ABCM Symposium Series in Mechatronics - Vol. 2 - pp.142-149

Numerical Analysis of a High Power Piezoelectric Transducer Used in the Cutting and Welding of Thermoplastic Textiles

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Abstract. *High power piezoelectric transducers have been used in the ultrasonic cutting and welding of thermoplastic textiles. The acoustical energy generated by a sandwich type power transducer is transferred to an wide blade-shaped horn through an acoustic amplifier. The transmission efficiency depends on the transducer and the horn assembly vibrational behavior. This paper presents a finite element analysis of a high power piezoelectric transducer used in ultrasonic cutting and welding of thermoplastic textiles. The transducer itself is analysed using an axisymmetric model. The acoustic amplifier and the wide horn are analyzed using a 3D model. The values of resonance and anti-resonance frequencies, electrical impedance and electromechanical coupling factor analyzed. The simulation has shown that increasing of the number of piezoceramics on the transducer configuration increases its electromechanical coupling factor and reduces its electrical impedance. The theoretical results are compared with experimental measurements of two prototypes of power transducers operating at 20 kHz showing good agreement. One of then has four PZT8 piezoceramic discs and the other has eight discs. The results of a harmonic analysis of the wide horn show good agreement with the experimental measurement of the displacements at the working surface using a laser interferometer assembly. It is observed that the vibration amplitude is not uniform along the wide horn working surface.*

Keywords: *sandwich transducer; cutting and welding; wide blade-shaped horn; vibrational behaviour; finite element analysis.*

1. Introduction

High power piezoelectric transducers have been used in several applications such as ultrasonic cleaning, welding, soldering, machining, sonars, chemical processing, etc (Gallego-Juárez, 1989).

An area deserving especial consideration is ultrasonic welding of woven and nonwoven fibers (SHOH, 1975). Thermoplastic textiles with up to 35% natural fiber content can be ultrasonically “sewn”. The “sew” besides give form, serve as reinforcement type to textile do not weave. The advantages include absence of thread and its color-matching problems, simultaneous execution of several stitches and numerous variations of simultaneous cut and seal operations.

In this process, the high frequency vibration of an ultrasonic transducer transferred to wide blade-shaped horn through an acoustic amplifier produces heat which melts the textile and performs the weld, while a hardened metal cylinder that posses stitch pattern turns, pulling the textile as shown in Fig. 1. Yet ultrasonically induced heat can be generated selectively, precisely at the interface of the parts being joined without indiscriminate heating of the surrounding material. Less weld energy is used, resulting in less distortion and material degradation since the heat is generated within the material and not conducted from a toll. The cut and weld efficiency depends of the wide blade-shaped horn vibrational behaviour attached to the ultrasonic transducer through mechanical amplifier, the quality of cylinder with stitch patterns and the applied pressure.

The high power piezoelectric transducers used in this process operates predominantly at frequencies around 20 kHz and output power up to 1kW. This transducer is a half-wave length resonator wich in a simple form, consists of paired discs of piezoelectric ceramics sandwiched betwen two metal blocks by a pre-stressing bolt (Gallego-Juarez, 1989).

The acoustic amplifier is used to increase the vibration amplitude of the transducer and to distribute the vibration in a region is used a mechanical device called wide blade-shaped horn attached to the acoustic amplifier. The design of the wide blade-shaped horn is currently based in try and error techiniques. The vibration produced by the sandwich transducer falls on a small region of the wide balde-shaped horn through acoustic amplifier. This vibration must be uniformly distributed along the working surface of the wide blade-shaped horn.

This paper presents a finite element analysis (FEA) of a high power piezoelectric transducer and an acoustic amplifier attached to wide blade-shaped horn used in ultrasonic welding and cutting of thermoplastic textiles. The FEA is a tool wich can be used with large advantages on the study of the power transducer assembly because it allows obtaining the vibrational characteristics of models that simulates the dynamic behaviour of the structure by using modal and harmonic analysis.

