

ASPECTS CONCERNING FEM MODELLING OF AN ULTRASONIC HORN USED AT MICRO-EDM DRILLING

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ABSTRACT: The paper deals with finite element modelling (FEM) of complex shape ultrasonic (US) horn that has its end a wire tool-electrode used for micro-drilling by ultrasonically aided electrical discharge machining (EDM+US). The US horn is the technological component of an ultrasonic chain actuated by a sandwich PZT transducer supplied from 40 kHz generator. The shape and dimensions of ultrasonic horn was determined through several stages of FEM modelling strategy, aiming at obtaining the resonance condition of ultrasonic chain, i.e. the equality between natural frequencies of the sandwich PZT transducer and the US horn with included tool. The influence of different constructive conditions of US horn on its natural frequency and amplification were established in order to replicate the modelling strategy for other horn complex form. Finally, the measurements related to resonance conditions validated the strategy of FEM modelling creating conditions of CAM application for horn achievement.

KEYWORDS: finite element modelling, ultrasonic, EDM.

1. INTRODUCTION

The hybrid process of ultrasonically aided electrical discharge machining (EDM+US) benefits from the synergy created by association of two components – the thermal one due to EDM and the cavitation one due to US assistance – in terms of: spectacular improving machining rate, volumetric relative wear, and surface quality, especially in case of very narrow working gap, e.g. fining and micro-machining modes [1, 2, 3, 4]; advanced materials difficult to machine with other means [5, 6, 7]. All these major improvements are based on controlled US cavitation in the gap, and correlation of US oscillation and ED pulse delivering moments [8].

There are also some drawbacks of EDM+US technology, consisting mainly in lack of flexibility due to necessity to obtain the resonance condition within the ultrasonic chain used at different applications, i.e. types of operations to fulfil. This condition, which determines the appropriate working of technological system, supposes: equality between own frequencies of the sandwich PZT transducers (f_{otr}) and the ultrasonic horn (f_{oh}), which includes the tool-electrode. This is very difficult to achieve in practice, especially in case of complex shape horns, involving several iterative cycles – adjusting/cutting, own frequency measurement. Coupling CAE means like finite element method (FEM) modelling and CAM systems allows really shortening the fabrication cycle, letting the construction of very performing ultrasonic chains, and complex shapes of ultrasonic horn, applicable to various machining operations [9].

2. PRELIMINARY DIMENSIONING OF STEPPED CYLINDRICAL HORN

In order to predetermine the dimensions of a simple stepped cylindrical horn, as entry data for FEM modelling of a complex shape horn, including the tool-electrode for EDM+US micro-drilling, the following relations are used for step lengths l_1 , l_2 - see figure 6 [10]:

$$l_1 = 1.5 / \alpha \text{ [m]}, \quad (1)$$

$$l_2 = 1.6 / \alpha \text{ [m]}, \quad (2)$$

where α is the wave number calculated as:

$$\alpha = 2 \pi / \lambda \text{ [m}^{-1}\text{]}, \quad (3)$$

and λ is the wave length calculated as it follows:

$$\lambda = \frac{c}{f} = \frac{1}{f} \sqrt{\frac{E}{\rho}} \text{ [m]}, \quad (4)$$

where f is the oscillation US frequency [Hz]; c - ultrasound velocity within a solid material [m/s]; E - Young's modulus of horn material [Pa]; ρ - density of horn material [kg/m^3].

The amplification (K), obtained with horn dimensions based on previous relations, is:

$$K = \frac{D_1}{D_2}, \quad (5)$$

where: D_1 , D_2 are the upper and lower step diameters of the horn [m].

In case of a horn made from Romanian OLC 45 steel, the characteristics from above are: $E=2.1 \times 10^{11}$ Pa, $\rho=7850 \text{ kg/m}^3$. The entry frequency for calculation is the nominal one, $f_{oi}=40.0 \text{ kHz}$, which

is lower than that of the transducer provided by the Institute of Solid Mechanics of the Romanian Academy - IMSAR (figure 1), to keep a margin for shortening the horn length. Therefore values of physical parameters from the above relations are: $\lambda=0.1293$ m, $\alpha=48.5674$ m⁻¹. So, the lengths of the steps are: $l_1=30.885$ mm; $l_2=32.944$ mm. The transducer used in this case has the own series frequency $f_{otr}=41.16$ kHz of interest for this application type [10], as target frequency for resonance condition.



