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DIMENSIONAL ANALYSIS OF A HIGH POWER ULTRASONIC SYSTEM USED IN ELECTRODISCHARGE MACHINING

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ABSTRACT: This paper discusses the theoretical and computational aspects of designing a 19kHz high power ultrasonic system used as supplement in electro discharge machining (EDM) systems. A theoretical part presents a numerical approximative 1D matrix method for computing the mechanical resonance frequency of components of ultrasonic systems with axial symmetry. The results obtained by this method, in the case of the concentrator part of the ultrasonic system, are compared with the one obtained from finite element method. A finite element analysis, with computation of the resonance frequency of mechanical vibrations mode around 19kHz, is also presented for the high power ultrasonic transducer and for the entire ultrasonic system.
KEY WORDS: high power ultrasonic system, resonance frequency.

1. INTRODUCTION

The analysis of ultrasonic systems is generally done both from the electrical [1], [5], [6], [8], [9], [10] and mechanical [1], [2], [3], [4], [7], [8], [11] point of view for an optimal coupling between the electronic generator and the acoustic chain, in terms of power and efficiency. In industrial applications, however, a specific working frequency is needed. And so the mechanical analysis concerning dimensioning of all the elements of the high power ultrasonic systems, and finding the nodal planes, at a given resonance frequency, is also needed.

An ultrasonic chain is composed by several elements with capabilities of concentrating or scattering the ultrasonic energy. One key element is the ultrasonic transducer that generate the ultrasonic energy, and composed by a backing part, the reflector, that reflect the ultroasonic energy, an active part, that trnsmit ultrasonic enery to the active tool, 2 piezoceramic rings, and 2 copper electrodes for connection to the elecronic generator, all of them prestresed with a central screw. The second key element is the active tool,, the concentrator, that guide the ultrasonic energy to the industrial process. This two parts are linked by a link screw, as seen in figure 1. O course the active part of the transducer and the concentrator can be done in one piece, but is better to make them separately, so the active tool, the concentrator, that is more rapidely wear in the industrial process, can be interchangeable.

Every ultrasonic system must have a specific resonance frequency, given by the industrial process requirements, and so a dimensional analysis must be done. All these elements are longitudinal resonators in half wavelength with continuous or step variations of the cross-section. Most of them have a circular cross-section, that enables an approximative 1D numerical matrix method, presented below, or 2D finite element dimensional analysis with axial symmetry.

This paper presents the case of the dimensional analysis of a high power ultrasonic acoustic chain resonator, used in the electrodischarge machining industrial porocess, called EDM, with both the piezoceramic transducer and concentrator used in the industrial process of electro-discharge machining, at a required frequency of 18kHz-20kHz. Both the transducer and the resonator elements are analyzed separately and as an assembly respectively, in order to find the precise resonance frequency.

2. THE NUMERICAL MATRIX METHOD

The numerical method used is the 1D matrix method. This numerical method considers the free longitudinal wave propagation analysis can be performed using equation of wave propagation in a dissipative media:

$$E\frac{\partial^2 w}{\partial x^2} = \rho\frac{\partial^2 w}{\partial t^2} + R\frac{\partial w}{\partial t} \tag{2.1}$$

where w - represents the displacements, x - the direction of propagation, t - the time, ρ - mass density, E - the modulus of elasticity, $E = \rho c^2$, c - the wave speed and R - the coefficient of friction that characterize the losses in the media.

For stationary waves the solution of (2.1) can be written:

$$w(x,t) = X(x)\cdot P(t) \tag{2.2}$$

One can consider for each straight portion of the beam, with length *l* and *i* and *j* its extreme sections indexes. In each section of abscissa *x*, it can be defined the column matrix named state vctor:

$$\{M(x)\} = \begin{bmatrix} W(x) \\ T(x) \end{bmatrix} \tag{2.3}$$

where $W(x)$ and $T(x)$ represents the displacements and stress in the Ox direction.

For the monochromatic wave of frequency $f = \omega/2\pi$, it can be considered $P(t) = e^{-\alpha t}\cos(\omega t - \varphi)$ where α represent the atenuation factor, and φ the phase shift, and so (2.2) becomes:

$$w(x,t) = X(x)e^{-\alpha t}\cos(\omega t - \varphi) \tag{2.4}$$

For $R = 2\alpha\rho$ eq. (2.1) becomes and ordinary differential equation:

$$X''(x) + \frac{1}{c^2}(\omega^2 + \alpha^2)X(x) = 0 \tag{2.5}$$

A matricial equation between the state vectors of sections *i* and *j* can be considered:

