

## STUDY ON ULTRASONIC STEPPED HORN GEOMETRY DESIGN AND FEM SIMULATION

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**Abstract:** The paper deals with study through Finite Element Method (FEM) of ultrasonic stepped horn used to aid electro-discharge machining (EDM+US). The thermal phenomena are dominant within EDM machining mechanism. The role of US aiding is to intensify the material thermal removal through cavitation phenomena. Several studies were carried on in order to analyze the influence of steps lengths and diameters and corner radius size on own frequency of stepped ultrasonic horns. A good agreement between the FEM results and theoretical and experimental data was emphasized. Methods to adjust the own frequency of stepped horns by adjusting the lengths, diameters and additional machining of a groove at gravity centre level of horn are presented.

**Keywords:** stepped sonotrode design, ultrasonics, FEM, eigenfrequency, EDM.

### 1. INTRODUCTION

Significant increasing in performance and qualitative improvements are achieved by using ultrasonic vibrations in machining technological processes. Applications of ultrasonic vibration energy in machining technologies are realized by two different approaches. The first approach, called as an ultrasonic machining, is based on abrasive principle of material removal. The tool which is shaped in the exact configuration to be ground in workpiece and it is attached to a vibrating horn. The second approach is based on the conventional machining technologies—ultrasonic aided machining.

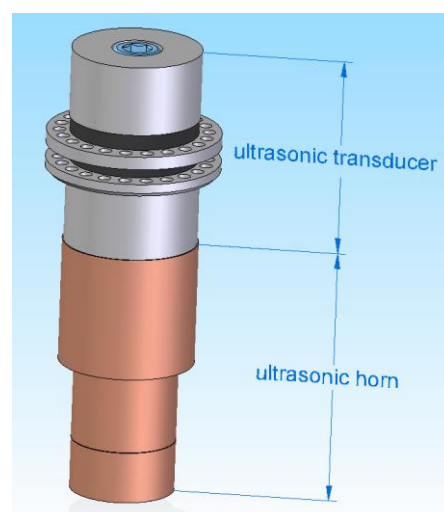
The ultraacoustic systems composed by the generator and the ultrasonic converter (transducer and wave adapting concentrator) can be built in order to work at a fix frequency named resonance frequency. The optimal frequency can be obtained starting from a lower own frequency close to resonance one of ultrasonic stepped horn (USH) and adjusting its dimensions [1].

The usual frequencies for ultrasonic aided EDM are 20 and 40kHz. In this paper, the first one was used.

The most frequently used shapes of ultrasonic horns are: cylindrical, tapered, exponential and stepped. To achieve optimal performance of ultrasonic machining system, is necessary to take into account all relevant effects and parameters that affect the dynamics of the system. One of the most important element of the ultrasonic system –

sonotrode (ultrasonic horn), must have the required dynamic properties, which must be determined already in design phase.

Ultrasonic chain (fig. 1) consists in typical transducer sandwich piezo-electric ceramics center-bolt (Langevin) design (the housing and electrode leads are not shown) and a stepped ultrasonic horn (USH). Ultrasonic transducer converts the electrical wave to mechanical vibration which is relative small and must be amplified using an acoustic horn.



**Fig. 1. Ultrasonic chain**

The primary function of the horn is to amplify the vibration of the tool to the level required for effective machining assistance, but it serves also as a means of transmitting the vibrational energy from the transducer.

It does so by being in resonance with the transducer.

The design and manufacture of the horn require special attention because an incorrectly manufactured horn will decrease machining performance and can lead to the destruction of the vibration system and cause significant damage to the generator.

