Finite Element Modelling and Analysis of Simlpe Ultrasonic Horns

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Abstract: - This paper presents the importance of design and computation of ultrasonic horns. Furthermore, the finite element analysis and modelling method is used for different types of horns. The oscillation amplitude along the generator of the horn is determined in an ultraacoustic system used in the cutting process.

Key-Words: - ultraacoustic, finite element method, amplitude, oscillations

1 Theoretical considerations

Ultrasonic horn is the key element in an ultrasonic system because it comes into direct contact with the material in which ultrasonic energy must be dissipated. Its role is to conduce, concentrate and focalize the ultrasonic energy in the spot of processing with the aid of a conveniently shaped tool. Computation and manufacturing of ultrasonic horns is made starting from the elastic waves propagation equation in a medium extended to an infinite shape [1]:

$$\frac{\partial^2 \phi}{\partial t^2} - c^2 \cdot \frac{\partial \phi}{\partial x} \cdot \frac{\partial}{\partial x}(\ln S_x) - c^2 \cdot \frac{\partial^2 \phi}{\partial x^2} = 0 \qquad (1)$$

in which: ϕ is the speeds potential; S_x –is the surface area of the bar section at x distance from origin; c – speed of propagation of acoustic waves within the material of the bar.

By solving equation (1) and assuming the limit conditions, the following computation steps can be obtained:

- determination of the multiplication factor;
- determination of the length of the horn in order for it to work under the resonance regime;
- determination of the variation coefficient of the surface section;
- determination of the shape depending on the types of waves excited within the horn;
- determination of the coordinates of the nodal points.

An output diameter greater than ¼ from the wavelength is not recommended due to possible transversal vibration modes. These modes will absorb the energy of the moving element with direct result the loss of the axial mode of vibration. If the ration between the input diameter and the output diameter is high, the transversal modes can produce only a nodal point in the center. This will have lead to a considerable loss of horn efficiency.

In order to obtain optimal results it is preferable that the construction material to have an acoustic impedance close to the coupled transducer.

For an optimum coupling, the rugosity and the straightness tolerance must be of the order of microns. A thin layer of oil or grease can improve coupling at the transducer-horn interface. The horns are also names impedance transformators due to the fact that they alternate the area that acoustic energy needs to cross and the acoustic impedance is directly related with this area ratio.

Large displacements with high efficiency at the output end are obtained in the case of acoustic systems with low impedance, i.e. small resistance when a force is applied. However, in current applications, considerations regarding impedance are close to zero. Main objective of the horns is to generate movement in the output area. These are used in applications such as: welding, abrasive processing, machining in all active applications.

The vibration amplitude of any movement system is determined by the lost energy inside it. It increases as long as any kind of loss (radiation, hysterezis or electromagnetic) is equal to the input energy or ruptures can appear in the materials due to stress [1].

Materials used to manufacture horns must have the property of dissipating in a small amount acoustic energy and therefore they must have a high mechanical quality factor Q (e.g. stainless steel, titan, aluminium). As opposed to these are copper, lead and nickel. Cast steel have a low transmission rate due to graphite particles that absorb ultrasounds.

Titan alloys of great resistance are better than other materials, being able to produce large displacements without structural damages (ruptures within the material).

Figure 1 presents a taxonomy of simple ultrasonic energy horns, as follows:

- conical;
- exponential;
- cathetenodal;
- fourier;
- cubical parabola, etc.

2 Finite element analysis and modeling of ultrasonic energy horns

For structural analysis of ultrasonic horns ANSYS finite element analysis software applications is used.

Geometrical dimensions of a horn used in applications derived from theoretical computations and adjusted from the resonance point of view are given in Figure 2.

The ultrasonic energy horn is build from carbon-steel with the following material properties:

PROPERTY TABLE	EX	0.20700E+12
PROPERTY TABLE	NUXY	0.29000
PROPERTY TABLE	ALPX	0.15100E-04
PROPERTY TABLE	DENS	78.50.0
PROPERTY TABLE	KXX	46.700
PROPERTY TABLE	C	419.00

For ANSYS main domain it uses selected the type of structural analysis that conditiones the selection of discrete elements library.

The discretization element selected from ANSYS library is SOLID 92, a 3D element with 10 tetrahedral nodes (depicted in Figure 3).