$$\begin{bmatrix} W_j \\ T_j \end{bmatrix} = \begin{bmatrix} M_{ij} \end{bmatrix} \cdot \begin{bmatrix} W_i \\ T_i \end{bmatrix} \quad (2.6)$$

or briefly:

$$\{M_j\} = [M_{ij}]\{M_i\} \quad (2.7)$$

where $[M_{ij}]$ is named field matrix and has the form:

$$[M_{ij}] = \begin{bmatrix} \cos al & \frac{1}{kal}\sin al \\ -kal\sin al & \cos al \end{bmatrix} \quad (2.8)$$

where :

$$a = \frac{\omega_a}{c} = \frac{\sqrt{\omega^2 + \alpha^2}}{c}, c = \sqrt{\frac{E}{\rho}},\ k = \frac{EA}{l}, \quad (2.9)$$

with ω - the angular frequency, *c* - the wave speed, *k* - the stiffness of the (*i*,*j*) medium of length *l*.

For an entire uniaxial structure, a global matricial equation between the state vectors of both ends with indexes *1* and *n*:

$$\{M_n\} = [M]\{M_1\}, \quad (2.10)$$

where the matrix $[M]$ is given by:

$$[M] = [M_{(n-1)n}][M_{(n-2)(n-1)}]\cdots[M_{23}][M_{12}]. \quad (2.11)$$

The element of the global matrix $[M]$, are function of angular frequency:

$$[M] = \begin{bmatrix} m_{11}(\omega) & m_{12}(\omega) \\ m_{21}(\omega) & m_{22}(\omega) \end{bmatrix}. \quad (2.12)$$

At the longitudinal resonance the stress on both ends of the structure must be null $T_n = 0$, and $T_1 = 0$, that implies:

$$m_{21}(\omega) = 0. \quad (2.13)$$

Equation (2.13) can be solved numerically without difficulties. It also can be seen that the longitudinal disctretization do not need to be uniform. However when the cross-section is not uniform, a large number of setions must be taken into account to approximate as good as possible the contour of the resonator.

3. RESULTS

An acoustic chain used in ultrasonic assisted EDM, as presented in figure 1, has been analyzed. First, the two elements of the acoustic chain, the concentrator and the high power ultrasonic transducer are analyzed separately, and then analyzed assembled. The requirement is that the two parts of the ultrasonic system must be half wavelength resonators. The industrial EDM process requires that the resonance frequency must be between 18kHz and 20kHz.

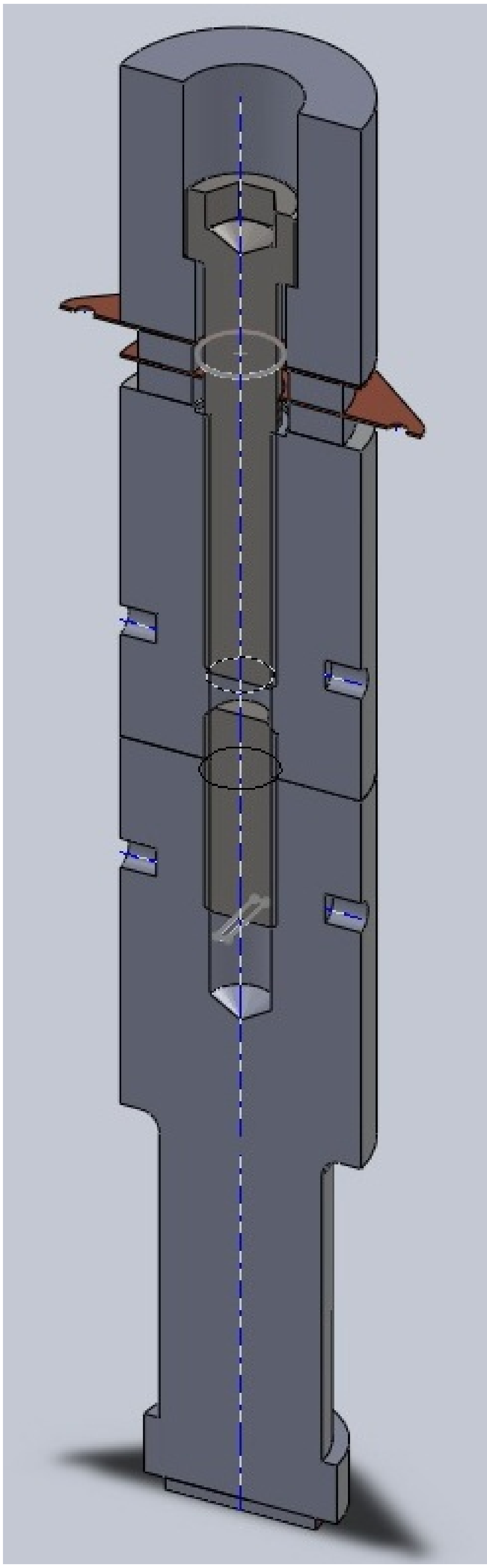

Figure 1. Acoustic chain used in ultrasonic assisted EDM

First the concentrator, is analyzed with both numerical methods the 1D matrix method and the finite element method, and after that only the finite element method for the transducer and the assembled acoustic chain.