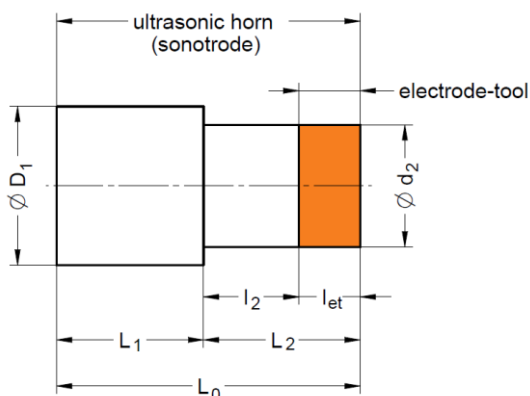
## 2. DESIGN PROCEDURE OF USH

The critical condition of USH design is own resonance frequency which must match the working frequency of the ultrasonic transducer [3], [4].

If so, the correct frequency must be attended. Amplitude of the horn tip displacement must be known. Last concern is that high stress occurs in nodal area where section area varies.

For conception and achievement of ultrasonic assembly, all the elements that compose the ultrasonic chain must be properly sized for that the system to perform at the resonant frequency. For this is necessary to cover the following steps:

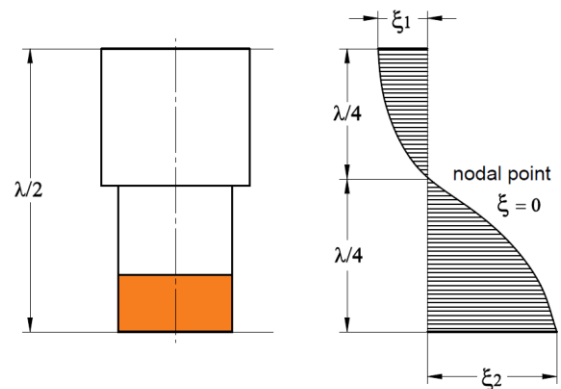
- frequency selection;
- selection of the proper material;
- determination of the sound propagation velocity in the selected material;
- calculation of the theoretical dimensions;
- realization of the documentation needed for execution of the ultrasonic assembly;
- achievement of the prototypes, accords, and test case of our experimental data.



**Fig. 2.** Stepped ultrasonic horn (geometry and main dimensions)

The length ( $L_0$ ) of the sonotrode normally corresponds to a half wavelength (fig.2). Calculations of sonotrode dimensions are based on the following input data:

- own frequency of the transducer 20250 Hz (specified by manufacturer);
- coupling diameter of transducer  $\varnothing$  52 mm;
- tool-electrode dimensions:  $\varnothing$  40 mm, height 20mm(resulted from EDM process demands);
- tool-electrode material copper (Cu – 99.5%);
- sonotrode material same as the electrode-tool;
- sonotrode type: stepped horn (total horn length equal with half wavelength –  $\lambda/2$ );
- frequency value of blank sonotrode (lower than final value) used for dimensional calculus  $f_{calc} = 19750$  Hz.



**Fig. 3.** Stepped ultrasonic horn (correlation  $L_0 - \lambda$  and amplitudes )

The transformation ratio (gain in amplitude) can be computed using (see fig.3):

$$K_t = \frac{\xi_2}{\xi_1} = \left( \frac{D_2}{d_1} \right)^2 \quad (1)$$

where  $K_t$  – is the theoretical amplitude gain.

For the present case  $K_t = 1,69$ .

The sound velocity measured on a standard sample made from the same material as the sonotrode (copper Cu–99,5%) is  $c_s = 4010$  m/s.

According to [2] the junction to the smaller diameter is on the nodal plane, and the total length of the acoustic horn  $L_0$  can be calculated using the relation (2):

$$L_0 = L_1 + L_2 = k_1 \frac{c_s}{4f_{calc}} + k_2 \frac{c_s}{4f_{calc}} \quad (2)$$

where the correction factors  $k_1$  and  $k_2$  depends on the given sonotrode cross-sections.

Assuming Merkulov și Kharitonov [1] theory the length of the stepped horn can be obtained using the following formulae:

$$L_1 = \frac{1,5}{k_u} \quad \text{and} \quad L_2 = \frac{1,6}{k_u} \quad [m] \quad (3)$$

where:  $k_u = \frac{2\pi}{\lambda}$  (4)

and  $\lambda = \frac{c_s}{f_{calc}}$  (5)

Using the input data mentioned above we achieved the following results:

$L_1=0,04805$  m and  $L_2=0,05125$  m.

