NEW ULTRASONICALLY ASSISTED DRIER FOR ATMOSPHERIC FREEZE-DRYING PROCESSES

PACS: 43.35.Zc.

Andrés García, Roque R.[1,2]; Cárcel, Juan A.[3]; Riera, Enrique[1]
[1] Dpto. Sensores y Sistemas Ultrasónicos, ITEFI, CSIC.
C/ Serrano 144, E28006 Madrid, Spain.
[2] Universidad Politécnica de Madrid, Madrid, Spain.
[3] Grupo ASPA, Food Technology Department, Universitat Politècnica de València.
E46022, Valencia, Spain.

roque.andres@csic.es

Palabras Clave: Ultrasonic processing; power ultrasound; ultrasonic transducers; lyophilization at atmospheric pressure

ABSTRACT.

Power ultrasonics provides a good performance in lyophilization at atmospheric pressure processes due to a lower energy consumption with high quality yield. The high intensity acoustic field generated by a power ultrasonic transducer contributes to intensify the moisture transport inside the samples and at the solid-gas interphase. The ultrasonic system presented in this work is composed by a dehydration chamber with the desired environmental conditions and a stepped circular plate transducer, vibrating in a flexural mode with seven nodal circles at 26 kHz.

RESUMEN.

La aplicación de ultrasonidos de potencia en procesos de liofilización a presión atmosférica permiten una mayor eficacia debido al menor consumo de energía, y a un producto de alta calidad. El campo acústico de alta intensidad, generado por el transductor ultrasónico de potencia contribuye a intensificar el transporte de la humedad en el interior de las muestras y en la interfase sólido-gas. El sistema ultrasónico presentado en este documento está compuesto por una cámara de secado, cuyas condiciones ambientales están perfectamente controladas, y un transductor de placa circular escalonada, vibrando en un modo flexural con siete círculos nodales a 26kHz.

INTRODUCTION

Food dehydration assisted by airborne power ultrasound is considered as a promising new technology because the lower energy consumption compared to other traditional dehydration methods, and because of the high quality of the final product.

First research analyzed the effects of applying ultrasound with the radiator in direct contact with the samples in food dehydration processes, obtaining a very high efficiency [1]. Nevertheless, the existence of a contact surfaces between the vibrating element and the food sample originates temperature increases in those surfaces, provoking the caramelization of the sugar or of the starch of the samples; or that the food adheres to the vibrating surface of the transducer radiator.

In order to avoid this problem, following studies considered a power ultrasonic transducer emitting in a fluid medium (air), where the food samples were situated. This technique implies energy losses because there is not a good impedance matching between the ultrasonic radiator and the gas medium; and a fast attenuation of the ultrasound when propagating. Therefore, this method is less efficient but safer in terms of quality of the food samples.

Next research carried out by the GSTU group of the ITEFI-CSIC was to improve ultrasonic systems for food dehydration assisted by airborne power ultrasound. A research project, on collaboration with the ASPA group of the Universitat Politècnica de València and with the GIA group of the Universitat de lles Illes Balears, was carried out in order to enhance food dehydration processes assisted by power ultrasound and to analyze the results in terms of energy consumption, processing time and quality of the final product.

A power ultrasonic transducer with cylindrical radiator was designed [2], showing a good performance in food dehydration processes under different temperature conditions [3, 4], and obtaining good quality in the final product [5, 6].

New transducer designs were studied. The basic composition of these transducers, presented in [7], remained. The main differences between the systems was the shape and size of the extensive radiator, like the use of circular [8] or rectangular shapes [9]; or the use of attached elements like reflectors [9].

I order to cause the desired effects in the food samples, the acoustic energy that reaches the solid needs high amplitude, therefore, the transducer has to vibrate in a specific operational mode with high displacements in its radiating surface. These requirements lead the system to work in a nonlinear regime [10], where some effects may appear in the generation (hysteresis, frequency shifts, heating, modal interaction…) [11-13] and in the ultrasonic wave propagation (harmonics, shock waves) [14].

