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Theoretical Research Regarding the Modeling of the Ultrasonic Piezoceramic Assembly

This paper presents the design of n transducer-tool of an ultraacoustic system for finishing processing through cutting. Finite element modeling of the horn-tool using ANSYS software package allows the analysis of the tension and deformations state along it showing especially the values of the amplitude in the active area.

1. Theoretical considerations

Ultraacoustic system is the most important part of a ultrasound finishing installation because it gives the acoustical parameters (acoustic intensity, density of the acoustic energy, oscillation amplitude, wave type, oscillation frequency) and mechanical parameters (static pressure, pressure force, amplitude).

The ultraacoustic system comprises n piezoceramic assembly and a horn. The piezoceramic assembly, tuned on 20 KHz generates the ultrasonic oscillation (mostly longitudinal). The ultrasonic horn is coupled with the piezoceramic assembly in the input section of the latter by the aid of a screw. The ultrasonic horn is designed by taking into account the material characteristic so that its length to correspond to a semi-wave length and so that it is working under the resonance regime. The role of the ultrasonic horn is to amplify oscillations and to conduce the ultrasonic energy in the processing area.

In order to obtain an optimal efficiency, the ultrasonic horn must be tuned with a few periods approximation to the frequency derived when the ultrasonic transducer is computed. Thus, the entire oscillation system needs to work under the resonance regime so that the amplitude of the speed of the particle at the top of the tool to be high and therefore the acoustic intensity to be high.

During the manufacturing stage, adjusting operation of the horn must be done so that the entire ultrasonic assembly to oscillate to the resonance frequency of the piezoceramic assembly.

The computation and dimensioning of the system is done so that it works under the resonance regime and takes into account all technological parameters of the finishing process. The modeling of the ultrasonic system is both difficult and necessary. After careful consideration of several modeling methods, we come to the conclusion that finite element modeling with ANSYS software package is the most suitable method.

Due to the high complexity of such an assembly, finite element modeling and analysis will be done separately for each component.

By working similarly with the case of determination of the propagation equation for the elastic waves in a environment extended to infinite, an volume element dV from the variable section bar is considered (Fig.1), given by [1]:

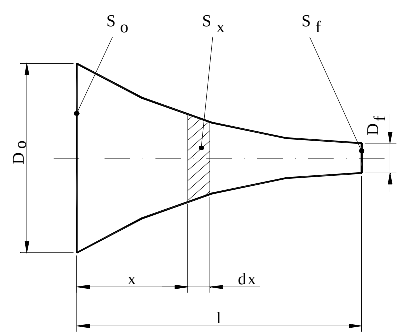

Figure 1. Section variation for the horn

$$dV = S_x dx \tag{1}$$

and the continuity equation is derived:

$$-\frac{\partial}{\partial x}\left(S_x \rho' v\right)dx = -\rho' \frac{\partial}{\partial x}\left(S_x v\right)dx \tag{2}$$

Considering the increase of the mass in the volume element considered by the shape of:

$$-\frac{\partial}{\partial t}\left(S_x \rho'\right)dx = S_x \frac{\partial \rho'}{\partial t} dx \tag{3}$$

by comparing the previous two expression, it is derived that:

$$S_x \frac{\partial \rho'}{\partial t} + \rho' \frac{\partial}{\partial x}\left(S_x v\right) = 0 \tag{4}$$

Taking into account that:

$$\rho' = \rho_o \left(1 + s\right) \tag{5}$$

where: *s* represents the condensation in the environment and neglecting the *sv* term, results:

$$S\rho_o \frac{\partial s}{\partial t} + v\frac{\partial S_x}{\partial x} + S_x \rho_o \frac{\partial v}{\partial x} = 0 \tag{6}$$

But,

$$s = \frac{\rho}{\rho_o c^2} = -\frac{1}{c^2}\frac{\partial \Phi}{\partial t} \text{ şi } \frac{\partial v}{\partial x} = -\frac{\partial \Phi}{\partial x} \tag{7}$$

making the necessary replacements in (6), results:

$$\frac{\partial^2 \Phi}{\partial t^2} - c^2 \frac{\partial \Phi}{\partial x}\frac{\partial}{\partial x}(\ln S_x) - c^2 \frac{\partial^2 \Phi}{\partial x^2} = 0 \tag{8}$$

in which: Φ represents the speed potential; S_x – the area of the bar section at distance x from its origin; c- the propagation speed of ultrasonic waves through the bar material.

By solving equations (1)…(8) at the limits, the following computation stages can be derived:

- determination of the multiplication factor;
- determination of the horn length, so that it will work under resonance regime;
- determination of the section variance coefficient;
- determination of the horn shape according to the types of waves excited in the horn;
- determination of the nodal points coordinates.