The transducer itself is studied using two axisymmetric models made with four and eight piezoceramic discs. The modulus and phase curves of the electrical impedance obtained numerically are compared with experimental curves obtained using an impedance analyzer equipment. The numerical values of resonance and anti-resonance frequencies, electrical impedance and electromechanical coupling factor are compared with experimental values. The acoustic amplifier and the wide blade-shaped horn are analysed using a 3D harmonic analysis is performed to verify the distribution of vibration in the working surface of the wide horn. This analysis compared qualitativelly with an experimental measurement of the displacements of the working surface obtained by a laser interferometer assembly. It was observed that the vibration amplitude is not uniform along the working surface.

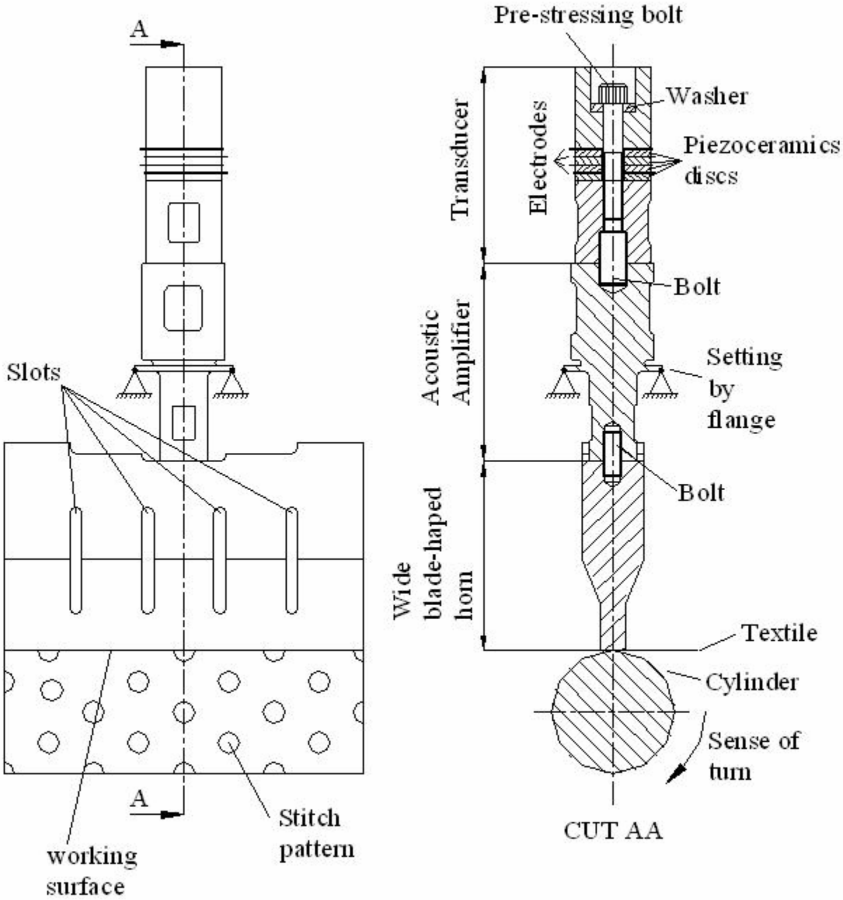

Figure 1. Schematic representation of the assembly of ultrasonic cutting and welding of thermoplastic textile.

2. Piezoelectric Ceramics

A suitable piezoceramic to be used in high power piezoelectric transducers is the PZT-8, which possess low mechanical losses, high mechanical strength, high resistance to the despolarization under mechanical stress, Curie temperature around 300 ^oC and low dieclectric losses under high electric excitation and high electromechanical coupling factor (Matuda, 1999). PZT-8 have been the material widely used in welding applicattions and it is the choice in this work.

An important parameter to be considered in piezoelectric material is the electromechanical coupling factor. This factor may be defined as the square root of the ratio of energy available in electrical (mechanical) form under ideal conditions to the total energy stored from a mechanical (electrical) source. Although the electrommechanical coupling factor provides a measure of the ability of the piezoelectric material to change energy from one form to another, it must not be tought of as a measure of transducer efficiency. In fact, this parameter does not take into account the losses in the system, and, in principle, the energy which is not converted remains in the initial form and can be recovered. The efficiency is the ratio of the power output to the power input.