In figure 2 the geometric dimensions of the concentrator and in figure 3 the geometric dimensions of the high power ultrasonic transducer are presented.

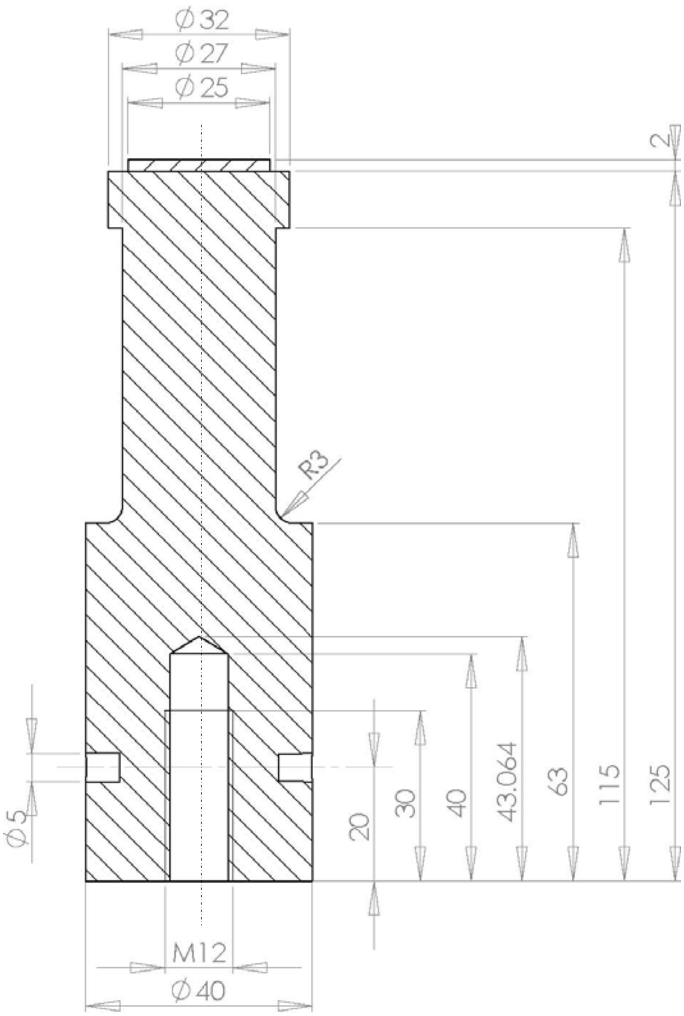

Figure 2. The concentrator of the acoustic chain used in ultrasonic assisted EDM.

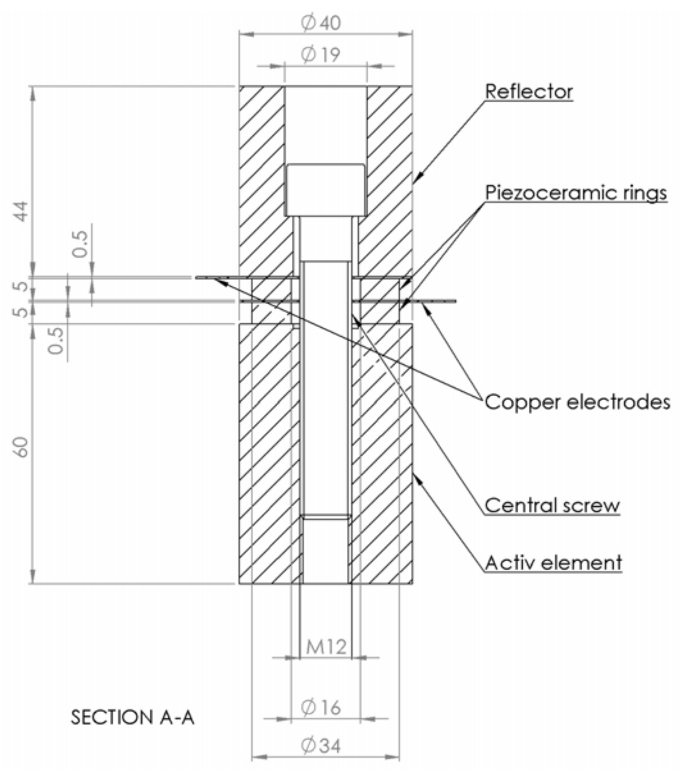

Figure 3. The transducer of the acoustic chain used in ultrasonic assisted EDM.

