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DETERMINATION OF EIGENFREQUENCIES FOR SOME ULTRASONIC HORNS SPECIFIC TO HYBRID ELECTROCHEMICAL MACHINING

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Abstract: *The paper deals with the modelling and simulation of some ultrasonic horns, each of them having attached a tool specific for electrochemical machining and micro electrochemical machining. The modelling and simulation were realized in COMSOL Multiphysics, in the module Eigenfrequency. The study provides information about the modelling steps, used parameters for each model developed and analyzed. A comparison was made between the own frequency of each ultrasonic horn, and the modified parameters to obtain the resonance frequency, considering the transducer used. Also, some charts regarding the amplification or elongation in relation to the length of ultrasonic horn were presented. Finally, the advantages and disadvantages were exposed, and some solutions of output technological parameters for further improvement.*

Key words: *Modelling, simulation, ultrasonic, horn, electrochemical machining, eigenfrequency, electrochemical polishing.*

1. INTRODUCTION

Electrochemical machining assisted by ultrasonic component (ECM+US) can be applied to electrically conductive materials, for complex geometries (micro-holes, deep holes, cavities that cannot be processes by conventional technologies), but also various fields (automotive, aerospace, medical, chemical, food industries, etc.).

In other domains like cold plastic deformation, the active elements of the dies are made using these technologies.

As it is known, electrochemical machining is based on the phenomenon of anodic dissolution through the controlled sampling of the workpiece material in an electrolytic cell, in this case, the workpiece being the anode and the tool the cathode. For a good process functionality, it is necessary to choose the correct electrolytic liquid, to fix the right process parameters and to dimension the tool in good conditions [1,2].

A lot of research has been done regarding combinations of electrical discharge machining and ultrasonic assistance EDM+US or EDM+ECM, but ECM is treated in most cases like a singular process, because of the reactions that can happen during the process and the additional mandatory protection.

So, to increase the productivity and the roughness of a surface, can be applied the ultrasonic component (to the tool, workpiece or in the electrolytic liquid). Before applying this vibration component, an ultrasonic horn has to be developed and some simulations have to be realized [3,4].

The ultrasonic technology represents a new trend in the area of manufacturing and a good element to improve the roughness of a surface for complex geometries or polishing.

Many industrial applications and manufacturing technologies are based on the application of ultrasound. In many cases, the phenomenon of ultrasound is also applied in the technological processes of material processing.

Significant performance increases and quality improvements are achieved through the use of ultrasonic vibrations [5,6,7].

Currently, ultrasonic processing technically have a very wide spread in industrially developed countries such as: USA, France, Russia, England, Japan, Germany, etc. [8,9].

2. STRUCTURE AND DIMENSIONING OF AN ULTRASONIC CHAIN

The structure of an ultrasonic chain is represented by: 1 - reflective bushing, 2 - piezo ceramic plates, 3 - copper blades, 4 - radiant bushing, 5 - ultrasonic horn, 6 - tool.

In figure 1, are presented two models of ultrasonic chain, one for machining a surface of 4 mm diameter and the other for polishing, using a tool with a diameter of 32 mm.

The size of the radiant bushing is chosen according to the diameter of the processed surface. In general, for surfaces up to 30 mm, the diameter of the radiant bushing is 38 mm, and the resonant frequency is 40 kHz, and for larger surfaces, the diameter is 52 mm and the resonant frequency is 20 kHz.

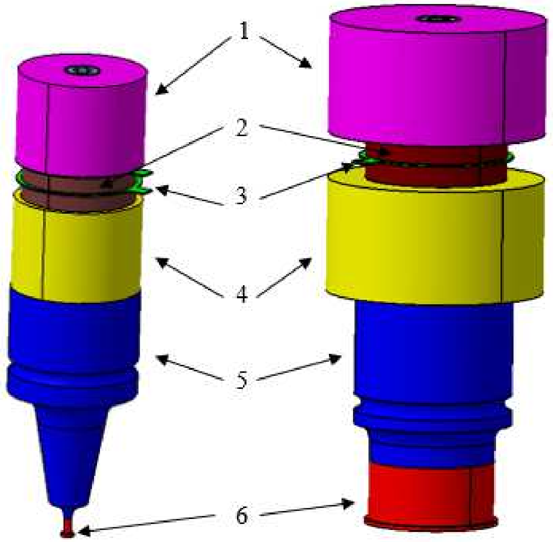


Fig.1. Ultrasonic chain components

The first model presented in figure 1 represents a conical type of horn, and the second one, that is for polishing a surface is cylindrical. The working parameters used to get these geometries will be related in chapter number 3, where it can be found information about all simulation.

