ULTRASONIC FIELD GENERATED BY DIFFERENT AIRBORNE POWER ULTRASONIC TRANSDUCERS WITH EXTENSIVE RADIATORS

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ABSTRACT

Industrial processes like food dehydration, particle agglomeration or supercritical oil extraction, among others may be enhanced when assisted by airborne power ultrasound.

Currently, there is a wide range of airborne power ultrasonic transducers designed for specific uses in fluids to enhance different industrial applications. The main types of such transducers may be classified as cylindrical, circular and rectangular plate radiators that generate ultrasonic fields suitable for different applications and show different advantages and disadvantages.

This work deals with the generation and measurement of acoustic fields of different airborne power ultrasonic systems designed for diverse industrial applications operating under different boundary conditions.

RESUMEN

Algunos procesos industriales como deshidratación de alimentos, aglomeración de partículas o extracción de aceites en fluidos supercríticos, pueden verse favorecidos cuando están asistidos con el uso de ultrasonidos de potencia.

Actualmente, existe un amplio rango de transductores ultrasónicos de potencia diseñados para diferentes aplicaciones industriales. Algunos de estos tipos de transductores se pueden clasificar como transductores de radiador de placa rectangular o circular o transductores de radiador cilíndrico, cada uno de los cuales es capaz de generar el campo ultrasónico más adecuado para cada aplicación.

En este trabajo se han analizado la generación y caracterización del campo acústico generado por diferentes sistemas ultrasónicos de potencia, diseñados para diferentes aplicaciones industriales y trabajando bajo diferentes condiciones de contorno.

INTRODUCTION

The use of power ultrasound in industrial processing is generally based on the adequate exploitation of a series of mechanisms activated by the ultrasonic energy such as heat, agitation, diffusion, interface instabilities, friction, mechanical rupture, and chemical effects. These mechanisms can be used to enhance a wide range of processes such us extraction [1], dryiing and dewatering [1], particle agglomeration [2] and defoaming in gas media [3], among others. The ultrasonic processes dramatically depend on the irradiated medium. A relevant characteristic of high-intensity ultrasonic waves is their ability to produce different phenomena in different media: particle agglomeration in gases and particle dispersion in liquid suspensions. This behavior is due to the different mechanisms that are activated.

For the efficient generation and application of power ultrasound in gases it is necessary to design and develop power ultrasonic transducers specifically adapted to the requirements of the medium. Gases present low acoustic impedance and high acoustic absorption. So, in order to obtain an efficient transmission of the energy, it is necessary to achieve a good impedance match between the transducer and the medium, large amplitude vibrations, and high directional or focused beams for energy concentration together with high power capacity and extensive radiating areas in the transducers.

At present, the most power commercial transducers are based on the classical Langevin-type transducer which has many limitations for airborne applications. Therefore, a new technology based on stepped or grooved plate transducers and cylindrical radiators, which implement high power capacity, efficiency, and directivity, have opened new possibilities for airborne ultrasound and their applications in different industrial areas, particularly in food and environmental processing. This technology comprises a variety of transducer types designed with the radiators adapted to different specific uses in gases and multi-phase media.

The stepped-plate or grooved-plate transducers and transducers with cylindrical radiators basically consist of an extensive flexural vibrating radiator driven at its center by a piezoelectrically activated Langevin-type sandwich transducer and a mechanical amplifier [4]. For the design, simulation, and dynamic analysis of the structure of the transducers the procedure is as follows: analytical transducer design, 3D/2D modeling by FEM, static analysis for the application of a defined prestress to the piezoelectric ceramic stacks, modal analysis to determine the natural frequencies of the system and operating mode, dynamic analisys with an applied harmonic load, and analysis of the acoustic-structure interaction in order to model the resulting acoustic field [5-9].

The scope of this work is to carry out a numerical and experimental study of the linear ultrasonic field generated by different configurations of power ultrasonic transducers with extensive radiators for different industrial applications.

DETERMINATION OF THE ULTRASONIC FIELD

The acoustic field generated by a power ultrasonic system can be determined by numerical and/or experimental means. The propagation of the acoustic waves generated by the transducer is determined by the constitutive model that requires four equations to describe the general motion of a viscous, heat-conducting fluid [10, 11]. These equations are the following:

Continuity equation that expresses the conservation of mass. Here, ρ represents the fluid density and $\vec{u}$ is the particle velocity:

$$\frac{\partial \rho}{\partial t} + div \rho \vec{u} = 0 \tag{1}$$

Equation of motion (Law of conservation of momentum), in absence of external body forces, is expressed by the Navier-Stokes equation. Here, *p* represents the pressure:

$$\rho\left[\frac{\partial \vec{u}}{\partial t} + \vec{u} div(\vec{u})\right] = -grad(p) \tag{2}$$

Energy equation (Heat transfer equation), expressed in terms of entropy (*s*), where *T* represents the absolute temperature, κ is the thermal conductivity and σ'_{ik} is the viscous stresses tensor:

$$\rho T\left[\frac{\partial s}{\partial t} + \vec{u} grad(s)\right] = -\sigma'_{ik}\frac{\partial u_i}{\partial x_k} + \kappa \Delta T \tag{3}$$