On the other hand, the environmental conditions in the dehydration chamber also play an important role in the dehydration process. If the process corresponds to freeze drying, the air density is higher, and the sound speed is lower. The food samples may also be affected by the low temperatures because the wet content inside is frozen, varying the porosity and equating the properties of different kind of samples. The presence of a more porous structure is probably due to the damage caused by the growth of ice crystals during the sample's freezing.

In order to maintain the desired environmental conditions of freeze drying processes, it is necessary to design a dehydration chamber capable to keep these conditions under the desired levels.

In this work, a new low temperature convective chamber for food dehydration is presented. The boundary conditions in this case are temperatures around -10ºC, relative humidity as close to zero as possible and atmospheric pressure. The power ultrasonic transducer working in the chamber has a stepped circular radiator, and works at an operational frequency around 26 kHz, vibrating in a seven nodal circles (7NL) mode.

DESCRIPTION OF THE AIRBORNE POWER ULTRASONIC TRANSDUCER

The ultrasonic field is generated by a power ultrasonic transducer, which is composed by a Langevin-type transducer, a mechanical amplifier and an extensive radiator. The Langevin transducer has two stacks of two piezoelectric ceramics, separated by a brass flange. The Langevin transducer is excited electrically and the piezoelectric ceramics transform this electric excitation into displacements at the same frequency and with analogous amplitude. The Langevin transducer is tuned into a thickness mode around the operational frequency, using the Eq. 1, proposed by Neppiras [15]:

$$tan\left(\frac{\omega l_c}{c_c}\right) tan\left(\frac{\omega l_i}{c_i}\right) = \frac{\rho_c c_c A_c}{\rho_i c_i A_i} \tag{1}$$

ω is the angular frequency, l_c, c_c, ρ_c and A_c are length, sound speed, density and area of the ceramics, respectively; l_i, c_i, ρ_i and A_i are length, sound speed, density and area of mass and backing mass.

The mechanical amplifier (or horn), made of a titanium alloy (Ti-6Al-4V), is composed by two cylinders with a $\lambda/2$ length each, and different sections, and provides a displacement amplification in order to obtain the maximum amplitude at its tip, where the extensive radiator is bolted.

Finally, the stepped circular plate radiator, which is also made of a titanium alloy (Ti-6Al-4V), vibrates in an operational mode with seven nodal circles (7NC) at around 26 kHz, and generates a coherent ultrasonic field due to the steps built in the surface [7], and with high amplitude due to the high displacements transmitted by the mechanical amplifier. The large surface of the circular radiator (20 cm in radius) allows a better impedance matching with the gas media. The transducer is presented in Fig. 1:

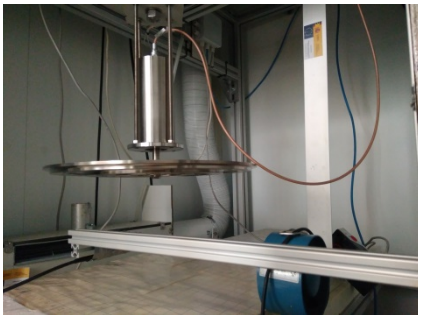
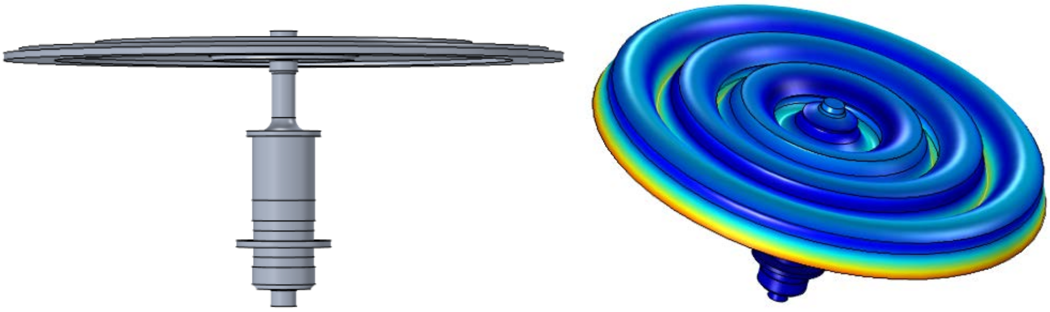


Fig 1. Stepped circular plate transducer in the dehydration chamber.