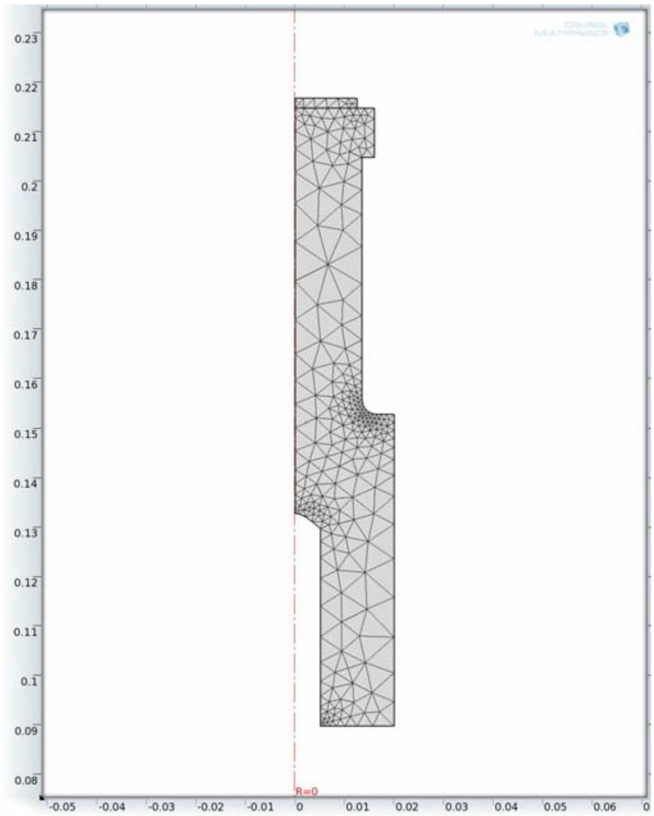

Figure 4. Mesh used in finite element analysis of the concentrator.

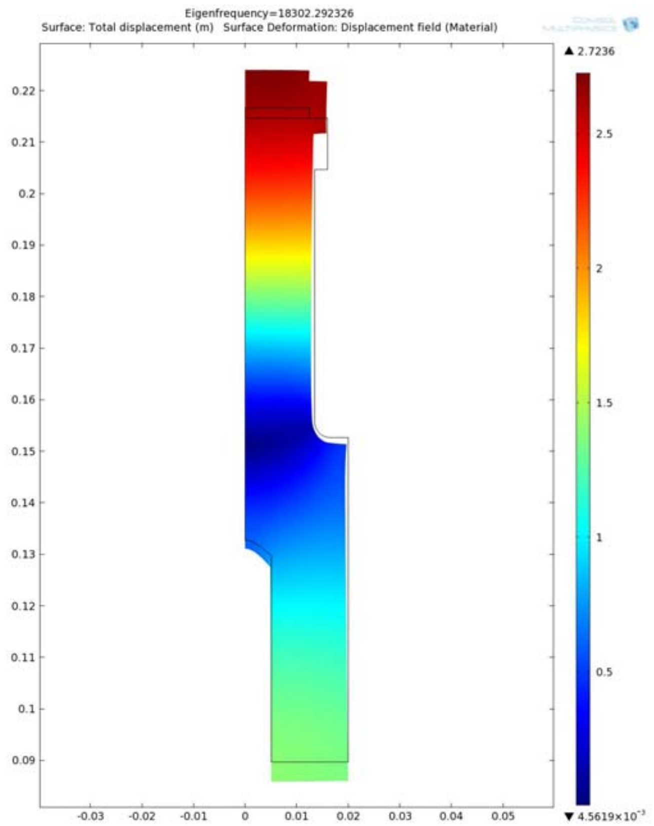

Figure 5. First vibration computed mode of the concentrator.