The ultrasonic horns help to fulfill the following functions [1]:

- Transfers the ultrasonic energy from the vibration generator to the place of processing.
- Concentrates and focuses the ultrasonic energy in the working area.
- Increase the amplitude of tool vibrations.
- Due to their very varied shape, it allow the use of ultrasound for a very wide range of classic processing operations.
- Maximize processing efficiency.

The size of ultrasonic horns is done according to the next factors [1]:

- Type of operation.
- The material of the part. Also, the material of the horn is so important. Aluminum is ideal for normal applications, while steel or titanium are suitable for complex and high-pressure applications. It must have good acoustic characteristics, high fatigue resistance, and high oscillation amplitude. In addition, the material of the concentrator must be resistant to corrosion, heat, high wear resistance, good elasticity, and fatigue resistance properties, but also high hardness value.
- Surface dimension.

Some relations were applied to get the dimensions of the components below, and the results are presented in tables 1 and 2 and it start with determination of amplification factor, K [1].

$$K = \left(\frac{D_1}{D_2}\right)^2 \qquad (1)$$

$$l_1 = \frac{1,5}{\alpha} \qquad [\mathrm{m}] \qquad (2)$$

$$l_2 = \frac{1,6}{\alpha} \qquad [\mathrm{m}] \qquad (3)$$

$$\alpha = \frac{2 \cdot \pi}{\lambda} \qquad (4)$$

$$\lambda = \frac{c}{f} = \frac{1}{f}\sqrt{\frac{E}{\rho}} \qquad [\mathrm{m}] \qquad (5)$$

$$\alpha = \frac{\lambda}{4} \qquad [\mathrm{m}] \qquad (6)$$

$$c = 2 \cdot l \cdot f_0 \qquad [\mathrm{m/s}] \qquad (7)$$

$$f_{transducer} = f_{horn} \qquad [\mathrm{Hz}] \qquad (8)$$

The relation number 8 is mandatory for a good functionality of the process. The frequency of the transducer must be the same as the frequency of the horn. It ensures good stability of the process. After the relations are applied, it is necessary to analyze in COMSOL and to modify some parameters of the horn, to determine the eigenfrequency. This study will be presented in chapter number 3 of this paper.

Table 1

Results for Model 1

Modulus of elasticity, E	2,10E+11	Pa
Material density C45, ρ	7850	kg/m3
Speed of sound in horn material, c	5172,19	m/s
Wave length, λ	0,132620363	m
Initial frequency, f_{us}	40000	Hz
Number of wave, α	47,35321079	m^{-1}
Length, l_1	0,031676838	m
Length, l_2	0,033788627	m
Radiant bushing size	38	mm
Transversal size of the surface to be processed	4	mm
Transducer target frequency	40100	Hz

Table 2

Results for Model 2

Modulus of elasticity, E	2,10E+11	Pa
Material density C45, ρ	7850	kg/m3
Speed of sound in horn material, c	5172,19	m/s
Wave length, λ	0,2722207368	m
Initial frequency, f_{us}	20000	Hz
Number of wave, α	23,081	m^{-1}
Length, l_1	0,064988	m
Length, l_2	0,069321	m
Radiant bushing size	52	mm
Transversal size of the surface to be processed	32	mm
Transducer target frequency	20100	Hz

The tools analyzed in the tables above are presented in a better view in figures 2 and 3.

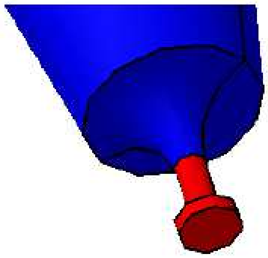


Fig.2. Tool for Model 1

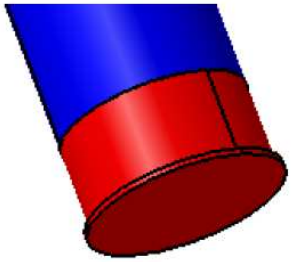


Fig.3. Tool for Model 2

After the applying of the relations related above, it is necessary to ensure a good working medium. Some of the tool materials and electrolytes characteristics are presented in the figures below.

Starting from these aspects, it can be pointed out that the state of resonance can be ensured more easily, compared to EDM+US. At the same time, the tool has zero wear, and the fact that there are no internal tensions in the processed material offers a much better quality of the processed surface [1].

