OPTIMIZATION OF ULTRASONIC CUTTING TOOL GEOMETRY

Anton MYDLIAR

Abstract: This article solves the optimization of the ultrasonic cutting tool geometry. The parameterizable model of ultrasonic cutting tool was created in finite element (FE) software Ansys. The eigenfrequencies and modal shapes were extracted by modal analysis. Harmonic analysis showed the improvement of the amplitudes and the mechanical stresses of optimized ultrasonic tool. The results and measurements are summarized in the conclusion.

Keywords: Optimization; Eigenfrequency; APDL; Ultrasound; Cutting tool.

1 INTRODUCTION

The article is focused on the optimization of ultrasonic cutting tool which is a part of ultrasonic cutting product and performs the technological cutting operation. The generators of ultrasonic energy provide the longitudinal vibrational movement [1], [2], [7]. The magnetostriction and piezoelectric effect are often used like ultrasonic energy generators in a science and industry.

The geometric shapes of resonators are constructed with uniform or stepped change of a section. The well-known resonators´ sections are circle, conic and exponential. The optimization of ultrasonic tool geometry was realized by length and material changes in the past.

The FEA (FE analysis) and optimization methods brings advantage and cost-reduction of a tool construction [1]. The ultrasound is defined in the frequency range 20 kHz – 10 GHz [8], [9]. The particles of matter (e.g. solids) do a periodic vibrational movements in UZ field, which is generated by ultrasound generators. The important improvement brings the usage of a resonator which aim is to gain the amplitude of ultrasonic transducer or the ratio $A_{\xi k}/A_{\xi m}$ (Fig. 1).

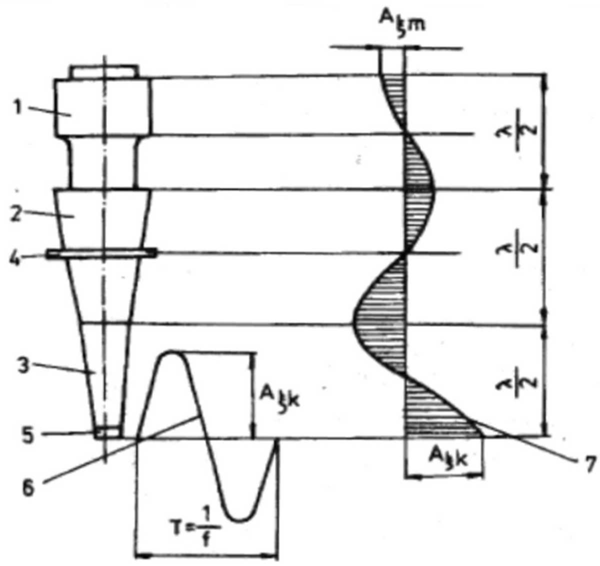


Fig. 1 The distribution of longitudinal vibration of ultrasonic vibrational product
1 – Ultrasonic transducer, 2 – primary resonator, 3 – secondary resonator, 4 – node, 5 – tool, 6 – time trend of displacement amplitude - oscillating movement, 7 – the wave trend along the vibrational product
Source: [7]

There is requested that ultrasonic tool which perform technological operation, vibrates with displacement amplitude 10-100 μm. This is possible to do with the resonators with variable change of a cross-section. They are called the mechanical transformers of displacement and velocity.

2 FE ANALYSIS AND MEASUREMENT OF ULTRASONIC CUTTING TOOL

To analyze ultrasonic cutting tool is necessary to create the parameterizable FE model in ANSYS. There were set the basic material constants (Young´s modulus, density and Poisson´s ratio), type of element and method of mesh with APDL macro.

The equations of motion for free vibration of undamped system with lumped parameters with n- degree of freedom are following

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{0} \qquad (1)$$

where $\mathbf{M}, \mathbf{K}, \ddot{\mathbf{x}}, \mathbf{x}$ are the mass matrix, stiffness matrix, the accelerations and displacements vectors, respectively.

The solution (2.1) we propose in the shape

$$\mathbf{x} = \mathbf{a}e^{i(\Omega t+\varphi)} \qquad (2)$$

where i and φ are complex number and phase angle, Ω is unknown angular frequency and $\mathbf{a}$ is unknown eigenshape or eigenvector [2], [8], [9].

The modal analysis shows the longitudinal vibrational shape is at frequency 28.64 Hz and there is the bending of the wedge (Fig 2).