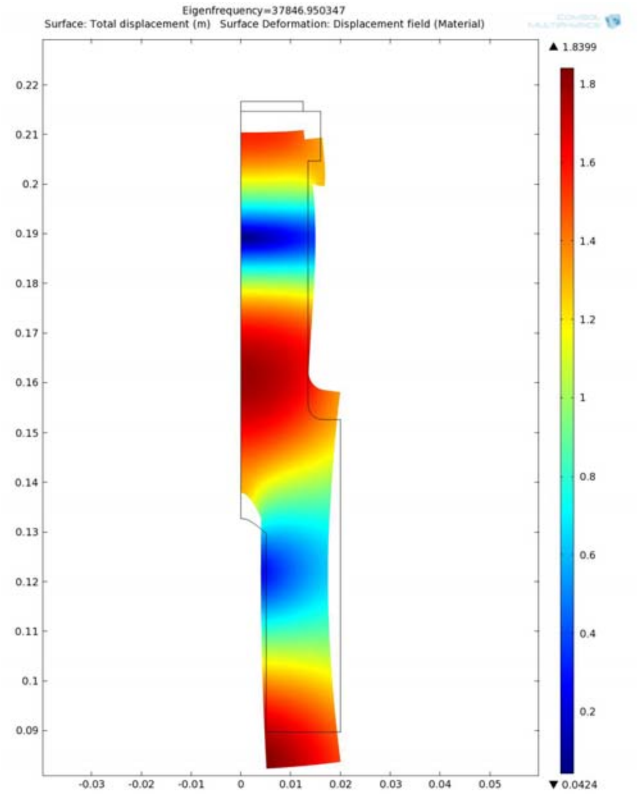

Figure 6. Second vibration mode computed of the concentrator.

The matrix method descripted above was applied to the considered concentrator, resulting a resonance frequency of 18.724 kHz. It has been taken a discretization of 2005 section of constant cross-setion, and elastic modulus and mass density of the duralumin and copper has been taken $E_{dural} = 71.0[MPa]$, $E_{cu} = 117.0[MPa]$, $\rho_{dural} = 2700[kg/m^3]$, $\rho_{cu} = 8940[kg/m^3]$. This method is very fast, being one-dimensional, but somewhat imprecise because it does not takes into account shear elastic properties, like the shear modulus or Poisson ratio, of the duraluminium and copper. It is therefore necessary, for comparison, an analysis with the finite element method specialized software Comsol 4.2.

In finite element method analysis, the elastic characteristics (modulus of elasticity, mass density and Poisson ratio, of the duralumin and copper) have been taken also $E_{dural} = 71.0[MPa]$, $E_{cu} = 117.0[MPa]$, $\rho_{dural} = 2700[kg/m^3]$, $\rho_{cu} = 8940[kg/m^3]$, $\nu_{dural} = 0.33$, respectively $\nu_{cu} = 0.33$. If the the gathering holes are neglected, the acoustic chain element presents axial symmetry, and the finite element analysis can be done in the 2D-axisymmetric case, on a half longitudinal cross-section computing the eigenfrequencies of the structure. The mesh discretization has been taken normal, and can be seen in figure 4, and firsts eigenfrequencies have been computed around 19 kHz. In figures 5 and 6 the vibration modes corresponding to frequencies 18302.29 Hz, 37846.95 Hz, are presented. Obviously only the first vibration mode corresponding to the longitudinal resonance is interesting. The calculation was made, for comparison, with a finer the grid mesh, but the difference between resonance frequencies corresponding to the first vibration mode did not exceed 10 Hz, leading to differences due to discretization of 0.05%, total considered negligible. Of course if the materials properties are taken slightly different, the difference between the resonance frequencies are bigger, but also neglijable.

The finite element analysis of the transducer was considered in 2 cases of the resonance frequency: the first case when the electrodes are in short circuit that corresponds to the series resonance frequency, and, in the second case, when the electrodes are in the gap that corresponds to the parallel resonance frequency.

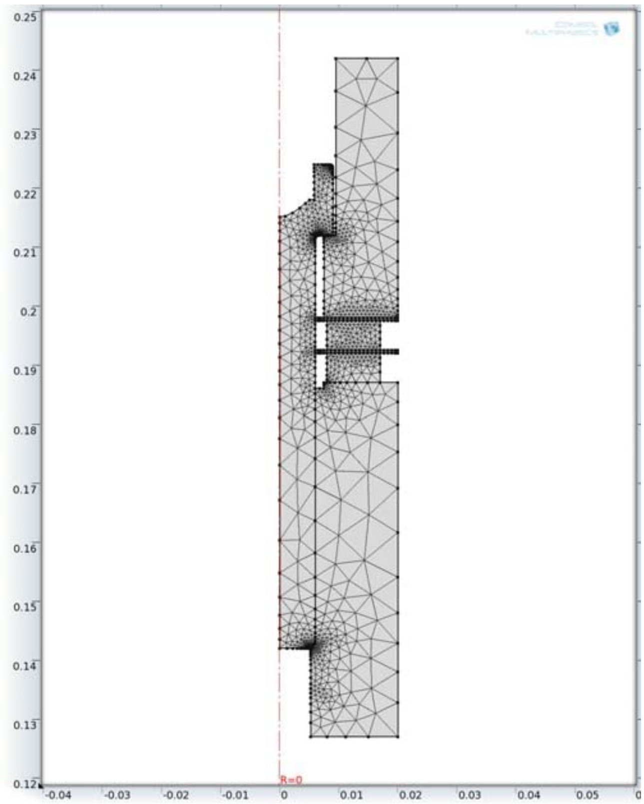

Figure 7. Mesh used in finite element analysis of the transducer.