Figure 1. IMSAR PZT transducer, $f_{otr}=41.16$ kHz

Its radiant bush, which joints the concentrator, has the output diameter $D_b=35$ mm, which represents the entry step (upper) diameter, $D_1=D_b=35$ mm. The output step (lower) diameter is preliminary taken as $D_2=20$ mm – see figure 6.

3. FEM MODELLING STRATEGY

Comsol Multiphysics with Structural Mechanics module, and Eigenfrequency submodule was used for FEM modelling and simulation of a complex ultrasonic horn, included the wire tool-electrode at horn end in an antinodal point, under conditions of standing waves formation within US chain.

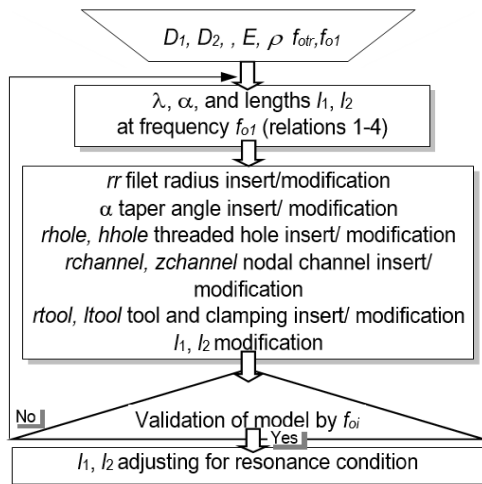


Figure 2. Logical scheme of FEM modelling strategy

Using FEM modelling strategy, only one constructive parameter of horn geometry was inserted or changed in each stage i , aiming at control of own frequency f_{oi} and amplification K_i , and thus aiming at resonance condition. The logical scheme of modelling strategy is presented in figure 2.

The 2D axis symmetric mesh was set to extrafine, with around 1800 elements for final model and average quality nearby 0.96 on 0-1 scale – figure 3:

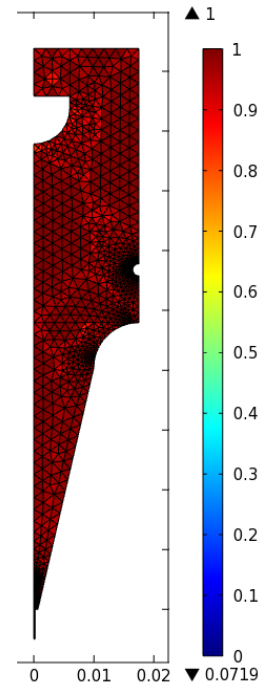


Figure 3. The meshing and its quality scale

The materials used for horn construction were Romanian steel for horn itself and assembling/clamping parts and copper for the wire tool-electrode as it is displayed in figure 4:

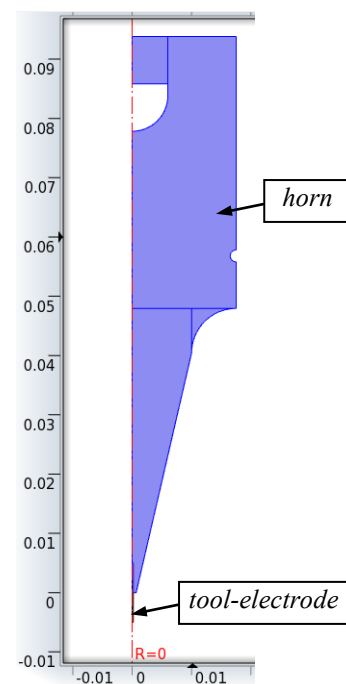


Figure 4. Allocation of materials within horn structure

The inserted and modified horn elements will be presented below together with their defining parameters.

4. FEM MODELLING RESULTS

The defined parameters in global definitions for initial stage are presented in figure 5. These comprised the dimensions of usual stepped cylindrical horn and its material characteristics (OLC 45 steel) related to US wave propagation within.

