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FINITE ELEMENT MODELING OF ULTRASONIC ENERGY CONCENTRATORS USED IN MECHANICAL PROCESSING

Constantin RADU, Paulina SPÂNU, Ana Maria BOGATU

Abstract: *The paper presents the importance of finite element design and modeling of ultrasonic energy concentrators used in mechanical processing. The use of the finite element method allows costs reducing research and reducing the time required to find the optimal variant of the geometric elements of the concentrator.*

The correct choice of the geometric shape of the concentrator allows obtaining an amplitude corresponding to the contact between the surface to be processed and the concentrator. A small amplitude is not enough and an amplitude that is too high can lead to premature damage of the concentrator.

This paper presents a comparison of the different geometric shapes used to create ultrasonic energy concentrators. Finite element modeling helps us to easily identify the nodal planes and the optimal operating frequency of the concentrator.

Key words: *Finite element modeling, ultrasonic concentrators, geometrical shapes, mechanical processing*

1. INTRODUCTION

The ultra-acoustic system is the most important subassembly of an ultrasonic cavitation processing installation because it produces the acoustic parameters (acoustic intensity, acoustic energy density, oscillation amplitude, wave type, oscillation frequency) and the mechanical parameters (static pressing pressure and pressing force). The calculation and sizing of the system is done in such a way that it operates in resonance mode considering all the technological parameters of the processing, which is why modelling the ultra-acoustic system is a particularly difficult and necessary problem. After reviewing different modelling methods it was concluded that finite element modelling using the ANSYS package is the most recommended [1], [6], [7]. Compound concentrators allow for easier fixation.

2. INFORMATION

To choose the appropriate geometrical shape of the concentrator for a given technological process we used finite element modelling for different simple geometrical shapes: conical, exponential, parabolic etc. or compound: cylindrical and conical, conical and exponential, conical and cylindrical etc.

This paper presents a comparison between a simple geometric shape and a compound geometric shape to see which has the higher shape-application factor. For the simple geometric form exponential concentrator was chosen and for the composite form the cone and exponential [1].

2.1. Finite element modelling of the ultrasonic energy concentrator.

The main phases of finite element modelling of a concentrator are presented below.

In the first phase, we start from the geometrical dimensions of a concentrator used in various processing resulted from calculation and corrected for resonance considerations [2], [3]. In the second phase, the main properties of the material from which the concentrator is made are introduced. In this case the concentrator is made of carbon steel (C45) having the following 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

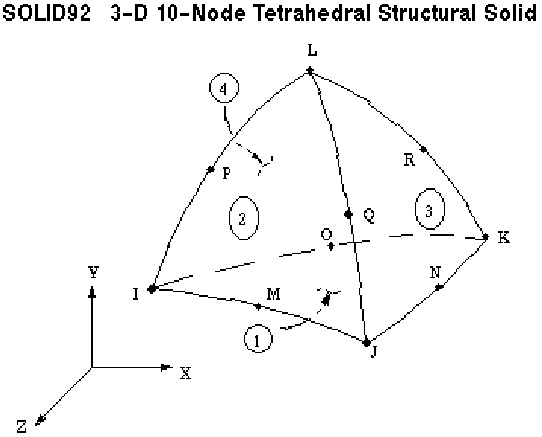

Fig. 1. Discretization element shape [2].

The third phase involves the choice of the type of analysis, and for the present case, from the main domain we opt for the type of structural analysis which also conditions the call of discretization element libraries [2], [3].

In the fourth phase, the discretization element is chosen from the ANSYS library, which is SOLID 92, defined by a 3-D element with 10 solid tetrahedral nodes, presented in Figure 1, [6], [7], [8].

The fifth phase involves creating the geometry of the concentrator volume using the ANSYS graphics module or one of the specialized software packages (Katia, SolidWorks, Mechanical Desktop, etc.) to create this volume. The geometry of the volume represented in figure 2 is generated from the main menu, by activating the PREPROCESSOR command.