3. High Power Piezoelectric Transducers

The high power piezoelcectric transducers are generally assembled as a sandwich, with paired discs of piezoceramics compressed between two metallic blocks by a high strength mechanical bolt as shown in Fig. 2. The piezoceramics are polarised on longitudinal direction, with the sense of polarisation alternated to each piezoceramic to enable parallel turn on. Between the piezoceramics and the metal blocks there are electrodes tied in parallel which are used for applyng the exitation voltage.

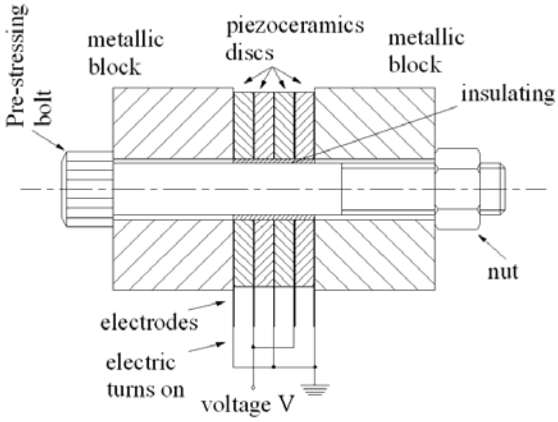

Figure 2. Sandwich piezoelcectric transducer in cut view.

Piezoelectric ceramics have more strength to compression than traction, therefore exists a need of pre-stress to avoid the despolarization and crack of the ceramics during the transducer operation. The pre-stress bolt shown in Fig. 2 serves to keep the piezoceramics under compression during operation. A typical compressive pre-stress for PZT-8 is around 30 MPa (Gallego-Juarez, 1989).

The metallic blocks are used to adjust the operation frequency and to amplify the displacement produced by piezoceramic. Besides that the thermal dissipation is favoured and the pre-stress can be better distributed on the pizoceramic surface.

The screw thread of pre-stress bolt must have a curvature on the furrows to reduce fatigue problems. An insulating material such as teflon is used to insulate electrically the bolt from the piezoceramics (Matuda, 1999).

4. Acoustic amplifiers

An acoustic amplifier is a device used to amplify the induced strain by a high power piezoelectric transducer. This elements are generally configured as a solid with a smaller diameter at the tip as shown in Fig. 3. A magnification in the strain occurs in the acoustic amplifier that in general is a function of the ratio of diameters. In addition the device is generally driven at the resonance to further amplify the strain. The resonance amplification is determined by the mechanical quality factor of the horn material and radiation damping while the length primarily determines the resonance frequency.

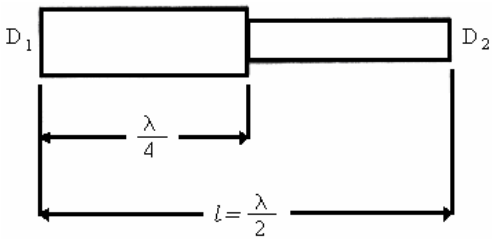

Figure 3. Half-wave Stepped scoustic amplifier.

The largest strain amplification is proportional to $(D_1/D_2)^2$ where D_1 is the base diameter and D_2 is the tip diameter (Sherrit et al., 2002). The length l of the amplifier is given by:

$$l = \frac{\lambda}{2} = \frac{c}{2f} \tag{1}$$

where λ is the wavelength, f is the frequency on resonance and c is the extensional velocity material (Amin, 1995):

$$c = \sqrt{\frac{Y}{\rho}} \tag{2}$$

where Y is the Young Modulus and ρ is the density of the acoustic amplifier material.

The use of cylindrical stepped acoustic amplifier is limited because it has high stress concentration at the sudden change in diameters (Amin et al., 1995). The plane of maximum stress occurs at the half lenght (quarter-wave-position) of the rod. An acoustic amplifier fabricated without a fillet at the junction of the two cylinders as shown in Fig. 3, would experience a high stress concentrations in the region where the diameter changes abruptly (Ensminger, 1988).

