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ORIGINAL ARTICLE

Correct Prediction of the Vibration Behavior of a High Power Ultrasonic Transducer by FEM Simulation

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Abstract This paper presents a study on three types of finite element analyses of high power ultrasonic transducer by using the finite element commercial software called ANSYS. The transducer geometry was treated as a 2D axisymmetric model, 3D quart and full 3D model. For all of the simulations the modeled transducer was used in modal analysis and harmonic solutions to understand its mechanical behavior and its natural frequency. A comparison was made between each type of modeling and experimental results. This comparison allows the parameters of FEM models to be iteratively adjusted and optimized and also leads to selection of the best modeling type. The achieved FEM results exhibited a remarkably high predictive potential of ANSYS in modeling and simulation and allowed control on the design and on the vibration behavior of the high power ultrasonic transducer.

Keywords Finite element modeling · Harmonic analysis · Modal analysis · Ultrasonic transducer

1 Introduction

High power ultrasound is nowadays used in a wide variety of applications ranging from medical devices, ultrasonic cleaning, ultrasonic welding and machining to sonochemistry [1]. Since Prof. Langevin developed the first sandwich ultrasonic transducer by embedding piezoelectric rings between two metals and employed it for high intensity vibration, there have been great efforts in modeling and formulating such transducers [2–5]. Finite element method (FEM) is one of the most reliable tools for analyzing the ultrasonic transducers [6–14].

In the present work, by using the analytical method, the dimensions of components of a 3 KW ultrasonic transducer were determined by assuming resonance frequency of 22 KHz. The analyzed transducer was composed of six PZT- 4 piezo- ceramic rings, a steel cylinder- shaped back mass (St 304) and an aluminum stepped front mass (Al 7075- T6). The bolt material was taken from steel. As the exact value of density and sound speed of the materials must be utilized in the design process, these two properties were accurately measured for backing and matching. Measurement of sound speed was made in the NDT Laboratory by using ultrasonic equipment ASCANWIN, E2.58, 2002. The time of flight (TOF) of the pulse which was transmitted and received by a single probe of 2 MHz, Φ24 was measured. By knowing the thickness of the specimens, the sound speed could be obtained by a simple calculation. The material properties of the components are as shown in Tables 1, 2, 3, 4, and 5. Figures 1 and 2 show the designed transducer.

The finite element method provided by commercial ANSYS was employed for 2D, 1/4 3D, and full 3D FEM modeling and analysis of the transducer to observe its vibration behavior through its simulation by modal analysis and to determine its natural frequency by harmonic analysis. This was also for finding the validity of the analytical results. At the end, a comparison was made between each type of modeling and the experimental results.

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Table 1 Material properties of aluminum matching [15]

Standard code	AL 7075- T6
Measured sound speed (m/s)	6210
Tut (MPa)	572
Modulus of elasticity $\left({}^{N}/_{m^2}\right)$	7.7×10^{10}
Major Poisson's ratio	0.33
Minor Poisson's ratio	0.33
Measured Density $\left({}^{Kg}/_{m^3}\right)$	2823

For the transducer design discussed in this paper, PZT- 4 was chosen as piezoelectric material. PZT- 4 is an appropriate choice for this application because it can generate high power similar to PZT- 5A [16].

Morgan Matroc Inc., a popular manufacturer of piezoelectric ceramics, lists the material properties of PZT- 4 as [16]:

Dielectric relative permittivity matrix at constant strain, $\lfloor\varepsilon_r^s\rfloor$(polarization axis along Y- axis):

$$[\varepsilon_r^S] = \begin{bmatrix} 730 & 0 & 0 \\ 0 & 635 & 0 \\ 0 & 0 & 730 \end{bmatrix}$$

Piezoelectric stress matrix (Stress developed/electric field applied at constant strain), [e] (polarization axis along Y- axis):

$$[e] = \begin{bmatrix} 0 & -5.2 & 0 \\ 0 & 15.1 & 0 \\ 0 & -5.2 & 0 \\ 12.7 & 0 & 0 \\ 0 & 0 & 12.7 \\ 0 & 0 & 0 \end{bmatrix} {}^{C}/_{m^2}$$

