IOP Conf. Series: Materials Science and Engineering **516** (2019) 012024 doi:10.1088/1757-899X/516/1/012024

Numerical modeling of ultrasonic waveguide with piezoceramic element

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Abstract. A model of an ultrasonic waveguide with a cos junction and optimization of the bolt attachment point and the length of the reflector was proposed. A numerical simulation of the proposed waveguide design was carried out in the Comsol Multiphysics program. According to the results of numerical simulation, the resonant frequency of the waveguide with the cos junction was found, the optimal length of the reflector and the point of attachment of the bolt ensuring its minimum deformation. Also the design of this waveguide was simulated in a developed program that provides parallel computations using OpenCL technology.

1. Introduction

Ultrasonic waveguides are used in technologies of ultrasonic welding [1, 2], cutting various materials [3–5], crushing [2], and also used in surgery [6, 7]. However, when developing ultrasonic instruments for medicine, it is necessary to take into account the specifics of the field of application. In particular, to evaluate the biological effect of ultrasound on living tissue and the possibility of obtaining the desired biological effect and the requirements of the doctor for ultrasonic instruments: the duration of continuous operation, reliability and efficiency, weight, heating, ease of operation. In medicine, ultrasonic waveguides are most often used with an operating frequency of 20 to 44 kHz. Already there are technologies for calculating and manufacturing ultrasonic instruments with various features of application [8–10]. There are two main ways to excite ultrasonic vibrations: based on the magnetostriction effect [11] and based on the piezoelectric effect [12]. Ultrasonic waveguides based on piezoelectric elements, as a rule, show a greater efficiency [12].

Waveguides are made in the form of bodies of rotation of variable diameter with stepped, conical or exponential transitions [8, 13, 14]. The most beneficial in terms of the possibility of obtaining significant amplitudes of displacements at low load are stepped waveguides, in which the amplitude gain factor is equal to the ratio of the areas of the input and output sections. Particularly promising are waveguides with smooth, exponential or radial transitions. The presence of a transitional exponential sector reduces the stress concentration and provides more favorable conditions for the propagation of ultrasonic vibrations, improves the strength properties. In addition, the presence of an exponential segment allows you to transform the load without a significant change in the resonant mode of the oscillatory system. Piezo elements are stacked to into Langevin packets [15], which allows multiply the amplitude of oscillations by number of elements. Langevin packets are connected to the ultrasonic resonator using a bolt tie [16] or cylinder [15].

One of the problems of ultrasonic instruments based on waveguides with a Langevin package is overheating of the package or its destruction due to deformation. The principle of constructing an ultrasonic tool based on a waveguide and a Langevin package with a bolt tie with optimization of the bolt attachment point and reflector length is proposed. At the same time it is proposed to consider the use of cos-like transitions for the form of a waveguide.

2. Principled model of ultrasonic waveguide

A model of an ultrasonic waveguide (Figure 1), consisting of a reflector, a piezoelectric element and a working part, was considered. We have solved the Helmholtz equation for considered structure. As a result of solving a system of differential equations, a mathematical model of an ultrasonic tool was obtained, which allows to estimate the resonant frequencies and select the optimal length of the reflector to maximize the amplitude of oscillations of the working part. By variation of parameters we have found optimal size of it's parts to minimize bolt deformation while maximizing vibrations of the waveguide end. The bolt attachment point in the working part was chosen so that its offset relative to the outer edge of the reflector was zero at the operating frequency. Thus, the minimum deformation of the tightening bolt during the operation of the tool is ensured, and the oscillation energy is mainly directed to the working part.

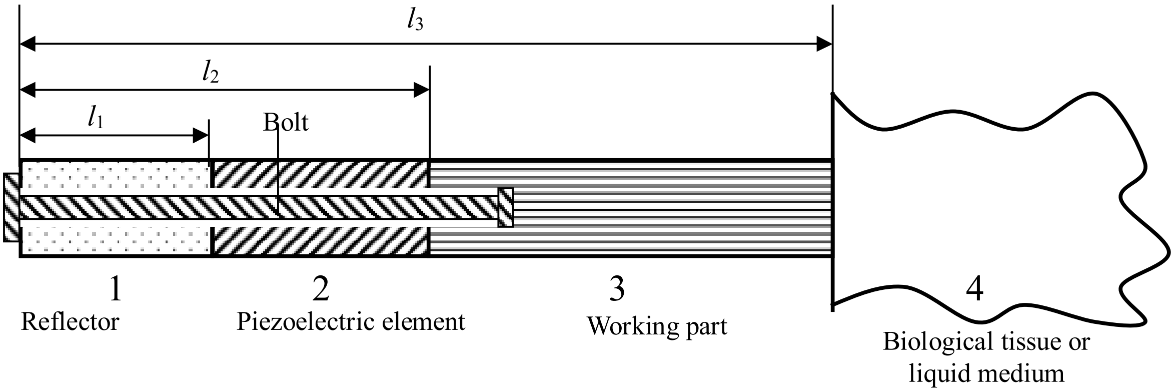

Figure 1. Considered construction of a composite waveguide.