In the sixth phase the discretization element and the size of the meshed element are chosen. The SOLID92 element discretization of this volume generates 15 468 elements with 9824 nodes as presented in Figure 3. The seventh phase implies choosing the type of analysis to determine the main frequencies on which the concentrator oscillates. After activating the "SOLUTION" processor, the harmonic analysis type is selected. In the eighth phase, the appropriate loadings are applied to the concentrator and respecting the physical reality, the ultrasonic energy concentrator is loaded with a displacement result in the input section (large head area), obtained from the analysis of the piezoceramic assembly [2], [3].

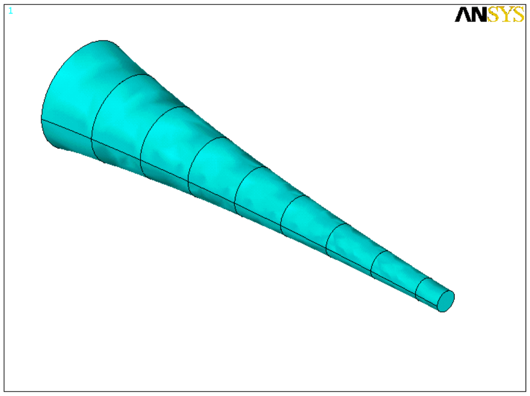

Fig. 2. Generation of concentrator geometry.

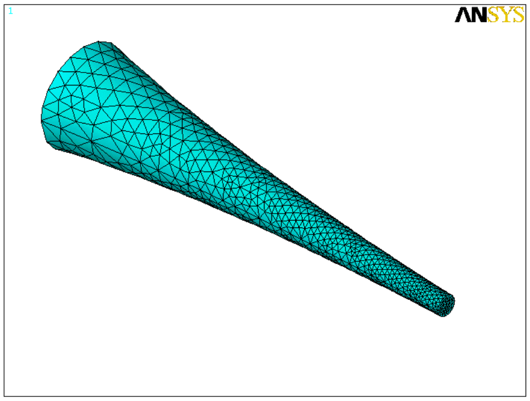

Fig. 3. Volume discretization with SOLID 92.

At the end of the analysis, by calling the GENERAL POSTPROCESSOR a set of frequencies chosen from the ultrasonic domain is obtained (Table 1). [6], [7].

Table 1

Frequency set obtained by calling the GENERAL POSTPROCESSOR

SET	TIME/FREQ	LOAD STEP	SUBSTEP	CUMULATIVE
1	16000.	1	4	4
2	17500.	1	5	5
3	19000.	1	6	6
4	20000.	1	7	7
5	22000.	1	8	8
6	23500.	1	9	9

7	25000.	1	10	10
8	26500.	1	11	11
9	28000.	1	12	12
10	29500.	1	13	13
11	31000.	1	14	14
12	32500.	1	15	15
13	34000.	1	16	16
14	35500.	1	17	17
15	37000.	1	18	18
16	38500.	1	19	19
17	40000.	1	20	20

Mode 4 (20,000 KHz) turns out to be the resonant frequency of the ultra-acoustic system (20 KHz). Then, depending on the settings previously made, you select what you want the ANSYS package to display such as: deformation state, stress state, heat variation, etc. The deformed and undeformed states, corresponding to this mode of vibration, for displacement in the Z-direction, represented by the graphical interface settings frontal, are presented in Figure 4. The representations of the obtained states are accompanied by a legend containing ranges of deformation values [4], [5], [6], [7].

The values for the displacements along the ultrasonic energy concentrator contained in the legend validate the theory and physical reality that it produces an amplification of the oscillation magnitude by the shape corresponding to the multiplication coefficient.

The vibration modes also highlight the wave types propagating in the ultrasonic energy concentrator and the magnitude of the oscillation amplitude, considering the deformed state, along the ultrasonic energy concentrator.

