

DETERMINATION BY FEM OF ULTRASONIC HORN PROFILE FOR VIBRATING THE WORKPIECE AT EDM ASSISTED BY ULTRASONICS

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ABSTRACT: The paper deals with determination through Finite Element Method (FEM) of a profiled ultrasonic horn for vibrating a disk shape workpiece at ultrasonically aided electrical discharge machining. This approach comprises several stages, starting from applying mathematical relations for preliminary determination of a basic profile stepped horn. The next stages are fully based on FEM modelling the horn profile, using Comsol Multiphysics, changing successively different constructive elements of the horn, and adding at its end, the workpiece to be vibrated at electrical discharge machining aided by ultrasonics (EDM+US), which is integrated part of ultrasonic chain. This method uses as entry data the dimensions and natural (own) frequency of transducer subassembly - component of ultrasonic chain - and covers the needed stages to meet the critical resonance condition. Based on applied method results, the horn was machined, proving real natural frequencies very close to those outcomes from FEM modelling.

KEY WORDS: Finite Element Method, ultrasonic horn, electrical discharge machining.

1. INTRODUCTION

Electrical discharge machining aided by ultrasonic vibrations (EDM+US) of electrode-tool or workpiece (the case of present paper) proved spectacular improvement of main technological parameters at finishing and micromachining, in terms of machining rate, precision/volumetric relative wear, and surface quality [1], [2], [3], and new materials with low machinability [4], [5], [6].

Nevertheless the problem of horn fabrication to meet the resonance conditions, i.e. the equality between own frequency of transducer subassembly (as entry data) and of horn which integrates the workpiece to be vibrated, creates an important lack of flexibility of EDM+US technology. The significant time consuming for resonance condition achievement, which usually comprises several iterative stages is justified on relative great volumes of fabrication. Under these conditions, the amelioration of this drawback, using FEM modelling of ultrasonic horn, associated with Computer Aided Machining of the horn, based on FEM results, becomes of utmost interest nowadays when the response time of a company to get market-ready products is critical.

Achieving new shape (profiles in case of revolution surfaces) of ultrasonic horn appropriate for diverse application [7], taking into account the unique character of horn shape in the relation to the type of machining [8], is a very important research direction, on which it is also framed the actual paper, based on FEM modelling.

2. PRELIMINARY DIMENSIONING OF AN USUAL ULTRASONIC HORN

A preliminary dimensioning was approached as a starting point for an usual cylindrical stepped horn, using some known relations, aiming finally at determination of profiled horn, integrating the workpiece to be vibrated.

According to Merkulov and Kharitonov [9], the amplification (K) in case of a stepped horn is equal with:

$$K = (D_1 / D_2)^2 \quad (1)$$

where: D_1 is the large end diameter [m]; D_2 is the small end diameter of the stepped horn [m],

when short (l_1) and long (l_2) section lengths of the stepped horn (upper and lower steps in figure 4) meet the following conditions:

$$l_1 = 1.5 / \alpha \quad [\text{m}] \quad (2)$$

$$l_2 = 1.6 / \alpha \quad [\text{m}] \quad (3)$$

α is the wave number calculated with the formula:

$$\alpha = 2 \pi / \lambda \quad [\text{m}^{-1}] \quad (4)$$

and λ is the wave length calculated as it follows:

$$\lambda = c / f \quad [\text{m}] \quad (5)$$

where f is the oscillation ultrasonic frequency.

The ultrasonics velocity (c) within a solid material is determined with the relation:

$$c = (E/\rho)^{1/2} \quad [\text{m/s}] \quad (6)$$

where E is Young's modulus of horn material [Pa], ρ - density of horn material [kg/m^3].

The transducer assembly provided by the Institute of Solid Mechanics of the Romanian Academy (fig. 1) has the own series frequency $f_{tr} = 20.1$ kHz – of interest for this type of applications – [10], and the output diameter of the radiant bush was ≈ 39 mm.