5. Wide blade-shaped horns

Wide horns are elements used in many high power ultrasonic systems, such as welding and cutting, where they either operate as tool directly acting on the work surface (Cardoni and Lucas, 2002). Generally, wide horns are tuned to the first longitudinal mode of vibration at an operating frequency in the low ultrasonic range of 20-40 kHz. For reliable operation of the block horn, the longitudinal mode frequency has to be insulated from other modes which can participate in the response at the operating frequency or can cause mode switching to occur during operation. The shape of wide horn that is commonly used for cutting and welding of thermoplastic textiles is the stepped wide-blade type (Ensminger, 1988), as shown in Fig. 4:

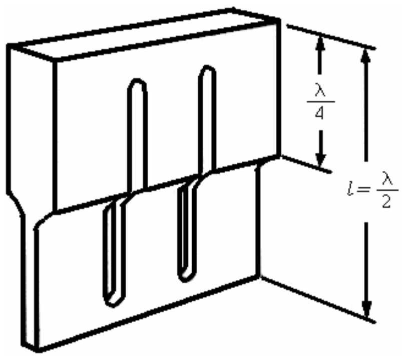

Figure 4. Wide blade-shaped horn.

The design of ultrasonic wide horns is focused on satisfying three main performance criteria: insulation of the operating frequency from close non-tuned modes, uniformity of amplitude at the working surface and high amplitude of the operating mode, that can be obtainable in wide horns with tapered profiles. Studies have shown that a better uniformity and frequency separation can be achieved by the inclusion of slots running parallel to the direction of longitudinal motion in the wide horn configuration (Cardoni and Lucas, 2002). The slotting also improves heat dissipation and thus preventing the creation of thermal “hot” spots in operation (Ensminger, 1988).

6. Finite Element Modelling

In this work, the numerical analysis of the high power piezoelectric transducers, acoustic amplifier and wide blade-shaped horn were performed using the ANSYS software. This package allows the simulation of such devices with good approach of it realness.

The simulations of the transducer were performed using 2D axisymmetric models due to high computational expense of the 3D models. The 2D axisymmetric models of the transducer with four and eight discs piezoceramics are shown in the Fig. 5:

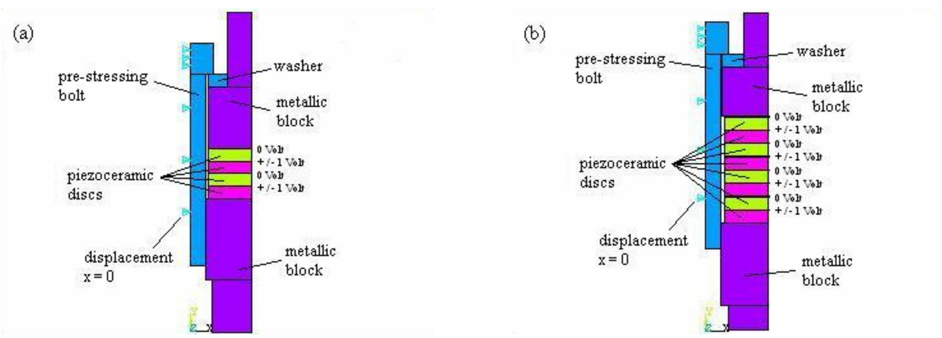

Figure 5. Model of the high power piezoelectric transducer (a) with four piezoceramic discs. (b) with eight piezoceramic discs.

All metalic elements that compose the tranducer are represented by axisymmetric solid structural elements with four nodes.The piezoceramics are represented by axisymmetric piezoelcectric elements with four nodes. The bolt and the washer are made of 4340 alloy steel. The metallic blocks are made of 7075 aluminium alloy and the piezoceramics are PZT-8. The piezoceramics are polarized on the longitudinal direction and are assembled with attached polarisation alternated to each piezoceramic. The electrodes are made of brass sheets with 0,2 mm thickness. The electrical contacts are modeled as coupled d.o.f. sets at each interface between the piezoelectric ceramic disks (Jonhson and Pal, 2000). Those models ignores the insulating material, often used between the ceramic disks an the bolt shank, forbids radial sliding between the parts, and does not include the pre-compression of the stack durring the assembly. Further, although transducer performance has been observed to drift slightly during operation as the ceramic warms up, temperature effects are ignored in this study.