Compliance matrix [s] for PZT- 4 under constant electric-field, [S^E] (polarization axis along Y- axis):

$$[S^E] = \begin{bmatrix} 12.3 & -5.31 & -4.05 & 0 & 0 & 0 \\ -5.31 & 15.1 & -5.31 & 0 & 0 & 0 \\ -4.05 & -5.31 & 12.3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 39 & 0 & 0 \\ 0 & 0 & 0 & 0 & 39 & 0 \\ 0 & 0 & 0 & 0 & 0 & 32.7 \end{bmatrix} \times 10^{-12m^2}/_{N}$$

Table 2 Material properties of steel backing [15]

Standard code	St 304
Measured sound speed (m/s)	5720
Tut (MPa)	505
Modulus of elasticity $\left({}^{N}/_{m^2}\right)$	20.7×10^{10}
Major Poisson's ratio	0.292
Minor Poisson's ratio	0.292
Measured Density $\left({}^{Kg}/_{m^3}\right)$	7868

Table 3 Material properties of steel bolt [15]

Modulus of elasticity $\left({}^{N}/_{m^2}\right)$	$20\ .7\times10^{10}$
Major Poisson's ratio	0.292
Minor Poisson's ratio	0.292
Measured Density $y\left({}^{Kg}/_{m^2}\right)$	7868

1.1 FEM modeling

For an ultrasonic transducer, modal analysis in FEM is normally used to determine the natural frequencies, mode shapes and the location of nodal plane. The natural frequencies and mode shapes are important parameters in the design of a transducer for dynamic loading conditions. These are also necessary if a spectrum analysis or a mode superposition harmonic or transient analysis is supposed to be implemented.

The block Lanczos method was chosen in this work to compute the natural frequency as this method is recommended by ANSYS instructions [17].

This analysis was performed under two separate statuses of electrical conditions. In the first case which is commonly called the "resonance" condition, a constant voltage of zero was applied at all electrical contacts of ceramic disks. This is a condition of "short- circuit" where all voltage potentials are connected to common ground. In the second case, called "anti- resonance", only one of the negative poles or the positive poles of the piezo- ceramic disks were connected to zero voltage of common ground and the other poles were left free without any connection. This represents an "open- circuit" condition. As the positive faces of the piezoelectric rings are electrically connected together and also the negative faces are electrically coupled together, the nodes on these faces are coupled together as equipotential points (voltage D.O.F[1]). This is a good assumption as the piezoelectric pieces actually have a thin silver coating to insure excellent electrical contact.

No structural constraint was used for the modal analysis. This produces a simulation of an unrestrained transducer assembly. This state is similar to the state of physical testing where the transducer rests on the table with no restriction.

This model ignores the presence of the electrically- insulating mechanically- aligning polymer (PTFE) bushes, normally used inside the ceramic disk holes around the clamping bolt shank, as they are free and not stressed during the assembly. Furthermore, although transducer performance has been observed to drift slightly during operation as the ceramic pieces warm up due to losses, the temperature effects were ignored in this study.

[1] Degree of freedom

Table 4 Material properties of nickel electrodes [15]

Modulus of elasticity $\left({}^{N}\!/_{m^2}\right)$	20.7×10^{10}
Major Poisson's ratio	0.31
Minor Poisson's ratio	0.31
Density $\left({}^{Kg}\!/_{m^3}\right)$	8880

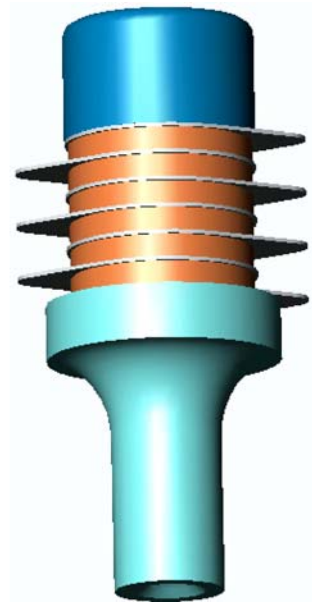

Fig. 1 Modeled high power ultrasonic transducer (3KW)

1.2 Modal analysis

1.2.1 2D FEM model

The 2D axi- symmetric model of the transducer was developed for both modal and harmonic analysis. The model must be defined on the plane passing over symmetrical axis of the transducer in position Z=0. The global Cartesian Y-axis was assumed to be the axis of symmetry and polarization (see Fig. 3).