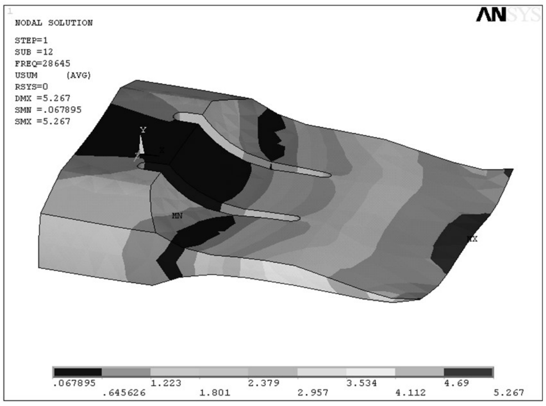


Fig. 2 Longitudinal eigenshape with the transversal wedge bending
Source: author.

2.1 Sensitivity analysis

There is importance to know the influence of parameter change on the vibrational modes. The ultrasonic cutting tool should have a uniform vibration of wedge and bending vibration should be minimalized or canceled.

There are the parameters depicted on Fig. 3 for a sensitivity analysis - SA.

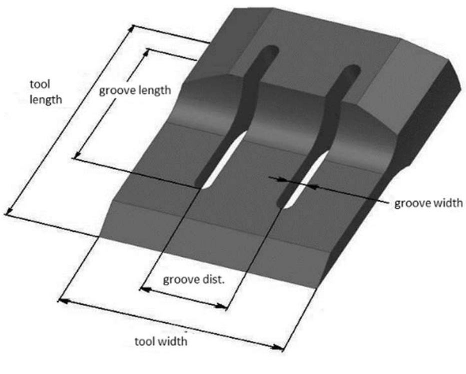
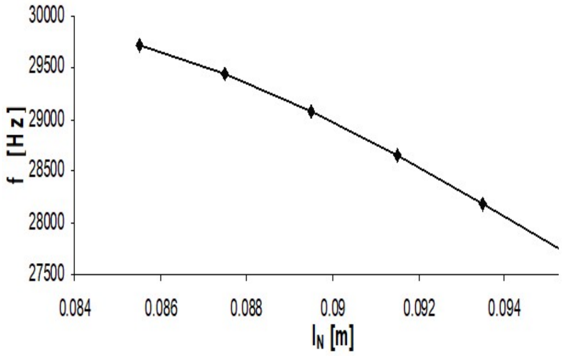


Fig. 3 Dimensions for SA
Source: author.

Graph 1 displays the evolution of the resultant eigenfrequencies for the different tool lengths.



Graph 1 Eigenfrequency versus tool length
Source: author.

There are depicted the eigenshapes for parameter tool length when it has minimum value – Fig. 4 and maximum value Fig. 5.

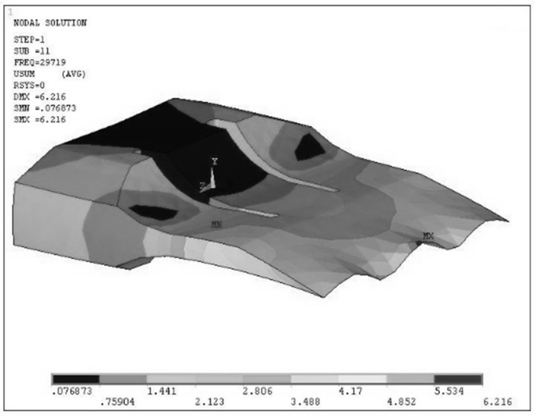


Fig. 4 Eigenshape at 29719 Hz - the minimum length of cutting tool
Source: author.

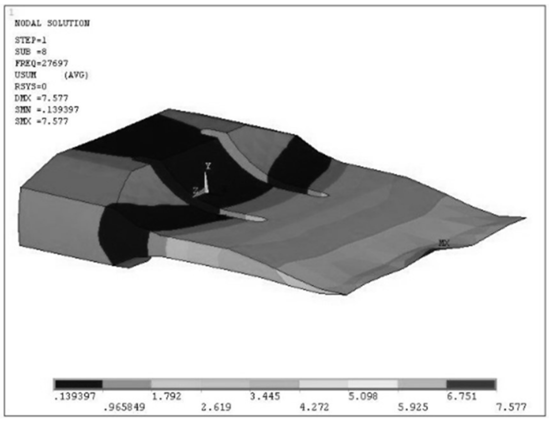


Fig. 5 Eigenshape at 27697 Hz - the maximum length of cutting tool
Source: author.