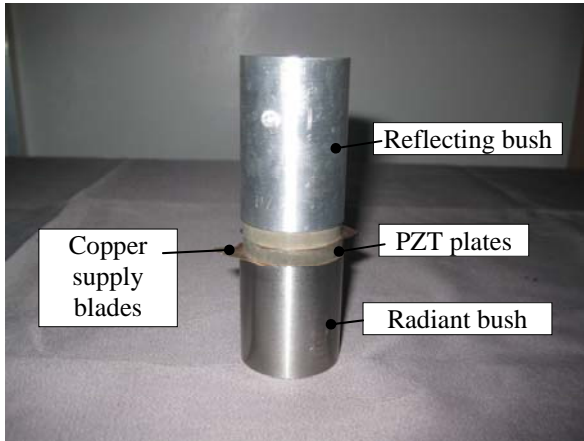


Figure 1. Transducer assembly used in ultrasonic chain for assisted EDM

In case of our horn made from OLC 35 steel with characteristics $E = 2.1 \cdot 10^{11}$ Pa, $\rho = 7850$ kg/m^3 , the entry frequency of the horn was $f_{o1} = 19.0$ kHz, lower than that of the transducer f_{tr} . Thus, the values of physical parameters from the relations presented above are: $\lambda = 0.26188$ m, $\alpha = 23.06951$ m^{-1} . Therefore, the steps lengths resulted: $l_1 = 65.02$ mm; $l_2 = 69.35$ mm. The entry diameter of the horn, is equal with that of radiant bush, $D_1 = 39$ mm.

These above preliminary results represented entry data for the first stage of FEM modelling.

3. FEM MODELLING STAGES OF ULTRASONIC HORN WITH WORKPIECE VIBRATION

For FEM modelling and simulation of an ultrasonic horn, which included a disk shape workpiece at its end that oscillates with maximum amplitude, Comsol Multiphysics 4.2, Structural Mechanics module, Eigenfrequency were used.

The adopted modelling strategy introduced or changed only one constructive parameter of the horn one time (per stage) to have a control of oscillation physical parameters, i.e. own frequency and amplification. Consequently, in order to achieve the needed profile of the horn, more than 20 modelling stages were covered.

The logical scheme of the modelling is presented in fig. 2. The following parameters were the subject to change in each modelling stage: steps lengths, fillet radius between steps, workpiece radius as disk shape

at the chain end, fillet radius and horn neck dimensions between workpiece and horn, nodal channel radius and its position, threaded hole for workpiece and horn assembling. After the most part of FEM stages, a first variant of horn was machined, measuring its own frequency in order to validate the model. Horn steps adjustments were done, then horn was CAM-ed, and resonance condition was fulfilled.