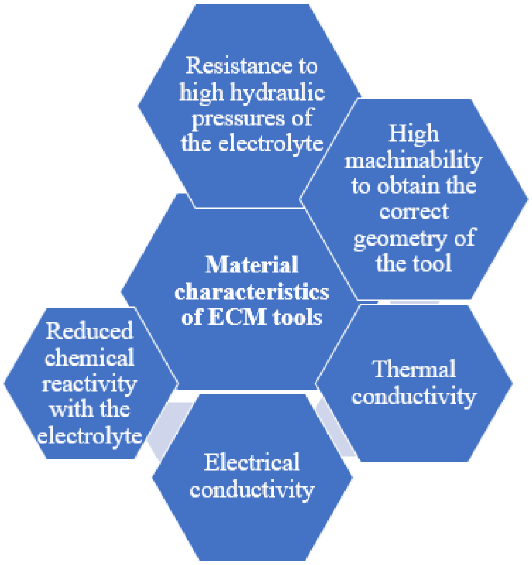


Fig.4. Tool characteristics

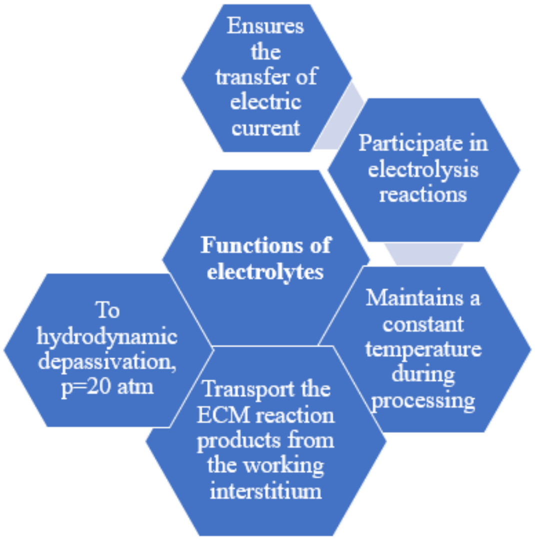
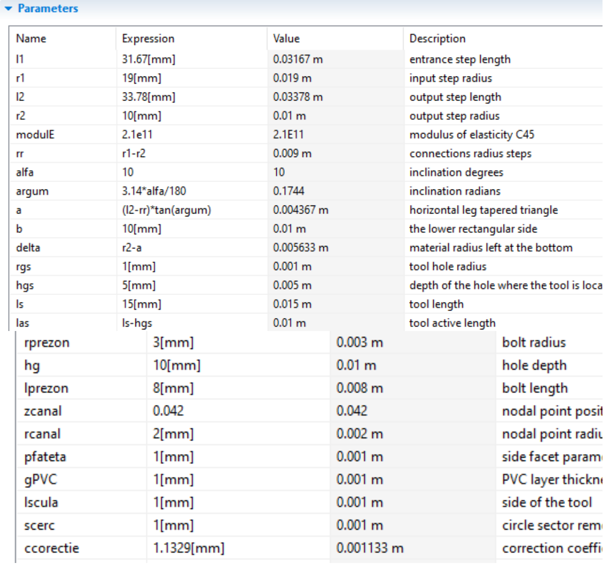


Fig.5. Electrolytes characteristics

3. FINITE ELEMENT MODELLING

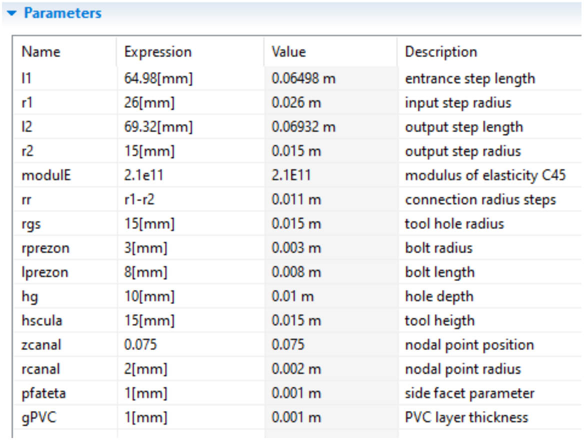
COMSOL Multiphysics, Structural Mechanics with Eigenfrequency variant was used for modelling the horn and tool. In figure 6 and 7, are presented the working parameters.

After the working parameters were defined, to build the concentrator and the tool, it was necessary to apply in COMSOL Multiphysics, geometry operations like Rectangle, Square, Circle and then some Booleans functions, Difference, Union. After this, to have a technological assembly was used Chamfer operation.