Parameters			
Name	Expression	Value	Description
l1	30.88[mm]	0.03088 m	upper step length
r1	17.5[mm]	0.0175 m	upper step radius
l2	32.94[mm]	0.03294 m	lower step length
r2	10[mm]	0.01 m	lower step radius
moduleE	2.1e11	2.1E11	steel Young's modulus
ro	7850	7850	steel density
rr	r1-r2	0.0075 m	steps fillet radius

Figure 5. Initial parameters for FEM modelling

The corresponding parameters of own frequency (eigenfrequency) and relative deformation, i.e. amplification are presented in figure 6.

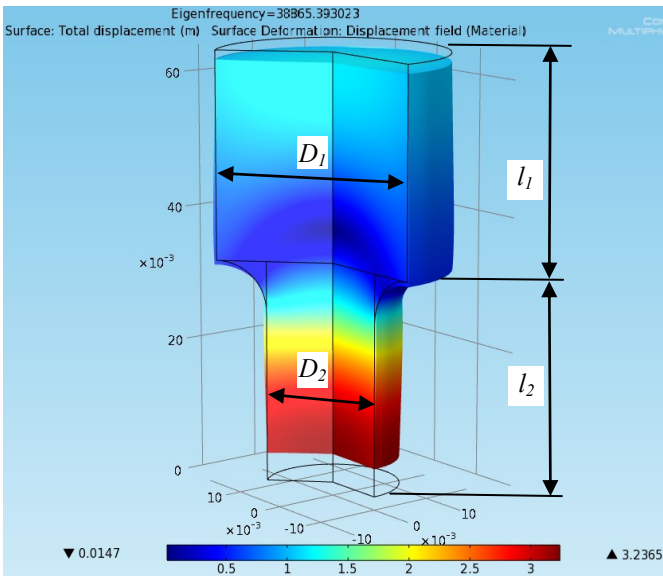


Figure 6. FEM results at initial stage of usual stepped horn

The insertion of fillet radius between steps determined the natural frequency growing in comparison with the variant without fillet.

The parameters belonging to the next stage of lower step taper insertion are presented in figure 7.

Parameters			
Name	Expression	Value	Description
alfa	1	1	taper angle
argum	alfa*3.14159/180	0.01745	tangent argument in radians
r3	12[mm]	0.012 m	width of inclined rectangle

Figure 7. Parameters for 1° taper insertion at lower step

In figure 8, the FEM results in case of introducing a taper at lower step are presented. As one can see, the own frequency of the horn was increased at $f_{o2}=39431$ kHz, as well as relative displacement at $K_r=3.86$ in comparison with the initial stage variant.

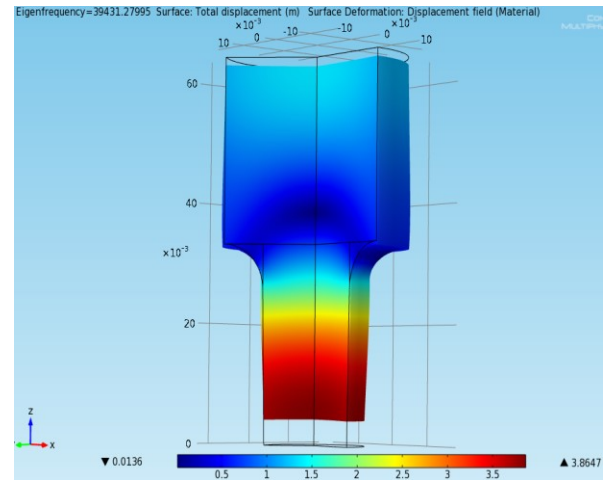


Figure 8. Eigenfrequency and relative displacement at 1° taper

In the following stages, the lower step taper was increased as it is presented in figures 9 and 10.