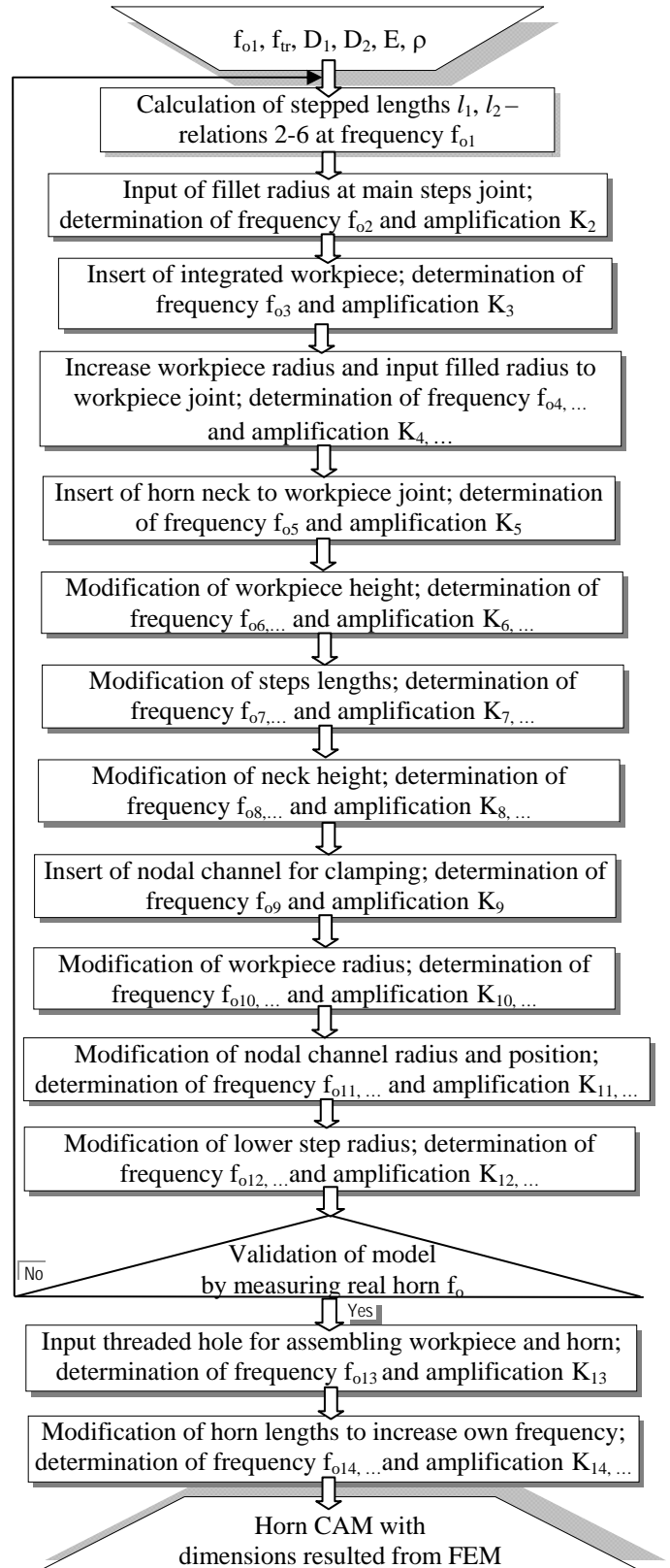


Figure 2. The logical scheme of the approached strategy for FEM modelling of the profiled stepped horn with integrated workpiece

A parametric model was achieved, aiming at efficiency of modelling, which is relatively laborious. The needed parameters were established in Global Parameters, and presented in fig. 3 for the first stage of modelling.

Parameters			
Name	Expression	Value	Description
l1	65.02[mm]	0.06502 m	upper step length
r1	19.5[mm]	0.0195 m	upper step radius
l2	69.35[mm]	0.06935 m	lower step length
r2	10[mm]	0.01 m	lower step radius
ModulE	2.1e11	2.1E11	Young's modulus of OLC45
rr	r1-r2	0.0095 m	fillet radius at main steps

Figure 3. The defined parameters in the first stage

The other elements for the generic modelling are synthesized underneath. The modelled horn geometry was created using axis symmetric module, based on defined parameters from Global definitions. The needed material properties for the horn construction were provided by Comsol Multiphysics Materials Library and were adjusted for OLC 45 steel. The boundary conditions for horn eigenfrequency (resonance) frequency were set on free for all boundaries of the created geometry. The mesh was set on extrafine, with more than 2300 elements for final models and average quality around 0.96 on a 0-1 scale.

4. FEM RESULTS AND ULTRASONIC HORN ACHIEVEMENT

The most important results obtained by FEM modelling, and the geometrical parameters of horn construction are presented beneath.