The boundary conditions were described in terms of the structural elements. All nodes along the Y- axis centerline (at X=0) should have the radial displacement of zero for satisfying the symmetry.

The transducer was modeled once with PLANE13 elements used for piezoelectric rings and other components and once with PLANE223 elements used for piezoelectric rings and PLANE13 elements used for other components. PLANE223 has structural- thermal, piezoresistive, piezoelectric, thermal- electric, structural- thermoelectric, thermal- piezoelectric field capability and has eight nodes with up to four degrees of freedom per node. PLANE13 has a 2-D magnetic, thermal, electrical, piezoelectric and structural field capability. This element is defined by four nodes with up to four degrees of freedom per node. For this modeling the element size was selected to be 1 mm.

1.2.2 2D Modal analysis

Mode shapes and location of nodes are shown in Figs. 4 and 5. The resonance and anti- resonance frequencies obtained were 17.308 kHz and 18.969 kHz, respectively.

1.3 3D FEM model

The piezoelectric transducer is modeled by using three 3D methods of modeling and meshing. In the first method, a one- quarter symmetry sector with symmetry boundary conditions and a volume meshing generated by filling the volume by appropriate selected- shape elements is used. In the second case a sector between zero and full (360°) shape modeling is possible by rotating/extruding meshed areas into meshed volumes. In the third method, full free meshed geometry modeling is made through free meshing by only pyramid (tetrahedral) elements type. In free meshing any type of geometry even with irregular shape can be meshed.

Table 5 Material properties of piezoelectric, PZT- 4

Measured density $\left({}^{Kg}\!/_{m^3}\right)$	7640

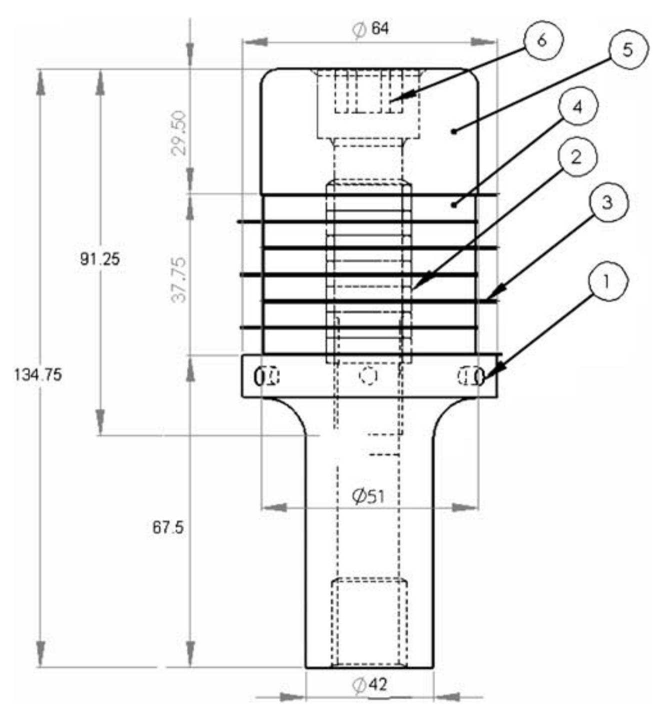

Fig. 2 Dimensions of the modeled high power ultrasonic transducer (3KW)

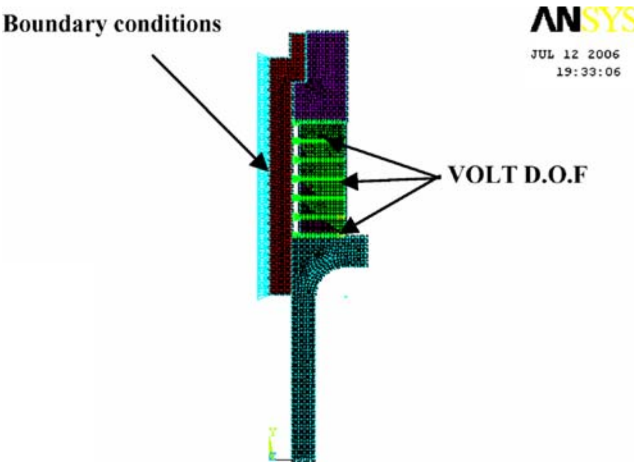

Fig. 3 2D axi- symmetric modeling with PLANE223 elements used for piezoelectric and PLANE13 elements used for other components