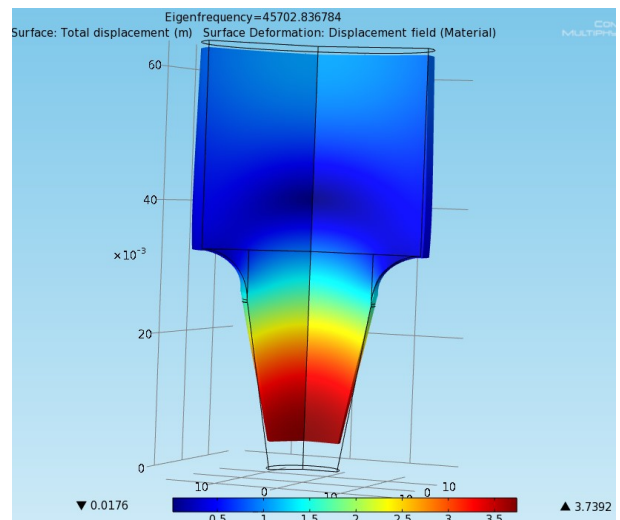


Figure 9. Eigenfrequency and relative displacement at 10° taper

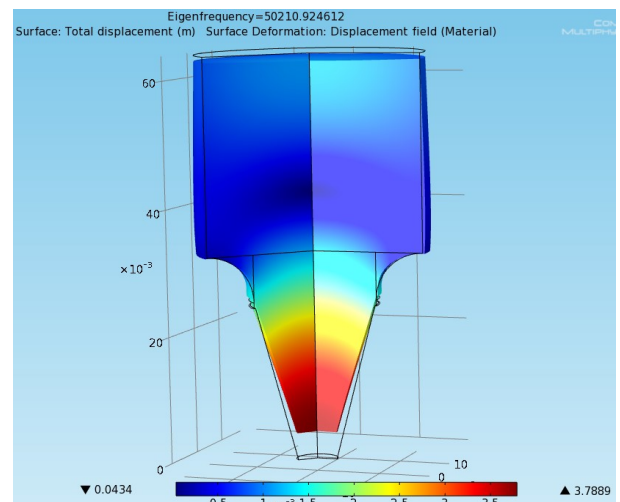


Figure 10. Eigenfrequency and relative displacement at 15° taper

As it can be seen from figures 9 and 10, the eigenfrequency and the relative displacement (amplification) were continuously increased, reaching $f_{05} = 50.21$ kHz, and amplification $K_5 = 3.78$ at taper angle 15° . The growing of taper angle at lower step is produced in order to create a smoother passing from the horn diameter to the tool-electrode one used for micro-drilling.

In the next stages, the eigenfrequency was gradually decreased in order to reach closer values to the target frequency, $f_{ov} = 41.16$ kHz. So, the lengths of the steps are increased with 10 mm, in the next stage as the following parameters display in figure 11.

Parameters			
Name	Expression	Value	Description
l1	40.88[mm]	0.04088 m	upper step length
l2	42.94[mm]	0.04294 m	lower step length

Figure 11. Increased lengths of horn steps

In fig. 12, the corresponding own frequency and amplification are presented, attaining respective values of 44475 Hz and 3.71.

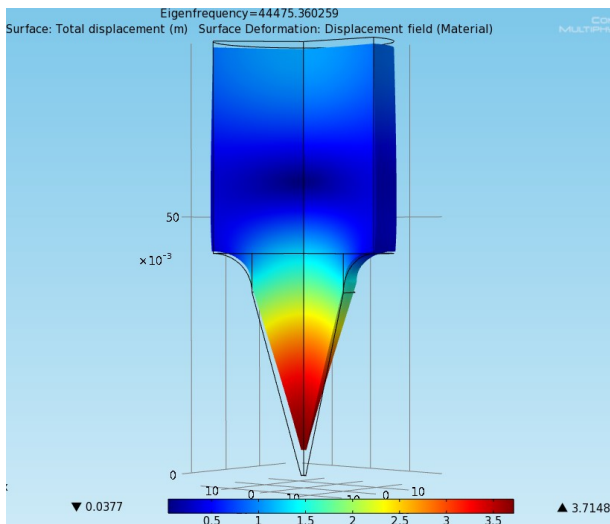


Figure 12. Eigenfrequency and relative displacement at step lengths growing with 10 mm

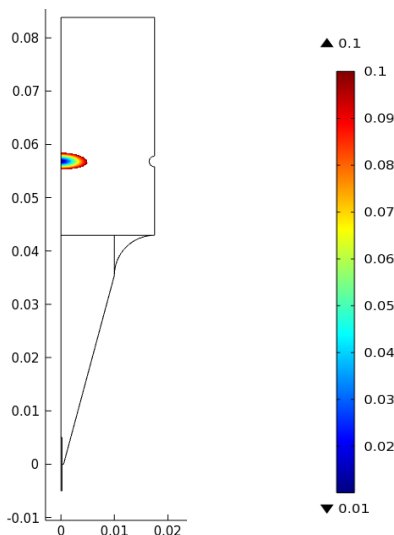


Figure 13. Identification of nodal point

In the next stage, a nodal channel was inserted, used for the functional roll of clamping the US chain. The position of nodal point was identified as figure 13 shows.

