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Investigation of ultrasonic waveguides for medical therapy

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Abstract

Theoretically it was determined that changing longitudinal rigidity of waveguide the longitudinal vibrations amplitudes are increasing. The cross-section of waveguide is decreasing from the generating point towards its free end. Experimental results show that the free end of the waveguide is influenced by longitudinal vibrations only, which could be used for blood vessels cleaning.

Keywords: ultrasound, vibrations, waveguide, cavitation

Introduction

During the last few years ultrasonic devices have been widely used in a medical therapy, expecialy in cardiology [1]. Unlike other alternative methods, ultrasonic waves methods have an enormous potential due to their considerable influence on biological tissues. Ultrasonic waves excite various physical and chemical phenomena, which are generally devided into three groups. The first – ultrasonic waves can be used to exert influence on biological tissues through the process of acoustic cavitation, that is'n interaction between ultrasonic field and water. The second – ultrasonic waves can influence chemical processes of drugs due to their high frequency vibration. Finally, the third group consists of those ultrasonic wave influences that are a result of vibrations because of the higher temperature on the border of two vibrating bodies. There are two methods to apply ultrasonic energy to treat the trombosis. The first one involves ultrasonic waves with a lower intensity than the cavitation threshold. The second one uses ultrasonic waves with intensities higher than the cavitation threshold. Low–intensity ultrasonic waveguide could be used for medical treatment with drugs. High–intensity ultrasonic waves could be used to destroy the clots of blood in blood vessels or aterosklerotic clots.

Extension of ultrasonic waves in the flexible waveguide of variable rigidity

Ultrasound devices are used in medicine, where the phenomenon of cavitation is applied to destroy tissues, for example, cleaning blood vessels, destroying aterosklerotic clots or other.

Energy transfer of elastic waves in solid bodies is spreading along energy lines tangential to the "Umov–Pointing" vector [2]. The energy of ultrasonic vibration is spreading along beam tubes. Trajectory of these beams can be obtained from the Ferma principle. The maximum of the function Ferma:

$$\tau = \int_{\mu_0}^{\mu} \frac{d\tau}{C(\mu)} \tag{1}$$

satisfies the equation of Lagrange–Oiller:

$$\frac{d}{d\tau}\left(\frac{\bar{\upsilon}}{c}\right) - \nabla c^{-1} = 0 \tag{2}$$

where τ is the distance along the beam trajectory, $c(M)$ is the velocity in a non – uniform medium, depending from the point M spatial coordinates, $\bar{v}$ is the vector perpendicular to the front of wave.

In the case of a plane surface of a non–uniform medium, equation of Lagrange–Oiller for the beam trajectory $y=y(x)$ is

$$\begin{gathered} \ddot{y} - \dot{y}\left(1+\dot{y}^2\right)f_1(x,y) + f_1(x,y)\left(1+\dot{y}^2\right) = 0, \\ f_1 = c^{-1}c,_x,\ f_2 = -c^{-1}c,_y. \end{gathered} \tag{3}$$

In the non–uniform medium, the rays and ray tubes are deviating to the side of a smaller medium hardness. Along the rays the law of conservation energy is maintained. Therefore, by changing the cross–section of rays it is possible to decrease or increase the ultrasonic waves displacement and stresses.

As an example, we will investigate the distribution of waves in the non-uniform medium perpendicular to lagers. The non–steady process is simulated by the following equation:

$$\sigma,_x = \rho(x)u,_{tt}\,. \tag{4}$$

Furthermore, taking into account the Hook's law

$$\left(E_{(x)}u,_x\right),_x = \rho_{(x)}u,_{tt} \tag{5}$$

and subseqently the influence of a monochromatic wave we get:

$$\left(E_{(x)}u,_x\right),_x + \rho_{(x)}\omega^2 u = 0\,. \tag{6}$$

Let us investigate the propagation of single impulse along non–uniform medium of the beam tube. By using ray series methods:

$$\mathrm{U}_n(x) = \bar{\mathrm{U}}_n\sqrt{\frac{\bar{\rho}(\bar{x})\bar{c}(\bar{x})}{\rho(x)c(x)}} + \int_{\bar{x}}^{x} A_{n-1}(\tau)\sqrt{\frac{\rho(\tau)c(\tau)}{\bar{\rho}(\bar{x})\bar{c}(\bar{x})}}\,d\tau \tag{7}$$

where $U_n(x)$ is the coefficient of the beam factor for the displacement

$$\begin{gathered} \mathrm{U}(x,t) = \sum_{n=0}^{\infty}\mathrm{U}_\mathrm{n}(x)f_n\left(t - S(x)\right) \\ A_{n-1} = \pm\frac{1}{2\rho c}\frac{d}{dx}\left(EH'_{n-1}\right) \end{gathered} \tag{8}$$

where the line is used in the magnitudes of points $x = \bar{x}$.

