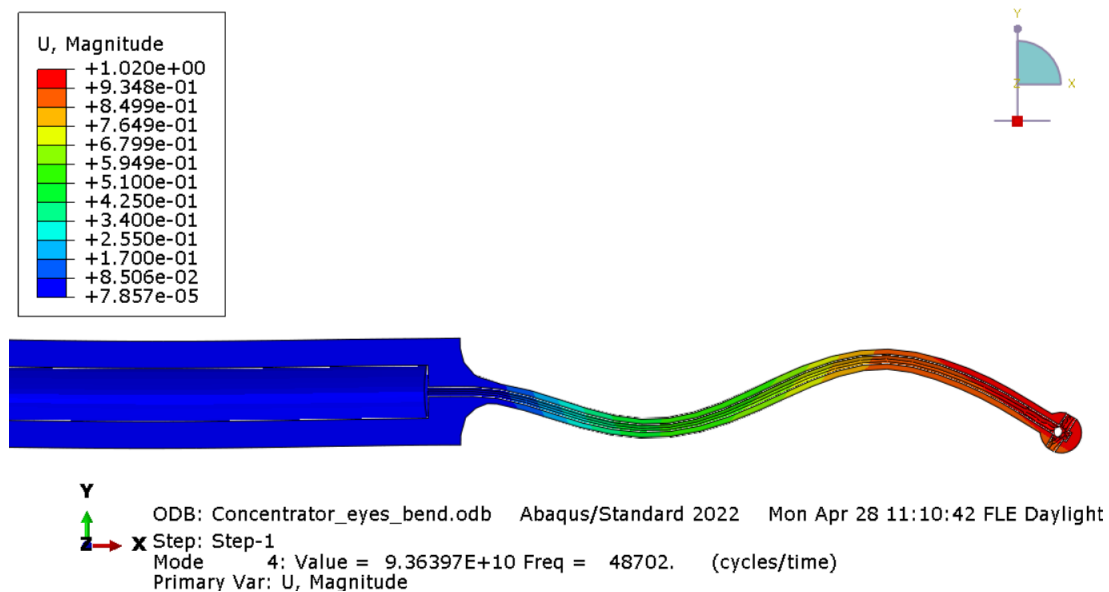


Fig. 9. Bending oscillations of the needle with an inclined tip and spherical end at the resonance frequency in an enlarged scale

As a result of the modeling, the resonant frequency of the scalpel vibrations was obtained – 48,373 Hz.

To increase the convenience of the surgical intervention and reduce the risk of damaging the internal elements of the eye, the tip of the ultrasonic scalpel needle is made inclined by approximately 15°. When longitudinal oscillations of the needle are excited, a transverse component is generated, which induces bending oscillations in the needle. Since the inclined part of the needle is approximately 2–3 mm long, such a structural inclination in the working frequency range of resonance frequencies (22–66 kHz) should not significantly affect the shape of the oscillations at the tip of the needle [9]. However, the considerable length of the needle, its small diameter with a longitudinal hole (wall thickness approximately 0.2 mm), as well as the inertial load in the form of the spherical tip, lead to the formation of bending oscillations in the needle, i.e., the final stage of the vibration velocity transformer of the scalpel (Figs. 8,9), which may result in fatigue failure of the needle.

The resonant frequency of the scalpel with a needle having an angled tip is noted to be 48,702 Hz.

### 3 Discussion

In medicine and in particular in ophthalmology, an ultrasonic scalpel of an ophthalmic phacoemulsifier has been introduced, which is widely used in the treatment of cataracts [15,16]. The discovery of phacoemulsification has been a boon for the medical community, since it has become possible to emulsify the cataracts through a small incision of 2–3 mm, providing ideal visual results for the patient. To date, several modifications of scalpels for cataract removal have been developed,

the structure of which has common features [15–19]: a source of excitation of ultrasonic vibrations in the form of an ultrasonic vibration drive of reciprocating and reciprocating movements, which contains an ultrasonic transducer and a transformer of oscillation speed with an end working surface and a through longitudinal sealed hole.

Furthermore, the scalpel contains a straight hollow needle, which is longitudinally tightly attached at one end to the end working surface of the oscillatory velocity transformer with the possibility of aspiration from the eye of destroyed lens particles from the surgical site. A flexible system for supplying a replacement irrigation fluid is attached to the hollow needle (phaco needle) from the outside, which helps remove the destroyed particles of the lens. During the operation, the lens is destroyed by creating intense movements of the end of the needle with an ultrasonic frequency.

However, all known ultrasonic scalpels of ophthalmic phacoemulsifiers [15–19] have a number of limitations: the area of the thin-walled end surface of the needle is very small, as a result of which the phenomenon of ultrasonic cavitation during needle oscillations is practically not observed, which makes it impossible to use the secondary effects that accompany the phenomenon of ultrasonic cavitation. It should also be noted that the scalpel tip is sharp, which can lead to injury and destruction of eye structures upon direct contact.

In addition, the known ultrasonic scalpels of the ophthalmic phacoemulsifier are not adapted and are not used in the treatment of such a common disease as glaucoma. Glaucoma is a disease that is very important to treat, given the large number of factors that cause it. The main one among them is an increased intraocular pressure due to the impaired outflow through the

trabecular apparatus of the eye, namely the trabecular meshwork, which becomes clogged with eye metabolic products throughout a person's life, increasing resistance to aqueous humor outflow from the eye.