Equation of state expressed in terms of pressure (*p*), density (*ρ*) and entropy (*s*):

$$p = p(\rho, s) = p_0 + \left(\frac{\partial p}{\partial \rho}\right)_s (\rho - \rho_0) + \frac{1}{2}\left(\frac{\partial^2 p}{\partial \rho^2}\right)_s (\rho - \rho_0)^2 + \left(\frac{\partial p}{\partial s}\right)_\rho (s - s_0) + \dots \tag{4}$$

From the four constitutive equations, the wave equation can be derived [12] as shown in Eq. 5:

$$\Delta p = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2} \tag{5}$$

Numerical Analysis

The determination of the ultrasonic field generated by a power ultrasonic transducer can be done numerically, using a finite element model (FEM) to solve the previous system [6]. A harmonic analysis is used to determine the ultrasonic field, assuming that the wave propagates through air, considered as an ideal fluid medium.

In FEM models, the domain where the acoustic field is determined is divided in elements where the equation system is solved. The size of the elements has to be as small as possible in order to minimize the error but taking into account that a model with too many elements requires higher computational resources.

In the determinations presented in this paper, the maximum element size considered had been one quarter of a wavelength of the sound in the medium.

Experimental Analysis

The experimental determination of the ultrasonic field generated by a power ultrasonic transducer can be done using a microphone-based system able to move in the three directions (X, Y, Z). The experimental setup is composed by an ultrasonic controller, whose task is to drive the transducer into the desired operational mode, and track this mode even if the working frequency moves. The signal goes to an impedance matching unit through the amplifier and then to the transducer. The ultrasonic field is measured by a 1/8'' pressure microphone (GRAS 40DP and a Power Module type 12AK), capable of measuring the acoustic frequency response up to 200 kHz. The microphone is attached to a robot that provides the required displacements in order to cover the desired space. The response of the microphone is processed with the Labview-based software application, which allows the plot of the sound maps in different planes and at different distances. The block diagram of the measurement setup is shown in Fig. 1:

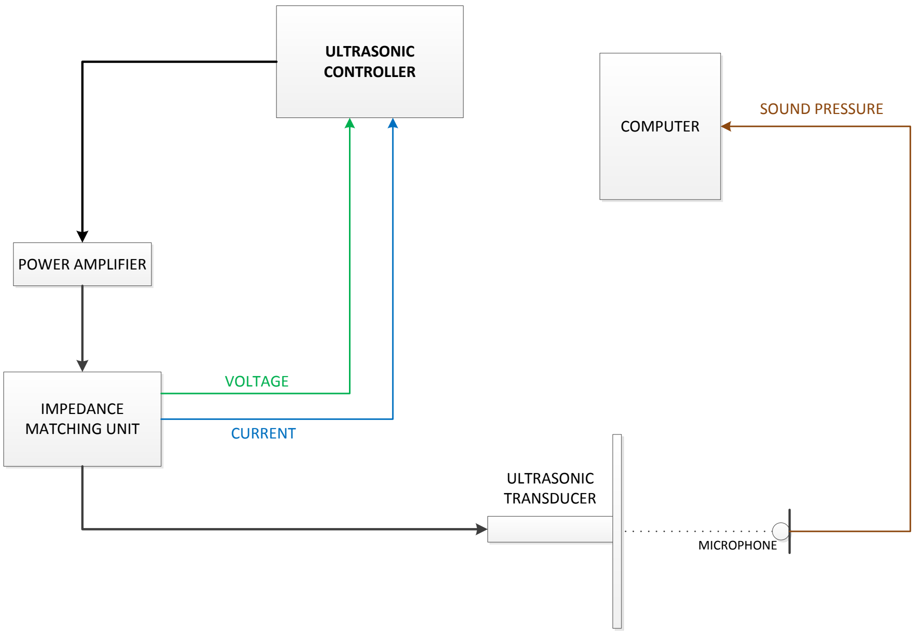
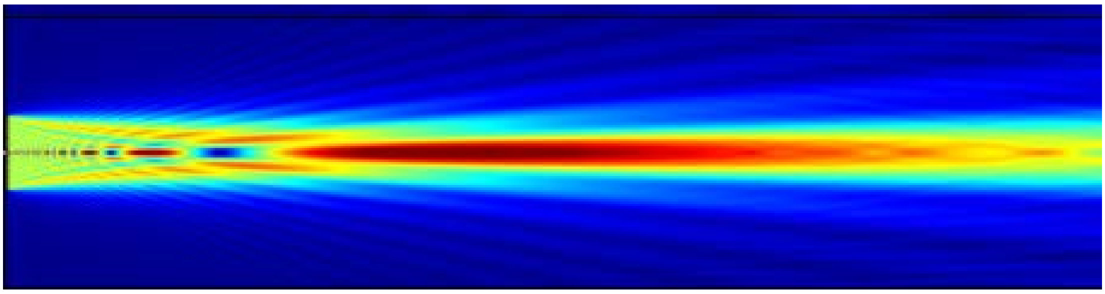


Fig 1. Block diagram for the X, Y, Z, ultrasonic field experimental setup.