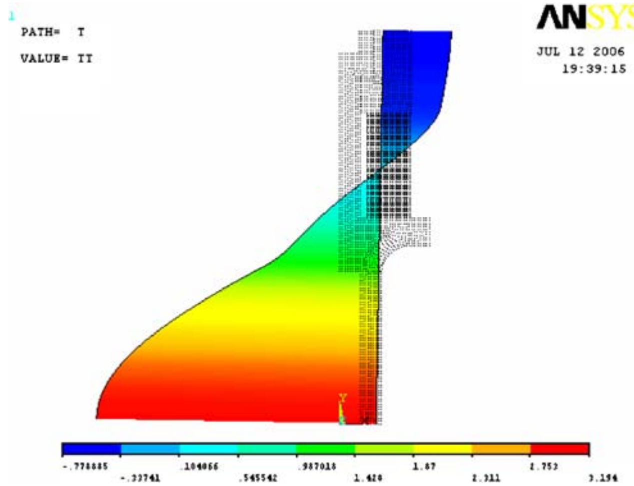

Fig. 5 Location of node from modal analysis in 2D modeling

In these analyses for 1/4 3D (first method) and full 3D (second method) modeling SOLID5 elements were used for piezoelectric and other components. Again, for 1/4 3D and for 3D free meshing, SOLID227 elements were used for meshing of piezoelectric rings and SOLID98 elements were selected for other components.

SOLID5 has a hexahedral geometry with a 3D magnetic, thermal, electric, piezoelectric and structural field capability. The element has eight nodes with up to six degrees of freedom at each node.

SOLID227 has a tetrahedral geometry with ten nodes with up to five degrees of freedom per node and has structural- thermal, piezoresistive, piezoelectric, thermal- electric, structural- thermoelectric and thermal- piezoelectric field capability.

SOLID98 is a ten nodes tetrahedral version extracted from the 8- node SOLID5 element. Each node has up to six degrees of freedom.

1.3.1 1/4 3D Modeling and analysis by using volume meshing by sweeping

In volume sweeping, the unmeshed volume is filled with sector elements between two boundary surfaces (called the “source area”). In the present study, the boundary surfaces were longitudinal cross sections of symmetric transducer having central angle less or maximum equal to 90°. If the source area mesh consists of quadrilateral (square) elements, the volume is filled with hexahedral (cylindrical, circular- annulus sector) elements. If the area consists of triangles, the volume is filled with circular- annulus wedges. If the area consists of a combination of quadrilateral and triangular elements, the volume is filled with a combination of hexahedral and circular- annulus wedge elements. In conclusion, in this method the volume is generated at the beginning and filled by the elements (see Fig. 6). For the present study modeling by SOLID5 ele-

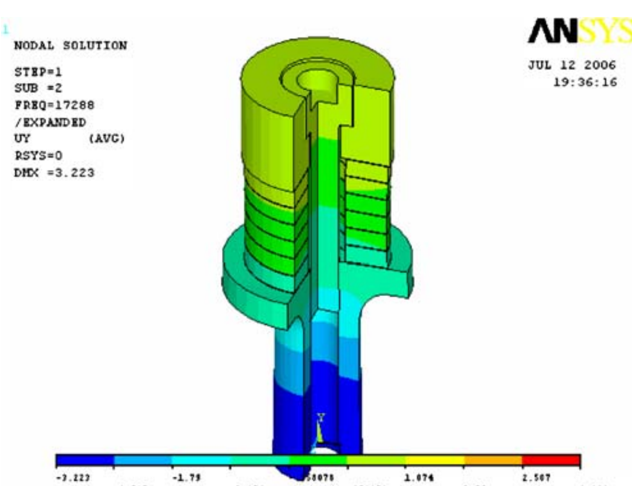

Fig. 4 Mode shape from modal analysis in 2D modeling (model rotated around Y- axis)