Figure 4 shows all the required dimensions for sonotrode manufacturing.

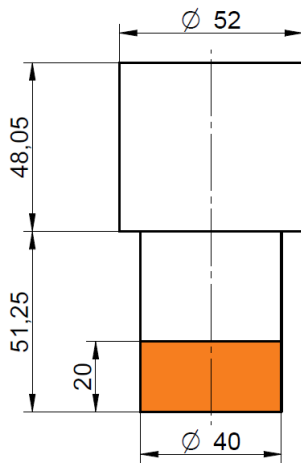


Fig. 4. Calculated dimensions of USH

### 3. FEM MODELLING OF USH

FEM, just as any analytical method, is used by engineers to model, analyze, and predict the performance of real physical systems. The accuracy of the model depends not so much on the particular analytical technique, but on the assumptions made in modelling the physical system. The accuracy of the model must be validated by benchmarking its predictions to experimental data and results from simpler problems. Results from the computer or any analysis should never be assumed to be correct just because one can “turn the crank” on the problem.

A physical problem is defined by its geometry, material properties, boundary conditions, and the external loads, which can be distributed in time and space. Sometimes these parameters for a particular problem are not that well understood. Material properties are often not accurately known, might have to be extrapolated from reference values, or might have a relatively high degree of variability. In such cases, once the model is known to be an accurate representation, the engineer performs parametric studies to

evaluate the effects of these variations to understand their impact on the results.

The adequate introduction of data into the calculus program leads to accuracy obtaining of the nodal zones and obtaining the maximum efficiency amplitude factor of the ultrasonic assembly elements.

### 4. FEM RESULTS

The COMSOL Multiphysics® “Structural Mechanics” - *Eigenfrequency* module was used to perform the modal analysis.

Defining characteristics of stepped horn material. In order to construct the sonotrode we use copper (Cu -99,5%) material whose technical parameters were introduced (sound propagation velocity, elongation modulus, density, Poisson coefficient):

Parameter	unit	value
Young's modulus	GPa	148.
Density	kg/m <sup>3</sup>	8800.
Poisson's ratio	-	0.33

**Mesh generation.** According to the basic principles of finite element method theory, the smaller the mesh element size is, the more accurate the results of an analysis will be. If the mesh element size is infinitely small, the theoretical model will approach the optimal solution. In the analysis process, when used elements are too small, the meshing will generate too many elements, nodes and degrees of freedom for the model in general.

This increases computational intensity, resulting a model that is either too time-consuming to be solved, or potential errors could occur. Reasonable mesh element size is a factor that has to be considered in the present modelling.