ULTRASONIC FIELD GENERATED BY CIRCULAR PLATE TRANSDUCERS

The basic configuration of a circular plate transducer would be a piston. The numerical determination of the ultrasonic field generated by a circular piston with a radius of 18 cm and a vibration frequency of 21 kHz is shown in Fig.2.a, and the intensity amplitude of the ultrasonic field along the axis is shown in Fig. 2.b.:



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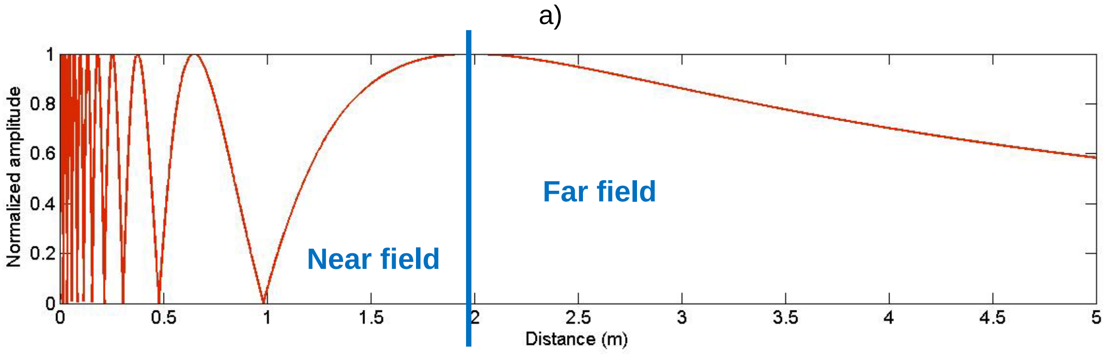
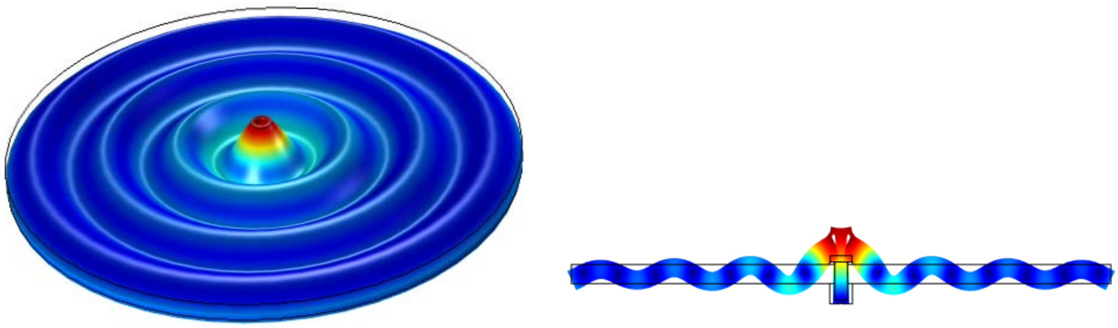


b)

Fig 2. Numerical determination of the ultrasonic field generated by a circular piston. a) 2D ultrasonic field in free field. b) 1D ultrasonic intensity along the axis.

In Fig. 2 it can be observed the field of the Fresnel region (near field) with maxima with the same amplitude and the evolution of the field in the Fraunhofer region (far field), with a constant decrease in its amplitude.

A flat circular plate transducer is excited in its center by the mechanical amplifier, so its behavior is different that the behavior of a circular piston. The chosen operational mode of this kind of transducers may be a mode with a number of nodal circles, as shown in Fig. 3.a for a flat circular plate transducer vibrating in a flexural mode with seven nodal circles (7NC), at 20745 Hz. The ultrasonic field generated by this transducer is shown in Fig. 3.b, and the acoustic intensity at the revolution axis appears in Fig. 3.c:



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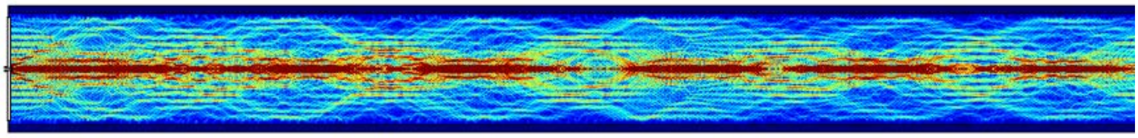

