



Characterization and modeling of the acoustic field generated by a curved ultrasound transducer for non-contact structural excitation



Songmao Chen^a, Alessandro Sabato^{a,*}, Christopher Niezrecki^a,
Peter Avitabile^a, Thomas Huber^b

^a Department of Mechanical Engineering, University of Massachusetts Lowell, 1 University Avenue, Lowell, MA 01854, USA

^b Physics Department, Gustavus Adolphus College, 800 College Ave, St. Peter, MN 56082, USA

ARTICLE INFO

Article history:

Received 2 September 2017

Received in revised form 8 June 2018

Accepted 11 June 2018

Handling Editor: Z. Su

Keywords:

Boundary element method

Experimental modal analysis

Ultrasonic transducers

Ultrasound radiation pressure

Ultrasound radiation force

ABSTRACT

Conventional excitation techniques typically use an impact hammer, piezoelectric actuator, or mechanical shaker excitation for experimental modal testing. However, the use of these devices may be challenging if accurate high-frequency dynamic measurements on small or lightweight structural parts have to be performed. To overcome these problems, the high-frequency radiation force generated by focused ultrasonic transducers (FUTs) can be used. This approach has shown potential to be used as a non-contact method for modal excitation of small-sized or flexible structures such as MEMS devices, small turbine blades, integral blade rotors (IBR), and biological structures. However, the sound radiation in the air of these ultrasonic transducers and the resulting radiation force imparted onto a structure is not well understood and critically crucial for performing accurate modal analysis and system identification. In this research, the technical development of ultrasound radiation pressure mapping and simulation is presented. Starting from the calibrated sound pressure fields generated by the spherically FUT, driven by amplitude modulated signals, the dynamic focused ultrasound radiation force is modeled and estimated. The acoustic pressure field of a FUT operating in the air is measured and used for validating the accuracy of a new numerical boundary element method (BEM) model in predicting the direct acoustic force generated in the high-frequency range (i.e., 300–400 kHz). The results show that an excellent agreement is found regarding both the pressure profile and amplitude. Pressure fields up to 1200 Pa can be generated as the transducer is driven at 400 kHz. Experiments also prove that the FUT is capable of creating a focal spot size of nearly 3 mm in diameter. To finish, the FUT's dynamic focused ultrasound radiation force is quantified and could be used to quantify a force-response relationship for experimental modal analysis purposes.

© 2018 Elsevier Ltd. All rights reserved.

* Corresponding author.

E-mail addresses: Songmao.Chen@student.uml.edu (S. Chen), Alessandro.Sabato@uml.edu (A. Sabato), Christopher.Niezrecki@uml.edu (C. Niezrecki), Peter.Avitabile@uml.edu (P. Avitabile), huber@gustavus.edu (T. Huber).

1. Introduction

The capability to perform accurate high-frequency dynamic measurements on small structural parts is essential for a wide range of industries and applications. Currently, some of the most widely used dynamic excitation techniques include using either modal impact hammers, electromagnetic shakers, electromagnetic excitation, and piezoelectric actuators [1]. When these excitation methods are employed, they require physical contact between the excitation source and the test object. The physical connection may lead to mass and stiffness loading effects, issues that distort structures' exact dynamic characteristics (e.g., natural frequencies, mode shapes, and damping) [2]. Moreover, these contact excitation types may be physically impossible to create due to space or bandwidth limitations [3]. Electromagnetic excitation overcomes the coupling effect issue, but it has a limited frequency range, requires the test article to be magnetic, and provides excitation over a broad surface area [4]. Piezoelectric actuators can be used for high-frequency excitation, but require being in contact with the target structure and the input force cannot be readily measured. Therefore, this approach involves an estimation of the force input to the system to perform modal analysis operations such as estimating the frequency response functions (FRFs) [5,6].

Providing mechanical excitation of small or lightweight structures without interfering with their dynamic characteristics to obtain information useful for performing modal analysis (e.g., estimation of FRFs, natural frequencies, mode shapes, damping, etc.) are still challenges that need to be addressed by the structural dynamics community. In recent years, non-contact excitation methods have been explored as potential approaches for exciting and detecting vibration on structures having a size ranging from the micro to macro scale. For instance, direct acoustic excitation has been used as a non-contact method for operational modal analysis for frequencies ranging from audio to up to nearly 40 kHz [7,8]. Unfortunately, the sound radiation generated by the transducers is not focused, and the resulting acoustic force is imparted over a distributed area, preventing an accurate estimate of the FRFs. By employing transducers emitting sounds at a higher frequency, the dimension of the area over which the excitation is applied can be reduced to a few millimeters, and the radiated sound may be used as an effective non-contact method for exciting small structures such as micro-cantilevers and miniature turbine blades. The operational principle of this technique for modal analysis relies on applying two modulated ultrasound signals with a difference frequency Δf to ultrasonic transducers (UTs). The emitted ultrasound waves impacting the same spot of the test object make it vibrate at the difference frequency as a result of their superposition [9]. As a result, excitation frequencies ranging from as low as 100 Hz to more than 1 MHz, can potentially be achieved and used for experimental modal testing by producing multi-frequency excitations of structures [10,11].

The steady acoustic radiation force has been used in a variety of applications, including the measurement of sound intensity and power out of UTs [12,13], acoustic manipulation of microparticles [14], and acoustic levitation [15,16]. More recently, dynamic ultrasound radiation force has found increasing potential applications in elasticity imaging [9] and material characterization [17,18] in fluids. Some efforts about the possibility of using ultrasound radiated force as structural excitation technique have also been made. In vibro-acoustography, an imaging method based on the ultrasound radiation force has been used for detecting resonance frequencies, compression and bending modes of a chalk sphere and a cylinder in water, and for imaging the mode shapes of a mechanical heart valve and arterial phantoms [19–21]. The acoustics community performed a considerable amount of work to understand the physics of the acoustic radiation pressure and force [22,23]. In particular, the work made by Westervelt has to be recognized as one of the first and most influential in this topic [24]. These studies include research on a variety of objects having different shape [25], submerged in a variety of fluids [26,27], and interacting with several different types of acoustic waves [28–30]. In addition to that, the FUT-generated acoustic pressure has been widely used in non-destructive testing (NDT) applications, and it is one of the most used techniques in the field of imaging for biomedical applications. Even if those topics are external to the aim of this research, the interested reader can consult [31] and [32] for NDT and medical applications respectively. With regards to vibrations, the ultrasound radiation force has been used as noncontact modal excitation technique in the air for measuring the frequencies and operating deflection shapes (ODSs) (i.e., the forced vibration of two or more points on an object [33]). It has also been used on structures such as a brass reed [34], classical guitar strings (e.g., resonance frequencies below 100 Hz) [3], hard drive suspensions [35], and micro-cantilevers [36] (e.g., resonance frequencies over 1 MHz). However, what is still missing is the ability to assess and monitor the real-time acoustic radiation pressure generated by an air-coupled UT used for applying an acoustic radiation force over a structure. That is possible only when appropriate sensors and acquisition hardware and software are available. Unfortunately, this is not always technically possible. Therefore, to perform experimental modal testing, the input force needs to be known to obtain the FRF (i.e., output/input response) of the system being tested and identify important modal parameters. To date, the inability to assess and monitor the acoustic radiation force prevents this approach from being used as a practical technique for calculating the FRFs in experimental modal testing and motivates this research. For this reason, the objective of this research focuses on quantifying the radiation force produced by a double sideband suppressed carrier (DSB-SC) amplitude modulated signal for it to be used as an input parameter in the calculation of the frequency response function of the excited target structure. In this study, the dynamic focused ultrasound radiation force generated by focused ultrasonic transducers (FUT) is quantified both experimentally and analytically by using a boundary element method (BEM) model based on the Rayleigh Integral. The model is used to simulate the FUT's behavior at higher frequencies (i.e., above 300 kHz) after being validated in the lower frequencies range (i.e., 50–80 kHz) via experimental comparison. This paper is organized as follows: Section 2 (Background) offers an outline of the theoretical principles on which this work is based. It explains the essential concepts of ultrasound radiation pressure and force, the principles of operation of ultrasound beam forming techniques for FUTs, and the description of the developed BEM. Section 3 (Ultrasonic transducer pressure field characterization) describes the tests

performed for validating the model and a back-to-back comparison between experimental data and numerical simulations. Estimation of the ultrasound radiation force generated by the FUT is presented in Section 4 (Force estimation); while, conclusions are drawn and future work is described in Section 5 (Conclusion).