The insertion of nodal channel in the horizontal plane, corresponding to the nodal point, was achieved based on the parameters from figure 14:

Parameters			
Name	Expression	Value	Description
zcanal	0.0568	0.0568	vertical coordinate of nodal channel
rcanal	1[mm]	0.001 m	radius of nodal channel

Figure 14. Parameters for nodal channel insertion

The eigenfrequency and relative deformation obtained as results of nodal channel introduction within US horn are shown in figure 15:

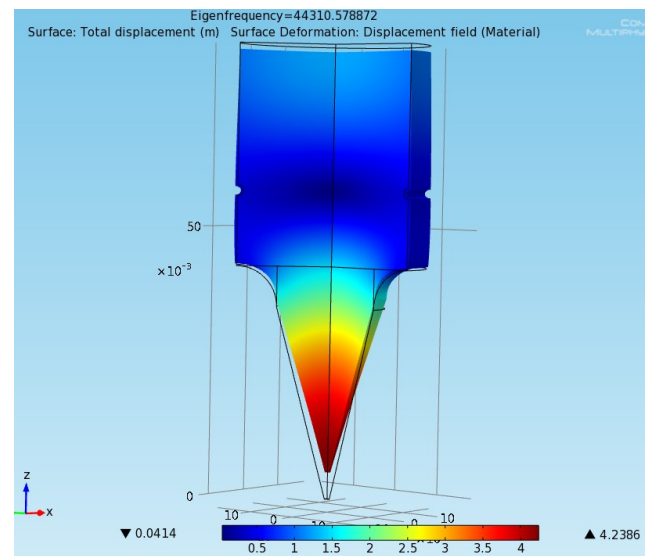


Figure 15. Eigenfrequency and relative displacement after nodal channel insertion

As one can see, the nodal channel insertion determined the own frequency decrease at 44310 kHz, contributing to reaching the target frequency.

The next stage was dedicated to insertion of tool-electrode for micro-drilling with the modelling parameters presented in figure 16:

Parameters			
Name	Expression	Value	Description
rscula	0.2[mm]	2.0E-4 m	tool radius
hgol	5[mm]	0.005 m	tool depth socket
lscula	5[mm]	0.005 m	tool length

Figure 16. Parameters for tool-electrode insertion

It was considered that the clamping system of the tool-electrode is made from the same material as the horn, to reduce its influence on own frequency.

The influence of tool insertion on the horn own frequency is presented in figures 17 and 18 at different lengths of the tool.