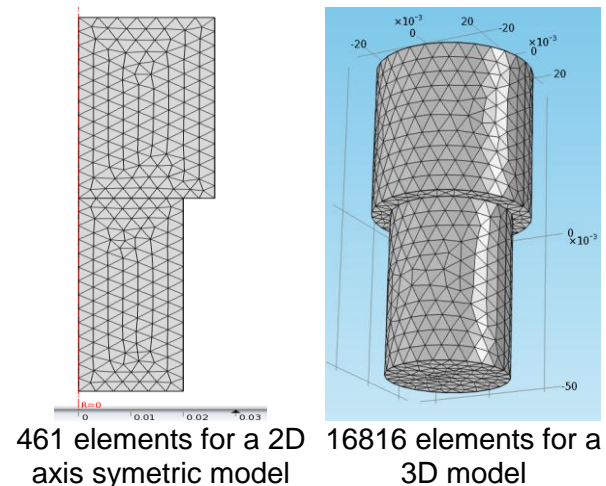
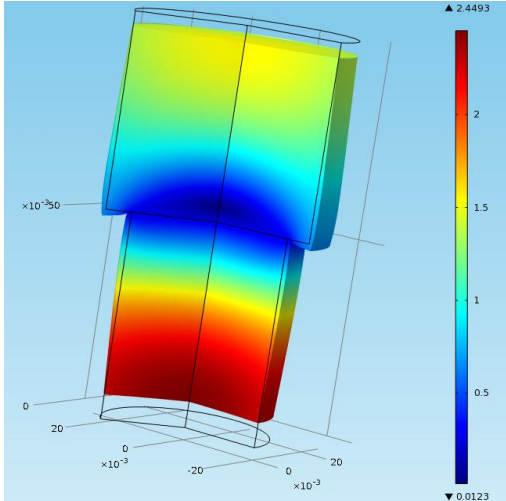
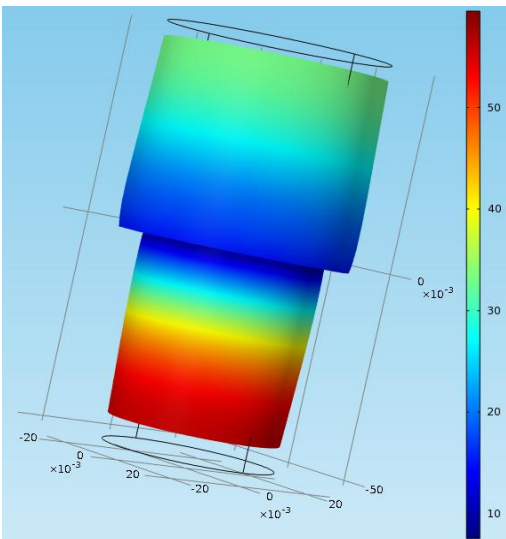


Fig. 5. Meshing statistics

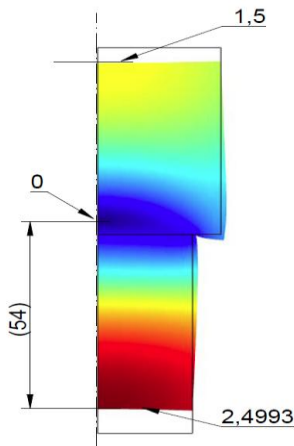
**Visualization of results** regarding the sonotrode modal shapes and the relative amplitude at resonance frequency is presented in fig. 6, 7 and 8:



**Fig. 6. The relative amplitude in case of a 2D axis symmetric model ( partial revolved)**



**Fig. 7. The relative amplitude for a 3D model**



**Fig. 8. Relative displacements of main points**

A good agreement between the results obtained from COMSOL application and theoretically computed data has been found as mentioned below:

$$f_{2D \text{ axisymmetric}} = 19615 \text{ Hz (relative error: -0,68\%)}$$

$$f_{3D} = 19686 \text{ Hz (relative error: -0,32\%)}$$

The frequency of the blank sonotrode is the result of additional material (generally 1-2 mm). This determines a frequency 500-1000Hz below the desired resonant frequency. The sonotrode reaches the required frequency after several iterations of shortening and remeasuring.

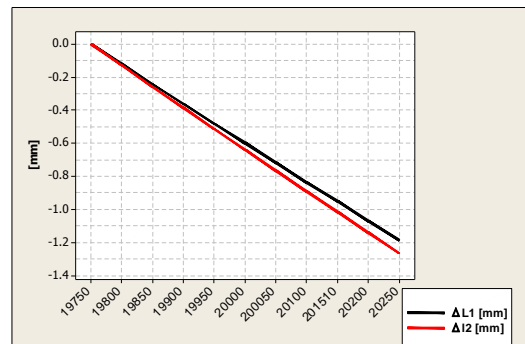
The sonotrode frequency measuring system is used to determine its natural frequency. The measuring system consists of a generator, an amplitude transducer and a frequency indicator. The resonant frequency has been obtained when the maximum amplitude is achieved on the reading instrument. Shortening must be done on both front surfaces (as seen on fig.10).