2. Background

In this section, the essential concepts and theories of the research are summarized. First, the basic notions of the ultrasound radiation force are introduced, followed by the description of common beamforming techniques used in the generation of the radiation force. To finish, this section concludes with the theoretical characterization of the novel BEM based on the Rayleigh Integral proposed for simulating the pressure field generated by the FUT in the higher frequency range of interest.

2.1. Ultrasound radiation force

The acoustic radiation force is generally interpreted as a time-averaged force exerted by an acoustic field on a structure placed within the acoustic waves' propagation path [37]. The acoustic radiation force vector $\mathbf{F}$ arising from the waves-structure interactions can be calculated using Eq. (1). It shows that its magnitude is proportional to the time-averaged energy density of the incident wave $\langle E \rangle$ at the object, the area S of the projected portion of the object, and to the drag coefficient vector $\mathbf{d}_r$ [24].

$$\mathbf{F} = \langle E \rangle S \mathbf{d}_r \quad (1)$$

The magnitude of the coefficient $\mathbf{d}_r$ depends upon a variety of factors such as the target object's shape and the incident beam's direction. From the perspective of physics, the drag coefficient is representative of the scattering and absorbing properties of an object, and can be calculated using Eq. (2):

$$\mathbf{d}_r = \mathbf{p} \frac{1}{S} \left(\Pi_a + \Pi_s - \int \gamma \cos \alpha_s dS \right) + \mathbf{q} \frac{1}{S} \int \eta \cos \alpha_s dS \quad (2)$$

where $\mathbf{p}$ and $\mathbf{q}$ are the unit vectors in and normal to the incident direction, Π_a and Π_s are absorption and scattering cross-sections (i.e., total power divided by the incident intensity) respectively, η the scattered intensity, α_s the angle between the incident and the scattered intensity, and dS the scattered area. For a planar object of perfect absorption, $\mathbf{d}_r = 1.0$; while for a planar object of perfect reflection, $\mathbf{d}_r = 2.0$ [24].

It has already been shown that an ultrasound impulse can produce a transient pulsed radiation force and sinusoidal modulation signals that can be used to generate a harmonically varying force [9,19]. This can be achieved by using the three different types of beamforming setups shown in Fig. 1: Amplitude Modulated (AM), confocal, and X-focal. In the first case, a single-element FUT is driven by a double sideband suppressed carrier (DSB-SC) amplitude modulated signal. In the confocal mode, the UT is composed of two confocal elements (i.e., a central disk and an outer annulus) driven with two high-frequency signals having a difference frequency Δf . To finish, in the X-Focal configuration, two single-element spherically shaped FUTs are arranged symmetrically around the test object and driven by two separate high-frequency signals with a difference frequency Δf .

As two ultrasound beams with frequencies f_1 and $f_2 = f_1 + \Delta f$ are superimposed, the constructive and destructive interferences between the beams produce a radiation force having a vibration frequency equal to the difference frequency $\Delta f = f_2 - f_1$. The total pressure field $p(\mathbf{r}, t)$ due to the two frequency components in a point distant $\mathbf{r}$ from the FUT can be evaluated using Eq. (3):

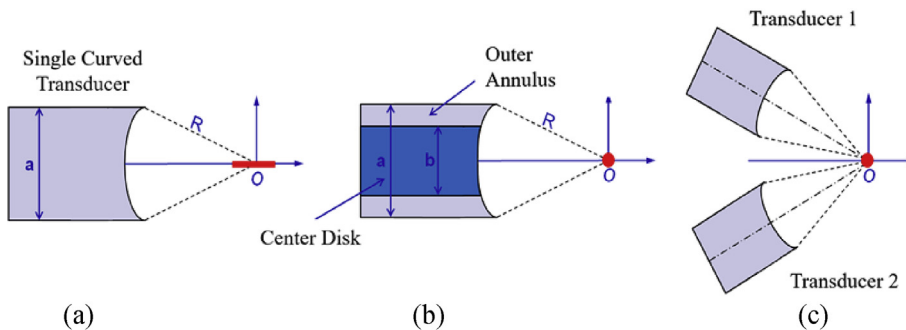


Fig. 1. Generation of a modulated ultrasound field by three types of beam forming setups: (a) single UT with AM, (b) confocal, and (c) X-focal.

$$p(\mathbf{r}, t) = P(\mathbf{r})\cos[2\pi f_1 t + \varphi_1(\mathbf{r})] + P(\mathbf{r})\cos[2\pi f_2 t + \varphi_2(\mathbf{r})] \quad (3)$$

If the two waves have difference frequency Δf far less than both f_1 and f_2 ; p_1 and p_2 can be considered to be almost the same and equal to $P^2(\mathbf{r})$ with phases $\varphi_1(\mathbf{r})$ and $\varphi_2(\mathbf{r})$ respectively. This research is based on Westervelt's plane wave theory [24]; therefore, under the assumption that the waves propagate with speed c in a fluid having density ρ in a planar way, the ultrasound beams behaves as a plane wave and the energy density is governed by the following Eq. (4):

$$E(\mathbf{r}, t) = \frac{p^2(\mathbf{r}, t)}{\rho c^2} = \frac{P^2(\mathbf{r})\cos[2\pi\Delta f t + \Delta\varphi(\mathbf{r})]}{\rho c^2} \quad (4)$$

which takes into account the frequency and phase differences Δf and $\Delta\varphi(\mathbf{r})$ introduced in Eq. (3). The total radiation force in time-varying form is the integral of Eq. (1) over the surface area of the structure impacted by the incident sound waves. For message frequencies much smaller than the carrier frequencies (i.e., $<1\%$), it can be calculated using Eq. (5) [38,39]:

$$\begin{aligned} F_{\Delta f}(\mathbf{r}, t) &= \int_S E(\mathbf{r}, t) d_r(\mathbf{r}) dS = d_r(\mathbf{r}) \int_S \frac{(p_1 + p_2)^2}{\rho c^2} dS \\ &= d_r(\mathbf{r}) \int_S \frac{P^2(\mathbf{r})}{\rho c^2} \cos[2\pi\Delta f t + \Delta\varphi(\mathbf{r})] dS \end{aligned} \quad (5)$$

When two incident planar waves having pressure p_1 and p_2 are considered, it should be noted that the resulting acoustic radiation force is in proportion to $(p_1 + p_2)^2$, which include a DC component, a summation component ($f_1 + f_2$), a doubling of frequency component ($2f_1$ or $2f_2$) and a difference frequency component ($f_1 - f_2$). As a result of the interaction of a test object with the ultrasound radiation force, the structure will be vibrated at the different frequency Δf , this quantity is relevant to this research. The other components will induce vibrations in the structure that are out of its range of interest or that have negligible magnitude. Therefore, by adjusting Δf , different structural excitation frequencies over a desired bandwidth are achievable as this technique is employed. It implies that as the transducer is operated with a modulation frequency much smaller than the carrier frequency, the generated wave can be considered a single-frequency plane wave and therefore used as a steady-state source of excitation for the target object [24].