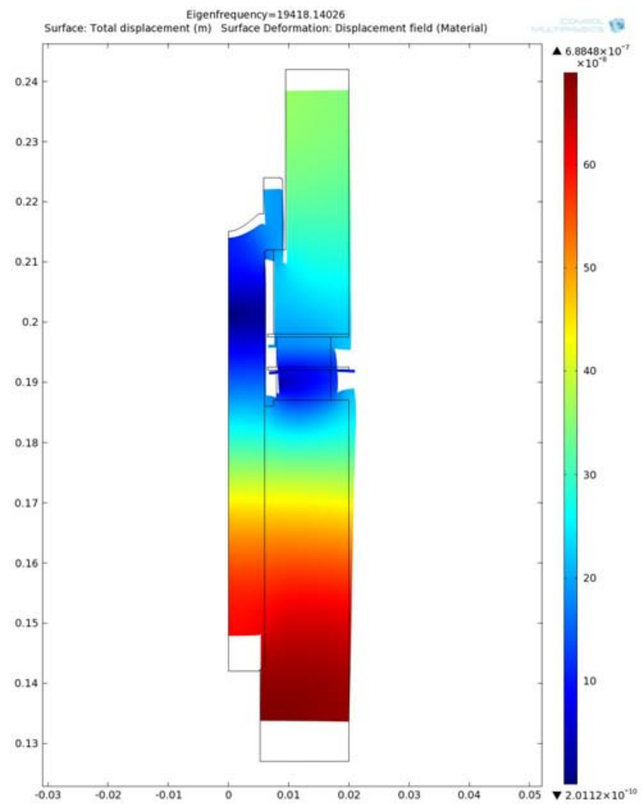

Figure 8. First vibration mode computed of the transducer.

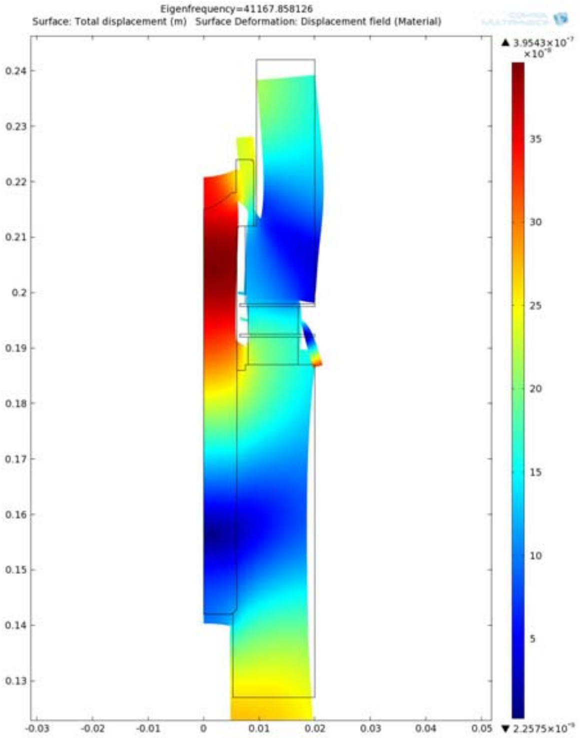

Figure 9. Second vibration mode computed of the transducer.

In the finite element analysis of the transducer the elastic properties of the steel, duralumin and copper electrodes have been taken

$E_{st} = 210.0[MPa]$, $E_{dural} = 71.0[MPa]$, $E_{cu} = 117.0[MPa]$, $\rho_{st} = 7800[kg/m^3]$, $\rho_{dural} = 2700[kg/m^3]$, $\rho_{cu} = 8940[kg/m^3]$, $\nu_{st} = 0.33$, $\nu_{dural} = 0.33$, $\nu_{cu} = 0.33$ respectively.