Practically, it supposes a number of iterative horn lengths adjustments in order to modify own frequencies and achieve desired frequency. Theoretically shortening lengths are revealed in table 1.

The correspondance between the USH frequency and shortening lengths is presented in table 1 and fig.9.

**Table 1. Theoretically shortening lengths**

$f$ [Hz]	$\Delta L_1$ [mm]	$\Delta L_2$ [mm]
19750	0	0
19800	-0,12134	-0,12942
19850	-0,24206	-0,2582
19900	-0,36218	-0,38632
19950	-0,48169	-0,5138
20000	-0,60061	-0,64065
20050	-0,71893	-0,76686
20100	-0,83667	-0,89245
20150	-0,95382	-1,01741
20200	-1,07039	-1,14175
20250	-1,18639	-1,26548



**Fig. 9. Shortening length vs. frequency**

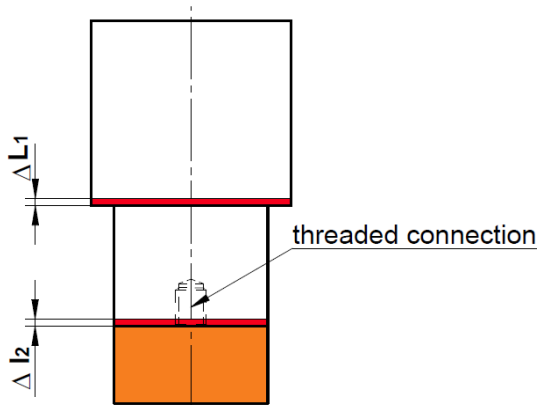


Fig. 10. Shortening length position

Results on radius corner (fig.11) influence on own frequency of the USH studied on a 3D shape model are presented in table 2.

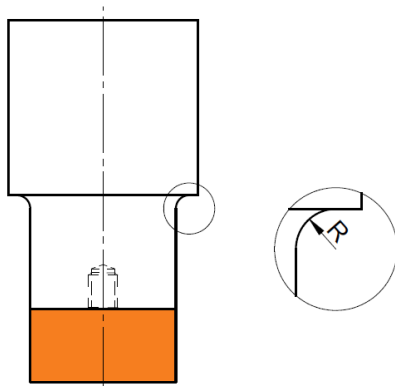


Fig. 11. Corner radius

Table 2. Radius vs. resonant frequency

R [mm]	frequency [Hz]	Δf [%]
0	19686	0%
0,5	19642	-0,22%
1	19666	-0,10%
1,5	19694	+0,04%
2	19707	+0,10%
2,5	19735	+0,25%
3	19763	+0,39%

The junction to the smaller cross-section should have a radius because there is a danger of cracking here [2].

For sonotrodes with maximum cross-sectional dimensions of 60 mm a R=10 mm has been found to be satisfactory.

According to some authors [1] there is no need of prescribing a specific radius, because it's close (or coincident) with the nodal plane where the displacements are theoretically 0 or small enough, resulting in small stresses.

Resonant frequency variations of stepped sonotrode with dimensional precision of sonotrode diameters resulting from manufacturing are specified in table 3.

Table 3. Diameters precision vs. frequency

D1 [mm]	ΔD1 [mm]	d2 [mm]	ΔD2 [mm]	f [Hz]	Δf [%]
52	0	40	0	19615	0%
51,9	-0,1	40	0	19624	+0,04%
52	0	39,9	-0,1	19606	-0,04%
51,9	-0,1	39,9	-0,1	19615	0%
52,1	+0,1	40	0	19606	-0,04%
52	0	40,1	+0,1	19624	+0,04%
52,1	+0,1	40,1	+0,1	19615	0%
52,1	+0,1	39,9	-0,1	19598	-0,08%

This results can be considered as a possible method on adjusting resonant frequency of ultrasonic horn.