An initial numerical study of the transducer was done using the finite element method (FEM) software COMSOL Multiphysics®. The aim of this design was to obtain a very resonant system, with a high quality factor, and the desired operational mode, that is a thickness mode of the Langevin transducer, an extensional mode of the mechanical amplifier and a flexural mode with 7NC of the plate radiator. On the other side, the circular radiator had to generate a coherent ultrasonic field, so, a stepped profile had to be designed in order to put in phase the acoustic waves generated by the transducer.
The whole design is shown in Fig. 2, where Fig. 2.a shows the geometry of the system, and Fig. 2.b presents the operational mode defined previously, and situated at 25427 Hz:



a) Geometric model b) Operational mode with seven nodal circles.
Fig 2. Model for numerical simulations and operational mode at 25427 Hz.

One of the main purposes of the numerical study is to determine in advance the possibility of a modal interaction when the transducer works at a high power regime. The excitation of close undesired modes may provoke a dramatic decrease in the efficiency of the system and other problems related to ultrasonic fatigue, noise, heating, instabilities, etc. Some physical changes may be applied in the radiator in order to avoid this undesired modal interaction by adjusting the mass balances between different parts of the radiator and, thus, strengthening the operational mode and weakening or separating the other close modes [7].

As a conclusion, the designed ultrasonic power transducer has an operational mode with 7NC at 25427 Hz and a very resonant behavior, with a bandwidth of 6 Hz and a quality factor over 4000.

DESCRIPTION OF THE DEHYDRATION CHAMBER

The dehydration chamber is the place where the food dehydration process takes place. In this case, the process corresponds to lyophilization at atmospheric pressure, that means that the temperature inside the chamber has to remain under the freezing point of water, and the relative humidity as close to zero as possible. Unlike lyophilization processes, which take place in vacuum, the pressure condition established for these experiments is atmospheric pressure because the ultrasounds need a medium to propagate. Therefore, the dehydration chamber has to be able to keep the desired environmental condition.

A scheme of the ultrasound-assisted low temperature drier can be observed in Fig. 3, where all the elements that take part in these kind of experiments appear:

As can be observed in Fig. 3, the principal elements inside the chamber are the airborne power ultrasonic transducer presented in the previous chapter and the weighing scale. The first component generates the ultrasonic field that provokes the desired effects in the food samples, while the second checks the evolution of the drying process by measuring the weight of the samples.

The transducer needs an electric supply and the guidelines to vibrate at the required frequency with the desired amplitude. Outside the chamber lies the signal generation system, composed by a dynamic resonance frequency control unit (ultrasonic controller), to give adjustable continuous power output at the resonance frequency of the transducer by keeping the voltage (V) and current (I) signals in phase, and tracking it when this frequency shifts during operation [16, 17]. The controller operates as a finely tuned electronic signal generator that sends the excitation signal to a broad-band power amplifier and then to the transducer through an impedance matching unit to allow maximum energy transfer between the electronics and the transducer.