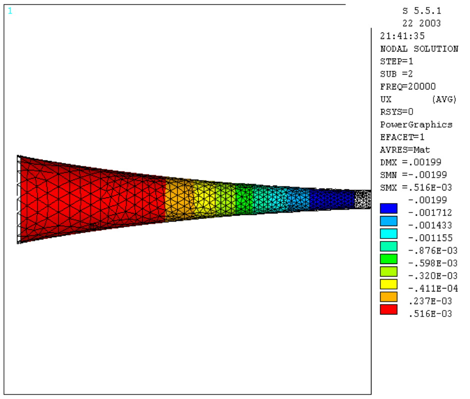

Fig. 4. Frontal representation of the concentrator.

Table 2 presents the amplitude magnitude values per generator of an exponentially shaped ultrasonic energy concentrator.

Table 2

Variation in the amplitude of the oscillation.

No.	Node number	Concentrator length [mm]	Amplitude of the oscillation [mm]
1	8	0	0.001302893
3	117	7.20852	0.001297254
5	6	19.99996	0.001280363
7	92	26.57094	0.001249121
9	94	32.7406	0.001203554
11	3	39.99992	0.001147801
13	52	47.60468	0.00107917
15	54	54.62524	0.001018184
17	4	59.99988	0.000949147
19	201	65.38214	0.000786714
21	203	70.05828	0.000613359
23	205	74.96048	0.000406324
25	15	79.99984	0.000169034
27	229	85.04428	-0.000099705
29	231	90.94216	-0.00044991
31	233	95.83928	-0.000759714
33	18	99.9998	-0.00103185
35	259	104.1654	-0.001318844
37	261	108.6206	-0.001641069
39	263	112.8624	-0.00195928
41	265	116.9035	-0.002266823
43	21	119.9998	-0.002496007
45	293	123.0986	-0.002722626
47	295	127.1219	-0.003028442
49	297	134.1095	-0.003536442
51	299	137.4445	-0.003764534
53	24	139.9997	-0.00392684
55	329	142.5575	-0.00408178
57	331	145.8798	-0.004274058
59	333	150.401	-0.004514342
61	335	154.6225	-0.004703826
63	337	157.6629	-0.004816856
65	27	159.9997	-0.004888992
67	377	161.9098	-0.00493776
69	375	163.7487	-0.004975098
71	373	165.8061	-0.00500761
73	371	168.0159	-0.00502843

2.2. Modeling a conical concentrator

The modelling of conical concentrators of different geometrical dimensions and their comparison on the size of the degree of amplification is presented below [8].

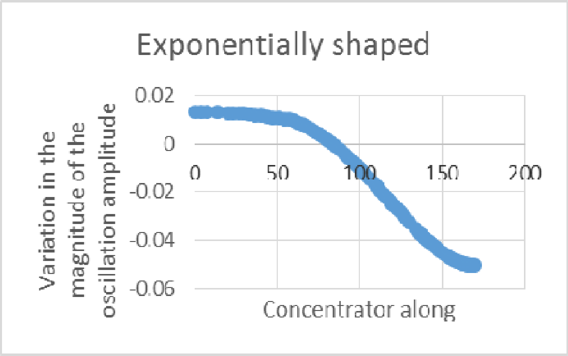

Fig. 5. Variation in the magnitude of the oscillation amplitude along the concentrator generator.

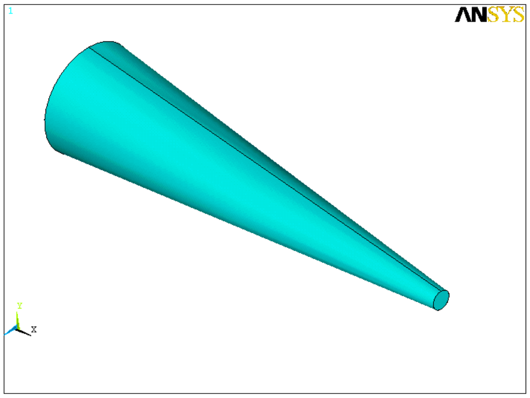

Fig. 6. Generating the geometry of a conical concentrator.