Analogically for stresses:

$$\sigma(x,t)=\sum_{n=0}^{\infty}\mathrm{P}_n(x)f_n(t-S(x)),$$

$$\mathrm{P}_n(x)=\overline{\mathrm{P}}_n\sqrt{\frac{\rho(x)c(x)}{\overline{\rho}(\overline{x})\overline{c}(\overline{x})}}+\int_{\overline{x}}^{x}c_{n-1}(\tau)\sqrt{\frac{\rho(x)c(x)}{\overline{\rho}(\tau)\overline{c}(\tau)}}d\tau, \qquad (9)$$

$$c_{n-1}=\pm\frac{\rho c}{2}\frac{d}{dx}\left(\frac{P_{n-1}^{'}}{\rho}\right).$$

From Eq. 8 and Eq. 9 we can see that in the case when rigidity is decreasing to the direction of waves, the amplitudes of displacements are increasing and stresses are decreasing, and when the rigidity is increasing, the amplitudes of displacements are decreasing and amplitudes of stresses are increasing. This is the law of conservation energy along beam tubes [2]

These investigations are applied for development of flexible ultrasonic waveguide with a variable rigidity.

The waveguide for the blood vessels operations with multistage concentrators of length nλ (where n – integer, λ – length of wave in the material of waveguide) can be developed to reach the big amplitudes (more than 100 μm). These waveguide, however are very sensitive to the change of loading and have a sharp curve of resonance. The systems with multistage concentrators have to be adjusted carefully according to frequency and work regime. Multistage waveguides have a very sufficient gain coefficient, but in the places of steps the big concentration of stresses occur, therefore the temperature of waveguides is increasing quite dramatically, therefore such waveguides can be broken. Using the exponential concentrator, the stresses in the steps are not changing so rapidly. Waveguides concentrators conical – type or cathode type by using the frequency higher than 25 kHz practically are on the same level as the exponential concentrators.

The geometry of a conical waveguide was simulated by finite element methods.

The analysis of waveguide was investigated in two stages [3]. The first stage – the determination of natural frequency vibrations. Two cases were determinated: the first "resonance" case and the second – "antiresonance" case. The natural vibration frequency in the range 18 kHz – 50 kHz was found:

Table 1

"resonance", Hz	"antiresonance", Hz
23808	24062
35045	35268
43623	43624

In the second stage the amplitude – frequency response of waveguide was obtained.

From Fig.1 we can see that the peak amplitude is equal to the first frequency of natural vibration.

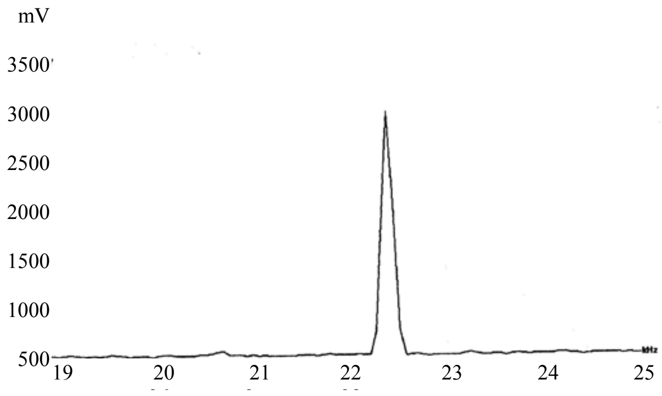


Fig.1.**The amplitude – frequency response of waveguide**

Experimental investigation of vibrations of the waveguide

The experimental investigation of vibrations of the waveguide was performed in the Mechatronics Center in Kaunas University of Technology. The steal waveguide with length of 900 mm and the cross–section of ∅0,6 mm near the vibration actuator and the cross–section of a free end ∅1,5 mm, was used in this experiment.

The investigation using the vibrometer based on the Doppler shift of a back scattered laser light is demonstrated in Fig. 2.