2.2. Beam forming methods of dynamic ultrasound radiation force

The ultrasonic radiation force can be static or dynamic. The former case is induced by a continuous wave ultrasound, which gives rise to a constant force when it hits the target structure, while the latter is generated as the incident ultrasound beam is modulated. Among the most common methods for producing dynamic effects are amplitude modulation (AM), double sideband suppressed carrier (DSB-SC) amplitude modulation, linear frequency modulation (FM), frequency shift keying [40], and spatial modulation [41]. These methods offer the opportunity to transfer energy, momentum, or radiation force at low frequencies by modulating the ultrasound to achieve the desired level of excitation. One of the merits of beamforming at ultrasound frequencies is that it allows focusing the radiation force, resulting in a structural dynamic response in the low-frequency range of interest at a level that can be measured by using equipment such as the laser Doppler vibrometer. AM ultrasound can be used to produce harmonic or multi-frequency radiation forces [42,43]. This type of radiation force has been used in vibro-acoustography [9,19], shear wave elasticity imaging [44], and non-contact modal excitation [34–36]. FM can be employed to cause a radiation force that alters frequency with time. Typically, the frequency shifts linearly through time and results in a “chirp.” Chirped ultrasound has been used in radiation force applications in vibro-acoustography as well [45,46]. However, in this research, only DSB-SC AM are employed and discussed. In particular, because a single-element FUT is utilized, the DSB-SC AM with randomly varying ultrasound carrier frequency is applied. The principle of generating these signals and formation of acoustic focal spot based on wave superposition using a single-element FUT is shown in Fig. 2.

The AM signal consists of an upper band (UB) $f_1 = f_c + 0.5 f_m$ and a lower band (LB) $f_2 = f_c - 0.5 f_m$ signals where f_c is the carrier frequency (i.e. in the kHz or MHz range), and f_m is the modulation frequency (i.e. the difference frequency in the frequency range of interest of test structure). In addition, it has been experimentally shown that for a difference-frequency below 50 kHz, no significant parametric array phenomenon are observed and Eq. (5) can be used without correction due to those effects [47]. In the current research, given the low frequency of the amplitude modulated frequency used, no parametric array effects have been observed. Nonetheless, it does not exclude the formation of those phenomena for very-high modulated frequencies are used in the DSB-SC AM process. It means that for $f_m < 0.01 f_c$, the magnitude of the radiation force does not change. The AM signal is amplified by a power amplifier, and then sent to drive the FUT. The transducer generates a focused ultrasound pressure field that has ultrasound beams of two different frequencies, f_1 and f_2 . By placing the test structure in the focal region of the acoustic field, the interaction between the pressure field and the structure results in the ultrasound radiation force that has multiple components due to the square effect of the superposition of the ultrasound waves at f_1 and f_2 , as described in Fig. 2. By sweeping different frequencies, multi-frequency excitations of structures can be

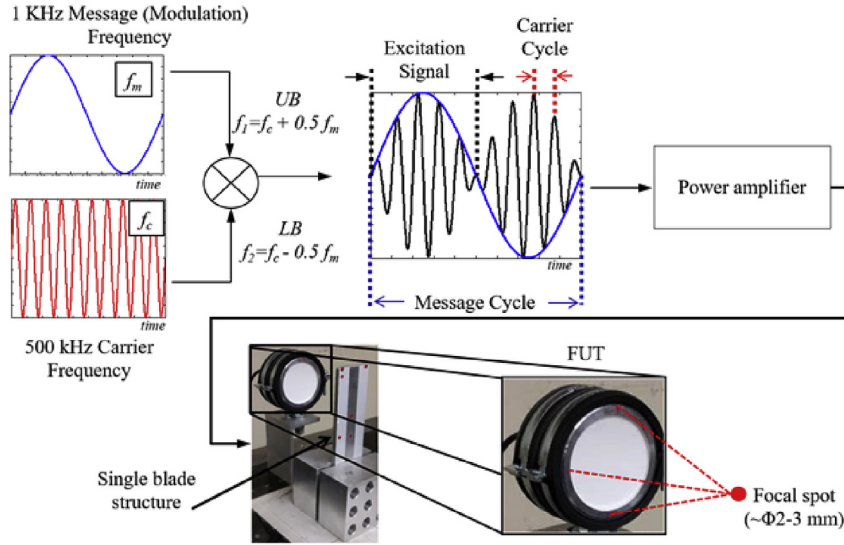


Fig. 2. Principle of generating the DSB-SC AM signals and forming focal acoustic spot using wave superposition.

achieved. The size of the focal spot is dependent upon the carrier signal wavelength. For a carrier frequency on the order of 0.5 MHz, the spot size will be in the range of 2–3 mm in diameter.

2.3. Modeling of acoustic field generated from the ultrasonic transducer

This research aims to develop a method that enables to quantify the non-contact excitation force imparted to test structures by implementing an acoustic BEM for characterizing the FUT's pressure field at different frequencies. The sound pressure of a field point $p_i(x, y, z)$ produced by a source element S_i is governed by Eq. (6) [48]:

$$p_i(x, y, z) = \frac{j\omega\rho U(x', y', z')e^{-jkr}}{2\pi r} dS \quad (6)$$

where r is the distance between the field point and the center of the source element, ω is the circular frequency of the vibration of the transducer surface, ρ is the fluid density, $U(x', y', z')$ is the amplitude of vibration velocity of the source element (which is going to be experimentally measured at its geometrical center), dS is the area of the i -th source element, and k is the wave number. Previous studies on plane ultrasound transducers by the authors have shown the effectiveness of this method [49,50]. In this study, with reference to Fig. 3 and to take into account for the curvature of the transducer, the geometrical terms of Eq. (6) can be calculated as:

$$dS = R \sin(\theta) d\Phi \cdot R d\theta \quad (7)$$

$$R = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2} \quad (8)$$

where R is the curvature radius of the FUT (i.e. experimentally determined to be approximately 140 mm in this study) and the terms x' , y' , z' , in Eq. (8) can be calculated like $x' = R \sin(\vartheta) \cos(\Phi)$, $y' = R \sin(\vartheta) \sin(\Phi)$, and $z' = R - R \cos(\Phi)$ respectively. It should be noted here that this approach is valid for mildly focused transducers. The pressure calculation method shown in Eq. (6) is derived for simulating pressure field of a plane piston. However, it can be considered accurate for slightly curved transducers (i.e., almost plane, which is the case analyzed in this study) as well.

The overall pressure at a field point is the superposition of pressure contributed from all of the N source elements and can be formulated using Eq. (9):

$$P(x, y, z) = \sum_{i=1}^N p_i(x, y, z) \quad (9)$$

with $N = 4501$ for lower frequency range, due by the fact that the tested FUT in this research has been discretized into an element at the center, and 25 annular sections each with 180 angular elements. For higher frequency range, $N = 15,000$ because more points are needed to avoid possible spatial aliasing. Eq. (9) is used to generate an acoustic radiation pressure

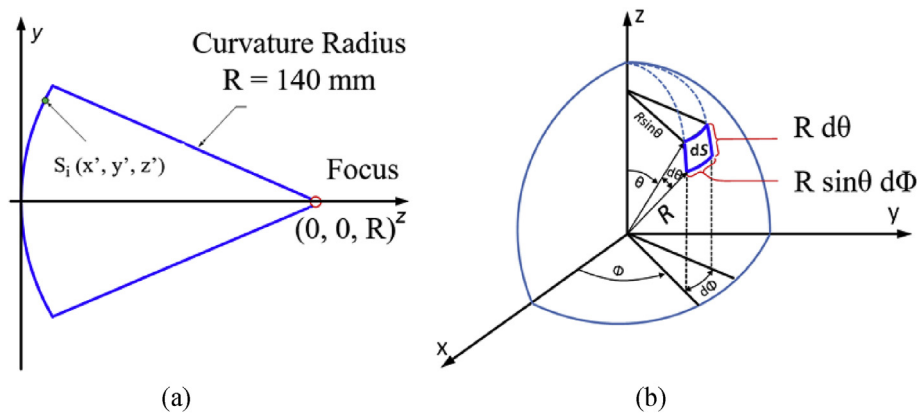


Fig. 3. Diagram of the coordinate system and BEM used to simulate the acoustic field generated by spherically curved ultrasonic transducers. (a) Section of the curved transducer, (b) an individual source element dS that represents a small area of the transducer.

profile for the FUT over numerous points representing an area of interest. The accuracy of the simulation will be validated comparing the numerical results with those obtained as the radiated pressure is experimentally measured using an acoustic microphone in the lower frequency range and will help to understand the FUT's radiation characteristics (e.g., pressure, directivity, and spot size) in the higher frequency range.