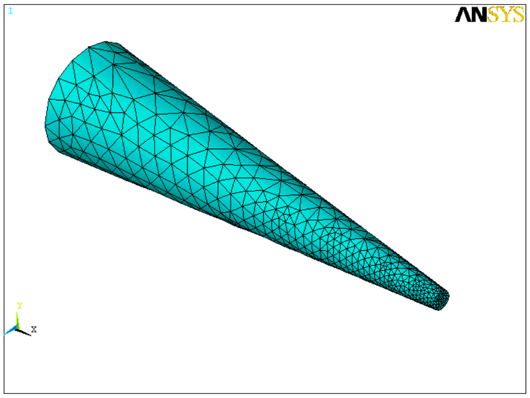

Fig. 7. Volume discretization with SOLID 92: 9853 - nodes; 6234 - elements.

Table 3

Frequency sets

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

The deformed and undeformed states corresponding to this vibration mode, for displacement in the Z-direction, represented by the graphical interface settings frontal are presented in Figure 8 [2], [3], [4], [5], [6], [7].

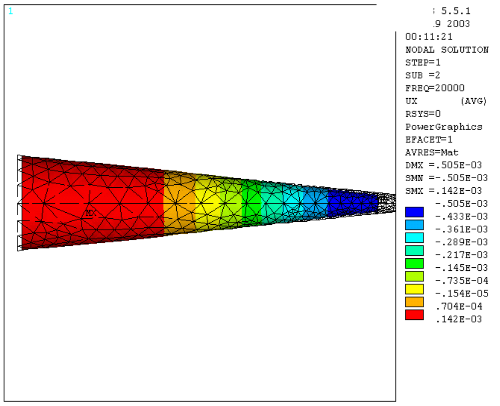

Fig. 8. Deformation and non-deformation of a conical concentrator, frontal representation.

Table 4 presents the amplitude magnitude values across the generator of a cone-shaped ultrasonic energy concentrator. [6], [7].

Table 4

Variation in the magnitude of the oscillation amplitude

No.	Node number	Concentrator length [mm]	Amplitude of the oscillation [mm]
1	4	0	0.0003587242
3	62	11.91006	0.0003541014
5	64	23.34006	0.0003431286
7	66	34.18078	0.0003264408
9	68	46.70806	0.0002990342
11	70	58.38444	0.000262763
13	72	69.27342	0.0001723619
15	74	79.42834	0.0000634746
17	76	88.89492	-0.000061368
19	78	97.73666	-0.000193855
21	80	105.9942	-0.000326009
23	82	113.7082	-0.000453339
25	84	120.9142	-0.000576478
27	86	127.6426	-0.000690626
29	88	133.9291	-0.000795045
31	90	139.8016	-0.000887933
33	92	145.288	-0.000970610
35	94	150.4112	-0.001042466
37	96	155.1965	-0.001103909
39	98	159.6669	-0.001156614
41	100	163.8427	-0.001198575
43	102	167.7441	-0.001231392
45	104	171.3865	-0.001255547
47	106	174.7799	-0.001271473

49	108	177.6197	-0.001279220
51	3	179.8015	-0.001281226

Figure 9 presents the variation of the oscillation amplitude magnitude along the concentrator and highlights the nodal plane.

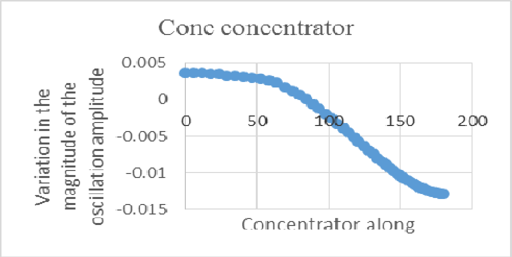

Fig. 9. Variation in the magnitude of the oscillation amplitude along the concentrator generator.

2.3. Modeling a compound cone-exponential concentrator

Following the above steps, finite element modelling of exponential concentrators is performed. [2], [3], [4], [5], [6], [7].