According to the acoustic scheme of the phacoemulsifier vibration drive, the scalpel needle tip is located at the antinode of the established longitudinal deformation wave, that is, it deforms with maximum oscillation amplitude. This leads to intensive heating of the working needle tip, which must be taken into account when adjusting the power consumed by the ultrasonic transducer. At the same time, additional heating of the aqueous humor and eye tissues due to heat energy release during cavitation bubble collapse in the developed cavitation region near the spherical surface at the needle tip must also be considered.

It should be noted that to date, the principle of trabecular meshwork cleaning using ultrasonic cavitation and its secondary effects, the sonocapillary effect, cleaning the pores of the trabecular meshwork, restoring and maintaining the elasticity of the trabecular meshwork, reducing the resistance to the outflow of aqueous humor and, as a result, reducing intraocular pressure for the successful treatment of glaucoma has not been considered by scientists as a method of treating glaucoma. In the literature available to us, we did not find a single literary source that described similar studies [20–22]. All this made the dissertation research relevant, determined the goal and objectives of this work and was reflected in the application for a patent for an invention (a 2025 02635, N-28866/2025, 03.06.2025) and a utility model (u 2025 02636, N-28873/2025, 03.06.2025).

The innovation we propose consists in modeling the tip of the scalpel with a new spherical surface shape, the diameter of which is larger than the outer diameter of the needle. The spherical tip of the scalpel has holes that are connected to the longitudinal aspiration channel of the needle. This will allow, due to the sonocapillary effect and secondary effects during the collapse of cavitation bubbles, to remove small particles of the products of the vital activity of eye cells and will help to restore microholes in the trabecular meshwork of the eye and restore its elasticity without injuring the surrounding tissues.

Generating an ultrasonic cavitation zone inside the eye is noted to facilitate non-pharmacological sterilization of the ocular fluid against harmful microorganisms through cavitation-induced oxidation, as well as thermal and mechanical effects [8]. Further research is required to assess the molecular stability of medicinal solutions used during surgical procedures under the influence of ultrasonic cavitation of varying intensities.

Implementing the proposed methodology will ensure the rational and safe application of ultrasonic cavitation and vibration, contributing to the advancement of minimally invasive glaucoma surgery.

## Conclusions

The simulation results confirmed that the proposed methodology allows for the calculation of all acoustic longitudinal dimensions of the  $1\frac{1}{2}$ -wavelength acoustic scheme of the ultrasonic scalpel and ensures its effective and safe application in ophthalmic practice during minimally invasive surgical treatment of glaucoma.

The resonance frequencies of the ultrasonic scalpel with a straight tip and an angled tip were calculated as 48,373 Hz and 48,702 Hz, respectively. Furthermore, the bending vibration mode shape for the angled scalpel needle tip was identified.

The implementation of the developed ultrasonic scalpel for glaucoma treatment is promising in solving an important scientific and applied task in modern ophthalmology and machine science.

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## Методика розрахунку ультразвукового скальпеля з $1\frac{1}{2}$ -хвильовою акустичною схемою та розвиненою поверхнею кавітації

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Використання ультразвукових факоемулсифікаторів та скальпелів при хірургічному лікуванні катаракти відкрило нову епоху для проведення малоінвазивних операцій на оці і можливостей виконання втручання при малих розрізах без побічних травматичних ушкоджень тканин ока. В той же час використання ультразвукової кавітації при хірургічному лікуванні глаукоми на сьогодні поки не знайшло свого належного застосування, хоча має явні перспективи для очищення трабекулярної сітки кута передньої камери ока, збереження і відновлення її еластичності і, як наслідок, зниження очного тиску. Розроблена математична модель ультразвукового скальпеля офтальмологічного факоемулсифікатора для лікування глаукоми на базі  $1\frac{1}{2}$ -хвильового вібраційного приводу поздовжніх переміщень з симетричним п'єзоелектричним перетворювачем, яка дозволила розрахувати акустичні поздовжні розміри та провести моделювання його роботи на резонансній частоті. Зворотно-обертові коливання голки скальпеля забезпечуються за рахунок виконання гвинтових канавок на поверхні ступеня більшого діаметра першого ультразвукового трансформатора коливальної швидкості, який безпосередньо контактує з п'єзокерамічним перетворювачем. Для збільшення зручності хірургічного втручання та зменшення ризику травмування внутрішніх елементів ока кінець голки ультразвукового скальпеля зроблено нахиленим приблизно на  $15^\circ$ . В результаті моделювання були розраховані резонансні частоти ультразвукового скальпеля із прямим та нахиленим кінцем, які склали 48373 Гц та 48702 Гц відповідно. Також визначено форму коливань при нахиленому кінці голки скальпеля, в якій присутня як поздовжня, так і згинальна складова, що підтверджує запропоновану ідею використання нахилоного кінця скальпеля для збільшення зручності хірургічного втручання та зменшення ризику травмування внутрішніх елементів ока. Впровадження розробленого ультразвукового скальпеля для лікування глаукоми є багатообіцяючим для вирішення важливого науково-прикладного завдання сучасної офтальмології та машинознавства.

**Ключові слова:** ультразвук; ультразвукова кавітація; звуко-капілярний ефект; еластичність; скальпель; глаукома; трабекула