For the piezoceramic rings the elastic and piezoelectric constants are the ones o the PZT-4, with symbols given by the constitutive equarions:

$$\sigma = c_E \varepsilon - e^T E$$
$$D = e\varepsilon + \varepsilon_0 \varepsilon_r E$$

- Mass density $\rho = 7500[kg/m^3]$,

- Elasticity matrix

$$c_E = \begin{pmatrix} 138.99 & 77.83 & 77.83 & 0 & 0 & 0 \\ & 138.99 & 77.83 & 0 & 0 & 0 \\ & & 115.41 & 0 & 0 & 0 \\ & & & 25.64 & 0 & 0 \\ & & & & 25.64 & 0 \\ & & & & & 30.58 \end{pmatrix} [\text{MPa}]$$

- the piezoceramic matrix constants have been taken for normal and reverse polarization (The two piezoceramic rings are mirror mounted, for bigger vibration amplitude):

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & 12.718 & 0 \\ 0 & 0 & 0 & 12.718 & 0 & 0 \\ -5.2028 & -5.2028 & 15.080 & 0 & 0 & 0 \end{pmatrix} \left[\text{C/m}^2\right]$$

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & -12.718 & 0 \\ 0 & 0 & 0 & -12.718 & 0 & 0 \\ 5.2028 & 5.2028 & -15.080 & 0 & 0 & 0 \end{pmatrix} \left[\text{C/m}^2\right]$$

- Relative permitivity matrix

$$\varepsilon_r = \begin{pmatrix} 762.5 & 0 & 0 \\ 0 & 762.5 & 0 \\ 0 & & 663.2 \end{pmatrix}.$$

The mesh has been taken normal, as presented in figure 7, and the firsts vibration modes have been computed around 19000 Hz. In figures 8 and 9, corresponding to vibration modes at frequencies 19418.14Hz and 41167.95Hz for the series resonance of the transducer, with electrodes in short circuit, are presented. Only the pure longitudinal vibration mode is interesting, the one with higher vibration amplitudes, at the 19418.14 Hz. For the parallel resonance, similar vibration modes are obtained, but the resonance frequencies are respectively 20597.67Hz and 41537.33Hz, far enough for the series resonance frequency, so that the elecronic generator to excite that modes, that can damage both the transducer and the electronic generator.

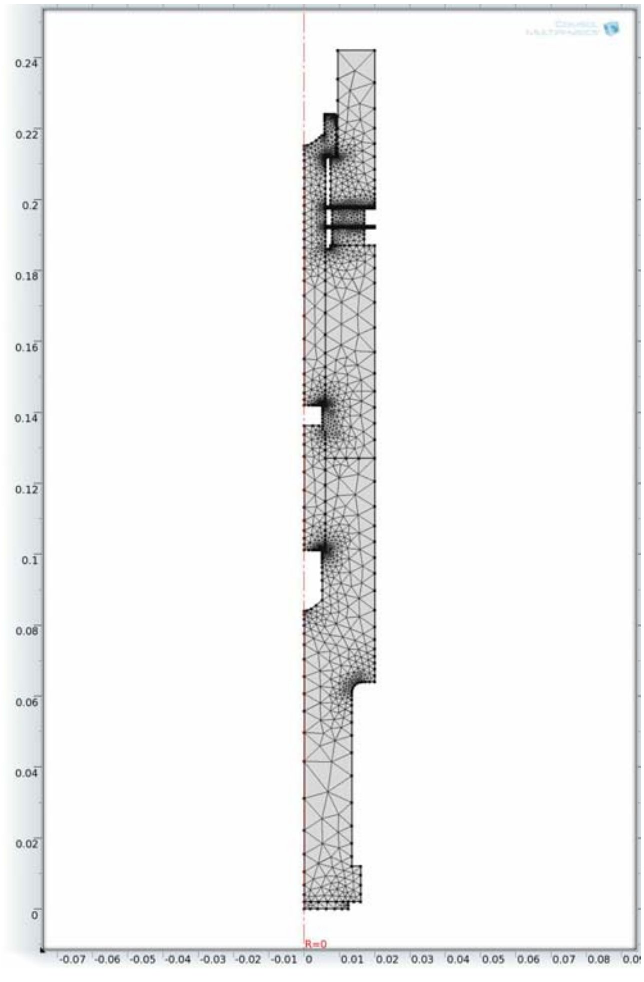

Figure 10. Mesh used in finite element analysis of the entire ultrasonic system.

In the dimensional analysis of the acoustic chain with finite element method, the same discretization "normal" was taken, as seen in figure 10. In this case, also, the vibration mode, presented in figures 11 and 12, were computed around 19 kHz, and for series resonance and their frequencies are 9910.18 Hz and 18253.14Hz. For parallel resonance, the vibration modes are obtained similar, but that resonance frequencies are 10063.51Hz and 18599.81Hz.

It can be seen a decrease in the frequency of resonance of acoustic chain, from those two parts. This is due to added link screw that connects all the components.