Harmonic analysis are performed considering the application of a voltage accross the piezoelectric ceramic disks. For the transcucer with four piezoceramic discs, the input varied sinusoidally between +/- 1 volt at the second and fourth electrical contacts, while the first, third and fifth contacts were set at zero voltage as shown in Fig. 5 (a). For the transducer with eigth piezoceramic discs, the imput varied sinusoidally between +/- 1volt at the second, fourth, sixth and eighth contacts, while the first, third, fifth, seventh and ninth contacts were set at zero voltage.

The analysis of the acoustic amplifier and the wide blade-shaped horn were performed using 3D models. Two planes of symmetry are considered thus reducing the model volume to a quarter. The models of the acoustic amplifier, wide horn and acoustic amplifier-wide horn assembly were designed in a CAD software and exported to ANSYS, as shown in Fig. 6. Those models are represented by 3D solid strucutral elements of ten nodes.

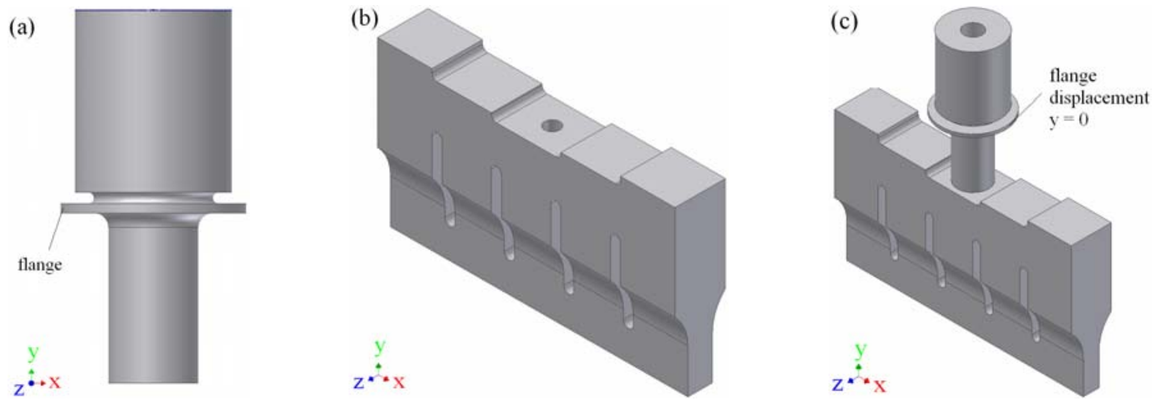

Figure 6. Models (a) acoustic amplifier. (b) wide blade-shaped horn. (c) acoustic amplifier-wide horn assemby.

Those models were simulated individually and assembled as shown in Fig. 6 (c). The material used in both elements is the 4340 alloy steel. For each model were performed a modal analysis and for the acoustic amplifier-wide horn assemby also were performed a harmonic analysis. The simulated distribution of the vibration amplitude along the working surface of the wide blade-shaped horn is qualitatively compared with measurements performed using a laser interferometer.

The harmonic analysis of the acoustic amplifier-wide horn assembly includes a structural support on the flange of the acoustic amplifier where displacement y = 0, as shown in Fig. 6 (c). This axial support represents a housing or case, in which the assembly is fixed on the ultrasonic cutting and welding machine.