Name	Expression	Value	Description
l1	31.67[mm]	0.03167 m	entrance step length
r1	19[mm]	0.019 m	input step radius
l2	33.78[mm]	0.03378 m	output step length
r2	10[mm]	0.01 m	output step radius
modulE	2.1e11	2.1E11	modulus of elasticity C45
rr	r1-r2	0.009 m	connections radius steps
alfa	10	10	inclination degrees
argum	3.14*alfa/180	0.1744	inclination radians
a	(l2-rr)*tan(argum)	0.004367 m	horizontal leg tapered triangle
b	10[mm]	0.01 m	the lower rectangular side
delta	r2-a	0.005633 m	material radius left at the bottom
rgs	1[mm]	0.001 m	tool hole radius
hgs	5[mm]	0.005 m	depth of the hole where the tool is loca
ls	15[mm]	0.015 m	tool length
las	ls-hgs	0.01 m	tool active length
rprezon	3[mm]	0.003 m	bolt radius
hg	10[mm]	0.01 m	hole depth
lprezon	8[mm]	0.008 m	bolt length
zcanal	0.042	0.042	nodal point posi
rcanal	2[mm]	0.002 m	nodal point radiu
pfateta	1[mm]	0.001 m	side facet param
gPVC	1[mm]	0.001 m	PVC layer thickn
lscula	1[mm]	0.001 m	side of the tool
scerc	1[mm]	0.001 m	circle sector rem
ccorectie	1.1329[mm]	0.001133 m	correction coeffi

Fig.6. Working parameters for Model 1



Name	Expression	Value	Description
l1	64.98[mm]	0.06498 m	entrance step length
r1	26[mm]	0.026 m	input step radius
l2	69.32[mm]	0.06932 m	output step length
r2	15[mm]	0.015 m	output step radius
modulE	2.1e11	2.1E11	modulus of elasticity C45
rr	r1-r2	0.011 m	connection radius steps
rgs	15[mm]	0.015 m	tool hole radius
rprezon	3[mm]	0.003 m	bolt radius
lprezon	8[mm]	0.008 m	bolt length
hg	10[mm]	0.01 m	hole depth
hscula	15[mm]	0.015 m	tool heigth
zcanal	0.075	0.075	nodal point position
rcanal	2[mm]	0.002 m	nodal point radius
pfateta	1[mm]	0.001 m	side facet parameter
gPVC	1[mm]	0.001 m	PVC layer thickness

Fig.7 Working parameters for Model 2

After defining the geometry of the ultrasonic chain, the materials were applied for each individual element as follows: steel for horn, the connecting radius between them, but also the pin, cooper for the tool-electrode, respectively silver for the tool soldering, a connecting radius being created between it and the output step of the horn. The polyvinyl chloride (PVC) was added for the protection of the horn, being immersed in electrolytic medium. The depth of PVC is around 1 mm.

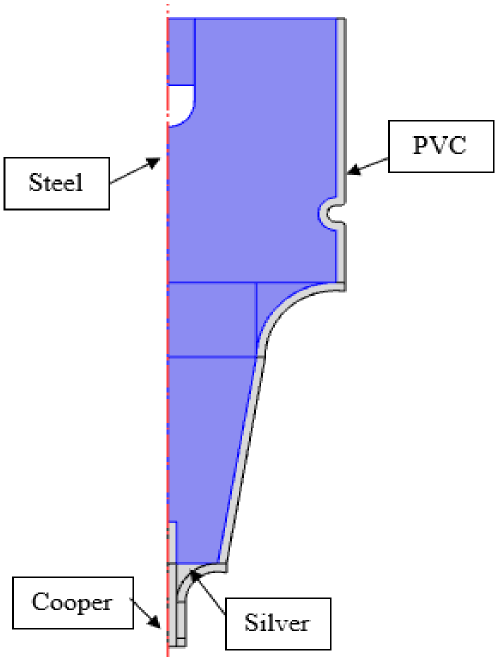
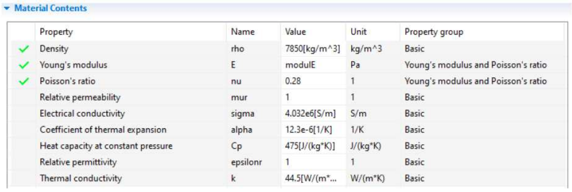


Fig.8. Horn and tool materials

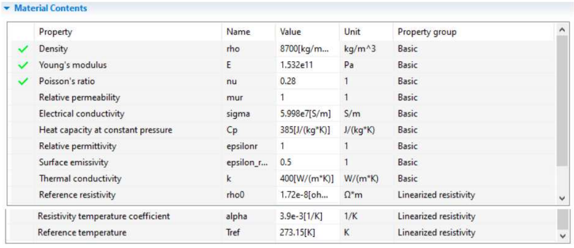
The materials characteristics are related in the next figures.