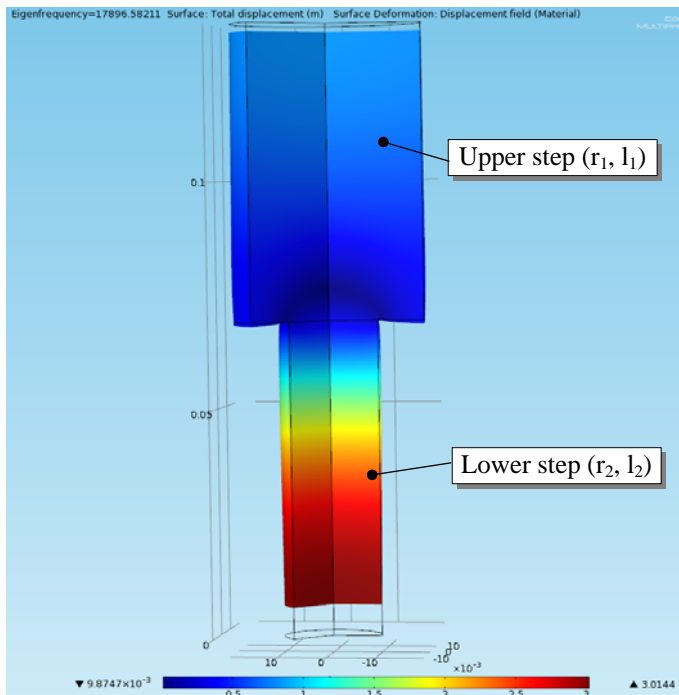


Figure 4. Resonance frequency and displacements at initial stage

The corresponding FEM results for the parameters defined in fig. 3, in terms of eigenfrequency (resonance) and deformations are presented in fig. 4.

The new value of the parameter used, when fillet radius between main steps was inserted in the next stage, is presented in fig. 5.

Parameters			
Name	Expression	Value	Description
rr	r1-r2	0.0095 m	fillet radius of main steps

Figure 5. Parameterized fillet radius of horn main steps

The corresponding FEM results are presented in fig. 6, where it can be noticed that fillet radius insertion produces an increase of horn natural frequency and of amplification, i.e. the ration between displacements at the two extremities of the horn – 1 is considered at superior surface of the horn.

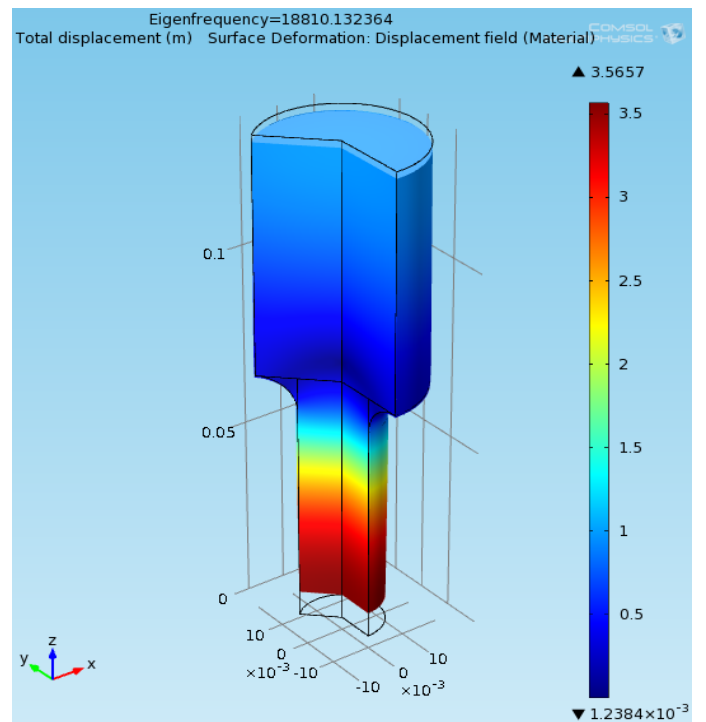


Figure 6. Resonance frequency and displacements at insertion of fillet radius between horn main steps

The new parameters introduced at workpiece insertion by modification of horn end are presented in fig. 7.

Parameters			
Name	Expression	Value	Description
l3	2[mm]	0.002 m	workpiece height
r3	12[mm]	0.012 m	workpiece radius
rrjos	r3-r2	0.002 m	fillet radius at workpiece

Figure 7. Parameters introduced for workpiece and its fillet radius modelling

The resonance frequency and displacements obtained with parameters values presented above are shown in fig. 8.