7. Results

7.1 High power piezoelectric transducers

From the harmonic analysis performed for the models shown on Fig. 5 (a) and (b) were obtained the modulus and phase of the electrical impedance as function of frequency. The values of ressonance (f_r) and anti-resonance frequency (f_a), electrical impedance in the resonance (Z_r), electical impedance in the anti-resoncance (Z_a) and electromechanical coupling factor that refers to the longitudunal tickness vibration (k_T), are ahown in Tab. 1. k_T is definied as (Gallego-Juárez, 1989):

$$k_T = \sqrt{\frac{f_a^2 - f_r^2}{f_a^2}} \tag{3}$$

The simulation results of the models with four and eigth piezoceramic discs were compared with measurements of prototypes assembled with four and eigth piezoceramic discs respectively. Experimental measurements were performed in a transducer built with four piezoceramics and another with eigth piezoceramic discs. The measurements were made with a HP 4194A Impedance/Gain Phase Analyser. This equipment measures the transducer response at very small excitation voltages over a user-selected frequency range, and graphically shows the resonance and anti-resonance frequencies, the phase angle between the input and response, and the electrical impedance of the transducer over the frequency sweep.

Fig. 7 shows the modulus and phase curves obtained numerically and experimentally of the transducer assembled with four piezoceramic discs:

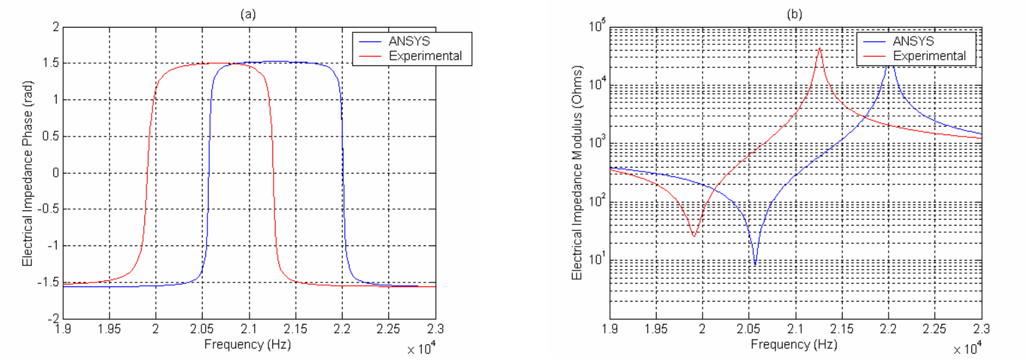

Figure 7. Electrical impedance phase curves. (a) of the transducer with four piezoceramics and (b) the transducer with four piezoceramic discs.

Table 1 shows the values obtained numerically and experimentally for the resonance frequency, anti-resonance frequency, electrical impedance in the resonance and anti-resonance frequency and electromechanical coupling factor:

Table 1. Values obtained numerically and experinentally for the transducer assembled with four piezoceramic discs

Transducer	f_r (Hz)	f_a (Hz)	Z_r (Ω)	Z_a (Ω)	k_T (dimensionless)
ANSYS	20566	22012	9	49317	0.36
Prototype	19912	21256	25	42658	0.35

Figure 8 shows the modulus and phase curves obtained numerically and experimentally for the transducer assembled with eight piezoceramic discs:

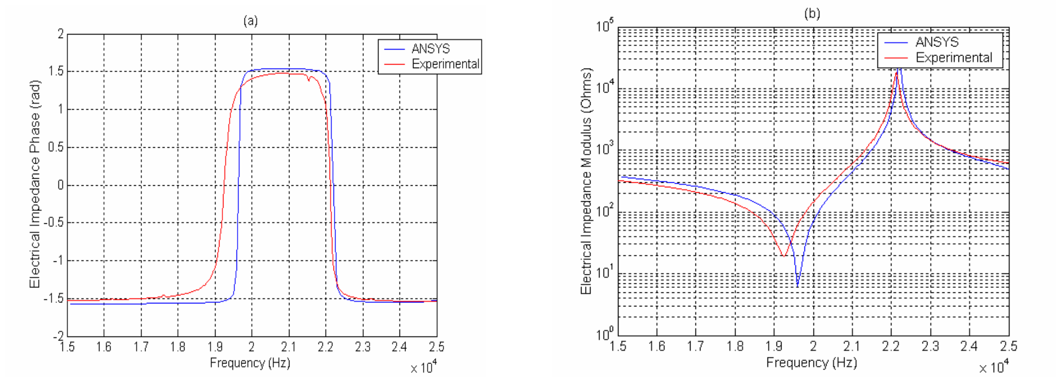

Figure 8. (a) Electrical impedance phase curves obtained for the transducer assembled with eight piezoceramic discs. (b) Electrical impedance modulus curves obtained for the transducer assembled with eight piezoceramic discs.