3. Numerical modeling of the ultrasound waveguide by finite elements method in the Comsol Multiphysics program

A numerical modeling of the ultrasonic instrument was carried out in the COMSOL program, which showed close resonant frequencies with an analytical model. Figure 2 presents the image of the longitudinal shift of the aluminum waveguide at a frequency of 23750 Hz. (Figure 1).

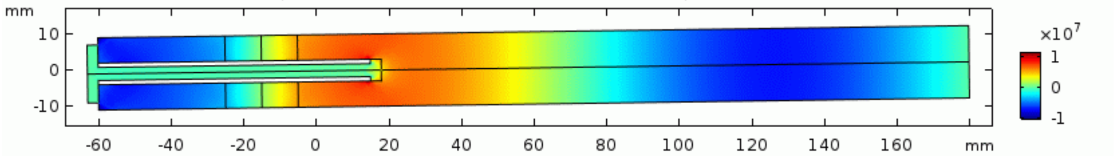

Figure 2. Deviation in the longitudinal direction at a frequency of 23750 Hz according to the results of numerical simulation of a waveguide in COMSOL medium for a cylindrical waveguide.

After changing the shape of the waveguide to a smooth transition in the form of a cos-like function 60 mm long, with a reflector length of 35mm bolt 78mm and piezoelectric elements 20mm long, the total length of the waveguide was 180mm, there was a slight change in the resonant frequencies. The resonant frequency under consideration has shifted to 25250 Hz. This is due to the fact that any changes in the dimensions of the waveguide geometry inevitably lead to a shift of the resonant frequencies. Figure 3 shows the longitudinal deviation of the aluminum waveguide at a given frequency.

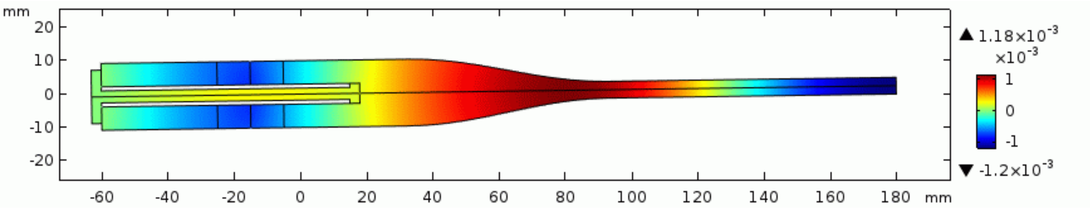

Figure 3. Deviation in the longitudinal direction at a frequency of 25250 Hz according to the results of numerical simulation of a waveguide in a Comsol software for a waveguide with a cos(x) transition.

According to the results of numerical simulation, we can conclude that the selected dimensions of the design of the ultrasonic waveguide are optimal. From Figure 3 it can be seen that with this design of the waveguide at a frequency of 25250 Hz, the maximum amplitude of oscillations of the end of the working part is achieved. This ensures minimal deformation of the bolt during the operation of the tool, and the oscillation energy is mainly directed to the working part.

4. Numerical simulation of the ultrasound waveguide by finite difference time domain approach

A numerical simulation of the design of the ultrasonic waveguide presented in Figure 3 by finite difference time domain approach was carried out. We have developed program that provides parallel computations using the OpenCL technology. In the simulation, the considered ultrasonic waveguide is represented as an array of particles in a cubic body-centered crystal grid. In addition, each particle has its own mass and speed. Particle dynamics is described by Newton's equations of motion. The forces of interaction between particles are characterized by a force function, which is the dependence of the force of attraction between particles by the distance. Near the point of equilibrium, the force of attraction is zero, which corresponds to a point of stable equilibrium of particles. The angle of inclination of the force function near the equilibrium point is proportional to the Young's modulus. Particles in the lattice are placed periodically, but there are two different distances between the neighboring particles: d and $d\sqrt{3}/2$. For each particle, we calculate the velocity and coordinate by numerical integration of the acceleration by time. The acceleration of a particle is calculated according to Newton's second law as the ratio of the force acting on the particle to its mass. The mass of the particle and the force of interaction determine the type of material. Such force dependence is characterized by the formula.