2.2 Optimization and results

In Ansys optimization toolbox is necessary to define:
1. Design Variables;
2. State variable;
3. Objective function.

The first order method was used in optimization process what is gradient method [1]. The trend of objective function for the prescribed restriction and design variables is depicted on Fig. 6.

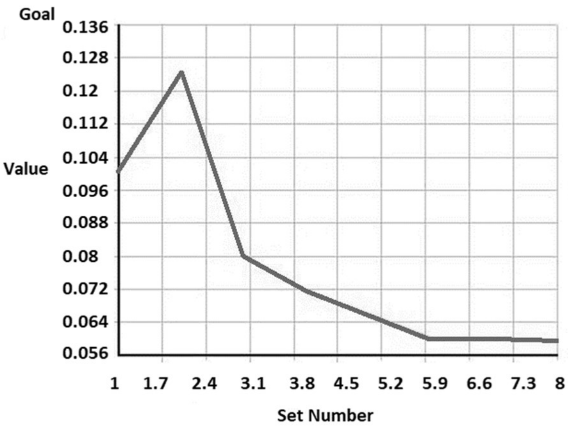


Fig. 6 Relation between trend of objective function and no. of iteration
Source: author.

The optimized eigenfreqency 30015 Hz and eigenshape is depicted on Fig. 7.

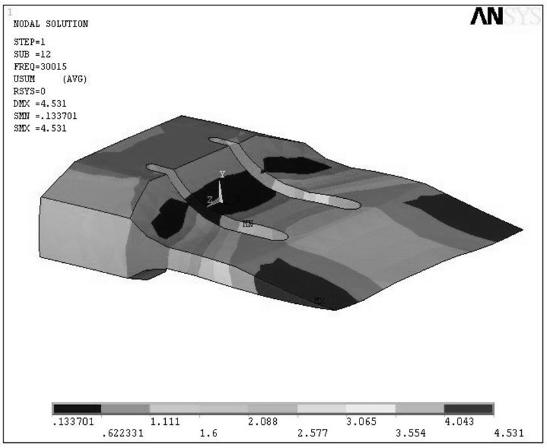


Fig. 7 Optimized eigenshape at 30015 Hz
Source: author.

2.3 Measurement

The measurement of electric quantities of piezoelectric transducer was performed on ultrasonic product. The piezoelectric transducer was connected to the source of alternating voltage (Fig. 8) [5], [6].

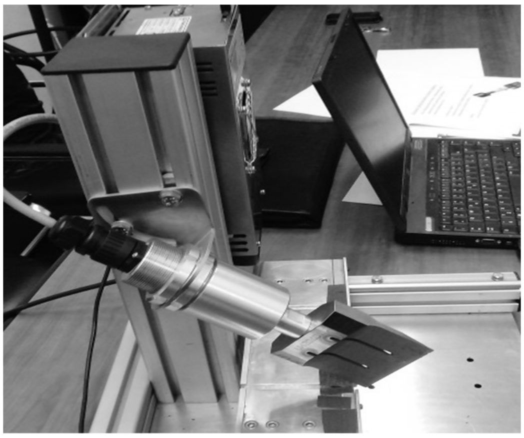


Fig. 8 Ultrasonic cutting tool
Surce: author.

The target of the experiment was the measurement of the frequency dependent electric quantities in electric circuit of PZT transducer of ultrasonic product [3], [4]. The measurement no.1 found the frequency 30.52 kHz and electric current, by which the ultrasonic cutting product vibrated longitudinal a provided the technological operation cutting. The measurement no. 2 found frequency 30.76 kHz, by which tool or ultrasonic product had bending eigenshape and working mode was worse and the tool could fail. There was acoustic disturbance in the frequency range 30.6 – 31kHz. The measurement no. 3 found electric voltage by osciloscope on PZT transducer by frequency which correspond longitudinal eigenshape of ultrasonic cutting tool. The measurements no. 1 and 3 show the same frequency 30.52 kHz. The measurement results are summarized in the Table 1.

Tab. 1 The measurement of frequency characteristic of ultrasonic transducer

Measurement no.	Frequency range [kHz]	f [kHz]
1	29-31	30.52
2	30.6-31	30.76
3	29-31	30.52

Source: author.