The Table 2 shows the values obtained numerically and experimentally for the resonance frequency, anti-resonance frequency, electrical impedance in the resonance and anti-resonance frequency and electromechanical coupling factor

Table 2. Values obtained numerically and experinentally for the transducer assembled with eight piezoceramic discs

Transducer	f_r (Hz)	f_a (Hz)	Z_r (Ω)	Z_a (Ω)	k_T (dimensionless)
ANSYS	19646	22212	8.5	34674	0.47
Prototype	19254	22117	16	17579	0.49

In this transducer, the number of piezoelectric ceramics was increased and the length of the meatallic blocks was decreased. From Tab. 1 and Tab. 2, it can be seen that the number of piezoelectric elements in the transducer affects the transducer performance. When the number of piezoelectric elements is increased, the resonance frequency is decreased while the antiresonance frequency and electromechanical coupling factor increases. This behaviour also was studied by Shuyu (2004).

7.2 Acoustic amplifier-wide horn assembly

For this assembly, was performed a harmonic analysis, applying a arbitrary force of 100 N on the acoustic amplifier face and verifying the response at the wide horn work face at 20 kHz frequency . The distribution of vibration obtained in the wide horn work face is qualitativelly comparated to results obtained from measurements performed using a laser interferometer. The vibration mode of the assembly obtained from harmonic analysis is shown in Fig. 9:

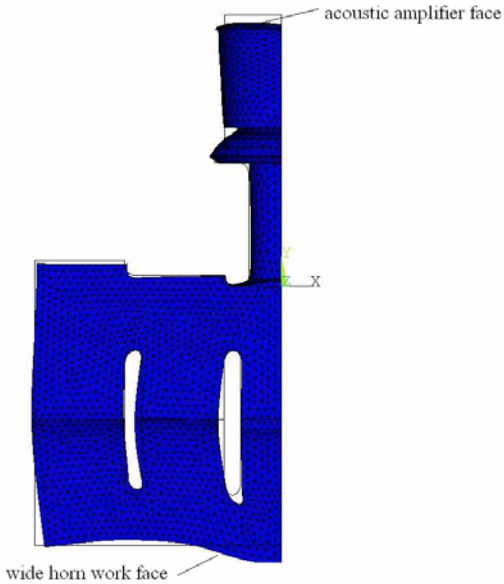

Figure 9. Vibration mode of the acoustic amplifier-wide horn assembly.

From harmonic analysis was obtained the topography of the displacement at the wide horn work face as shown in Fig 11 (a). The displacement measurements at the wide horn work face were performed using a laser interferometer (Nader, 2002), is shown in Fig. 11 (b). A Michelson-type quadrature interferometer, as shown in Fig. 10, was applied to measure displacement at the wide horn work face. There were performed 24 measurements in the 240 mm wide horn.

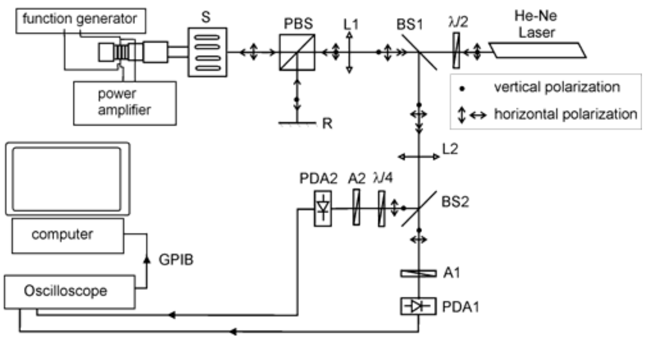

Figure 10. Experimental setup of Michelson-type quadrature interferometer.