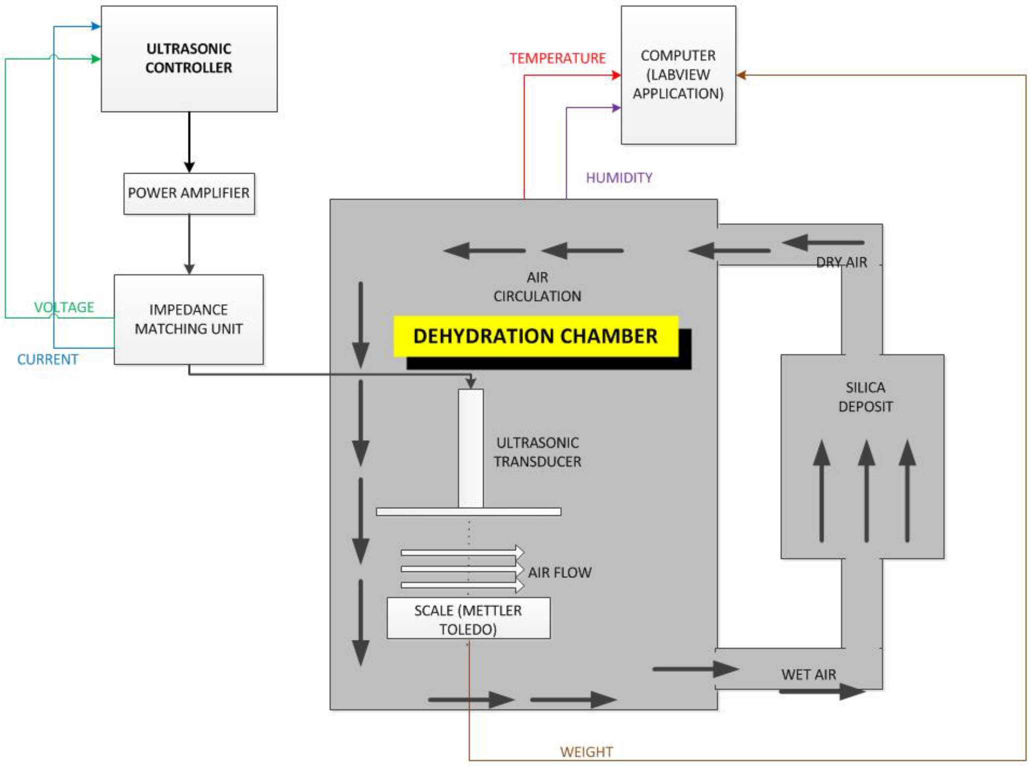


Fig 3. Representation of the dehydration chamber.

The electrical response of the transducer can be measured at the output of impedance matching unit by sampling the voltage and current signals that are sent back to the controller. This displays information about voltage, current, power, impedance, frequency and phase.

The environmental variables (temperature, relative humidity and air flow velocity) inside the chamber are logged in a computer using a Labview application designed for this purpose. The most adequate humidity value inside the chamber is as close to zero as possible, because the dehydration process follows the Fick's diffusion laws, meaning that there is a transfer of the wet content from places with higher amount of water to places with smaller amount of water. If the humidity, or wet content, in the environment is zero, it is easier for the water inside the food sample to move outside. Silica gel is a good water adsorbing material, so, this is a good solution to keep low values of humidity. A forced air circulation inside the chamber transport the wet air through a deposit of silica gel where the water is adsorbed, returning dry air into the chamber.

The Labview application also allows the setting of the desired value of temperature inside the chamber, and the velocity of the air flow generated by a small fan, and which flows through the food samples to improve the dehydration process. This air flow must not be confused with the forced air circulation.