2. Finite element modeling of the piezoceramic assembly

The active elements of the ultrasonic system are the piezoceramic discs made of PZT4 with the geometrical dimensions presented in Figure 2.

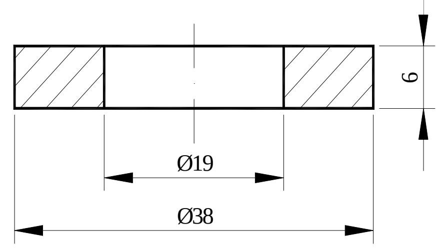

Figure 2. Geometrical dimensions of the piezoceramic element

The material properties of piezoceramic elements are understood by the ANSYS software package through three arrays: dielectric, piezoelectric and elastic ones. The values contained in these arrays are chosen from the catalogues exsitent on the market provided by piezoceramic materials manufacturers.

In the case of PZT4, the program lines that contain the arrays with their corresponding dielectrical, piezoelectrical and elastical parameters are:

MP,DENS,1,7800 for the material density
!*
MP,PERX,1,22.6E-9 for the dielectric array
MP,PERY,1,22.6E-9
MP,PERZ,1,33.6E-9
!*
TB,PIEZ,1 for the piezoceramic array
TBDATA,3,-14.8
TBDATA,6,-14.8
TBDATA,9,21.6
TBDATA,11,19.8
TBDATA,13,19.8
!*
TB,ANEL,1 for the dielectric array
TBDATA,1,6.0E10,-0.17E10,-0.13E10
TBDATA,7,6.0E10,-0.13E10
TBDATA,12,5.32E10
TBDATA,16,2.6E10
TBDATA,19,2.6E10
TBDATA,21,2.2E10

From the main menu the type of structutral analysis and magnetic nodal analysis is selected that conditiones the call of appropriate libraries with discretisation elements.

The volume geometry is generated with the optin PREPROCESSOR form the main menu. The common surfaces constitutes a nodal plane (zero oscillation). The two volumes are then joined.

The discretisation is done with SOLID98 element (3-D with 10 nodes tetrahedral solid). Thus, 1790 elements with 3249 nodes are obtained.

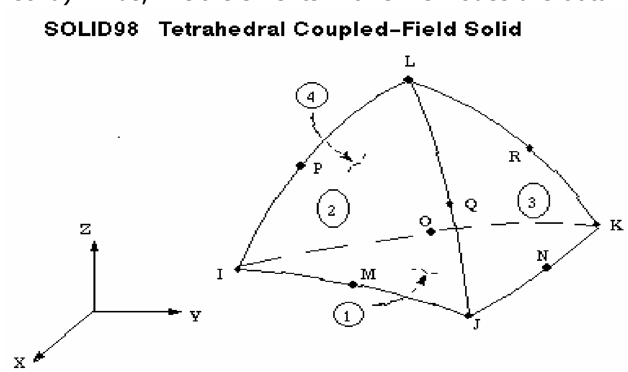

Figure 3. SOLID98 element

The volume geometry is generator by selecting the PREPROCESSOR from the main menu. In figure 4, the volumes of two coupled piezoceramic discs with opposed polarisation ways are represented.

Figure 5 depicts the discretisatino of the discs with the previous chosen discretisation element. Taking into account the physical reality, the nodes placed in the common surfaces of the volumes are given all degrees of freedom and their corresponding symbols are shown in Figure 6.

In the physical reality, the power source (the ultrasonic generator) brings on the electrodes placed on the polarisation direction of the piezoceramic discs, electrical potentials with the required frequency of working under the resonance regime of the ultrasonic assembly (in the present case 20 KHz). In figure 7 are shown the symbols coresponding to the electrical potentials applied to the nodes placed in between the surfaces with the electrodes, with values in the range of 00 ÷ 800 V.

After the activation of the SOLUTION processor, the static analysis is selected. The results of its calculations are visualized by running the GENERAL POSTPROCESSOR. What is important to see is the deformed and not-deformed states of the studied structure. These can be viewed in several ways by selecting the appropriate options in the graphical interface. Each graphical representation includes a legend with range of deformation values.