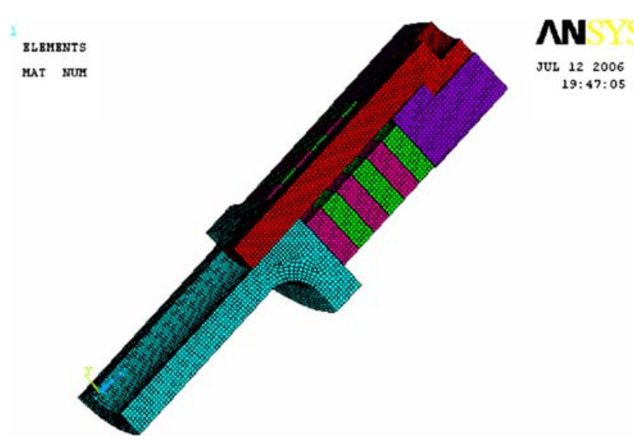

Fig. 6 1/4 3D modeling with SOLID5 elements used for all components

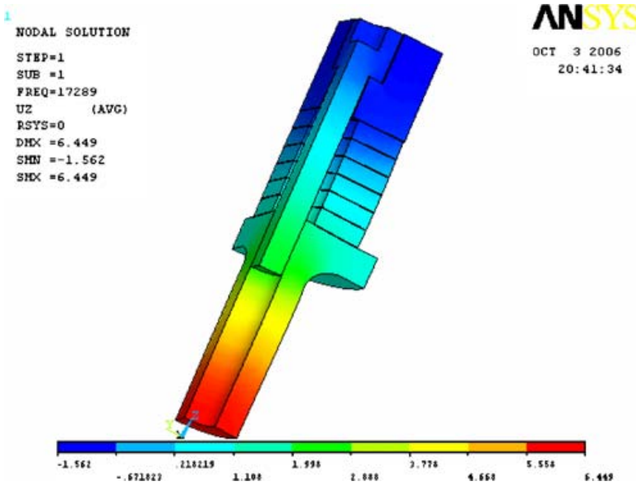

Fig. 7 Mode shape from modal analysis in 1/4 3D modeling with SOLID5 used for all components

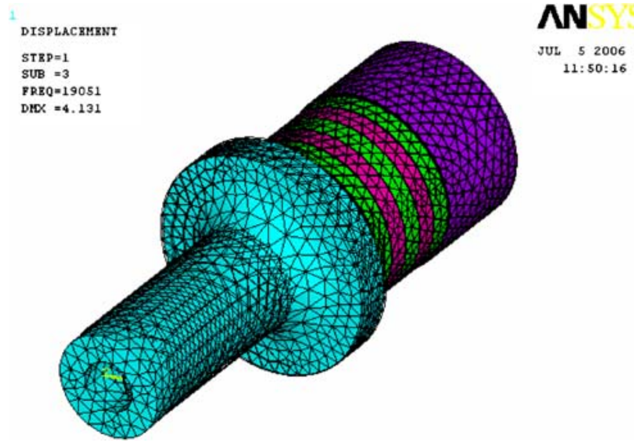

Fig. 9 Full 3D free meshing modeling with SOLID227 elements used for piezoelectric rings and SOLID98 elements used for other components

ments were used for piezoelectric and other components. The element size was selected to be 1 mm. Mode shapes and location of node are shown in Figs. 7 and 8. The modal analysis resonance and anti- resonance frequencies were found to be 17.309 kHz and 18.970 kHz, respectively. Next, modeling was performed by using SOLID227 elements for piezoelectric rings and SOLID98 elements for other components. For 4 mm element size the resonance and anti- resonance frequencies were found to be 17.329 kHz and 18.984 kHz, respectively.

By employing rotating/extruding full 3D method and by using SOLID5 elements of 2.5 mm size , the resonance and anti- resonance frequencies were found to be 17.368 kHz and 19.055 kHz, respectively. Increased size of elements to 4 mm resulted in 17.418 kHz and 19.142 kHz resonance and anti- resonance frequencies respectively. For full 3D free meshing method, when using SOLID227 elements for piezoelectric rings and SOLID98 elements for other components (see Fig. 9), for 2.5 mm element size, location of nodes and mode shapes are as shown in Figs. 10 and 11. The resonance and anti- resonance frequencies were found to be 17.311 kHz and 18.970 kHz, respectively.