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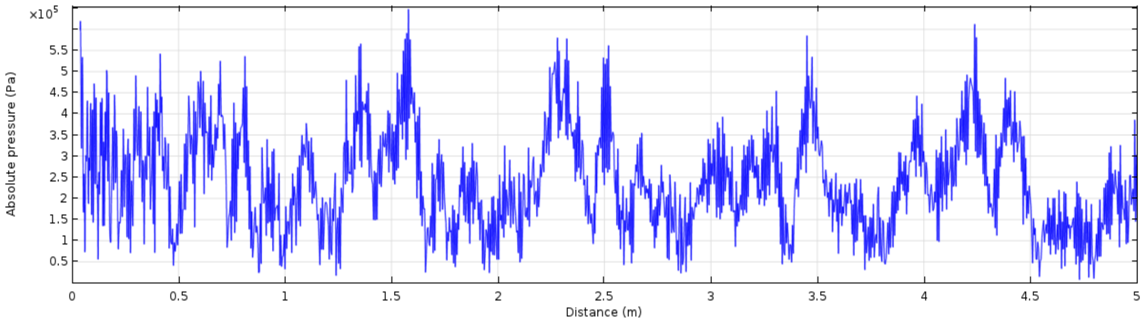
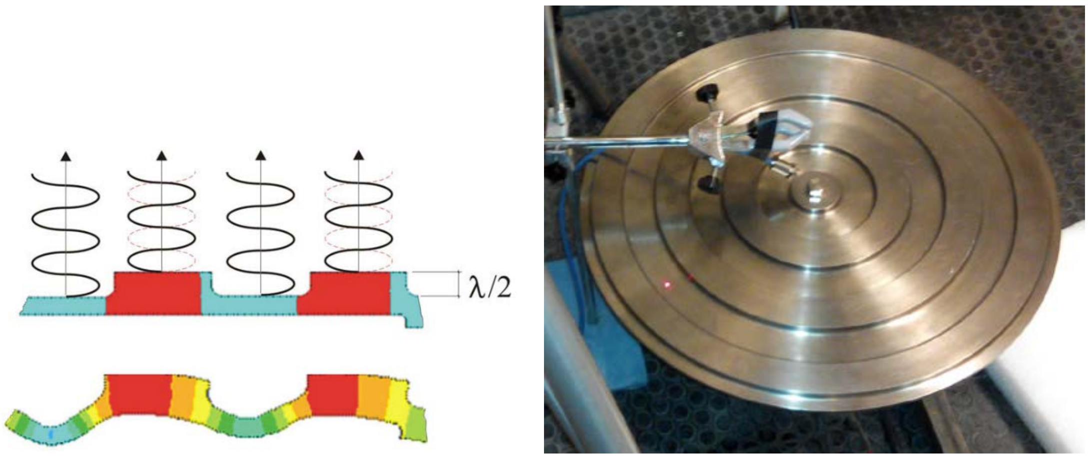


c)

Fig 3. Numerical determination of the ultrasonic field generated by a circular plate transducer. a) Vibrating in a flexural mode with 7NC. b) Ultrasonic field. c) Acoustic intensity in the axis

The field generated by the piston corresponds to a plane wave inside a cylindrical chamber (Fig. 2), while the field generated by the flat circular radiator is affected by the vibrational mode. If the specific industrial application requires a coherent ultrasonic field or a focused field, some modifications can be applied to the circular plate, like the design and development of steps or grooves [4]. A coherent field, similar but not equal to the field generated by a circular piston, can be achieved applying steps in the radiating surface of the circular plate. These steps allow an in-phase radiation, as it can be observed in Fig 4.a and Fig 4.b [4]. The ultrasonic field generated by a stepped circular plate transducer is shown in Fig. 4.c and the ultrasonic intensity along the axis is shown in Fig. 4.c:



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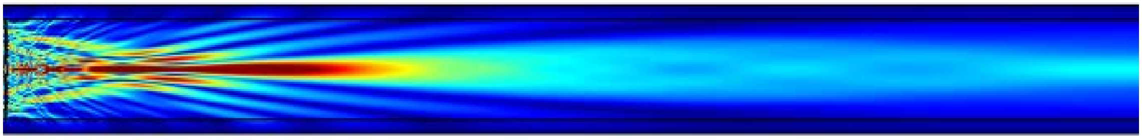

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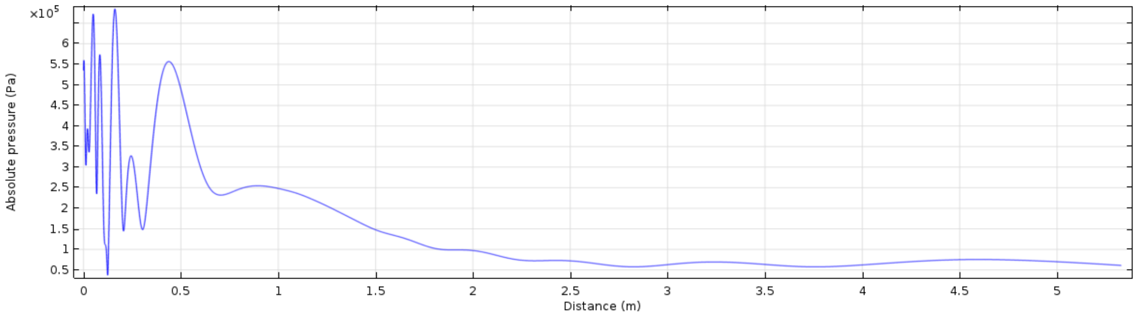

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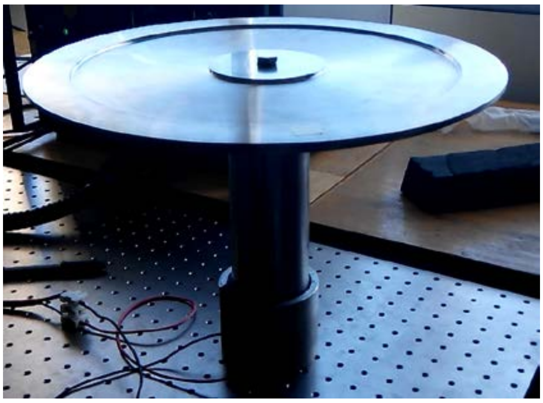
Fig 4. Ultrasonic field generated by a stepped circular plate transducer. a) Stepped circular radiator and generation of a coherent field. b) Ultrasonic field obtained by FEM. c) Acoustic intensity along the axis of the plate transducer obtained by FEM.