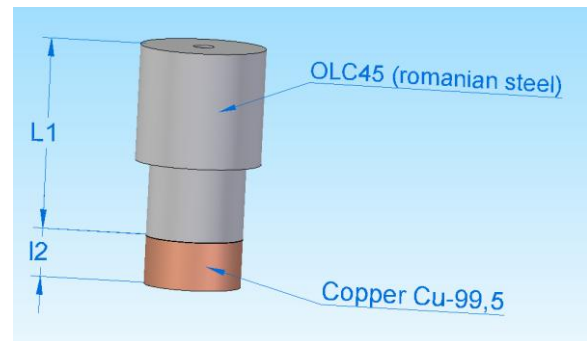


Fig. 12. Stepped sonotrode using different materials

Another problem that can be solved by this method is in case the body of the sonotrode is made from one material and the electrode-tool from another, in order to obtain lower materials costs.

An example of such case used in EDM+US is showed in figure 12, and the corresponding materials properties are presented in table 4 and 5.

Table 4. Considered materials properties

Material	E [Gpa]	ρ [kg/m <sup>3</sup> ]	ν
OLC 45 (Romanian steel)	210	7830	0,31
Copper-99,5%	148	8800	0,33

Table 5. Sound velocity

Material	unit	value
OLC45	m/s	5125
Cu – 99,5%	m/s	4010

When sonotrodes which have already been attuned are reworked by adjusting their length frequency  $f_0$  becomes higher.

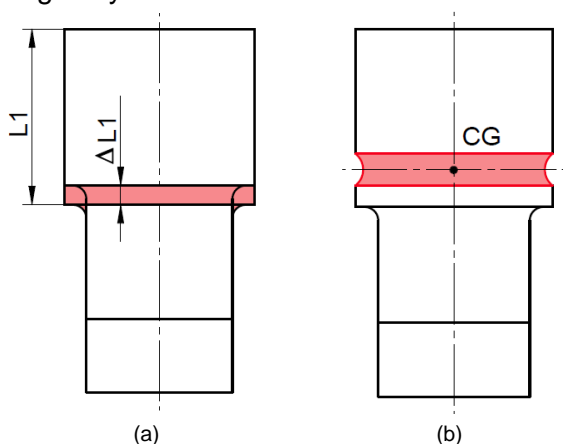
Afterwards it's possible the sonotrode frequency can quit the permissible tolerance

interval and can not operated on a specific transducer.

It is also possible to reduce it's resonant frequency again slightly-downwards, using one of the methods presented in figure 12.

(a) – by shortening length  $L_1$  with  $\Delta L_1$ ;

(b) – by making a groove at the center of gravity.



**Fig. 13. Methods for reducing sonotrode resonant frequency [2],[5],[6]**

## 5. CONCLUSIONS

It is very important to know the resonance frequency and amplitude at every point of the ultrasonic horn, because: it allows precise determination of the nodal plane position for locking in place of the ultrasonic system for desired processing; the parameters of the ultrasonic system can be correlated with technological parameters, especially at EDM+US, in order to avoid short-circuits between electrode-tool and workpiece; finite element method allows testing of various shapes of ultrasonic horns without the need to manufacture a real prototype; it allows the correct selection of the horn shape for a particular machining process demands. It is also important the selection of horn material for desired amplitude of vibration.

If the FEM has been performed properly, then the performance predicted by FEM should agree reasonably with the real sonotrode performance.

Agreement between modelling results and real results should be especially good if similar resonators have been previously modeled and validated. Exact agreement should not be expected, either because of

limitations of the FEM or because of measurement errors for the real resonator.

From our previous studies, it was established that the stability of EDM+US finishing process was obtained increasing the working gap through ignition voltage growing and amplitude decrease of US oscillations.

FEM modelling of sonotrodes described on this paper enables design time and manufacturing costs to be effectively reduced in practical EDM+US technological system achievements.

Further studies must be carried on the various geometrical shapes of sonotrodes as one of the most important elements of the ultrasonic assisting system. The main dynamics characteristics (natural frequencies and amplification factors) of sonotrode in the resonant state should be studied according to the geometric shape and dimensions.

## ACKNOWLEDGEMENTS

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