1.4 2D and 3D harmonic analysis

For harmonic analysis of the above models, it was assumed that the structure of the transducer is under no constraint. The harmonic analysis was performed over a frequency span inside which the resonance frequency was expected (0.95 to 1.1 times the frequency obtained by modal analysis). This frequency span was divided into 20 steps for checking the amplitude and to obtain the frequency at

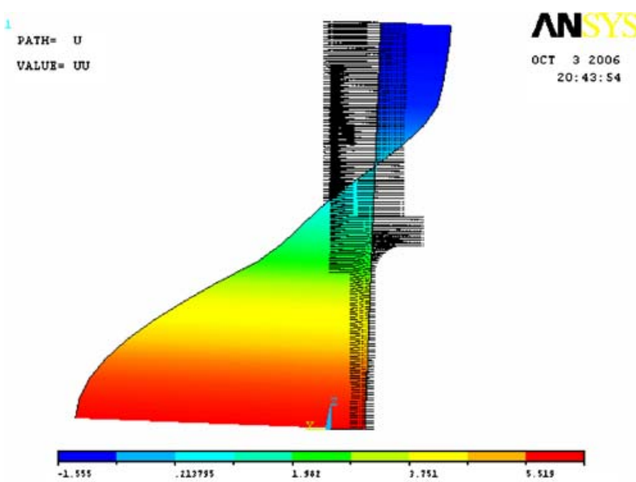

Fig. 8 Location of node from modal analysis in 1/4 3D modeling with SOLID5 elements used for piezoelectric and other components2.2. Full 3D modeling and analysis

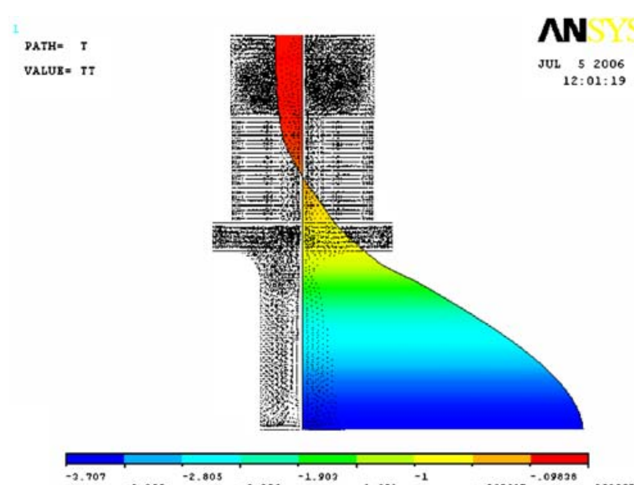

Fig. 10 Location of node from modal analysis in full 3D free meshing modeling with SOLID227 elements used for piezoelectric rings and SOLID98 elements used for other components

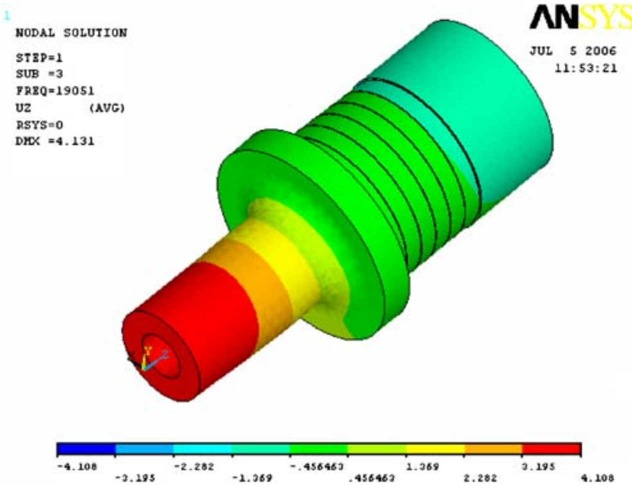

Fig. 11 Mode shape from modal analysis in full 3D free meshing modeling with SOLID227 elements used for piezoelectric rings and SOLID98 elements used for other components