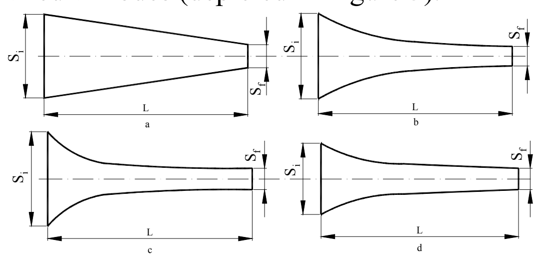

Fig. 1. Examples of simple horns:
a – conical; b – exponential; c - Cathetenodal ;
d – cubical parabola.

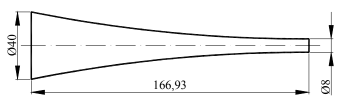

Fig. 2. Geometrical dimensions of an exponential horn

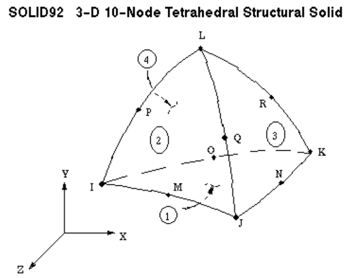

Fig. 3. The shape of dicretization element

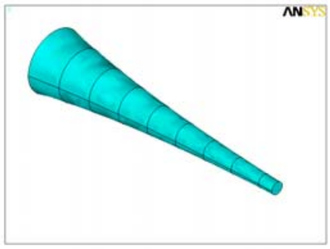

Fig. 4. Geometry generation of the horn

Option PREPROCESSOR is selected from the main menu, responsible for generating the 3D geometry, depicted in Figure 4 [2].

Discretization with SOLID92 element of this volume generates 15 468 elements with 9824 nodes, as presented in Figure 5.

After the activation of the SOLUTION processor, harmonic analysis is selected [2].

Taking into account physical reality, the ultrasonic horn receives a displacement as workload in the input section obtained from the global analysis of the piezoceramic assembly.

At then end of the analysis, through GENERAL POSTPROCESSOR, a set of chosen frequencies from the ultrasonic domain are obtained (depicted in Table 1).

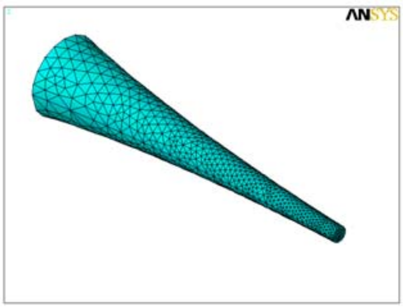

Fig. 5. Volume discretization with SOLID92

Table 1

Set of frequencies obtained through the aid of GENERAL POSTPROCESSOR

SET	TIME/FREQ	LOAD STEP	SUBSTEP	UMULATI
1	19000	1	6	6
2	20500	1	7	7
3	22000	1	8	8
4	23500	1	9	9

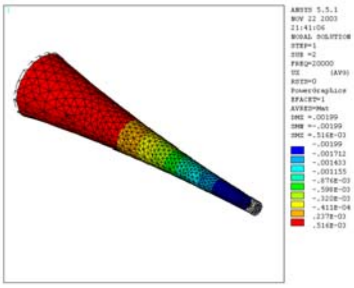

Fig. 6. Isometric view of the ultrasonic horn.

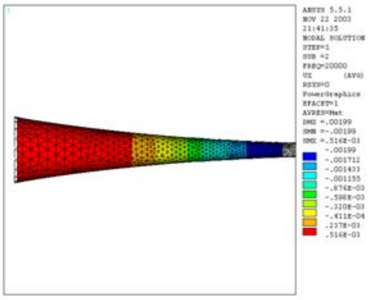

Fig. 7. Frontal view of the ultrasonic horn.

Mode 4 (20,500 KHz) has proven to be the closest to the resonance frequency of the ultracoustic system, initially computed at 20 KHz.

In figure 6 and 7 are presented mode 4 corresponding states of deformation, for displacement on the Z axis (isometric and frontal view).

Along with the deformation images, a legend containing sets of values of deformation are also presented.

Displacements along the length of the ultrasonic horn included in the legends validate the physics theory according to which an amplification of the oscillation amplitude is produced through the corresponding value of the multiplication coefficient.

Furthermore, the vibration modes highlight the types of waves that are propagating within the ultrasonic horn and the magnitude of the oscillation amplitude, assuming deformation along the length of the ultrasonic horn.

3 Finite element modeling of conical ultrasonic horns

The following paragraphs present the modeling process of conical horns of various geometrical sizes and a comparison from the amplification obtained at the active part (output).