2.4 Harmonic analysis of ultrasonic product

Model of ultrasonic product was built in ANSYS. The model consists of ultrasonic transducer, resonator and cutting tool. Modal analysis found eigenfeqeuncy and eigenshape for optimized tool. The electric voltage excited PZT transducer and for harmonic analysis of coupled field the distribution of displacement amplitudes in the direction of Z are depicted on Fig. 9. The cutting edge has the displacement amplitudes between 4 -11 µm.

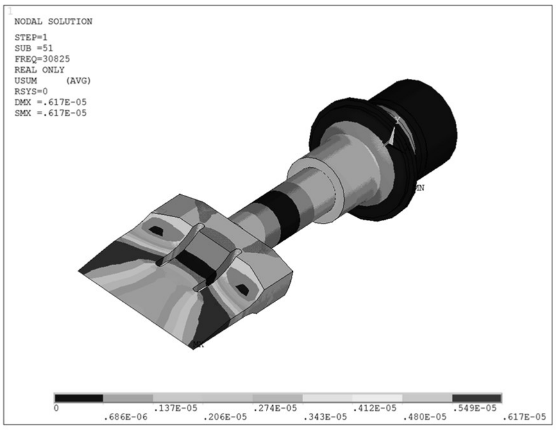


Fig. 9 Eigenfrequency 30.8 kHz and the amplitude distribution in the Z axis direction
Source: author.

The next model of ultrasonic cutting tool was analyzed and the displacements are depicted on fig. 10. The difference are e.g. longer holes and others construction changes.

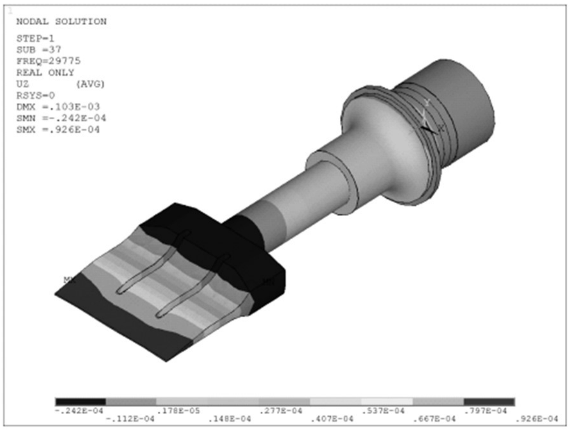


Fig. 10 Eigenfrequency 29.8 kHz the amplitude distribution in the Z axis direction
Source: author.

The displacement amplitude has the maximal values 88 µm.

3 CONCLUSION

The optimization of geometry gives the model which satisfies the range of design variables and achieves the objective function during optimization process. The vibrational optimizations of the resonators with the complicated geometries require the usage of FEA with the mathematical models for an optimization.

By optimization of the ultrasonic cutting tool geometry was achieved the variants where the conditions were satisfied for eigenfrequency and eigenshape. The optimization tuned the longitudinal eigenshapes at frequency 30 kHz. Dynamic harmonic analysis confirmed that optimized tool vibrates longitudinal.

By the measurement frequency dependent electric quantities (electric current and power) of PZT transducer was found the working frequency of ultrasonic product. The measurements no. 1 and 2 showed the trends of electric current and power in dependency on frequency. The measurement 3 was conducted by oscilloscope direct on PZT transducer in working mode. The measurements no. 1 a 3 found the same vibrational eigenshape of ultrasonic product at 30.52 k kHz. The measurement no. 2 found the bending eigenshape where was acoustic disturbance.

The amplitude-frequency characteristic determined the displacement amplitudes of ultrasonic cutting product wedge in range 4-11 µm at 30.8 kHz. The next model was showed the uniform displacement amplitude of wedge (in cutting direction) about 88 µm at 29.8 kHz.

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Dipl. Eng. Anton **MYDLIAR**, PhD.
Armed Forces Academy of General M. R. Štefánik
Demänová 393
031 01 Liptovský Mikuláš
Slovak Republic
E-mail: anton.mydliar@aos.sk

Anton Mydliar - was born in Ružomberok, Slovakia in 1984. He graduated from Slovak University of Technology in Bratislava in 2018 where he received Ph.D. on Department of Applied Mechanics. He is the assistant professor at the Department of Mechanical Engineering, Armed Forces Academy of General M. R. Štefánik in Liptovský Mikuláš.