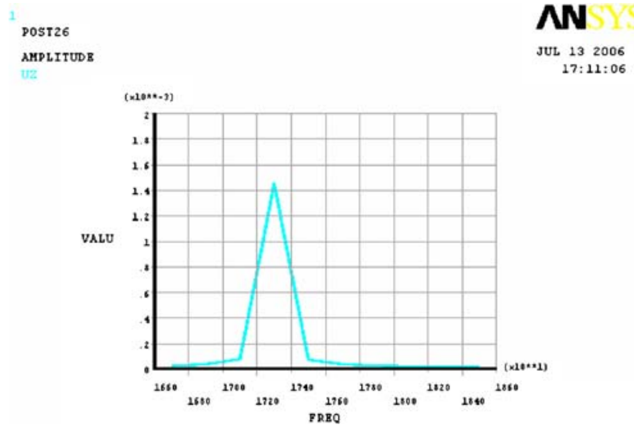

Fig. 13 Amplitude versus freq. from Harmonic analysis in 1/4 3D modeling (Polarization along the Z- axis with SOLID5 elements used for piezoelectric and other components)

which the highest amplitude is reached. At each frequency, ANSYS computed the steady- state response of the system to a sinusoidal varying input voltage of +/− 1000 volts across the piezo- ceramic rings.

Results from harmonic analysis showed that in 2D and 1/4 3D modeling, only the axial vibration was pronounced and the other modes of vibration like asymmetric modes were vanished. It was found that only a full three dimensional model could take all the modes of vibration into consideration. It must be noted that, the full three-dimensional model is more difficult to be constructed and more time consuming to run.

The harmonic analysis was performed to validate the correct modeling and correct modal analysis results. This is verified when the frequency obtained from harmonic analysis is near to or the same as the modal analysis frequency. Typical frequencies obtained from ANSYS harmonic analysis are given in Figs. 12, 13, and 14. Results show a good agreement between the modal and the harmonic analysis frequencies. Test of the fabricated transducer

To measure the actual resonance frequency of the designed and fabricated ultrasonic transducer a Network Analyzer of ROHDE & SCHWARZ was employed, the sweeping frequency of this device was within 9 kHz–4 GHz with a resolution of 10 Hz. The sweeping frequency was set between 10 kHz to 30 kHz and phase- versus-frequency diagram was drawn (Fig. 15) in which series and parallel frequencies are both illustrated. The measurement was made with the transducer loaded and unloaded. It should be noted, however, that simulation of the loading condition is greatly dependent upon the transducer application. The results showed that the resonance frequency was $f_s = 17200$ Hz in the unloaded condition.

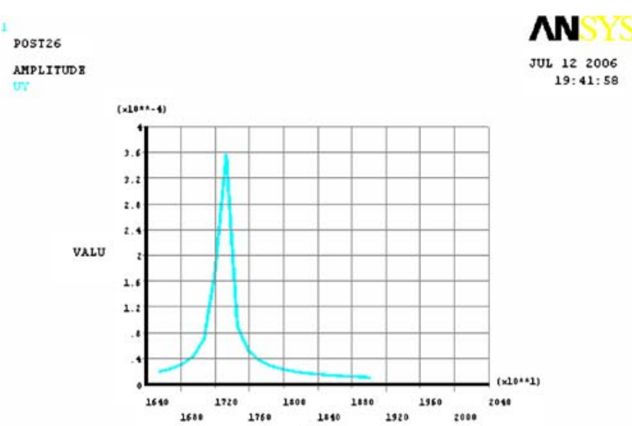

Fig. 12 Amplitude versus freq. from harmonic analysis in 2D modeling (Polarization along the Y- axis with PLANE223 elements used for piezoelectric and PLANE13 elements used for other components)

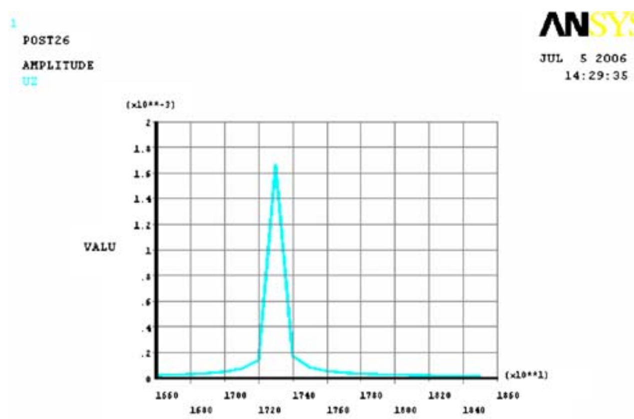

Fig. 14 Amplitude versus freq. from harmonic analysis in full 3D free meshing modeling (Polarization along the Y- axis with SOLID227 elements used for piezoelectric and SOLID98 elements used for other components)