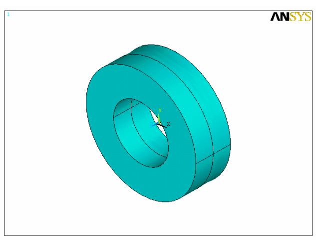

Figure 4. Volume geometry of two coupled piezoceramic discs

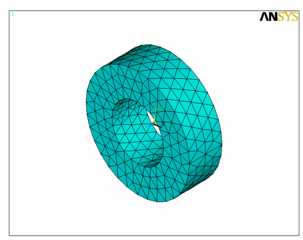

Figure 5. Discretisation with finite elements of the piezoceramic discs

Figure 8 shows the frontal view of the deformation and normal states of the assembly and Figure 9 shows the isometric view of the same assembly in the case when on the external electrodes appear positive electrical potentials in the nodal plane.

Figure 10 shows the frontal view of the deformation and normal states of the assembly and Figure 11 shows the isometric view of the same assembly in the case when on the external electrodes appear negative electrical potentials in the nodal plane.

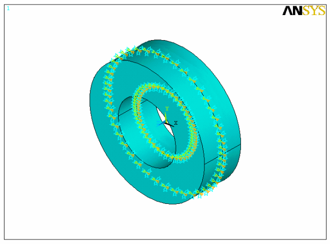

Figure 6. Embedding of the nodes in the nodal plane

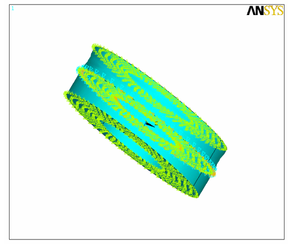

Figura 7. The apply of electrical potentials

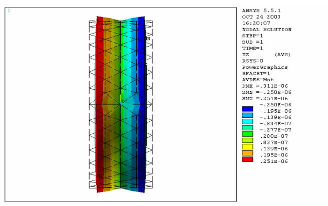

Figure 8. Frontal view of the deformation and normal states for positive electric potentials

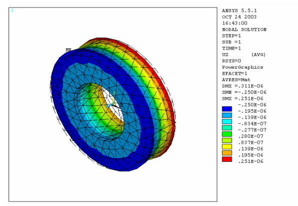

Figure 9. Isometric view of the deformation and normal states for positive electric potentials

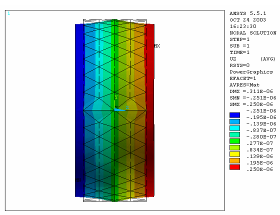

Figure 10. Frontal view of the deformation and normal states for negative electric potentials

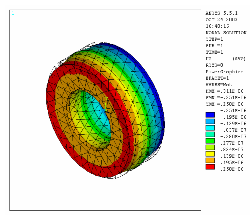

Figure 11. Frontal view of the deformation and normal states for negative electric potentials

Through the harmonic analysis for the desired resonance frequency of the peizoceramic assembly (20 KHz), the oscillation amplitude (nodal displacements) can be obtained.

The results of this analysis for a range of values depending on the electric voltage supplied (attack voltage) by the power generator (0…1000 V) is given in Table 1.

The graphical representation of these values (Fig.12) shows the linear response of the amplitude with the attack tension of the piezoceramic discs.

Table 1. Oscillation amplitude depends on the input voltage applied to the piezoceramic discs

Attack voltage applied to the piezoceramic discs [V]	Oscillation amplitude [μm]
0	0
100	0.102
200	0.204
300	0.306
400	0.408
500	0.510
600	0.612
700	0.714
800	0.816
900	0.918
1000	1.020

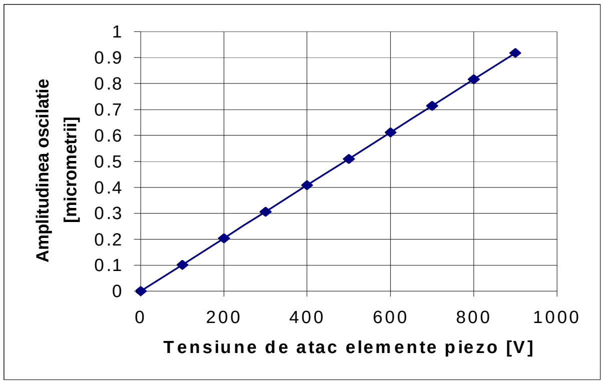

Figure 12. The linear response of the oscillation amplitude vs. attack tension of the piezoceramic disc

In the piezoceramic assembly, the piezoceramic discs 2 are screwed in between an reflective element 3 and a diffusion element 1 made of metallic materials o various densities (Fig.13).