3. Ultrasonic transducer pressure field characterization

In this research, a noncontact circular FUT (model NCG500-D50-P150 from the Ultran Group), with an actual focal length of ~ 140 mm, has been used. It has a nominal diameter of 50 mm and a nominal operating frequency of 500 kHz [51]. To characterize the dynamic behavior of the transducer, two sets of experiments were performed. The first one consisted of using a conventional microphone for measuring the generated acoustic pressure field in the lower frequency range (i.e., 50–80 kHz). The second experiment used a scanning laser Doppler vibrometer (SLDV) (PSV-400 manufactured by Polytec, Inc.) to measure the vibrational characteristics and the velocity profile of the transducer surface at two different frequency ranges: low-frequency (i.e., 50–80 kHz) and high-frequency (i.e., 300–400 kHz). In the lower frequency range, the BEM acoustic model is validated by comparing numerical results with experimental data recorded using the microphone; while the model is then used for predicting the higher frequency range behavior of the FUT utilizing the velocity profiles measured with the SLDV.

3.1. Pressure field mapping of the FUT in the lower frequency range

The predicted ultrasound pressure field needs to be compared with the experimentally measured results to verify the effectiveness of the acoustic BEM model. The entire procedure has been performed for frequencies below 100 kHz because that value represents the upper calibrated measurement limit for the commercially available acoustic microphones. In this research, the actual pressure field has been experimentally mapped by placing two precise $\frac{1}{4}$ " acoustic microphone Model 378C01 manufactured by PCB Piezotronic, Inc. [52] on a manual translation stage in the acoustic field in front of the FUT in a setup similar to that shown in Fig. 4, where the SLDV PSV-400 is used to generate a signal for exciting the FUT.

In particular, measurements were made in the three vertical planes P1, P2, and P3 (in the XY direction), and one horizontal plane P4 (in the XZ direction) as shown in Fig. 5. The distance between the planes P1, P2, and P3 and the transducer surface

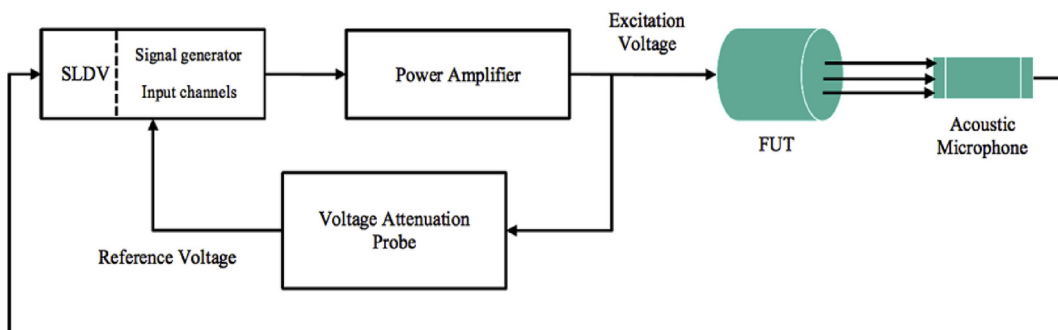


Fig. 4. Schematic diagram for the acoustic pressure field mapping experiment.

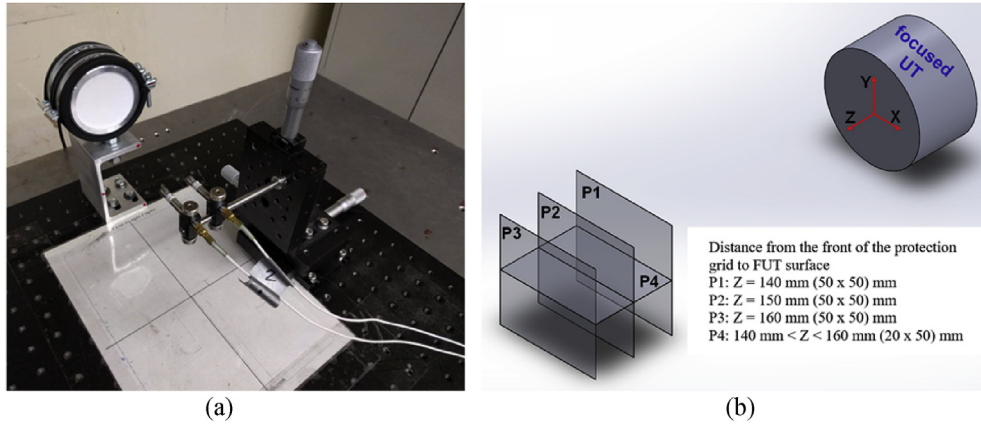


Fig. 5. Acoustic pressure field mapping: (a) Experimental setup; (b) measurement planes.

were 140, 150, and 160 mm, respectively. The plane P4 was symmetric about P2, and located at the center of the test transducer, with its near and far ends spaced 140 and 160 mm from the FUT. These distance values were measured from the front of the microphone protection grid to the surface of the test transducer plane considering that the acoustic radiating surface of the FUT was located in the plane at $Z = 0$.

In order to calculate the sound pressure generated by the vibrating surface of the FUT using the BEM based on the Rayleigh Integral using Eq. (6), it is necessary to know the amplitude of vibration (i.e., velocity) of the source elements $U(x', y', z')$. The velocity profiles of the FUT were experimentally measured in the range 10–80 kHz using an SLVD PSV-400 manufactured by Polytec, Inc. [50] in a setup similar to that shown in Fig. 6. As shown in Fig. 6, a total of 181 scanning points were used to cover the effective focused UT radiating surface to measure the velocity profiles under sinusoidal excitations at 50, 60, 70, and 80 kHz. The measured velocity profiles were then fed into Eq. (6) to compute the sound pressure of a field point. In the simulation, a pressure field of $100 \times 100 \times 450$ mm with a spatial resolution of 5 mm was used. The full pressure fields computed with the BEM using the measured velocity profiles at 50, 60, 70, and 80 kHz are shown in Fig. 7.

Here, a focal region can be identified. Also, it is possible to notice that as the excitation frequency increases, the focal region gets smaller and the pressure magnitude becomes larger ranging from 3.7 Pa for the 50 kHz excitation to 9 Pa for the 80 kHz case. From the full pressure field, the pressure in P1, P2, and P3 can be easily extracted. For example, the pressure field in P2 at 50 kHz is shown in Fig. 8, in which a focal spot having a diameter of ~ 10 mm can be observed.

Finally, the predicted ultrasound pressure field needs to be compared with the experimentally measured results obtained using the acoustic microphones to verify the effectiveness of the acoustic BEM model. Fig. 9 shows the results obtained for the 50 kHz excitation case. The experimental data and numerical simulations are in excellent agreement. The comparison indicates that the pressure values are close and the pressure profiles are similar. To be accurate, the simulation results seem to underestimate the actual value of the maximum acoustic pressure value, but the average error is equal to 0.15 Pa and can be considered relatively small. Comparison at 60, 70, and 80 kHz exhibit similar behavior and are not shown here for the sake of brevity. The experimental comparison demonstrates that the acoustic BEM model can be used to represent the physics of the FUT effectively and it is capable of accurately predicting the acoustic emission by using the vibration velocity shapes experimentally measured from the transducer. From Fig. 9, it should be observed that the focal spot is not symmetric with the selected X, Y coordinate system. This is because the microphones used for performing the experiments (and the translation

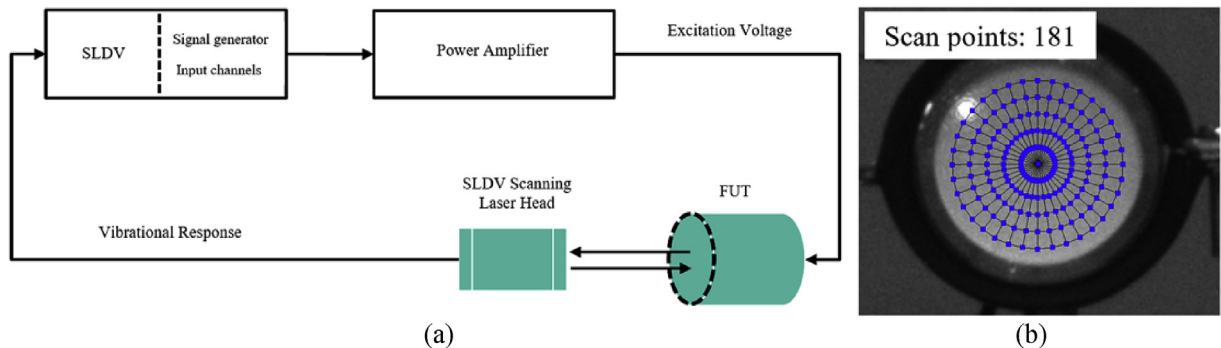


Fig. 6. Vibration velocity profile measurement of the FUT: (a) Schematic diagram, (b) Scanning pattern of the FUT surface.