Figure 8 depicts the discretization process of the conical element used for SOLID92.

Again, at the end of analysis (GENERAL POSTPROCESSOR), a set of selected high-frequencies (ultrasonic) is obtained (presented in Table 2) [2].

Table 2

Sets of frequencies

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	19 000	1	1	1
3	20 000	1	2	2
5	21 000	1	3	3
7	22 000	1	4	4
9	23 000	1	5	5
11	24 000	1	6	6
13	25 000	1	7	7

In Figure 9 and 10 are presented the corresponding states of deformation, for displacement on the Z axis (isometric and frontal view).

Table 3 depicts minimum values for the amplitude of a conical ultrasonic horn [2].

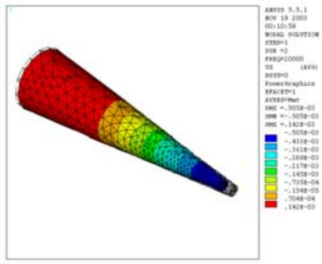

Fig. 9. Isometric view of the conical ultrasonic horn

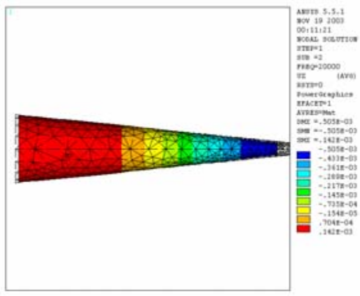

Fig. 10. Frontal view of the conical ultrasonic horn

Table 3

Oscillation amplitude variation

No.	Node no.	Horn length L [mm]	Oscillation amplitude A [mm]
1	4	0	0.003587242
2	62	11.91006	0.003541014
3	64	23.34006	0.003431286
4	66	34.18078	0.003264408
5	68	46.70806	0.002990342
6	70	58.38444	0.00262763
7	72	69.27342	0.001723619
8	74	79.42834	0.000634746
9	76	88.89492	-0.000613689
10	78	97.73666	-0.001938553

11	80	105.9942	-0.00326009
12	82	113.7082	-0.004533392
13	84	120.9142	-0.005764784
14	86	127.6426	-0.00690626
15	88	133.9291	-0.007950454
16	90	139.8016	-0.008879332
17	92	145.288	-0.009706102
18	94	150.4112	-0.010424668
19	96	155.1965	-0.011039094
20	98	159.6669	-0.011566144

Figure 11 depicts the variation of oscillation amplitude along the generator, showing the nodal plane coordinate for an conical ultrasonic horn.

Figure 12 presents the variation of oscillation amplitude along the horn for three conical horns of various dimensions.

4 Finite element modeling of exponential horns

One of the problems that reality face is the establishing of the nodal plane for fixing in place, clamping and locking the ultrasonic system. One way to solve this problem is to use the finite element analysis for the whole ultrasonic system.

Figure 13 depicts the discretization of the exponential element by using the SOLID 92 element [3].

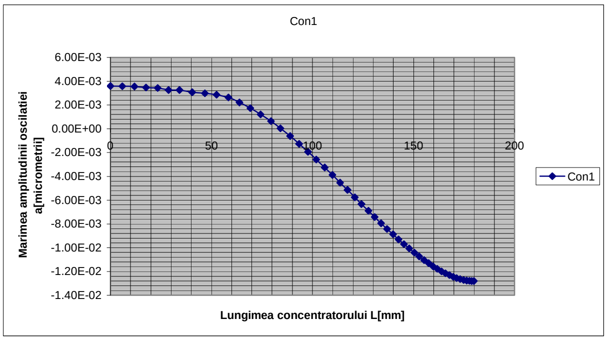

Fig. 11. Variation of oscillation amplitude along the generator of the horn.

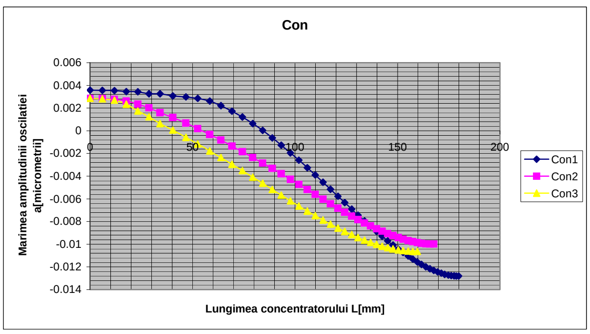

Fig. 12. Variation of amplitude oscillation along the horn for three different conical horns.