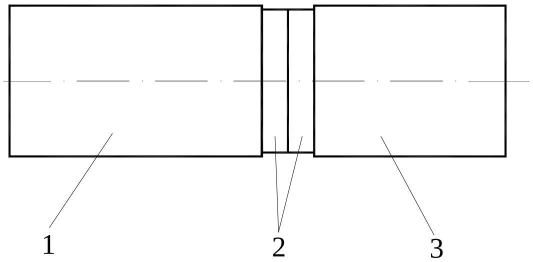

Figure 13. Piezoceramic assembly:
1 – diffusion element AL; 2 – piezoceramic discs; 3 – reflective element OL

The finite element modeling of the piezoceramic assembly offers a prediction of its behavior in terms of both the amplitude of deformations and of the states of tensions.

Figures 14, 15, 16 and 17 depict the stages construction stages of the piezoceramic assembly model and front and isometric view of the deformation and normal states for the resonance frequency of 20 KHz.

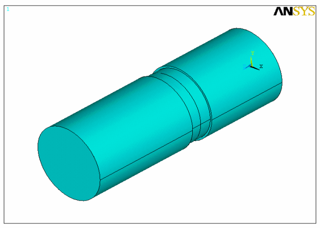

Figure 14. Volume geometry of the pizeceramic assembly

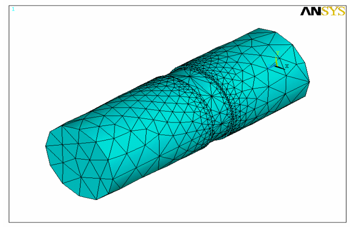

Figure 15. Finite element discretisation of the piezoceramic assembly volume

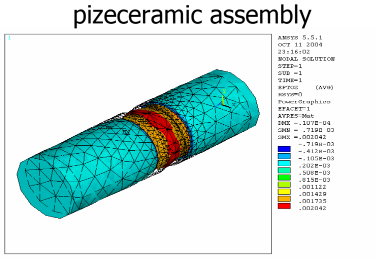

Figure 16. Isometric view of the deformation /normal states of the piezoceramic assembly

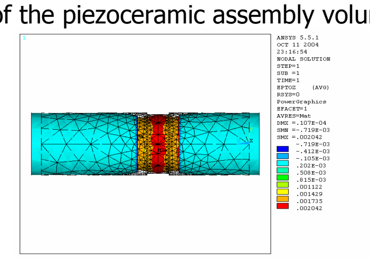

Figure 17. Frontal view of the deformation /normal states of the piezoceramic assembly

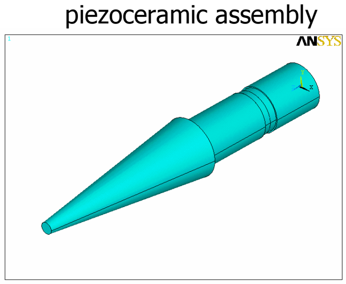

Figure 18. Volume geometry of the piezoceramic assembly-horn

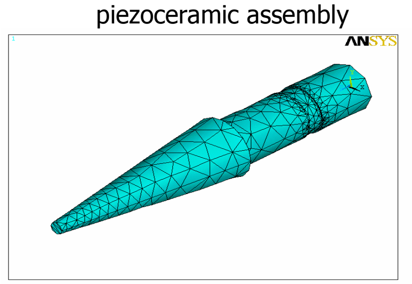

Figure 19. Finite element discretisation of the piezoceramic assembly-horn volumes

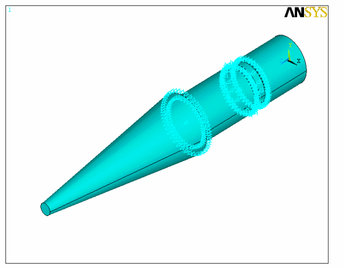

Figure 20. Electric potential and displacement applied to the horn

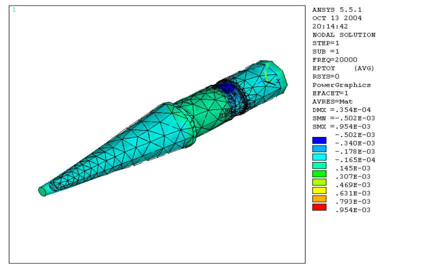

Figure 21. Isometric view of the deformation and normal states of the piezoceramic assembly-horn

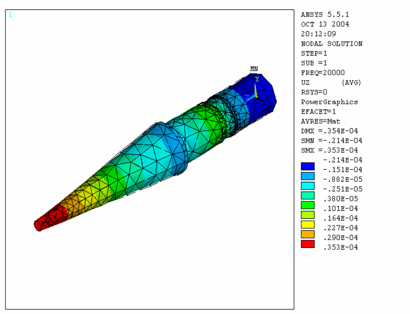

Figure 22. Isometric view of the translation along the piezoceramic assembly-horn axe