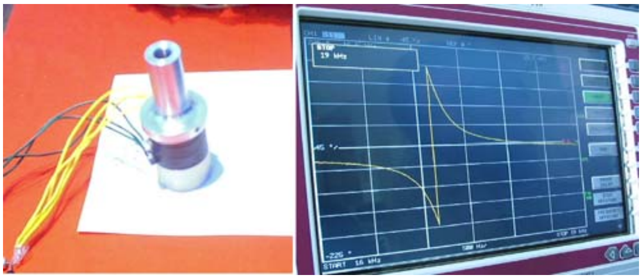

Fig. 15 Fabricated transducer and the diagram of phase versus frequency generated by Network Analyzer in unloaded condition discussion

The finite element approach presented in this paper was implemented by the general- purpose finite element package ANSYS release 10. Table 6 shows the summary of the results obtained from FEM modeling of an ultrasonic transducer with nominal frequency of 22 kHz by using different modeling techniques.

As shown in the Table 6, the two 2D axi- symmetric models give similar results which are very close to the actual value take from the Network Analyzer test. The 2D techniques give not only, the most accurate resonance frequency, but also they are the fastest in analysis speed. In 1/4 3D modeling, SOLID5 modeling is much slower and yet more accurate in solving the problem. The results obtained under full 3D modeling show that, smaller element sizes give more realistic results. Full 3D free meshing method is much slower in solving the problem but it gives more acceptable results. Only full 3D modeling can generate and show all modes of vibration. Comparison of the resonance frequencies obtained from modal and harmonic analysis shows a good agreement between the two techniques.

The results obtained are showing that the capabilities of the ANSYS software can be used successfully as a powerful and reliable tool for prediction of behavior of high power sandwich- type piezoelectric transducers.

2 Conclusions

The study presented in this paper concludes:

1. Comparison of the actual network analyzer results and modal analysis results for two different 2D axi- symmetric and for five different 3D modeling techniques proves that there is a good agreement between the frequencies obtained.
2. The use of a 2D axi- symmetric model greatly reduced the modeling and analysis time compared with that of equivalent 3D models.
3. There is a possibility of further increasing the accuracy of the results (e.g., resonance frequency) obtained from a 2D axi- symmetric analysis compared with an equivalent 3D analysis because of the possibility of reducing the size of the elements without remarkable change in analysis time.
4. The FEM model is a computer approximation of an actual structure. The error of this approximation will depend on the consideration of all the system components, their accurate properties, correct selection of the elements and refinement of the model.
5. There is good agreement between the modal analysis frequency and harmonic analysis results.
6. All modes of vibration are taken into consideration only when a full three-dimensional model is used.
7. The results obtained show that the capabilities of the ANSYS software can be used successfully as a powerful and reliable tool for prediction of behavior of high power sandwich-type piezoelectric transducers.

Table 6 Resonance and anti-resonance frequencies for the FEM modeling of a high power ultrasonic transducer (3KW)

Modeling type	Polarized axis	Element type of Piezo.	Element type of other components	Element size (mm)	Nominal resonance freq. (kHz)	Resonance freq. (kHz) From fEM-modal	Anti-resonance (kHz) from FEM- modal	Measured resonance freq. (kHz)	Time spent for modal analysis (min)
2D	Y	PLANE 13	PLANE 13	1	22	17.308	18.969	17.2	<1
2D	Y	PLANE 223	PLANE 13	1	22	17.308	18.969	17.2	<1
1/4 3D	Z	SOLID5	SOLID5	1	22	17.309	18.970	17.2	20
1/4 3D	Y	SOLID227	SOLID98	4	22	17.329	18.984	17.2	1
Full 3D	Y	SOLID5	SOLID5	4	22	17.418	19.142	17.2	1
Full 3D	Y	SOLID5	SOLID5	2.5	22	17.368	19.055	17.2	1
Full 3D Free meshing	Y	SOLID227	SOLID98	2.5	22	17.311	18.970	17.2	60

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