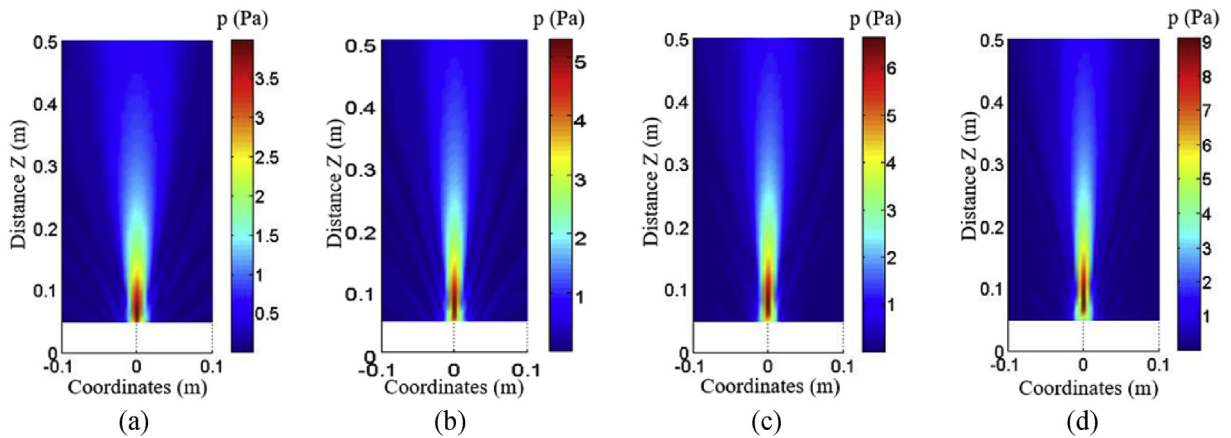


Fig. 7. Predicted pressure fields computed using the BEM in conjunction with the transducer's laser vibrometer velocity measurements for different frequencies: (a) 50 kHz, (b) 60 kHz, (c) 70 kHz, and (d) 80 kHz.

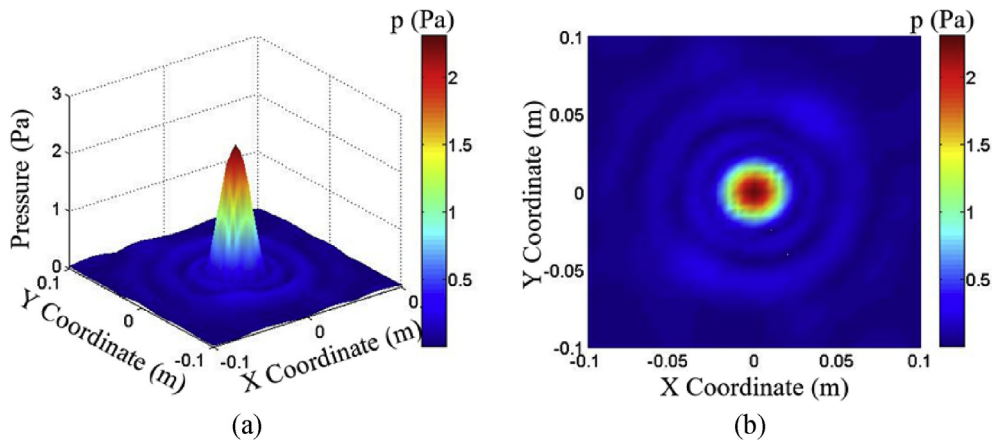


Fig. 8. Ultrasound pressure field in P2 ($z = 150$ mm) computed for a 50 kHz excitation: (a) 3D isometric view and (b) 2D top view.

stage used for moving the microphones) were not perfectly aligned with the focal point of the transducer (i.e., shifted 1 or 2 mm to the left). Of course, this feature is not presented in the model's results as the origin of the coordinate system has been superimposed to the geometrical center of the FUT.

3.2. FUT pressure field simulation in the higher frequency range

With the availability of the validated acoustic BEM model, the ultrasound pressure field in the higher frequency range (i.e., the carrier frequency range of the FUT) can be predicted. Before proceeding with this operation, the frequency response of the FUT has been studied for determining the optimal frequency that gives the highest vibration response. This can be done using electrical impedance measurement for the transducer; in the specific case, the FUT's impedance measurement was performed from 10 to 500 kHz and provided the results shown in Fig. 10. Because the transducer is a capacitive element, the electrical impedance decreases with the inverse of frequency. However, it can be seen that a dip in the electrical impedance occurs at ~ 359 kHz, coinciding with a significant phase shift. This value corresponds to the frequency at which the transducer generates the maximum vibration and acoustic response. Based on the results of the impedance test, vibrational FRF testing on the FUT was conducted to determine the velocity profile of the UT at a higher frequency. In the experiment, to avoid spatial aliasing, a total of 15,000 scan points were used, including spots on the FUT housing to check how it performed when the transducer was excited. The vibrational FRF pattern used for scanning the surface of the FUT is shown in Fig. 11.

During the test, frequencies in the range 300–400 kHz were scanned with an increment of 6.25 kHz. To take into account both the frequency range of interest and the time consumption due to the large number of scan points a pseudo-random excitation signal was used. Several representative vibrational FRFs are shown in Fig. 12. It can be seen that the tested FUT vibrates with the highest response at ~ 362.5 kHz, confirming the results found with the electrical impedance measurement.