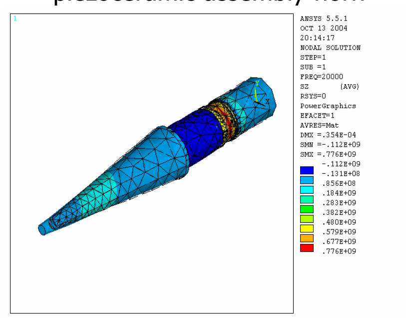

Figure 23. Isometric view of the effort of the piezoceramic assembly-horn

Figures 18, 19, 20, 21, 22 and 23 depicts the construction stages of the piezoceramic assembly model coupled with the ultrasonic horn and the isometric view of the deformation and normal states, translation and effort for the resonance frequency of 20 KHz.

For the validation process of the obtained date through finite element modeling, a set of experiments were realized. The experiments determined the oscillation amplitude of the attack section of the top of the horn for a range of attack tensions for the piezoceramic transducer.

The results of these experiments for attack tensions generated by the generator in a range of values supported by the piezoceramic elements of the ultrasonic transducer are given in Table 2.

Table 2. Experimental values of the oscillation amplitude

Attack tension [V]	Input amplitude in the horn (estimation) [μm]	Input amplitude in the top of the horn (measured) [μm]
0	0	0
50	0.10	6.91

100	0.20	13.82
150	0.30	20.74
200	0.40	27.65
250	0.50	34.57
300	0.60	41.48
350	0.70	48.40
400	0.80	55.31
450	0.90	62.22
500	1.00	69.14
550	1.10	76.05
600	1.2	82.97
650	1.3	89.88
700	1.4	96.80
750	1.5	103.71
800	1.6	110.62

Table 2 shows both the amplitude oscillation of the attack section of the tool and the estimated values of the oscillation amplitude produced by the piezoceramic transducer and fed in the input section of the horn.

The graphical representation corresponding to the data from Table 2 is depicted in Figure 24. As expected, for a constant step increase of the attack tension os the piezoceramic discs of the piezoceramic transducer, a linear variation of the oscillation amplitude in the attack plane of the tool placed at the top of the horn.

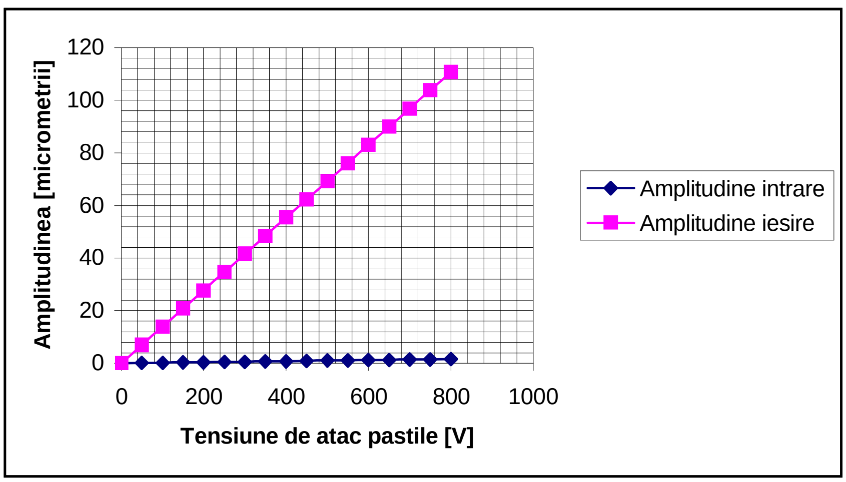

Figure 24. Amplitude variation with the attack tension of the piezoceramic discs

2. Conclusions

The experimental results confirmed the theory in the sense of a very good approximation of the theoretical values with the measured ones.

The measured values were fed as input data for the finite element analysis of these prelucration systems.

The amplitude minimum value is the essential element in the optimization of any ultrasonic prelucration process or treatment, because it gives not only the productivity and efficiency of the work, but also the working precision.

The behavior of the horn during work and at different vibration modes was analyzed using the finite element method from the ANSYS software package. The oscillation amplitude at the top of the horn, the types of waves excited in the horn depending on its dimensions, are elements that defines the processing precision and the quality of the processed surfaces.

The determination of the oscillation amplitude in anay point of the ultrasonic horn is very important due to:

- allows the precise determination of the nodal plane position for the ultrasonic system point of placement in order to start the process;
- the processing productivity is determined depending of the oscillation amplitude at the top of the horn;
- the amplitude determined the ultrasonic system parameters;
- finite element analysis allows testing of various shapes of horns without their manufacturing;
- allows the selection of the corresponding shape for the shape of the surface that needs to be processed.

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