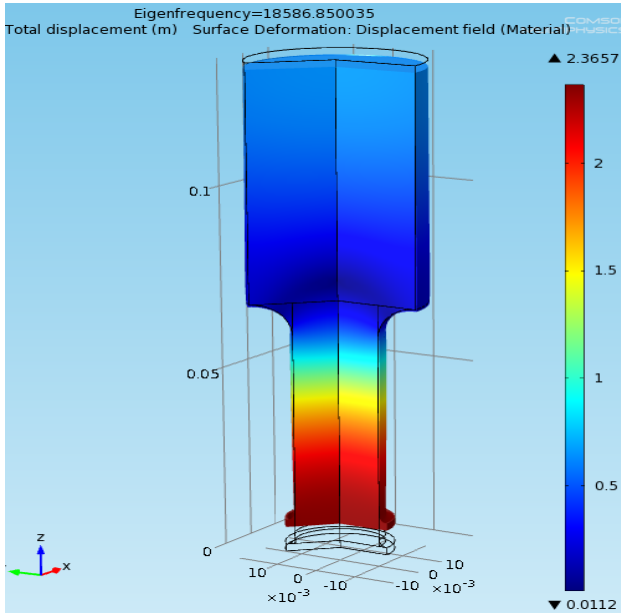


Figure 8. Resonance frequency and displacements at insertion of workpiece and its fillet radius

A decrease of horn resonance frequency was noticeable in this case against the previous stage and also of the amplification.

The parameters needed to insert the neck between the workpiece and the rest of the horn, aiming at increase of its stiffness, are presented in fig. 9.

Parameters

Name	Expression	Value	Description
l4	1[mm]	0.001 m	neck height
r4	11[mm]	0.011 m	neck radius

Figure 9. Parameters introduced for neck modelling

The resonance frequency obtained in this stage and the corresponding displacements of the horn are presented in fig. 10. Slight decrease of horn own frequency and amplification was produced in comparison with previous shape.

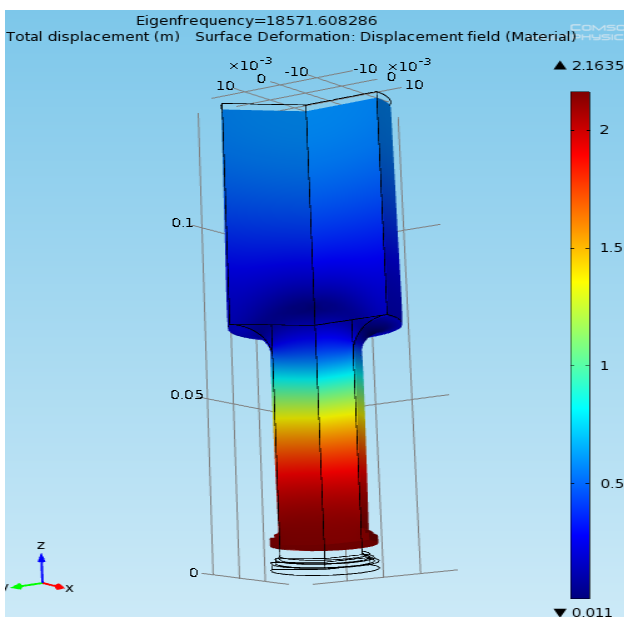


Figure 10. Resonance frequency and displacements at insertion of neck between horn and workpiece

The next stage was dedicated to insert the nodal channel needed to clamp the ultrasonic horn. Firstly, a nodal level was determined (minimum oscillation amplitude) as it is presented in fig. 11.