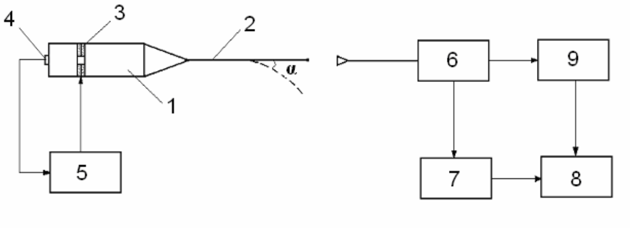
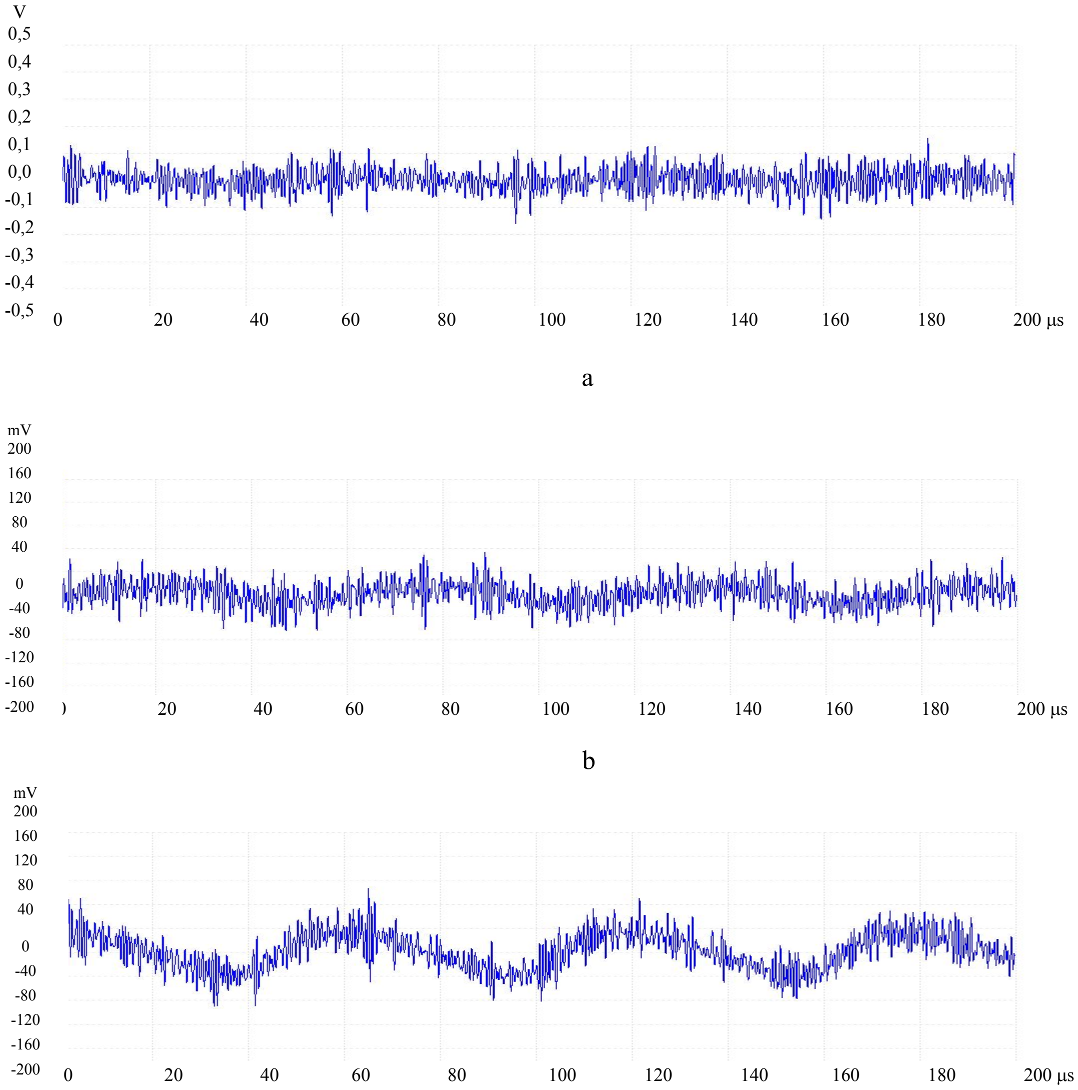


Fig.2. **Experimental measurement schema: 1 - concentrator of vibrations; 2 - waveguide; 3 - piezorings; 4 - sensor of vibrations; 5 - control unit of the system of vibration excitement; 6 - laser interferometer "Polytec" OFV-512, 7 - analog-digital converter type ADC-2424(pico,GB); 8 - PC; 9 - vibrometer controler „Polytec OFV –5000".**

The piezoshaker is fixed in the holders. The concentrator is attached to the piezoshaker head in order to amplify and concentrate the vibrations transmitted to the waveguide. The waveguide is attached to the concentrator. Piezoshaker and vibrometer are assembled on the isolation table, in order to avoid external vibrations, which can influence the final results of the experiment.

The vibrations of the waveguide are analyzed in the most characteristic point. This point is at the conical end, where the whole mass of the waveguide is concentrated, thus the vibrations are most intensive.

The example of the obtained results after the experimental investigation of the waveguide by the means of the vibrometer, based on the Doppler shift of the backscattered laser light are presented in Fig. 3.



a

b

c

Fig. 3. **Results of the same frequency (17 kHz), but different amplitudes: a – 100 mV; b – 400 mV; c – 600 mV.**

Conclusions

From the mathematical analysis is determined that changing longitudinal rigidity of waveguide the amplitudes of longitudinal vibrations are increasing. The cross-section of the waveguide is decreasing from the generating point towards its free end. The waveguide section has to be smooth, because of the stresses concentrations.

Experimental results show that the free end of the waveguide is influenced by longitudinal vibrations only.

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Ultragarsinių bangolaidžių medicininei terapijai tyrimas

Reziumė

Teoriškai nustatyta, kad, keičiant bangolaidžio išilginį standumą, išilginių virpesių amplitudė didėja. Bangolaidžio skerspjūvis mažėja nuo bangolaidžio tvirtinimo prie žadinimo šaltinio iki jo laisvojo galo. Bangolaidžio skerspjūvis turi būti glotnus dėl atsirandančių įtempių koncentracijos. Eksperimentiniai rezultatai parodė, kad bangolaidžiu sklinda tik išilginiai virpesiai, kurie gali būti naudojami kraujagyslių rekanalizacijai.

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