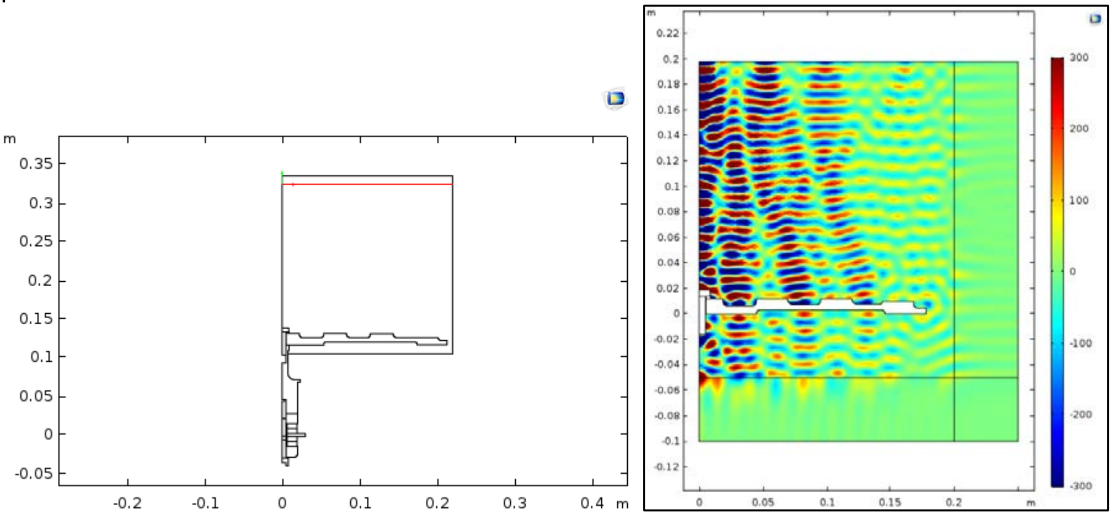
Finally, the way to determine the evolution of the dehydration process is by weighing the food samples. The samples are composed by a solid matrix and water. The solid matrix experiences no major changes in this process, but the wet content is being transferred to the media. So, the weight of the sample decreases continuously because the wet content disappears by sublimation. A weighing scale is placed inside the chamber to weight the samples in intervals of about 15', and sends the data to the computer to be processed with the Labview application.

The dehydration kinetics are represented as the evolution of the weight of the food samples along the operation time.

ACOUSTIC FIELD INSIDE THE DEHYDRATION CHAMBER

The distribution of the acoustic energy inside the dehydration chamber is important to determine the areas with higher energy concentration, where the efficiency of the process will be higher. The acoustic analysis has been done by numerical and experimental means.

The first approach to the ultrasonic field generated by the transducer has been done numerically with the FEM software COMSOL Multiphysics®. The simulation has been done in a 2D axisymmetric model (Fig. 4.a). It can be observed that the ultrasonic distribution is determined in the near field, in an area with 20 cm depth. The acoustic simulation considers a PML in the side wall and a reflecting surface in the front wall. The acoustic pressure distribution (in Pa), obtained for an operational mode of the transducer with 7NC at around 25 kHz, with the indicated boundary condition and considering the gas as a thermoviscous media, is presented in Fig. 4.b, where it can be observed that there is a higher energy concentration in the central part of the field:



a) 2D axisymmetric model b) Pressure distribution (Pa)

Figure 4: Ultrasonic near field generated by the transducer.

As mentioned in [18] for a circular plate transducer vibrating in a mode with 5NC, the steps built in the surface of the radiator allow a coherent field in free field, similar as the field generated by a piston, but no equal. On the other side, the amplitude of the vibrations of the plate is not uniform in the whole surface, but they follow a Bessel function from the center to the extreme of the radiator. This implies higher pressure amplitude in the central part of the field [19]. This transducer, with a circular plate vibrating in a flexural mode with 7NC behaves in the same way, generating a more or less coherent field because the displacements of its surface follow a Bessel function.

The same energy distribution has been determined experimentally, using a 1/8" microphone (GRAS 40DP) connected to a signal adapter (B&K NEXUS 2690) and then to LabVIEW® application designed for this purpose, to process all the data and obtain the ultrasonic field. Due to the axisymmetrical behavior of the system, the results presented in Fig. 5 correspond to a 200x200 mm area between the transducer and the scale. The transducer is working in an operational mode with 7NC at about 25 kHz, with an excitation of 50W.