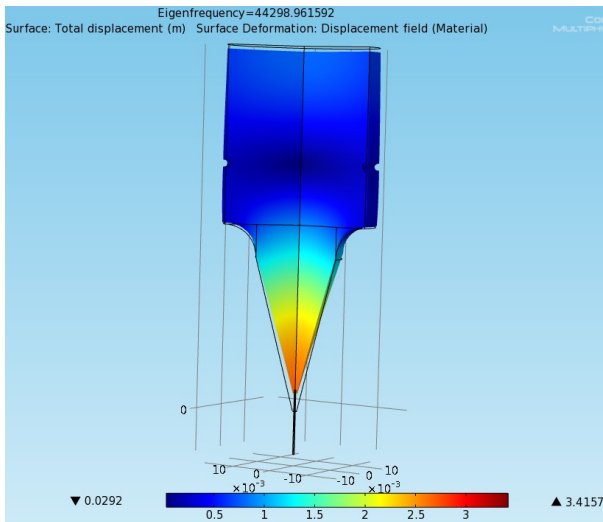


Figure 17. Eigenfrequency and relative displacement at tool length of 10 mm

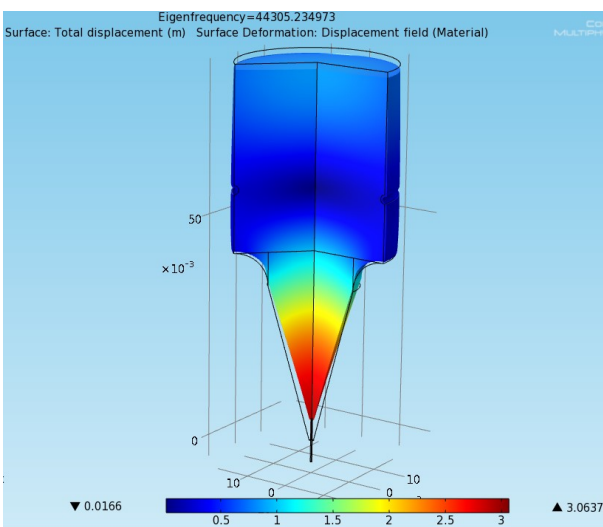


Figure 18. Eigenfrequency and relative displacement at tool length of 5 mm

As it can be observed, as such low mass of tool-electrode, the influence on horn eigenfrequency is insignificant even at 50% wear tool (decrease of tool length from 10 to 5 mm), which is possible during EDM micro-drilling.

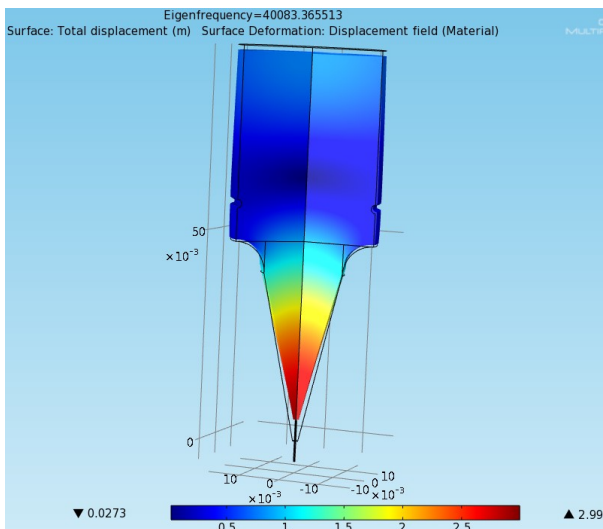


Figure 19. Eigenfrequency and relative displacement at taper angle of 13°

This variation of resonance frequency can be easily compensated by the adaptive control generator.

The clamping mean from the same material as the horn was considered with threaded bolt between tool holder and horn, so its influence on resonance frequency is neglected.

In the next stage, the taper angle was adjusted at 13°, the results being presented in figure 19. As it can be observed, the own frequency of the horn was decreased at 40083 kHz, and also relative displacement, 2.99.

The next stage was dedicated to threaded bolt assembly of the horn with transducer sandwich (see figure 1), determining horn own frequency decrease at 40048 Hz –figure 20.

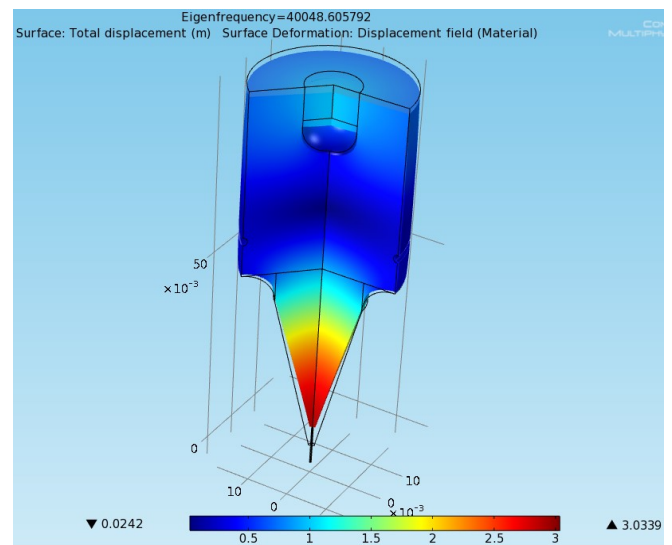


Figure 20. Eigenfrequency and relative displacement at bolt assembly insertion

The final shape of horn integrating the tool is presented in figure 21, by adjusting both steps lengths and lower taper angle, obtaining 41159 Hz.