Material Contents

	Property	Name	Value	Unit	Property group
✓	Density	rho	7850[kg/m^3]	kg/m^3	Basic
✓	Young's modulus	E	modulE	Pa	Young's modulus and Poisson's ratio
✓	Poisson's ratio	nu	0.28	1	Young's modulus and Poisson's ratio
	Relative permeability	mur	1	1	Basic
	Electrical conductivity	sigma	4.032e6[S/m]	S/m	Basic
	Coefficient of thermal expansion	alpha	12.3e-6[1/K]	1/K	Basic
	Heat capacity at constant pressure	Cp	475[J/(kg*K)]	J/(kg*K)	Basic
	Relative permittivity	epsilonr	1	1	Basic
	Thermal conductivity	k	44.5[W/(m*...	W/(m*K)	Basic

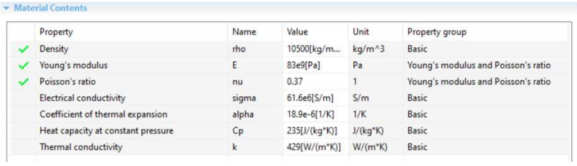
Fig.9. Steel AISI 4340



Material Contents

	Property	Name	Value	Unit	Property group
✓	Density	rho	8700[kg/m...	kg/m^3	Basic
✓	Young's modulus	E	1.532e11	Pa	Basic
✓	Poisson's ratio	nu	0.28	1	Basic
	Relative permeability	mur	1	1	Basic
	Electrical conductivity	sigma	5.998e7[S/m]	S/m	Basic
	Heat capacity at constant pressure	Cp	385[J/(kg*K)]	J/(kg*K)	Basic
	Relative permittivity	epsilonr	1	1	Basic
	Surface emissivity	epsilon_r...	0.5	1	Basic
	Thermal conductivity	k	400[W/(m*K)]	W/(m*K)	Basic
	Reference resistivity	rho0	1.72e-8[oh...	Ω*m	Linearized resistivity
	Resistivity temperature coefficient	alpha	3.9e-3[1/K]	1/K	Linearized resistivity
	Reference temperature	Tref	273.15[K]	K	Linearized resistivity

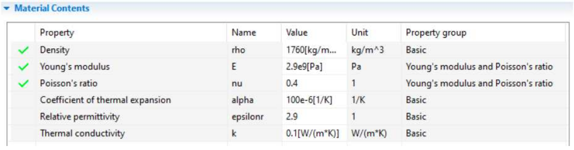
Fig.10. Cooper



Material Contents

	Property	Name	Value	Unit	Property group
✓	Density	rho	10500[kg/m...	kg/m^3	Basic
✓	Young's modulus	E	83e9[Pa]	Pa	Young's modulus and Poisson's ratio
✓	Poisson's ratio	nu	0.37	1	Young's modulus and Poisson's ratio
	Electrical conductivity	sigma	61.6e6[S/m]	S/m	Basic
	Coefficient of thermal expansion	alpha	18.9e-6[1/K]	1/K	Basic
	Heat capacity at constant pressure	Cp	235[J/(kg*K)]	J/(kg*K)	Basic
	Thermal conductivity	k	429[W/(m*K)]	W/(m*K)	Basic

Fig.11. Silver



Material Contents

	Property	Name	Value	Unit	Property group
✓	Density	rho	1760[kg/m...	kg/m^3	Basic
✓	Young's modulus	E	2.9e9[Pa]	Pa	Young's modulus and Poisson's ratio
✓	Poisson's ratio	nu	0.4	1	Young's modulus and Poisson's ratio
	Coefficient of thermal expansion	alpha	100e-6[1/K]	1/K	Basic
	Relative permittivity	epsilonr	2.9	1	Basic
	Thermal conductivity	k	0.1[W/(m*K)]	W/(m*K)	Basic

Fig.12. PVC

Then, to determine the own frequency of the horn, the boundary conditions are entered in Physics menu in the form of Free 1. It is necessary to eliminate all mechanical constraints. In the next figures, it can be seen the results of analyzed models.

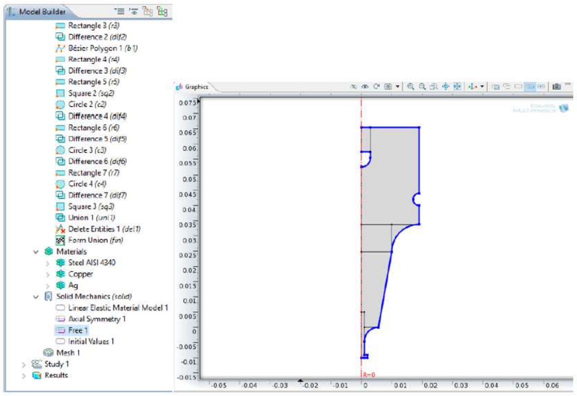


Fig.13. Boundary conditions for determining the natural frequency of the concentrator - Model 1