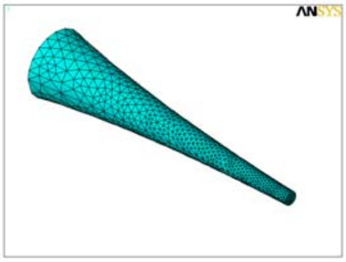

Fig. 13. Discretization with SOLID 92 element

Fig. 14. Symbol for applying load to the exponential horn.

Figure 14 presents the symbols for applying displacement from the piezoceramic assembly to the ultrasonic horn.

The mode of vibration is shown in Figure 15 and 16 (isometric and frontal view).

In Table 4 are represented the value of the oscillation amplitude of an ultrasonic exponential horn.

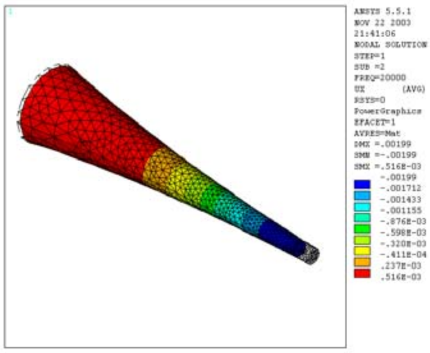

Fig. 15. Isometric view of the exponential horn vibration

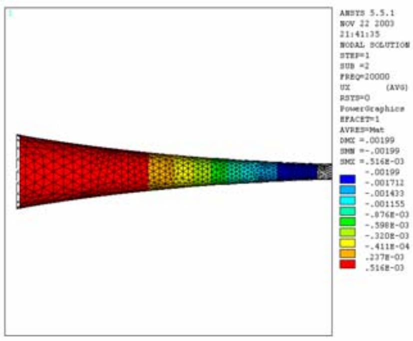

Fig. 16. Frontal view of the exponential horn vibration

Table 4

Variation of the oscillation amplitude for an exponential horn

No.	Node no.	Horn length L [mm]	Oscillation amplitude A [mm]
1	8	0	0.01302893
2	117	7.20852	0.01297254
3	6	19.99996	0.01280363
4	92	26.57094	0.01249121
5	94	32.7406	0.01203554
6	3	39.99992	0.01147801
7	52	47.60468	0.0107917
8	54	54.62524	0.01018184
9	4	59.99988	0.00949147
10	201	65.38214	0.00786714
11	203	70.05828	0.00613359
12	205	74.96048	0.00406324
13	15	79.99984	0.00169034
14	229	85.04428	-0.00099705
15	231	90.94216	-0.0044991
16	233	95.83928	-0.00759714
17	18	99.9998	-0.0103185
18	259	104.1654	-0.01318844
19	261	108.6206	-0.01641069

Figure 17 depicts the oscillation amplitude along the horn showing the coordinate of the nodal plane for an exponential ultrasonic horn.

Figure 18 presents the variation of the oscillation amplitude along three exponential horns of different dimensions [2].

5 Finite element analysis of parabolic cubical horns

The mode of vibration is shown in Figure 20 and 21 (isometric and frontal view).

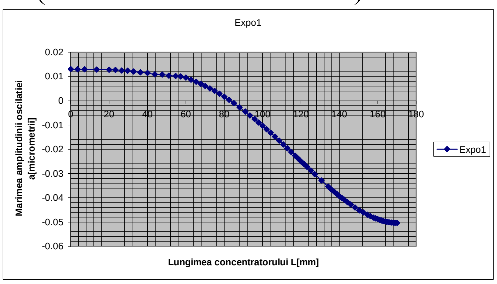

Fig. 17. Variation of the oscillation amplitude along the ultrasonic horn

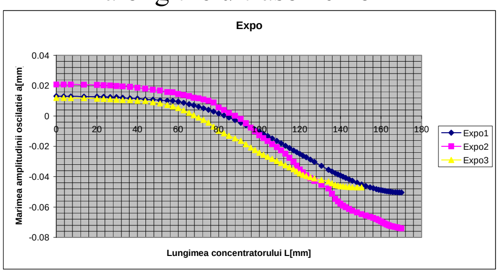

Fig. 18. Variation of the oscillation amplitude along the ultrasonic horn for three types of exponential horns [4]

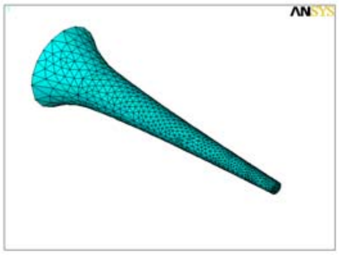

Fig. 19. Discretization of the volume with SOLID 92

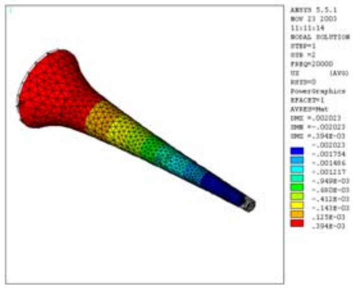

Fig. 20. Isometric view of a parabolic cubical horn.