It can be observed how the energy is concentrated in the axis of the transducer, as it was predicted in the numerical simulation.

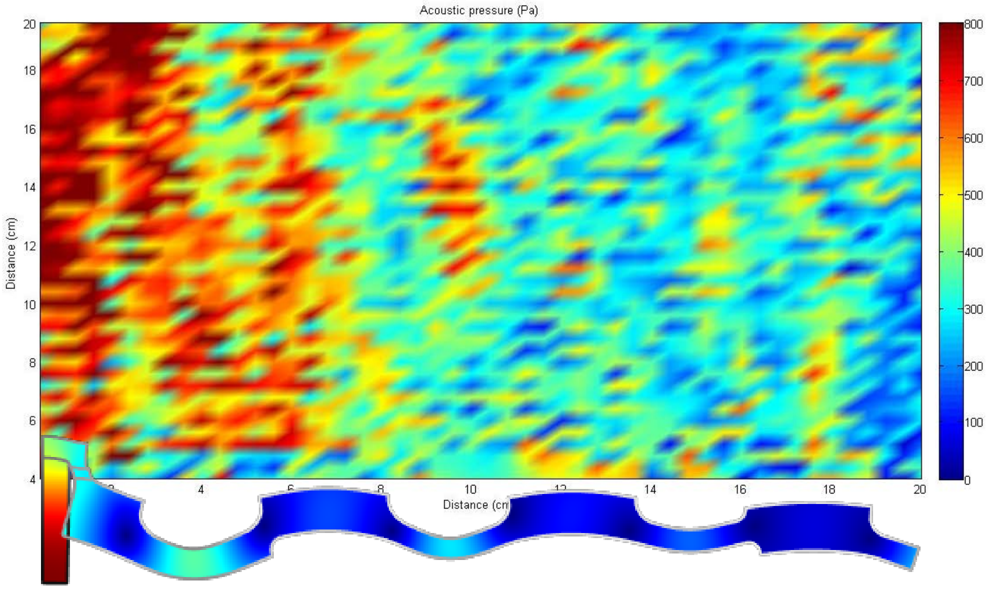


Figure 5: Experimental acoustic field generated by a power ultrasonic transducer with stepped circular plate.

CONCLUSIONS

A new ultrasonic assisted freeze drier, composed by an airborne power ultrasonic transducer and a dehydration chamber has been presented in this work. It is important to maintain the environmental conditions inside the chamber under the previously defined limits, and to keep the transducer working under the desired operational conditions. The acoustic field generated by the transducer in the dehydration chamber has been determined, showing higher energy concentration in the central part of area of interest, as it has been proved both numerically and experimentally.

ACKNOWLEDGMENTS

This work has been supported by the project DPI2012-37466-C03-01 funded by the Spanish Ministry of Economy and Competitiveness; and by INIA-ERDF throughout the project RTA2015-00060-C04-02

BIBLIOGRAPHY

[1] J. A. Gallego-Juarez, G. Rodriguez, J. C. Gálvez, and T. S. Yang, "A new high-intensity ultrasonic technology for food dehydration," *Drying Technology,* vol. 17, pp. 597-608, 1999/03/01 1999.

[2] E. Riera, J. V. García-Pérez, J. A. Cárcel, V. M. Acosta, and J. A. Gallego-Juárez, "Computational study of ultrasound-assisted drying of food materials," in *Innovative Food Processing Technologies: Advances in Multiphysics Simulation*, ed: Blackwell Publishing Ltd., 2011, pp. 265-301.

[3] J. V. García-Pérez, J. A. Cárcel, S. de la Fuente, and E. Riera, "Ultrasonic drying of foodstuff in a fluidized bed: Parametric study," *Ultrasonics,* vol. 44, pp. e539-e543, 12/22/ 2006.