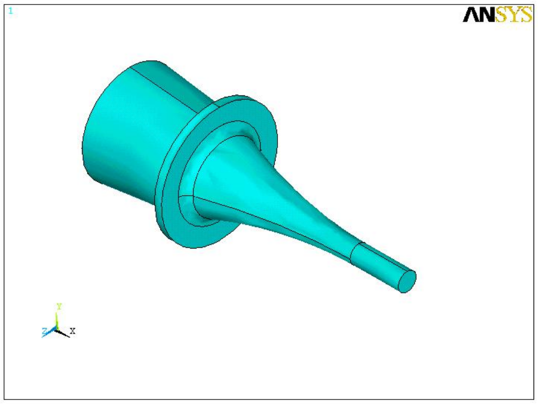

Fig. 10. Generating the geometry of a combined concentrator.

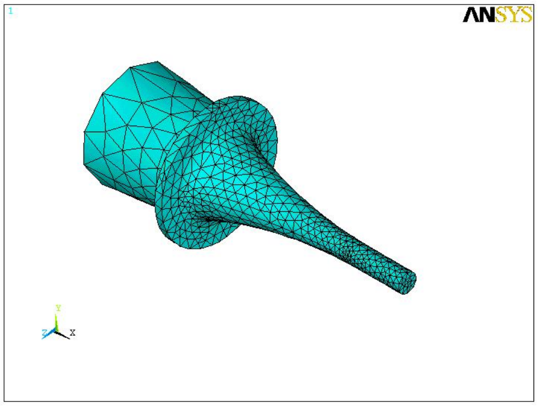

Fig. 11. Volume discretization with SOLID 92: 21 871 - nodes; 28 574 - elements.

Table 5 presents the amplitude magnitude values across the generator of a combined-form ultrasonic energy concentrator [2], [3], [4], [5].

Table 5

Variation of oscillation amplitude size on generator.

No.	Concentrator length L [mm]	Amplitude of the oscillation A [mm]
1	0	0.000257073
2	2.378378	0.000256718
3	4.756756	0.000061575
4	7.135134	0.000051905
5	9.513512	0.000048941
6	11.89189	0.000048633
7	14.270268	0.000045618
8	16.648646	0.000043094
9	19.027024	0.000042047
10	21.405402	0.000041732
11	23.78378	0.000040043
12	26.162158	0.000038156
13	28.540536	0.000037843
14	30.918914	0.000035121
15	33.297292	0.000032225
16	35.67567	0.000031918
17	38.054048	0.000029520
18	40.432426	0.000026589
19	42.810804	0.000024765
20	45.189182	0.000023298
21	47.56756	0.000019287
22	49.945938	0.000014917
23	52.324316	0.000009538
24	54.702694	0.000003474
25	57.081072	-0.000004102
26	59.45945	-0.000012415
27	61.837828	-0.000022162
28	64.216206	-0.000032662
29	66.594584	-0.000044717
30	68.972962	-0.000058499
31	71.35134	-0.000074643
32	73.729718	-0.000092083
33	76.108096	-0.000108618
34	78.486474	-0.000126121
35	80.864852	-0.000143279
36	83.24323	-0.000161458
37	85.621608	0.000257251
38	87.999986	0.000257073
39	90.378364	0.000256718
40	92.756742	0.000061575
41	95.13512	0.000051905
42	97.513498	0.000048941
43	99.891876	0.000048633
44	102.270254	0.000045618
45	104.648632	0.000043094
46	107.02701	0.000042047
47	109.405388	0.000041732
48	111.783766	0.000040043
49	114.162144	0.000038156

50	116.540522	0.000037843
51	118.9189	0.000035121
52	121.297278	0.000032225
53	123.675656	0.000031918
54	126.054034	0.000029520
55	128.432412	0.000026589
56	130.81079	0.000024765
57	133.189168	0.000023298
58	135.567546	0.000019287
59	137.945924	0.000014917
60	140.324302	0.000009538
61	142.70268	0.000003474
62	145.081058	-0.000004102
62	147.459436	-0.000012415
64	149.837814	-0.000022162
65	152.216192	-0.000032662
66	154.59457	-0.000044717
67	156.972948	-0.000058499
68	159.351326	-0.000074643
69	161.729704	-0.000092083
70	164.108082	-0.000108618
71	166.48646	-0.000126121
72	168.864838	-0.000143279
73	171.243216	-0.000161458

The deformed and undeformed states corresponding to this mode of vibration, for displacement in the Z-direction, represented by the graphical interface settings frontal are presented in Figure 13 [2], [3], [4], [5].