This interferometer uses a He-Ne laser source (λ=632.8 nm). A half-wave plate is used to control the intensity ratio to reference mirror (R) and wide horn analysed (S), which are reflected and transmitted by a polarizing beam splitter (PBS). The convergent lens L1 is applied to focus the laser beam in the reference mirror and sample surface. Between the two beam splitters (BS1 and BS2) there is no interference, because the reflected light from R and S are orthogonal polarized. After the polarizer A1 (at 45°), the reference and sample lights are in the same polarization, then, there is interference. The light reflected by BS2 passes through a quarter-wave plate ($\lambda/4$) at 45°, which is the $\pi/2$ phase shifter, in this application. After the quarter-wave plate the light passes through a polarizer A2 (at -45°). The interference patterns acquired by amplified and balanced photo-diodes (PDA1 and PDA2), are shifted by $\pi/2$. A convergent lens L2 is applied to expand the laser beam and enlarge the interference pattern on PDA1 and PDA2. The main advantage of the quadrature interferometer is that it is a non-stabilized interferometer less subjected to the enviromental vibrations.

The electronic apparatus is composed by a digital oscilloscope and a computer, which acquires the signals from channel 1 and 2 from the oscilloscope by a GPIB interface. The transducer was excited by 360 Volts peak to peak electric voltage and by an harmonic 20 kHz cycle sine.

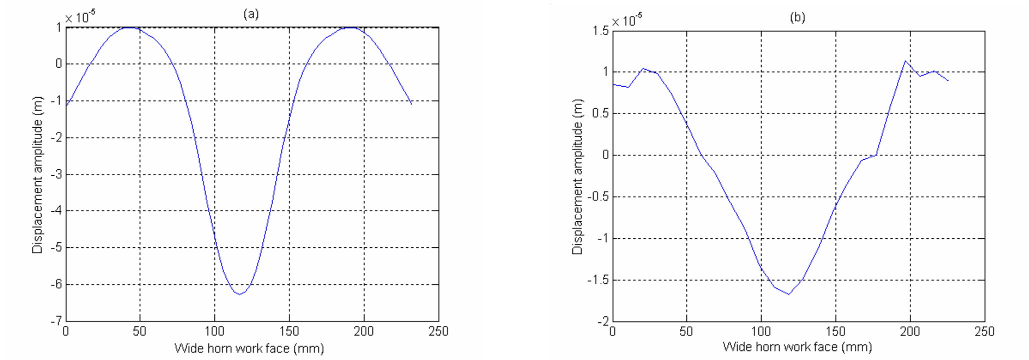

Figure 11. (a) Topography of the diplacement at work face wide horn obtained numerically. (b) Topography of the displacement at work face wide horn obtained experimentally.

8. Conclusions

In the models of the piezoelectric transducers, is noted that the values of resonance and anti-ressonance frequencies are above of the experimental values. Such divergence can be due to uncertainnes in the materials properties and some simplifications used in the models. On the other hand, higher frequencies are expected because the models are more rigid than the prototypes due to the modelling which considers rigid bonds between the piezoceramics and the metallic blocks.

The number of piezoelectric elements in the sandwich transducer affects the transducer performance. When the number is increased, the resonance frequency is decreased, while the anti-rsonance frequency is decreased. On the other hand, when the length is increased, the electromechanical coupling factor is increased. Increasing the number of piezoceramic discs, also increases the electrical power capacity of the transducer. However, the losses increase due to the increase in the number of interfaces between piezoceramics.

The results of the measurements of the displacement of points in the working surface of the wide horn work face show that the vibration produced along the working surface falls with major amplitude on a small region located in its center. Although the use of slots in the wide horn configuration can improve the distribution of displacement in the work face, these slots are not sufficient for obtaining the points of the working surface vibrating with the same amplitude.

9. Acknowledgements

The autors thank following sponsor: CAPES (Coordenação de Aperfeiçoamento de Pessoal de Nível Superior), CNPq and CTPETRO/ FINEP.

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