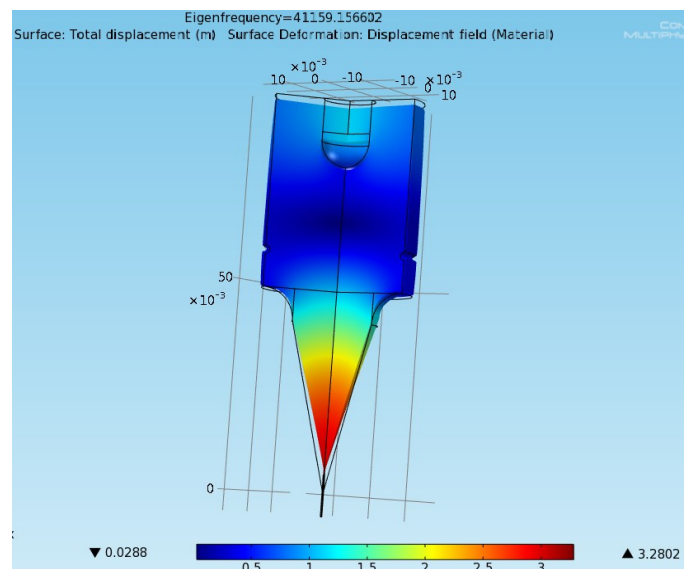


Figure 21. Eigenfrequency and relative displacement at final stage

In figure 22, the testing stand is displayed, used for models validation in different stages of FEM modelling strategy.

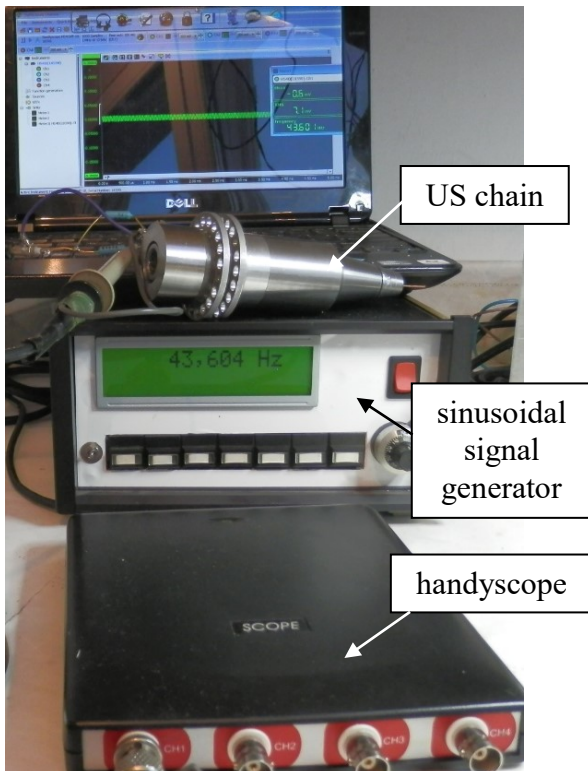


Figure 22. Test stand of US chain, including PZT transducer, horn, and tool-electrode

The final shape of US horn was tested in terms of resonance frequency, which was slightly under frequency target of 41.16 kHz. Finally, the horn was executed by CAM, having a margin of adjustment aiming at resonance condition achievement.

5. CONCLUSIONS

A cycle CAE-CAM was approached in case of a complex shape ultrasonic horn achievement with a tool-electrode inserted at its end, conceived for EDM+US micro-drilling. A high taper angle is provided at lower step of the horn in order to diminish the load concentrator at passing from the horn out section to the tool section.

Several finite element modelling stages were covered modifying gradually some constructive elements of the horn and observing their influence on its natural frequency, f_{oh} . Thus, the decrease of step lengths, the increase of taper angle, fillet radius determined the f_{oh} increase. On the contrary, the nodal channel, and threaded bolt insertions determined the f_{oh} decrease.

The high tool-electrode wear, even with 50% does not significantly affect the own frequency of US horn, the generator with frequency adaptive control is able to easy follow the resonance condition during micro-EDM process.

This approach contributed to improve lack of flexibility of ultrasonic assistance EDM.

6. ACKNOWLEDGEMENTS

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