On the other hand, if a specific industrial application, like defoaming, requires high energy focused in a small area, grooves can be applied in the radiating surface in order to obtain a focused ultrasonic field [4]. This particular ultrasonic field can be observed in Fig. 5:



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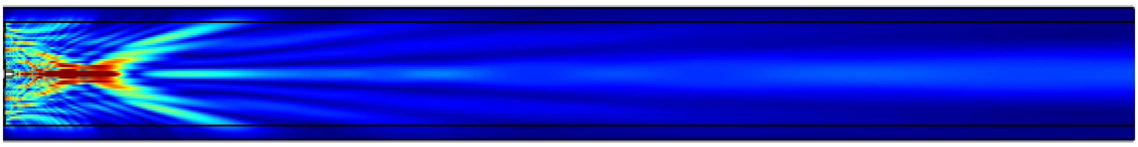

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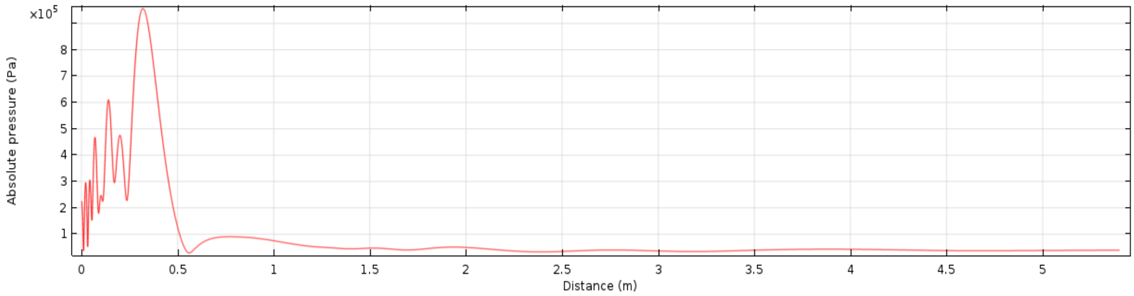

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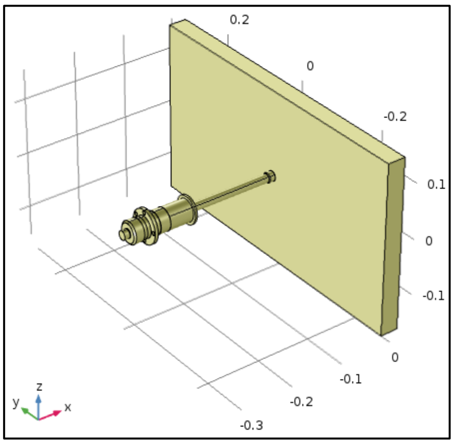
Fig 5. Ultrasonic field generated by a grooved circular plate transducer. a) Grooved circular radiator. b) Ultrasonic field obtained by FEM. c) Acoustic intensity in the axis obtained by FEM.

ULTRASONIC FIELD GENERATED BY RECTANGULAR PLATE TRANSDUCERS

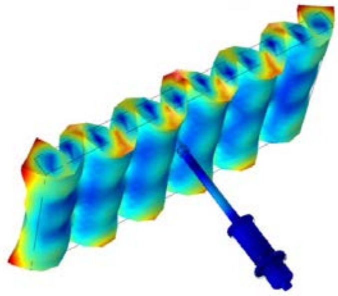
Another configuration of an airborne power ultrasonic transducer uses a rectangular radiator. Compared to stepped circular plates, rectangular radiators show a more uniform distribution of vibration displacements; nevertheless, they can also be prone to modal interactions. The non-axisymmetrical shape of the plate results in a more complicated vibrational behavior, with high modal density, which is known to facilitate both modal coupling and nonlinear modal interactions [8]. The ultrasonic system is presented in Fig. 6:



a) b)

Fig 6. a) Ultrasonic system with flat rectangular radiator. b) Representation of the transducer for the numerical analysis and axis definition.

In the same way as systems with circular plates, a good design of the rectangular plate transducer is crucial. The physical properties (dimensions and materials) of all components define the vibrational behavior of the assembly. In this case, the chosen operational mode corresponds to an extensional mode of the Langevin sandwich transducer and the mechanical amplifier and a flexural mode of the plate with 12 nodal lines (12NL). This mode appears at around 21 kHz and can be observed in Fig.7.a. The ultrasonic field in the plane XY, according to the axis definition of Fig. 6.b, generated by this transducer is shown in Fig.7.b:



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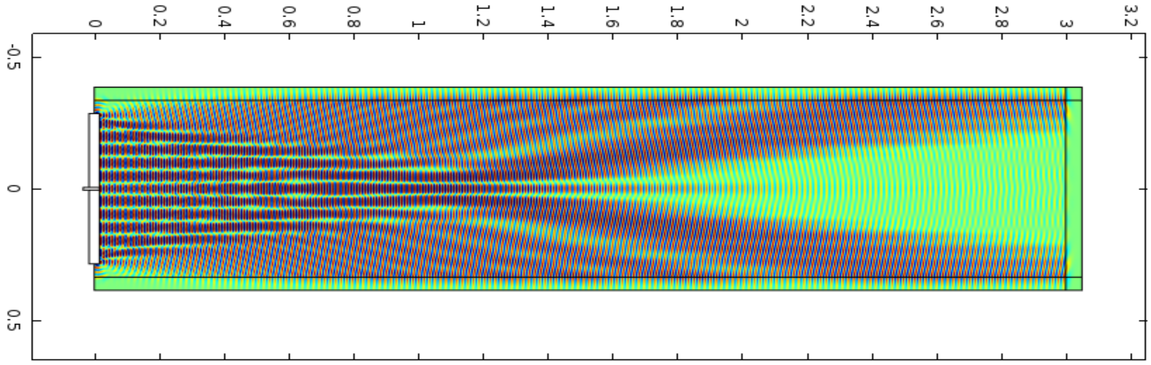


b)

Fig 7. Numerical determination of the ultrasonic field generated by a flat rectangular plate transducer. a) Modal shape with 12 NL. b) 2D Acoustic pressure map.

The results obtained after the experimental determination of the ultrasonic field are shown in Fig 8, where two different views of the acoustic field are presented. These views correspond to the planes XY and XZ:

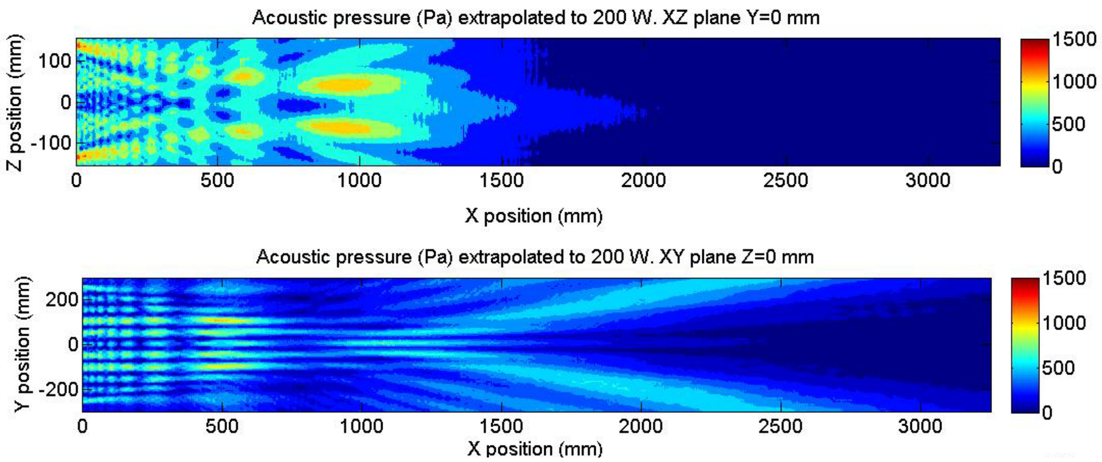
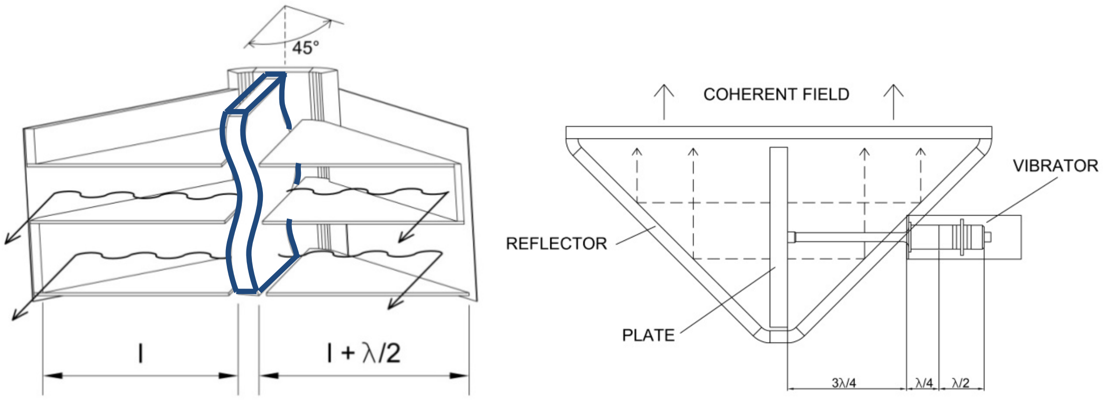


Fig 8. Experimental determination of the ultrasonic field generated by a flat rectangular plate transducer vibrating in a flexural mode with 12NL.

As it can be observed in Fig.7.b and in Fig. 8, the ultrasonic field is neither coherent nor homogeneous, with two easily visible areas, the Fresnel zone or near field and the Fraunhofer zone or far field. In the near field, the first 1.4 meters, the acoustic amplitude experiments small variations when going away from the source and the nodal lines of the radiator can be easily observed. In the far field, the ultrasonic field forms angles about 15º with the longitudinal axis. The behavior of this system is very different from the behavior of a piston.