Figure 14 presents the variation of the oscillation amplitude magnitude along the generator, highlighting the nodal plane coordinate for a combined shape concentrator.

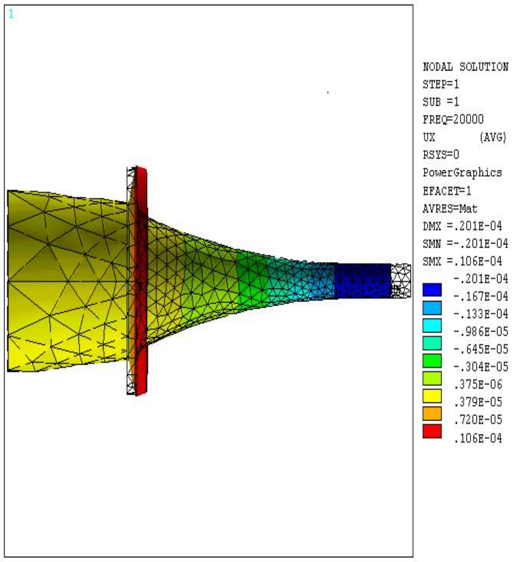

Fig. 13. Deformation and non-deformation of a combined concentrator, frontal representation.

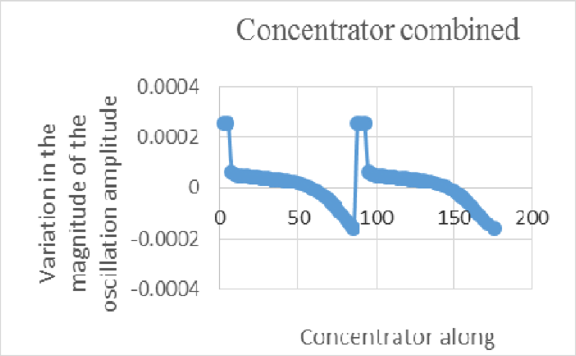

Fig 14. Variation in the magnitude of the oscillation amplitude along the concentrator generator.

The measurement of the amplitude at the tip of the ultrasonic energy concentrator and the variation of the amplitude magnitude along the concentrator are essential elements to determine its energy efficiency, concentrator stress and processing accuracy.

Therefore, it was necessary to measure the magnitude of the amplitude not only when the ultra-acoustic system was running idle but also when under load, as amplitude is the basic acoustic parameter in assessing the productivity of machining materials by cutting [2], [3], [4], [5]. Determining the size of the amplitude is a particularly difficult problem because its size is in the micrometric or submicrometric range and the frequency of the oscillation is high (above 16kHz). From the analysis of the methods applied by other researchers and considering the experimental results obtained in the processing of different materials, an original method and a stand for rapid measurement of the amplitude both at idle and under load was designed.

4. CONCLUSION

1. The ultra-acoustic system is the most important sub-assembly of any ultrasonic cavitation processing installation because it achieves both acoustic parameters (acoustic intensity, acoustic energy density, frequency of ultrasonic oscillations and amplitude of oscillations) and mechanical parameters (pressing force and static pressing pressure). The ultra-acoustic system must be designed, calculated and built in such a way that it works

at resonance, its active part working at a certain amplitude at a certain frequency.