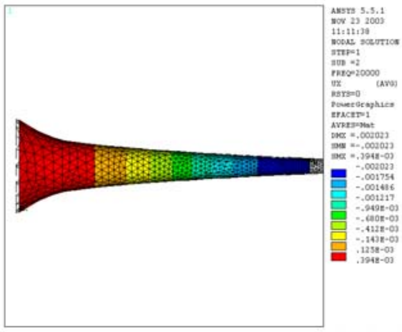

Fig. 21. Frontal view of the parabolic conical view.

Table 5

Amplitude oscillation for a parabolic conical horn

No.	Node no.	Horn length L [mm]	Oscillation amplitude A [mm]
1	23	0	0.00999998
2	387	8.460994	0.009737598
3	389	14.91767	0.008915654
4	5	20.00021	0.007789164
5	47	25.47645	0.00626999
6	49	30.16275	0.004695952
7	51	35.29863	0.00266573
8	4	40.00017	0.000585267
9	89	44.70425	-0.00166784
10	91	51.22443	-0.00528091
11	93	56.18759	-0.00830351
12	9	60.00013	-0.01065327
13	121	63.81267	-0.0131478
14	123	68.69455	-0.01650441
15	125	73.55611	-0.01995907
16	127	77.20355	-0.02257857
17	12	80.00009	-0.02458161
18	155	82.79663	-0.026543
19	157	86.06307	-0.02888234
20	159	88.84945	-0.03085338
21	161	91.69679	-0.03285744
22	163	94.78035	-0.03498342

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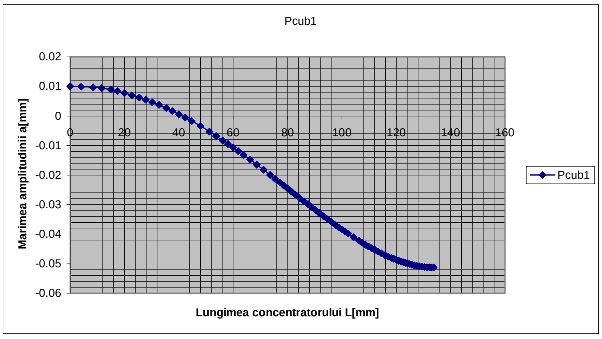

Fig. 22. Variation of the oscillation amplitude along the horn

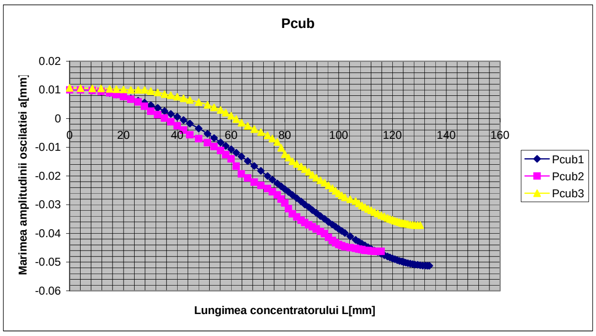

Fig. 23. Variation of the oscillation amplitude along the horn for three different sized parabolic conical horns

Table 5 presents the oscillation amplitude of a parabolic conical horn [2].

Figure 22 depicts the variation of the amplitude oscillation along the horn showing the coordinate of the nodal plane for a parabolic cubical horn.

Figure 23 presents the variation of the amplitude oscillation along three parabolic conical horns of different dimensions.

6 CONCLUSIONS

It is very important to know the amplitude at every point of the ultrasonic horn, because:

- allows precise determination of the nodal plane position for locking in place of he ultrasonic system for desired processing;
- the parameters of the ultrasonic system can be determined dependant of the amplitude at the top of the horn;
- finite element modeling and analysis allow testing of various shapes of ultrasonic horns without the need to manufacture a real prototype;
- allows the possibility of selecting the right shape for the desired procedure.

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