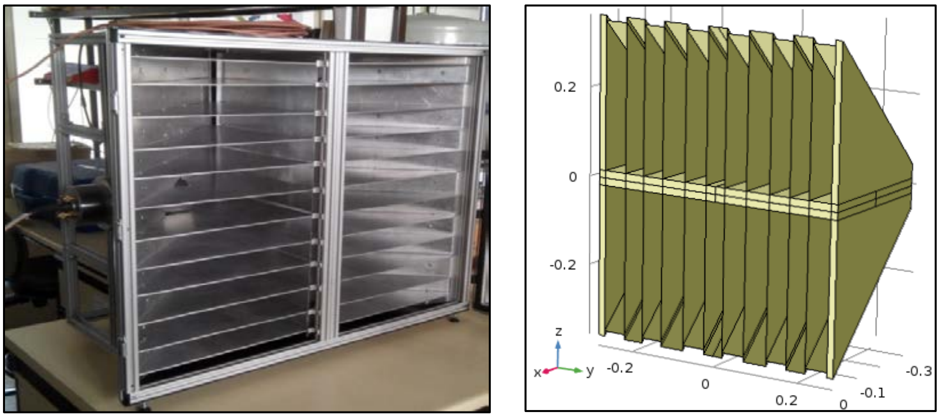
A way to generate a coherent field would be the application of steps as in the case of circular plates. Nevertheless, previous researches proved the difficulty of this solution [8], because of the appearance of energy leakages to harmonics and subharmonics when applying high power. Another solution is the application of those steps in a reflectors system [13] that allows a coherent field and the use of the energy generated by both faces of the radiator. Fig. 9 shows how this coherent field can be obtained with the reflectors system:



a) b)

Fig.9. System composed by a flat rectangular plate transducer and a reflector structure adapted to the transducer; a) Description of the generation of a coherent field. b) Plant view of the airborne power ultrasonic transducer and the reflector system.

This ultrasonic system with reflectors is shown in Fig. 10.a. The model for the numerical simulation and the axis definition are presented in Fig. 10.b:



a) b)

Fig.10. a) System composed by a flat rectangular plate transducer and reflectors; b) Representation of the ultrasonic system for the numerical analysis and axis definition.

The ultrasonic field measured in an anechoic chamber is presented in Fig. 11, for the planes XZ and XY, according to the axis definition shown in Fig. 10.b:

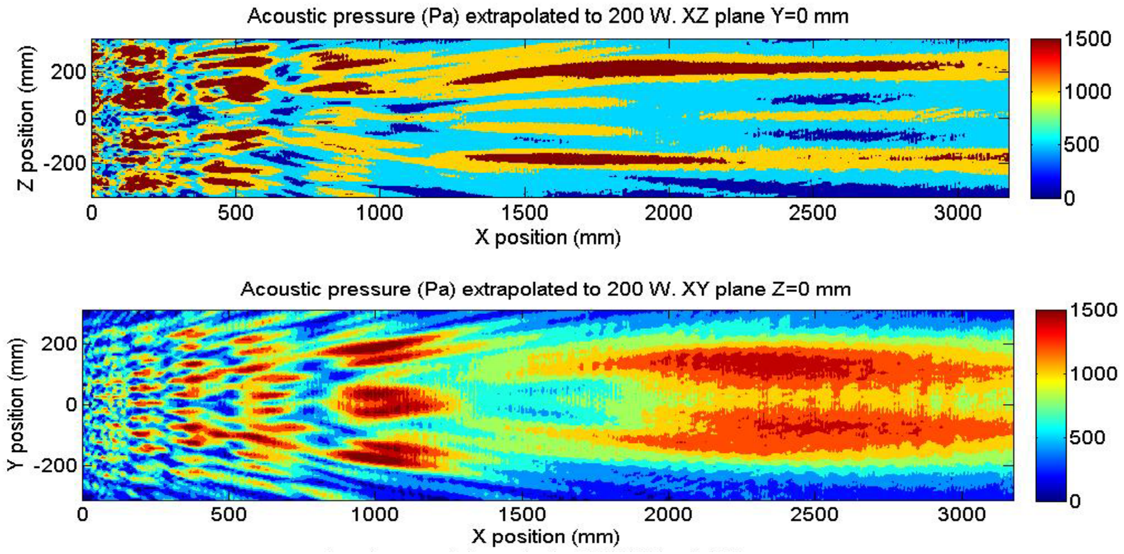


Fig 11. Experimental determination of the ultrasonic field generated by an ultrasonic system composed by a flat rectangular plate transducer and reflectors.

As can be observed in Fig.11, the system with reflectors generates an ultrasonic field with higher amplitude and covering a wider space. The higher level is consequence of a coherent radiation, with constructive interferences of waves.

ULTRASONIC FIELD GENERATED BY A TRANSDUCER WITH CYLINDRICAL RADIATOR

The third configuration included in this work is an airborne power ultrasonic transducer with a cylindrical radiator, suitable for industrial applications like food dehydration. In this case, the acoustic energy is stored inside a cylinder that is vibrating in a desired mode.