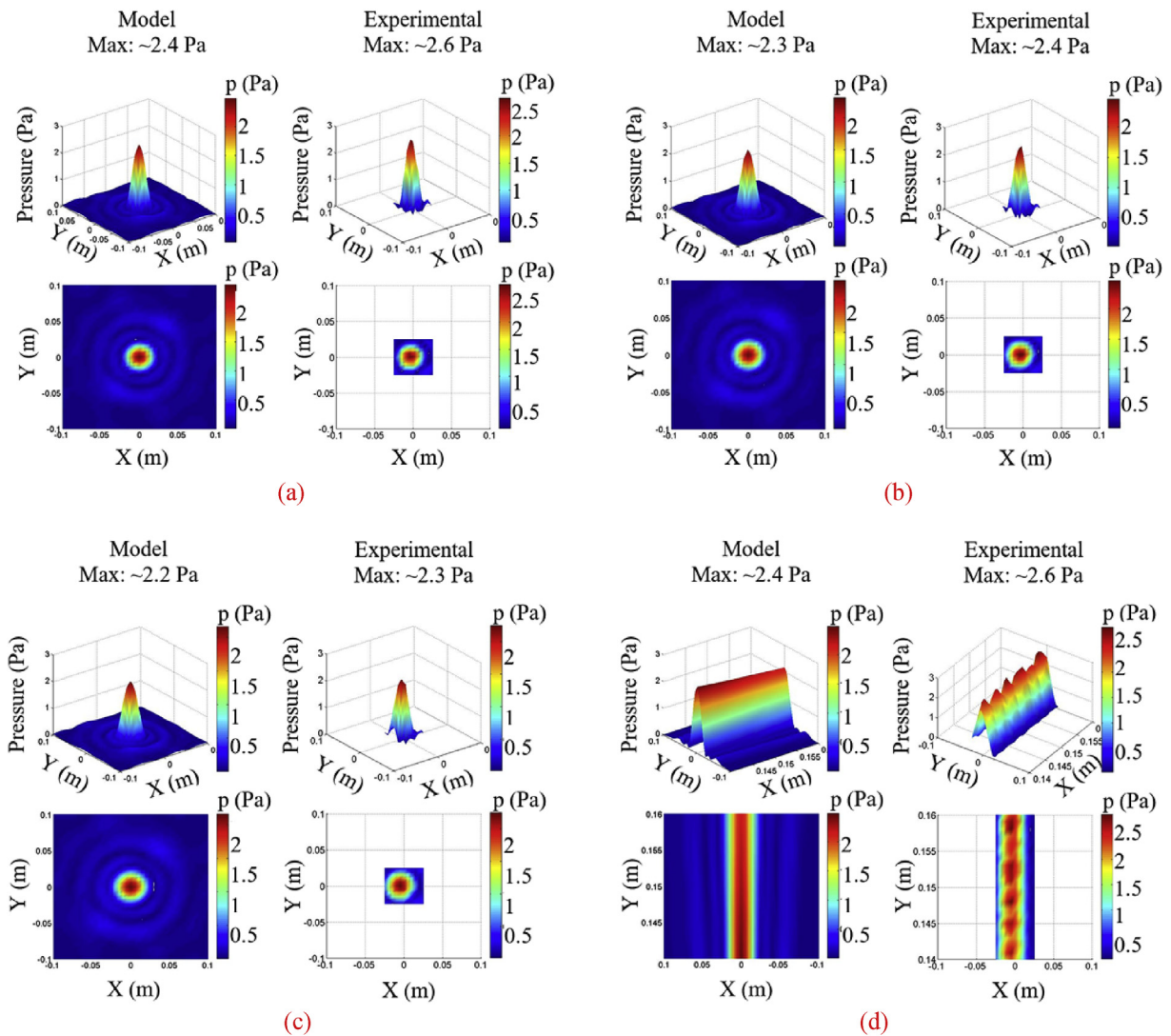


Fig. 9. Comparison of model and experimental ultrasound pressure when the FUT is excited at ~ 25 Vrms and 50 kHz for the four measurement plane slices: (a) P1 = 140 mm, (b) P2 = 150 mm, (c) P3 = 160 mm (a), and (d) P4 = 140–160 mm.

Moreover, it is observed that when scan points get farther away from the transducer center, the velocity response decreases. At the edge of the radiating surface of the FUT, the response is minimal, as demonstrated by the vibrational FRF of scan point #13900 shown in Fig. 12.

Once the velocity profiles in the range 300–400 kHz have been measured using the laser vibrometer, the acoustic spatial field in front of the FUT can be predicted for a section in front of the transducer having length of 300 mm and a width of ± 10 mm in the X and Y direction with a spatial resolution of 0.4 mm. The full ultrasound pressure field at three different frequencies (i.e., 325, 362.5, and 400 kHz) is shown in Fig. 13. Compared with the results at lower frequencies, the pressure value at carrier frequency level is approximately three orders of magnitude higher on the level of 1000 Pa.

Also, the results display a highly focused region, the characteristics of which can be further understood as the pressure in specific planes is examined. In particular, three transversal planes at Z = 130 mm, 140 mm, and 150 mm and a longitudinal plane from Z = 130 mm to Z = 150 mm were analyzed and shown in Fig. 14 through 17.

It is possible to observe that a highly focused acoustic spot can be found and it has a diameter of ~ 3 mm, and the maximum value of the ultrasound pressure increases as frequency increases reaching peaks higher than 1200 Pa as the 400 kHz excitation is considered. The focal region extends primarily from Z = 130 mm to Z = 150 mm, as shown in Figs. 13 and 17. It implies that throughout this area, the pressure is nearly constant. This phenomenon has significance for modal analysis purposes because it enables the user to have some variability in positioning of the transducer while still being able to effectively excite the structure under test even though the working distance changes (i.e., $140 \text{ mm} \pm 10 \text{ mm}$).

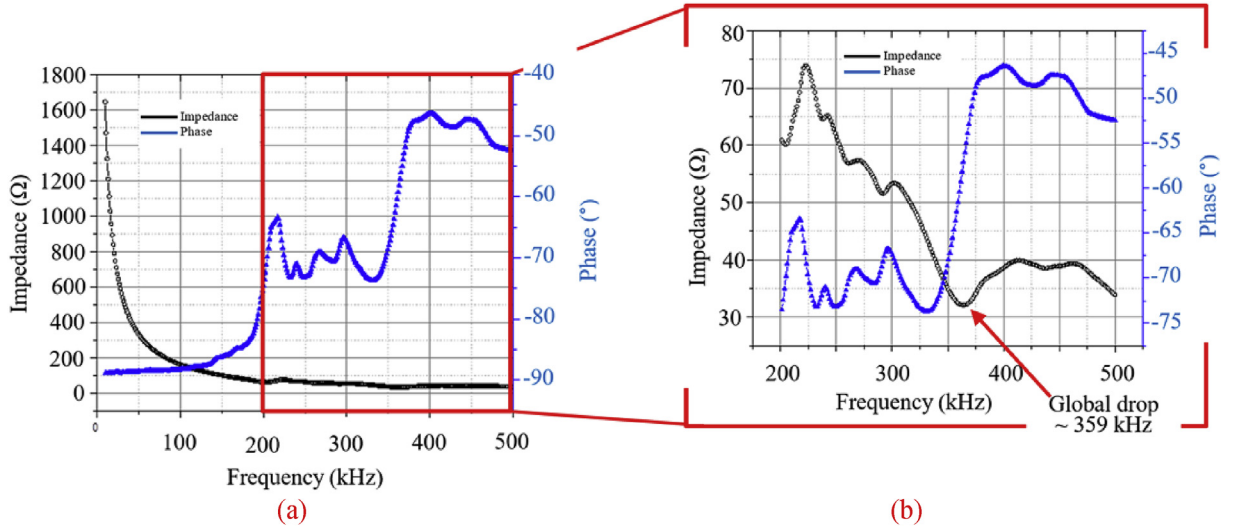


Fig. 10. Impedance curve of the FUT: (a) from 10 to 500 kHz and (b) detail of the curve in the 300–400 kHz range.

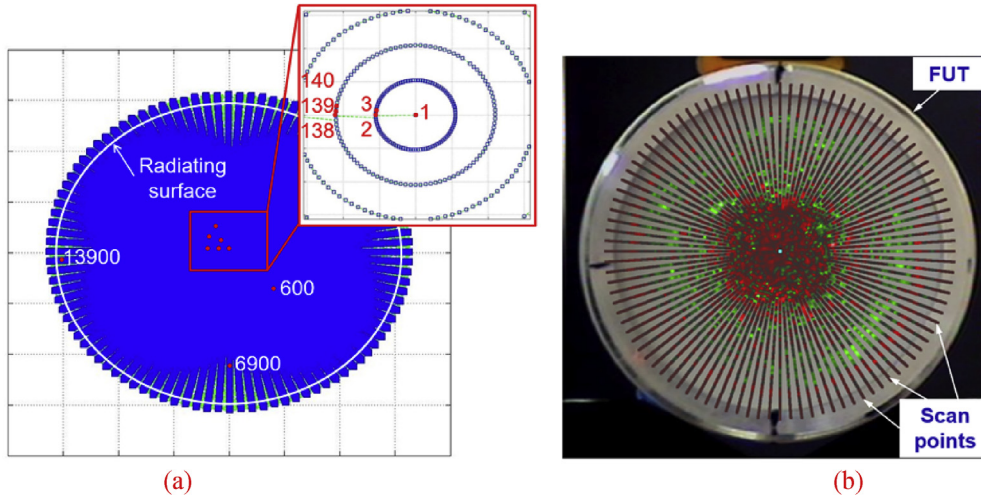


Fig. 11. Measurement pattern: (a) 15,000 scan points for the vibrational FRF measurement, (b) photo of the scan points superimposed to the FUT.