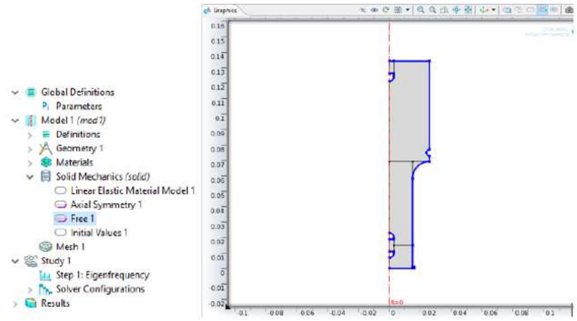


Fig.14. Boundary conditions for determining the natural frequency of the concentrator - Model 2

The discretization is performed with precise triangular elements, by choosing the Finer button and it is shown with the corresponding quality obtained by selecting the Statistics function from the Mesh menu. Elements are finer to increase accuracy.

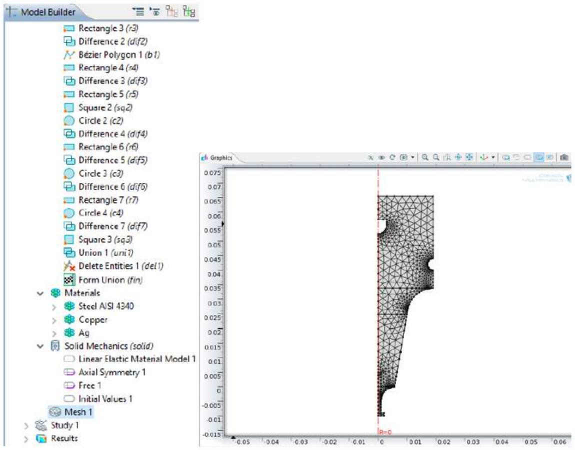


Fig.15. Discretization with triangular elements and its quality - Model 1

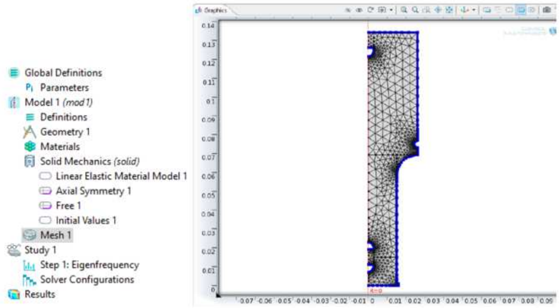


Fig.16. Discretization with triangular elements and its quality - Model 2

For each model was searching for a frequency around 40 kHz, respectively 20 kHz, applying the function named Study.

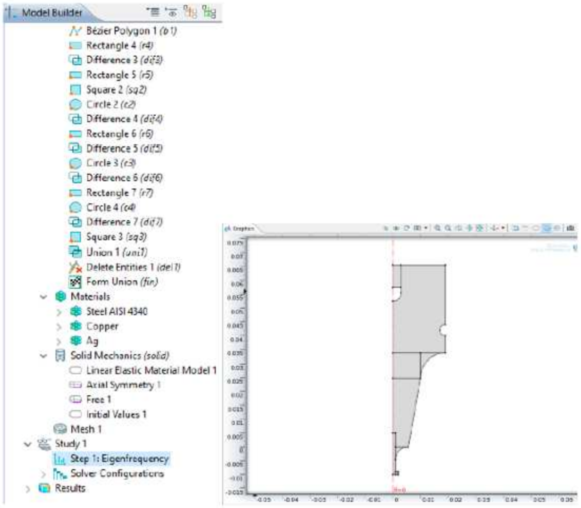


Fig.17. Applying Study function and setting the parameters - Model 1

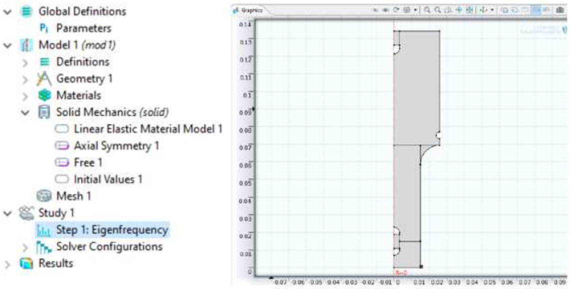


Fig.18. Applying Study function and setting the parameters - Model 2

The result of the simulation is presented below. At the same time, in these images can be seen the nodal point, marked with blue. It allows the horn to be clamped in a flange and then in the working area of the machine. To identify the nodal point, the displaying of the amplification was reduced.