[4] J. V. García-Pérez, J. A. Cárcel, E. Riera, C. Rosselló, and A. Mulet, "Intensification of low-temperature drying by using ultrasound," *Drying Technology,* vol. 30, pp. 1199-1208, 2012.

[5] C. Ortuño, I. Pérez Munuera, A. Puig, E. Riera, and J. V. García-Pérez, "Influence of power ultrasound application on mass transport and microstructure of orange peel during hot air drying," *Physics Procedia,* vol. 3, pp. 153-159, 2010.

[6] M. Villamiel, J. Gamboa, A. C. Soria, E. Riera, J. V. García-Pérez, and A. Montilla, "Impact of power ultrasound on the quality of fruits and vegetables during dehydration," *Physics Procedia,* vol. 70, pp. 828-832, 2015.

[7] J. A. Gallego-Juárez, G. Rodriguez, V. M. Acosta, and E. Riera, "Power ultrasonic transducers with extensive radiators for industrial processing," *Ultrasonics Sonochemistry,* vol. 17, pp. 953-964, 2010.

[8] R. R. Andrés, A. Blanco, E. Riera, and A. Guinot, "Description of an ultrasonic technology for food dehydration process intensification," *Proceedings of Meetings on Acoustics,* vol. 28, p. 045003, 2016.

[9] R. R. Andrés, V. M. Acosta, M. Lucas, and E. Riera, "Modal analysis and nonlinear characterization of an airborne power ultrasonic transducer with rectangular plate radiator," *Ultrasonics,* vol. 82, pp. 345-356, 2018/01/01/ 2018.

[10] J. A. Gallego-Juárez, G. Rodríguez, V. M. Acosta, E. Riera, and A. Cardoni, "Power ultrasonic transducers with vibrating plate radiators," in *Power Ultrasonics*, J. A. Gallego-Juárez and K. F. Graff, Eds., ed Oxford: Woodhead Publishing, 2015, pp. 159-193.

[11] M. Umeda, K. Nakamura, and S. Ueha, "Effects of vibration stress and temperature on the characteristics of piezoelectric ceramics under high vibration amplitude levels measured by electrical transient responses," *Japanese Journal of Applied Physics,* vol. 38, pp. 5581-5585, 1999.

[12] N. Aurelle, D. Guyomar, C. Richard, P. Gonnard, and L. Eyraud, "Nonlinear behavior of an ultrasonic transducer," *Ultrasonics,* vol. 34, pp. 187-191, 6// 1996.

[13] J. A. Gallego-Juárez, E. Riera, and V. M. Acosta, "Modal interactions in high-power ultrasonic processing transducers," *AIP Conf. Proc.,* vol. 1022, pp. 595-604, 2008.

[14] O. A. Sapozhnikov, "High-intensity ultrasonic waves in fluids: nonlinear propagation and effects," in *Power Ultrasonics*, J. A. Gallego-Juárez and K. F. Graff, Eds., ed Oxford: Woodhead Publishing, 2015, pp. 9-35.

[15] E. A. Neppiras, "The pre-stressed piezoelectric sandwich transducer," *Ultrasonics international 1973,* pp. 295-302, 1973.

[16] A. Ramos, J. A. Gallego-Juárez, and F. Montoya, "Automatic system for dynamic control of resonance in high power and high Q ultrasonic transducers," *Ultrasonics,* vol. 23, pp. 151-156, 7// 1985.

[17] Y. Kuang, Y. Jin, S. Cochran, and Z. Huang, "Resonance tracking and vibration stablilization for high power ultrasonic transducers," *Ultrasonics,* vol. 54, pp. 187-194, 1// 2014.

[18] L. Elvira, E. Riera, and J. A. Gallego-Juárez, "Study of the near field radiated by stepped plate ultrasonic transducers in air," in *Ultrasonics International 93*, ed: Butterworth-Heinemann, 1993, pp. 181-184.

[19] L. L. Beranek, *Acoustic measurements*. New York: John Wiley & Sons, 1949.