4. Quantification of ultrasound radiation force and its experimental verification

Based on the theoretical analysis of ultrasound radiation force provided in Section 2, once the pressure field is known, the ultrasound radiation force $F_{\Delta f}(\mathbf{r}, t)$ for a given carrier frequency of the FUT can be estimated using Eq. (5). The distribution of the predicted ultrasound radiation force for 325, 362.5, and 400 kHz is shown in Fig. 18 under the assumption of perfect reflection of sound waves by test article (i.e. drag coefficient d_r in Eq. (5) sets equal to 2). It can be found that the majority of ultrasound radiation force is confined within a range of ~ 3 mm in diameter around the geometrical center of the FUT, confirming the findings highlighted in the previous section, and that it has a maximum value of $\sim 1.3 \times 10^{-5}$ N, 2.7×10^{-5} N, and 3.5×10^{-5} N for the three frequencies considered.

To verify the accuracy of the radiation force calculated from the ultrasound pressure field predicted using the BEM, direct experimental measurement of the ultrasound radiation pressure was performed to indirectly evaluate the acoustic force acting on the test structure starting from the analysis of the pressure field generated by the FUT. For this reason, an acoustic microphone was used to map the radiation pressure resulting from the interaction between the ultrasound waves and the microphone, which acts as the test structure. The schematic diagram and the experimental setup used for performing this test are shown in Fig. 19. In this case, to generate a signal having two frequencies using only one FUT a DSB-SC AM signal has been chosen as excitation. In particular, the carrier frequency has been centered at 359 kHz with a random variation of 20 kHz. It should be noted that a random change in the carrier frequency helps to prevent interference between the incident and

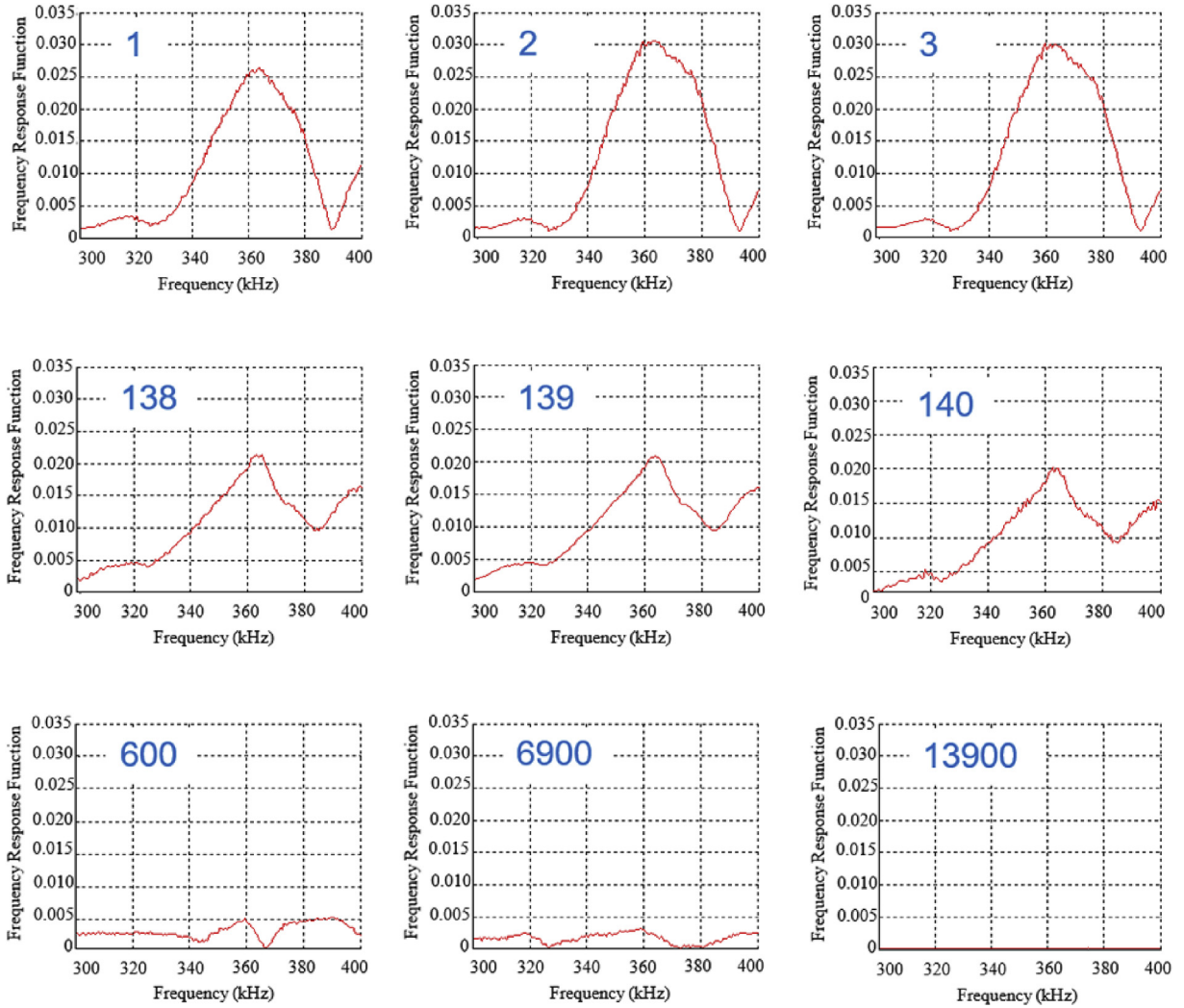


Fig. 12. Representative vibrational FRFs of the FUT in the 300 and 400 kHz frequency range for the different points labeled in Fig. 11, (Unit: mm/s/V).

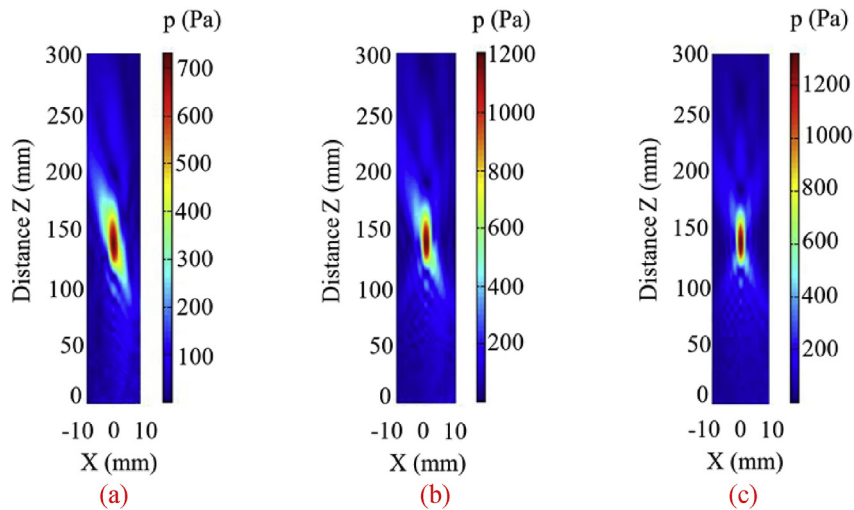


Fig. 13. Full ultrasound pressure field at different frequencies: (a) 325 kHz, (b) 362.5 kHz, and (c) 400 kHz.