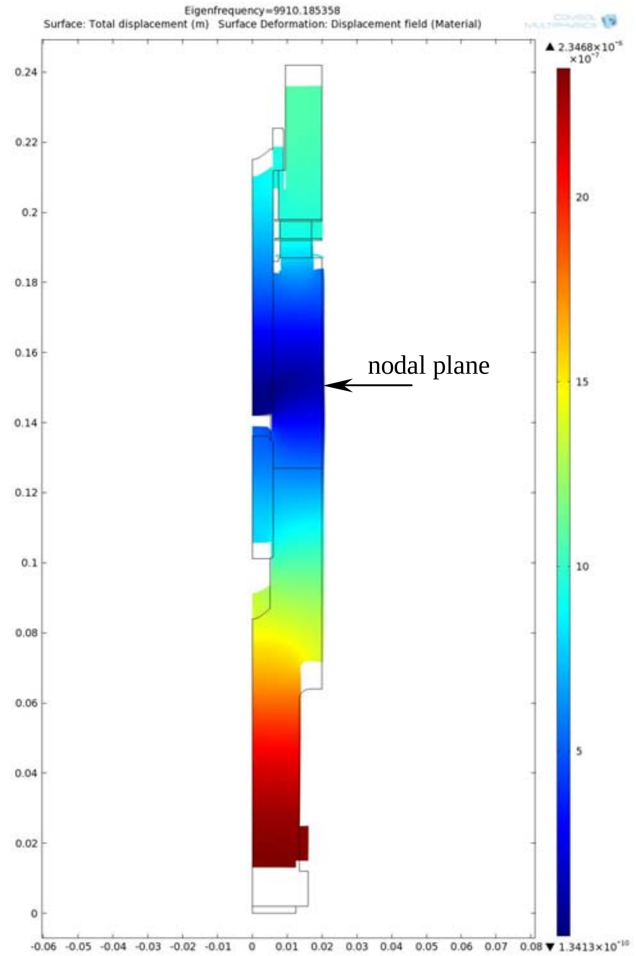

Figure 11. First vibration mode computed of the entire ultrasonic system.

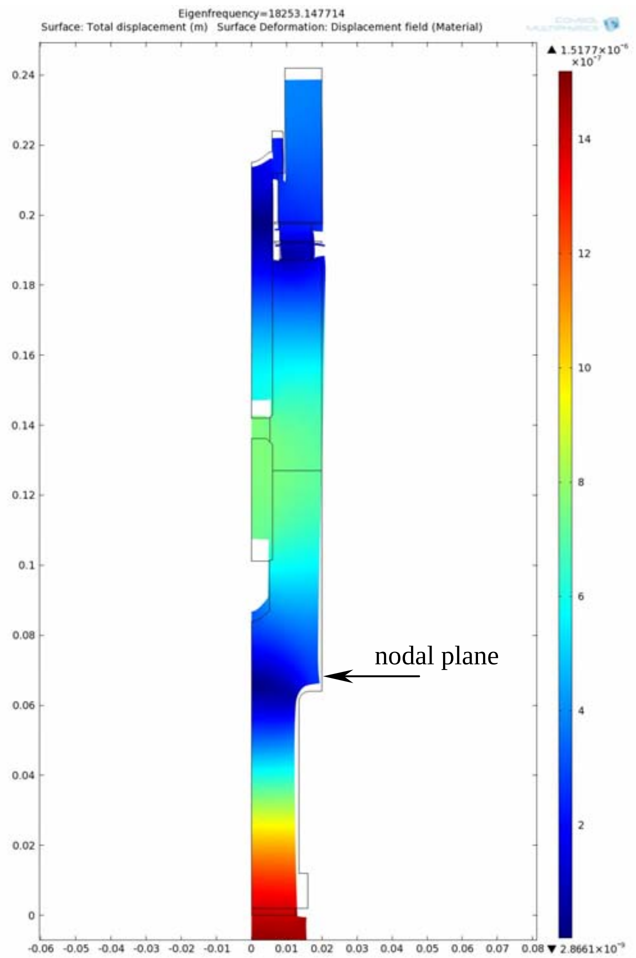

Figure 12. Second vibration mode computed of the entire ultrasonic system.

Obviously we are interested only pure longitudinal vibration mode. It can be seen that there are two modes of vibration of this type. The nodal planes corresponding to these two vibration modes are different. The vibration mode corresponding to the frequency 9910.18Hz, is in half wavelenght, for the entire acoustic chain. It seems more convenient, but it is sonic not ultrasonic, which can be annoying, for the human ear. We must therefore choose one of them as a way of working, the one corresponding to the frequency 18253.14 Hz.

4. CONCLUSIONS

The 1D numerical matrix method approximates well enough the resonance frequency of the elements of the ultrasonic system.

Dimensional analysis of the ultrasonic chain meets the requirements imposed by the electronic generator and the of the electrodischarge machining process, the ones that pure longitudinal vibration mode corresponding to the series resonance frequency being between 18kHz and 20kHz.

5. ACKNOWLEDGEMENTS

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