2. It is found that for simple concentrators the shape amplification factor is higher than for the combined one.

3. In the combined concentrator it is found that the amplitude size is smaller than in the simple form concentrators. The most used are magneto strictive materials (have a lower yield but allow higher static forces to be applied) and piezoceramic materials (have a higher yield but do not withstand high static compressive forces);

4. Combined concentrators are much more rigid and their performance is lower than single concentrators. Mathematical modelling of systems is required to optimize the design and calculation of an ultra-acoustic system. Finite element modelling, in this case the ANSYS package, is proving invaluable for highlighting the behavior of ultra-acoustic systems evolving at high frequencies. This method relieves the researcher of the laborious experimental program required to build a statistical model that satisfactorily represents the real phenomenon under study. Most of the time only one input data taken by measurement is needed to scale the model to reality. A result obtained from a given analysis is sufficient as input for a subsequent analysis.

The results obtained by modelling both the piezoceramic assembly and the ultrasonic energy concentrator are close to coincident with those observed and measured in practice.

Finite element modelling, using the ANSYS package, of an ultra-acoustic system for ultrasonic machining with special reference to surface finishing machining of parts used in the machine-building industry, modelling which finally allows a certain dimensioning and construction according to the vibration modes required in operation. The vibration modalities highlight the types of waves propagating in the ultrasonic energy concentrator.

The calculation and design of ultrasonic energy concentrators uses a mathematical modelling of the elastic wave propagation equation in a medium extended to infinite, an equation that has different forms in relation to how the concentrator cross-section varies along it. Depending on the nature of the processing operation, the following elements are of interest in the ultrasonic energy concentrator: particle velocity on the initial section and especially on the final section; acoustic pressure along the concentrator and especially at its tip, the amplification factor, the length of the concentrator calculated in such a way as to work in a resonance mode, the coefficient of variation of the section along the concentrator, the size of the amplitude of the concentrator tip and its variation along the concentrator, the position of the nodal planes and the frequency correction due to the additional mass. Finite element modelling of different types of ultrasonic energy concentrators using the ANSYS package allowed the development of an optimal calculation and construction system considering: the state of stresses and deformations along the ultrasonic energy concentrator, the vibration modes and resonance frequency, the amplitude size and especially the amplitude variation along the ultrasonic energy concentrator, the type of wave excited in the concentrator.

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MODELAREA CU ELEMENTE FINITE A CONCENTRATOARELOR DE ENERGIE ULTRASONICE FOLOSITE ÎN PRELUCRAREA MECANICĂ

Rezumat: Acest articol prezintă importanța proiectării și modelării cu elemente finite a concentratoarelor de energie ultrasunete folosite în prelucrarea mecanică. Utilizarea metodei elementelor finite permite reducerea costurilor de cercetare și scurtarea timpului necesar pentru găsirea variantei optime a elementelor geometrice ale concentratorului. Alegerea corectă a formei geometrice a concentratorului permite obținerea unei amplitudini corespunzătoare contactului între suprafața de prelucrat și concentrator. O amplitudine mică nu este suficientă, iar o amplitudine prea mare poate duce la deteriorarea prematură a concentratorului. Acest articol prezintă o comparație a diferitelor forme geometrice utilizate pentru a crea concentratoare de energie ultrasunete. Modelarea cu elemente finite ne ajută să identificăm cu ușurință planele nodale și frecvența de funcționare optimă a concentratorului. Modelarea cu elemente finite a concentratoarelor de energie ultrasunete folosite în prelucrarea mecanică.

Constantin RADU, S.L. DR. ING., UPB, Romania, Email: rcdnd@yahoo.com, Tel 0721 813 179
Paulina SPÂNU, CONF. DR. ING. UPB, Romania, Email: pauspa16@yahoo.com, 0766 782 100
DEPARTAMENT: TEHNOLOGIA CONSTRUCTIILOR DE MASINI (TCM)
Ana Maria BOGATU, S.L. DR. ING., UPB, Romania, Email: bogatu_ana_maria@yahoo.com, 0755 512 314, DEPARTAMENT: INGINERIA CALITATII SI TEHNOLOGII INDUSTRIALE (ICTI)