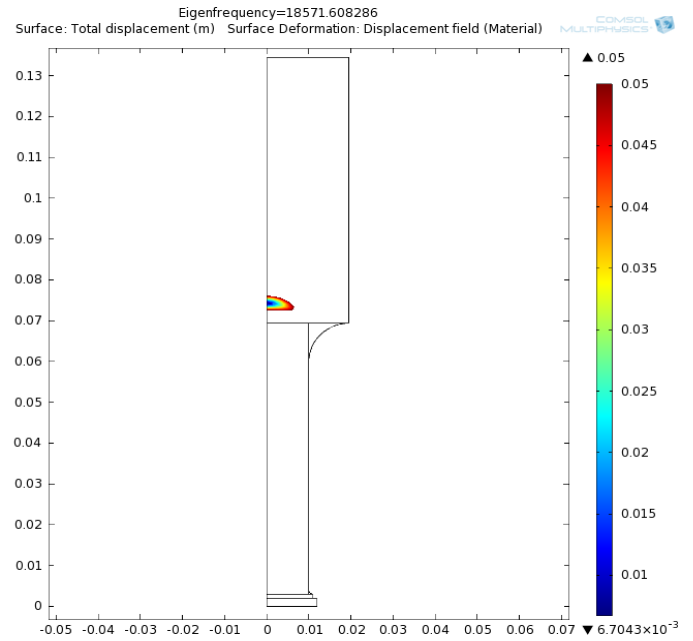


Figure 11. Nodal level determination

At this level, a radial channel was modelled, which served to catch the horn by four pointed radial screws, which enter the channel.

The parameters needed to model this horn shape are presented in fig. 12.

Parameters

Name	Expression	Value	Description
rchanal	3[mm]	0.003 m	channel radius
zchanal	0.0742	0.0742	channel position quota

Figure 12. Parameters needed to insert nodal channel

The own frequency and displacements due to nodal channel introducing were represented in fig. 13.

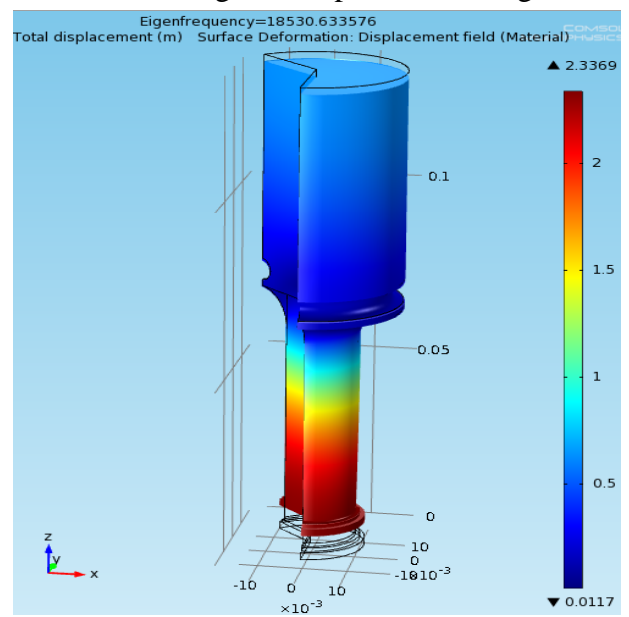


Figure 13. Resonance frequency and deformations at nodal channel insertion

As it can be observed, the nodal channel insertion produced a decrease of horn natural frequency and amplification.

In order to extend the diameters range of the workpieces to be vibrated at EDM+US, the radius of workpiece was increased progressively. The value of this parameter assigned in this stage is presented in fig. 14.

Parameters

Name	Expression	Value	Description
r3	13[mm]	0.013 m	workpiece radius

Figure 14. Value assigned to workpiece radius

The natural frequency and displacement resulted with this setup were presented in fig. 15. It can be noticed that workpiece radius increase determined resonance frequency and amplification decrease.