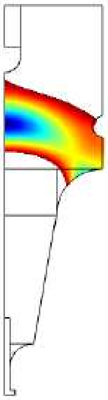


Fig.19. Nodal point for Model 1

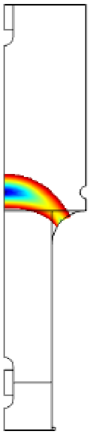
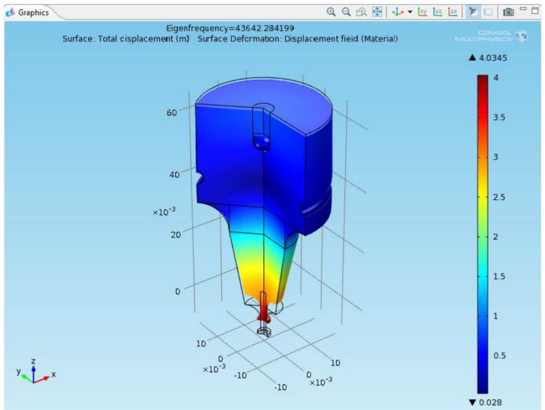


Fig.20. Nodal point for Model 2

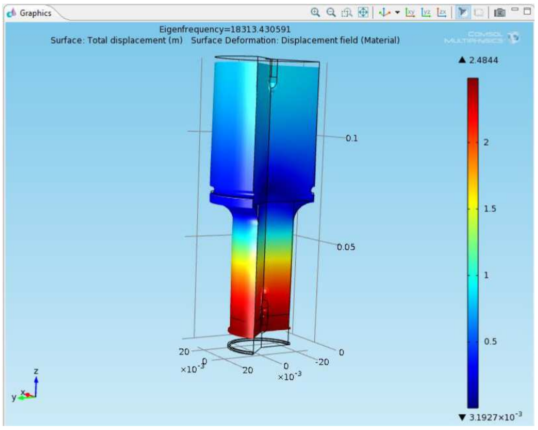
Also, the 3D models of the horn-tool assembly are exposed in the next pictures.



Eigenfrequency=43642.284199

Surface: Total displacement (m) Surface Deformation: Displacement field (Material)

Fig.21. Eigenfrequency and amplification for Model 1



Eigenfrequency=18313.430591

Surface: Total displacement (m) Surface Deformation: Displacement field (Material)

Fig.22. Eigenfrequency and amplification for Model 2

Achieving the resonance condition is highly practical, being dependent on factors that are difficult to control: the structure of the horn material, the quality of the junctions in the ultrasonic chain, the temperature of the components during operation, etc.

For the first model, the own frequency of the concentrator obtained based on the model created in COMSOL is 43642 Hz and for the second one is 18313 Hz, according to the pictures above.

Next, in the practice, the iterative shortening of lengths of the two stages of the horn is carried out, until the equality between the own frequency of the concentrator and the transducer, 40100 Hz (resonance condition) is obtained.

In tables 3 and 4, the results of the analysis made in COMSOL, until bringing the assembly to the resonance frequency, were exposed.

Table 3

Results for Model 1

Initial frequency	Frequency with PVC	Resonance frequency	Modified parameters
43642 Hz	42407 Hz	40091 Hz	l_1 = 37.3 mm l_2 = 35 mm

Table 4

Results for Model 2

Initial frequency	Frequency with PVC	Resonance frequency	Modified parameters
18313 Hz	18098 Hz	20128 Hz	l_1 = 63.5 mm l_2 = 60 mm

Some charts regarding the amplification or elongation in relation to the length of ultrasonic horn are exposed.