$$F_1(x)=\begin{cases} k\dfrac{d}{\left(3-2\sqrt{2}\right)}\left(1-\dfrac{d}{x}\right)\left(\sqrt{2}-\dfrac{x}{d}\right)^2 & if \quad \left(x<d\sqrt{2}\right) \\ 0 \quad if \quad \left(x\geq d\sqrt{2}\right) & \end{cases}$$

$$F_2(x)=\begin{cases} k\dfrac{d\sqrt{3}/2}{\left(3-2\sqrt{2}\right)}\left(1-\dfrac{d\sqrt{3}/2}{x}\right)\left(\sqrt{2}-\dfrac{x}{d\sqrt{3}/2}\right)^2 & if \quad \left(x<d\sqrt{3/2}\right) \\ 0 \quad if \quad \left(x\geq d\sqrt{3/2}\right) & \end{cases} \tag{1}$$

Where $F(x)$ – interaction force between particles, x – the distance between particles, k – coefficient of elasticity. Mass and force function determine the density and speed of sound in a particular material, which allows you to associate modeling with processes in real materials. Figure 4 shows the design of the ultrasonic waveguide with ultra wide band vibrations of particles speed represented by color. This construction is considered as monolithic. In numerical modeling, the speed of sound and the density of the material were set. The speed of sound in aluminum is set to 5050 m/s, the density is 2712 kg/m^3. Ceramic PZT-8 was used as piezoelements, sound speed 3200 m/s, density 7600 kg/m^3.

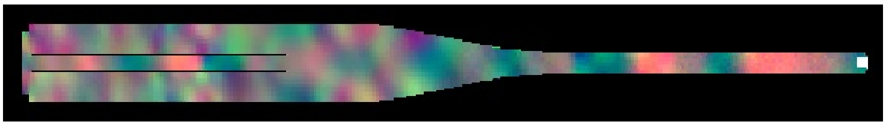

Figure 4. The design of the ultrasonic waveguide in the developed program.

A short pulse was applied as the exciting signal. Different colors represent the speeds with which the particles oscillate. When a short pulse propagates in the system, the system begins to respond at all its frequencies. At the end of the waveguide a monitoring particle was placed, which allows to record deviations of the coordinate and velocity of the particle. As a result of the numerical modelling, a resonance frequency spectrum of the structure being modeled was obtained. During the simulation, the coordinate X (t) of the monitoring particle is controlled. As a result of numerical simulation, we obtained the function X (t) and calculated its spectrum. The spectrum of edge spatial oscillations is presented in Figure 5.

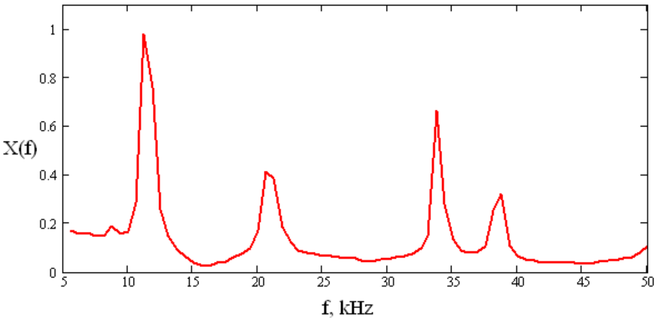

Figure 5. The resonant frequency spectrum of a monolithic ultrasonic waveguide with a cos (x) transition in the developed program.

In the numerical modeling of the monolithic structure of the ultrasonic waveguide, Figure 3 by the Comsol Multiphysics program, the spectrum of the resonant frequencies of the working part of the ultrasonic waveguide was close to the spectrum of resonant frequencies obtained in the developed program Figure 6.

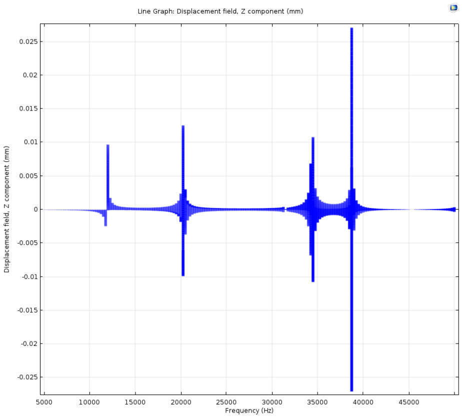

Figure 6. Resonance frequency spectrum of a monolithic ultrasound waveguide with a cos (x) transition in the Comsol Multiphysics program.

That allows to judge the reliability of the results of numerical modeling in the developed program.

5. Conclusion

As a result of the work, the proposed design of a waveguide with a cos junction was considered. A numerical simulation was carried out, in the program Comsol Multiphysics, based on the results of which, the resonance frequency, the optimal reflector length and the bolt attachment points were checked to ensure minimal deformation. For comparison, we modeled this waveguide design using finite difference time domain approach. As a result a resonance frequencies spectrum was obtained close to the spectrum obtained in the Comsol Multiphysics program.

Acknowledgments

The work was supported by the Ministry of Education and Science of Russia within the framework of the project "Creation of a high-tech complex of ultrasound surgery" (Unique identifier of the project RFMEF157517X0163).

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