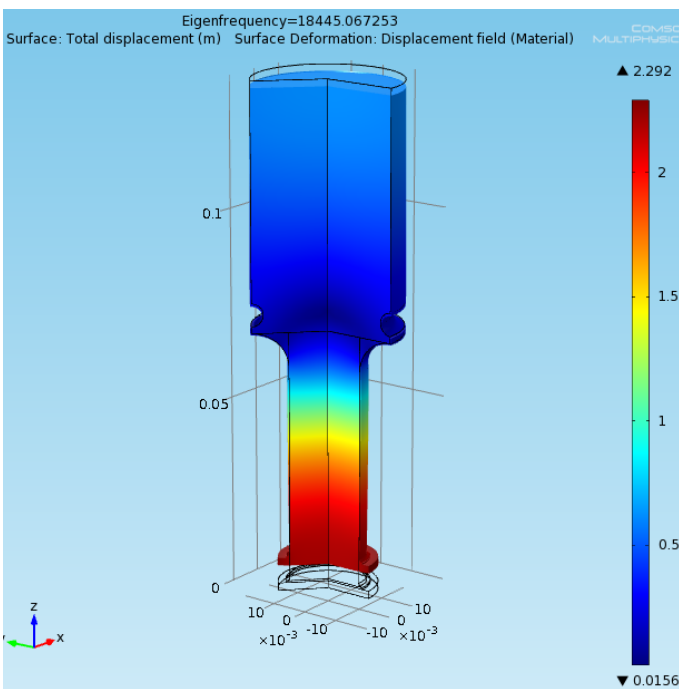


Figure 15. Resonance frequency and displacements at increase of workpiece radius

The parameters modified in the following stages are presented in fig. 16, and horn natural frequency and displacements were presented in figure 17.

Parameters

Name	Expression	Value	Description
r2	15[mm]	0.015 m	lower step radius
r3	20[mm]	0.02 m	workpiece radius
rchanal	1[mm]	0.001 m	channel radius
l4	0.5[mm]	5.0E-4 m	neck height

Figure 16. Values assigned to parameters

The above values of the parameters led to increase of natural frequency and of amplification. Through increase of own horn frequency, it is aimed at obtaining the resonance condition, i.e. equality between the one of horn and transducer, which is higher.

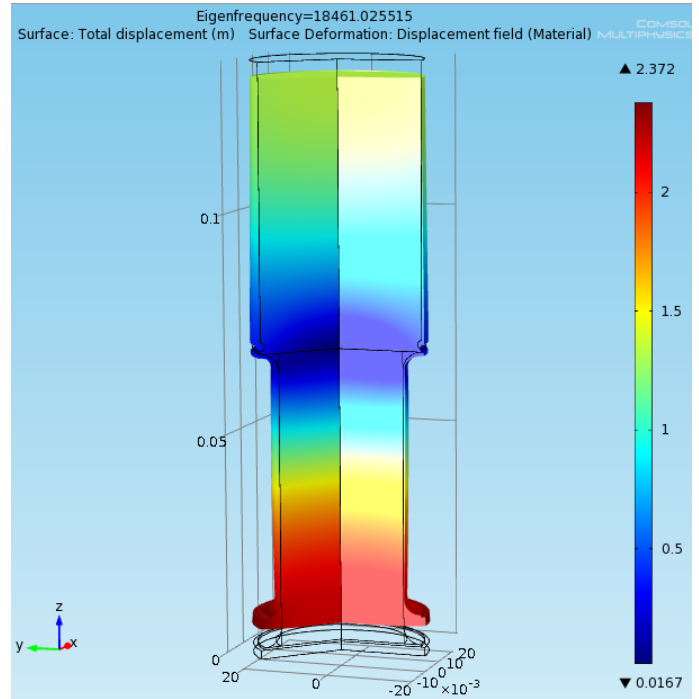


Figure 17. Resonance frequency and displacements at adjustment of channel radius, lower step radius, neck height, and workpiece radius

Measuring the resonance frequency of ultrasonic horn and chain assembly under working conditions (cavitation in the liquid in which the workpiece is immersed) is presented in fig. 18. This is done after horn CAM, needed to validate the model before machining the final shape of the horn. The setup from fig. 18 is also needed for the accordance of the ultrasonic generator on nominal frequency, its adaptive control working within ± 1 kHz range.