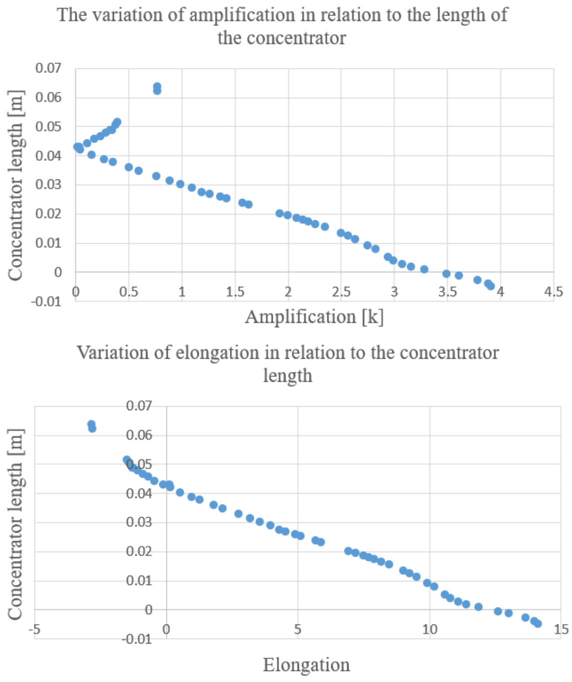


Fig.23. Amplification and Elongation for Model 1

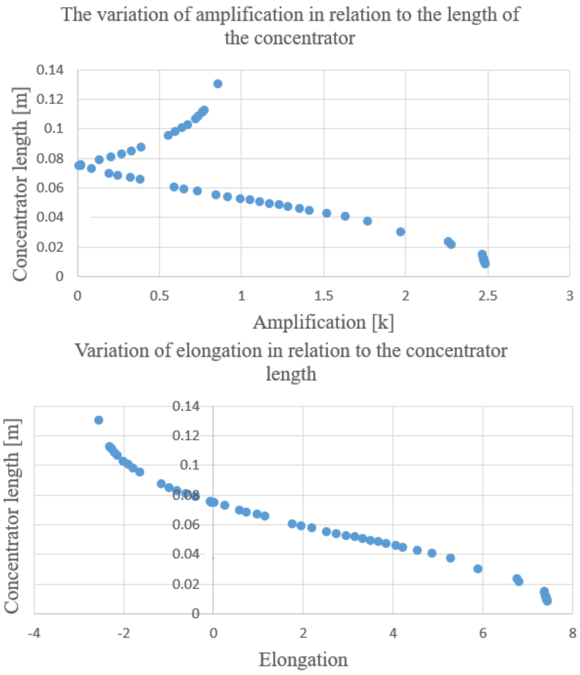


Fig.24. Amplification and Elongation for Model 2

4. CONCLUSION

The study proposes the development, simulation, and analysis of ultrasonic chains, which aim to improve surface roughness and increase the productivity of electrochemical processing.

The most important step to make such a system work is to bring it to the resonance frequency, and then, being electrochemical machining, a way must be found to cover the concentrator with a material resistant to the electrolytic environment. All the necessary properties of the tools and the materials to be processed are specified in the paper.

In the analysis of the first model, the initial frequency was 43642 Hz. Then after adding a protective layer of PVC, it became 42407 Hz, and to be able to determine the resonance frequency which finally resulted in a value of 40091 Hz, parameters l_1 and l_2 of the concentrator have been increased from 31.67 mm to 37.3 mm, respectively from 33.78 mm to 35 mm.

For the second model it started from a frequency of 18313 Hz. The PVC helped to decrease to 18098 Hz, and to reach the frequency of 20128 Hz, parameters l_1 and l_2 decreased from

64.98 mm to 63.5 mm, respectively from 69.32 mm to 60 mm.

It is found that for the first model, designed for a surface with a diameter of 4 mm, an increase of parameters l_1 and l_2 is necessary to reach the resonance frequency, while for a polishing equipment for a surface with a diameter of 32 mm, it is necessary a decrease of parameters l_1 and l_2.

If we refer to the addition of the PVC layer of about 1 mm, it can be pointed out that for a 40 kHz concentrator, with slightly smaller steps, the frequency drop is about 1235 Hz, and for a 20 kHz concentrator, with slightly higher steps the frequency dropped by only 215 Hz. Hence it follows that the addition of the protective material has a greater effect on the resonant frequency for a larger surface area.

In future research these simulations realized in COMSOL Multiphysics and then projected in Catia V5, will be manufactured and tested in laboratory to see the roughness, the quality of the surfaces and the parameters that were improved adding this ultrasonic component.

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Determinarea frecvențelor proprii ale unor concentratoare ultrasonice specifice prelucrării hibrid electrochimice

Lucrarea are ca scop modelarea și simularea unor concentratoare ultrasonice, fiecare având atașată scula specifică prelucrărilor ECM, respectiv micro-ECM. Modelarea și simularea au fost realizate în programul Comsol Multiphysics, aplicând modulul Eigenfrequency. În cadrul lucrării, sunt prezentate etapele modelării, dar și parametrii de lucru pentru fiecare model dezvoltat și analizat. S-a făcut o comparație între frecvențele proprii ale fiecărui concentrator, dar și între parametrii modificați pentru a aduce fiecare model la frecvența de rezonanță, ținând seama de transductorul utilizat. De asemenea, grafice privind amplificarea, respectiv elongația în raport cu lungimea concentratorului, au fost prezentate și analizate. În final, avantaje și dezavantaje au fost expuse și câteva soluții privind îmbunătățirea proceselor ECM, micro-ECM, adăugând componenta ultrasonică.

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