The design and characterization of this transducer has been presented in [6]. The basic configuration of this system is similar to other transducers with extensive radiators (rectangular or circular). It is composed by a Langevin-type sandwich transducer and a mechanical amplifier tuned into an extensional mode; and, in this case, a cylindrical radiator tuned into a flexural mode. The transducer and its vibrational mode are shown in Fig.12:

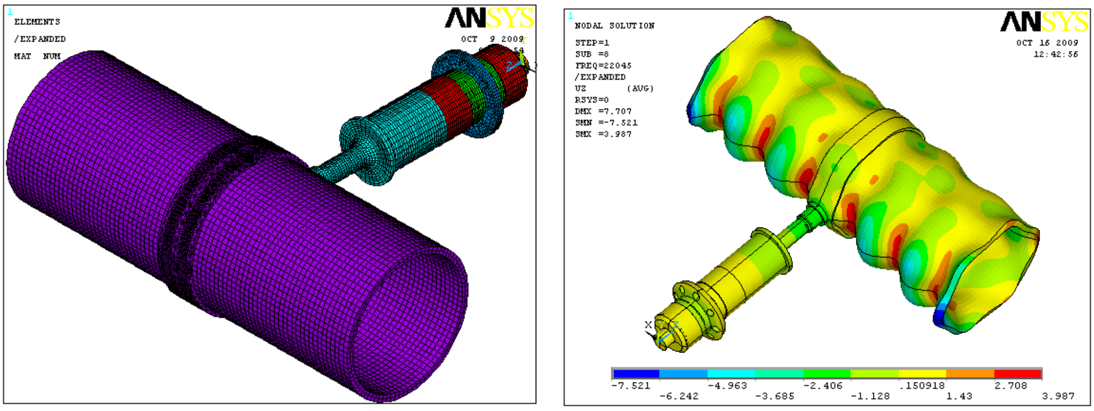


Fig.12. Power ultrasonic transducer with cylindrical radiator and operational mode with 12 NL

Food dehydration processes happen inside the cylinder, where the acoustic energy is confined. The stationary ultrasonic field can be observed in Fig.13. The field is not homogeneous at all. From these measurements, the average SPL obtained inside the cylindrical radiator was about 154 dB with an electrical power applied of about 90 W. Such good results confirm the FEM predictions for the acoustic field and, as a consequence, the feasibility of using such a system for convective drying intensification.

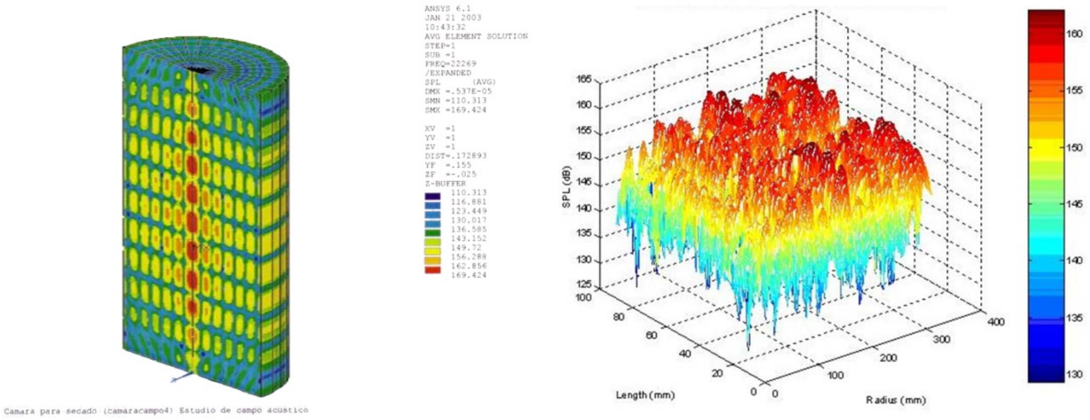


Fig 13. a) Numerical determination of the ultrasonic field generated by a cylindrical radiator vibrating in a mode with 12 NL. b) Ultrasonic field inside the cylindrical radiator, obtained experimentally.

CONCLUSIONS

In this work, the acoustic fields generated by three different ultrasonic systems have been presented. These systems are airborne power transducer with circular and rectangular plates (extensive radiators) and a system with cylindrical radiator.

When using systems with flat extensive radiators (flat circular plate or flat rectangular plate), the ultrasonic field in free field is much different from a plane wave generated by a piston, and is not coherent at all. The acoustic energy disperses rapidly. In order to obtain a coherent field or a focused field, some modifications have to be made in the systems.

In the case of circular plates, it is necessary to build steps in the front face of the radiator to obtain a coherent field and it is necessary to build a grooved profile in the front face of the plate to obtain a focused field.

For rectangular plates, the steps have to be built in an external reflector system. This enables the coherent field and doubles the efficiency of the system by the use of the energy generated by both faces, the front face and the rear face.

Finally, the cylindrical radiator generates a high intensity cylindrical stationary ultrasonic field inside the cavity. Experimental measurements confirm the feasibility of using such system to assist ultrasonically convective drying at high and low temperatures (liofilization at atmospheric pressure).

ACKNOWLEDGMENTS

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