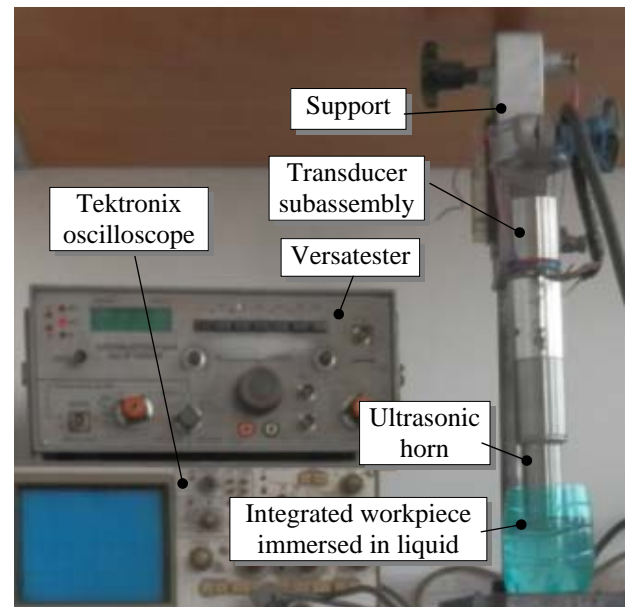


Figure 18. Measuring stand for natural frequency of ultrasonic horn and chain used at assisted EDM and generator accordance

The measured natural frequency differs with less than 1% than that resulted from FEM modelling. On this basis, the final stage of ultrasonic horn modelling was approached. The last horn model was

created, including a longitudinal threaded hole for workpiece assembling, using a M6 central screw with conical head, represented in fig. 19.

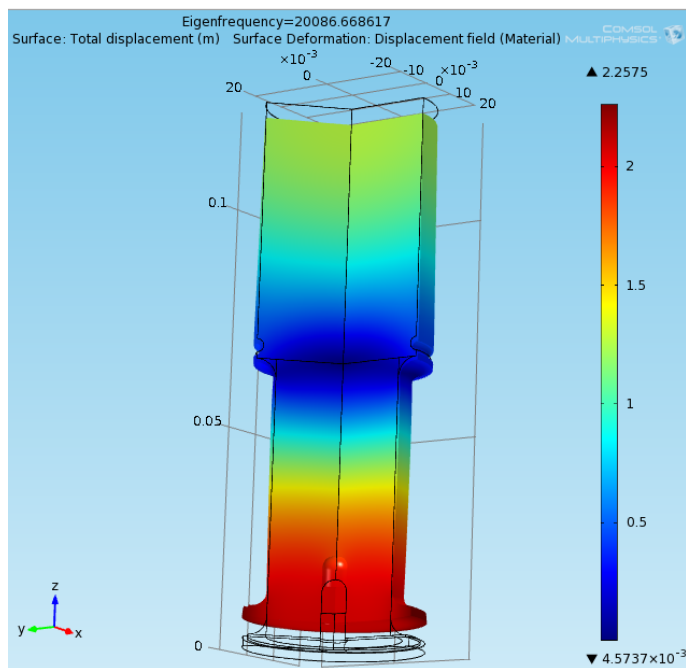


Figure 19. Final modelling of ultrasonic horn

The horn was obtained by CAM, and the probe workpiece was detached from the horn by WEDM, being later assembled with the horn. Using these constructive solutions, the resonance condition was achieved, needed for proper working of ultrasonic chain at EDM+US.

5. CONCLUSIONS

From FEM modelling, the influence of some constructive elements of ultrasonic horn was identified. Fillet radii are able generally to increase the natural frequency as well as its amplification. Other elements like radii extension of disk shapes inserted in horn construction produced lowering of natural frequencies and its amplification. The same influence was exerted by radial channels introducing, but lower radius of its profile increased the horn natural frequency.

Based on FEM modelling the ultrasonic horn with disk shape workpiece at its end was achieved. Measuring the real horn natural frequency indicated a difference lower than 1% against the natural frequency determined by FEM. Thus, this facilitated the resonance condition achieving at ultrasonic chain used at EDM+US.

This FEM modelling approach contributed to a significant decrease of time consuming for needed setup related to ultrasonic assistance of technologies. Ultrasonics assistance brings the desired decrease of environmental impact of EDM mainly by spectacular reducing of machining time.

6. ACKNOWLEDGEMENT

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