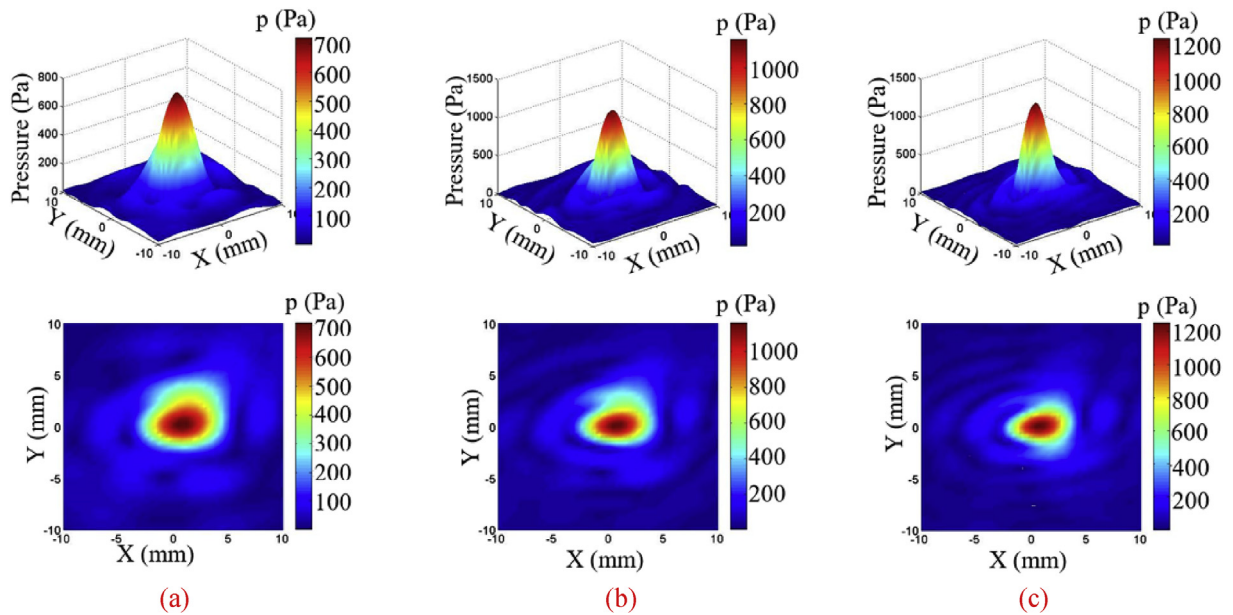


Fig. 14. Ultrasound pressure field in the plane P1 = 130 mm at (a) 325, (b) 362.5, and (c) 400 kHz.

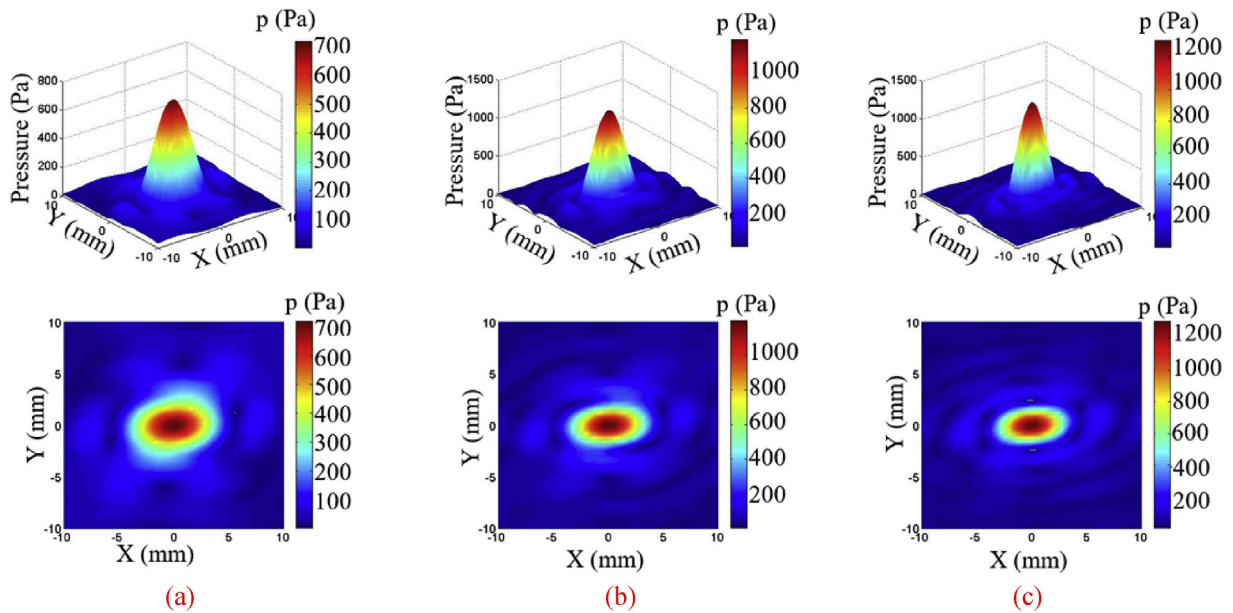


Fig. 15. Ultrasound pressure field in the plane P2 = 140 mm at (a) 325, (b) 362.5, and (c) 400 kHz.

reflected waves and avoid the formation of standing waves. As a result, the difference frequency Δf acting on the acoustic microphone can vary from 100 Hz to more than 20 kHz. A $\frac{1}{4}$ " acoustic microphone type 4939, manufactured by Brüel&Kjær has been used to map the produced radiation pressure profile and used as a test object located 140 mm away from the center of the transducer itself. The size of the measurement plane selected for the test was 5×5 mm with a spatial resolution of 0.5 mm [53]. It should be noticed that the pressure calculated using the microphone, has to be considered as an average of the pressure field acting on its membrane. More accurate results can be obtained by using fiber optic microphones having a sensing element's dimension on the order of a few microns [54].

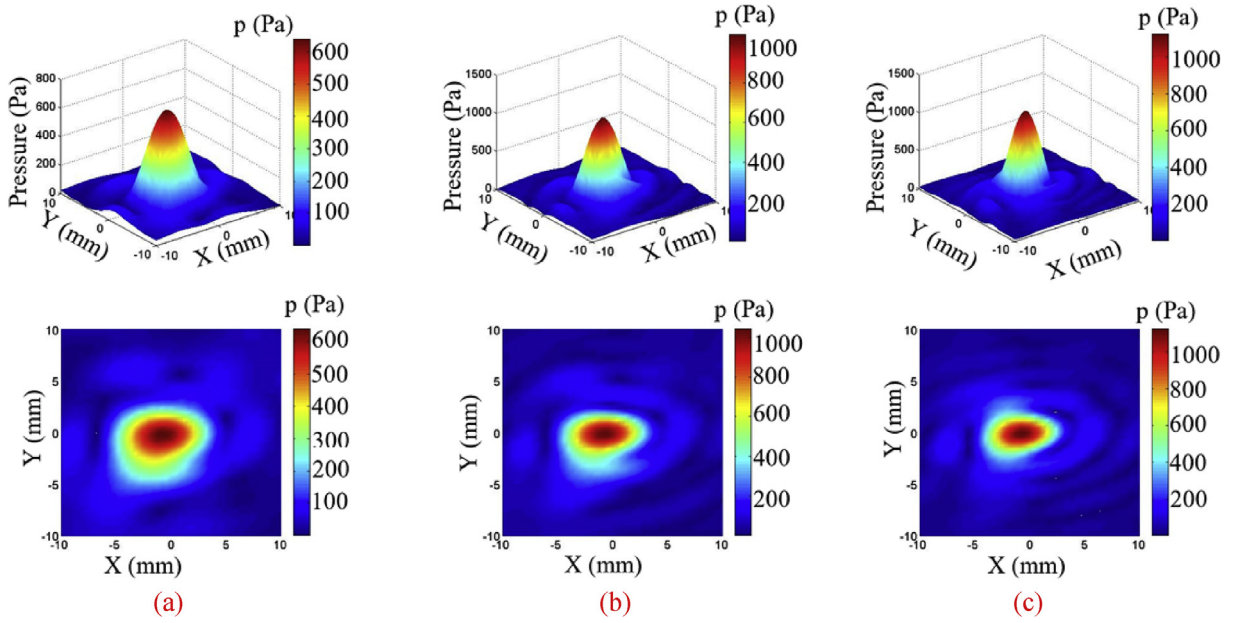


Fig. 16. Ultrasound pressure field in the plane P3 = 150 mm at (a) 325, (b) 362.5, and (c) 400 kHz.

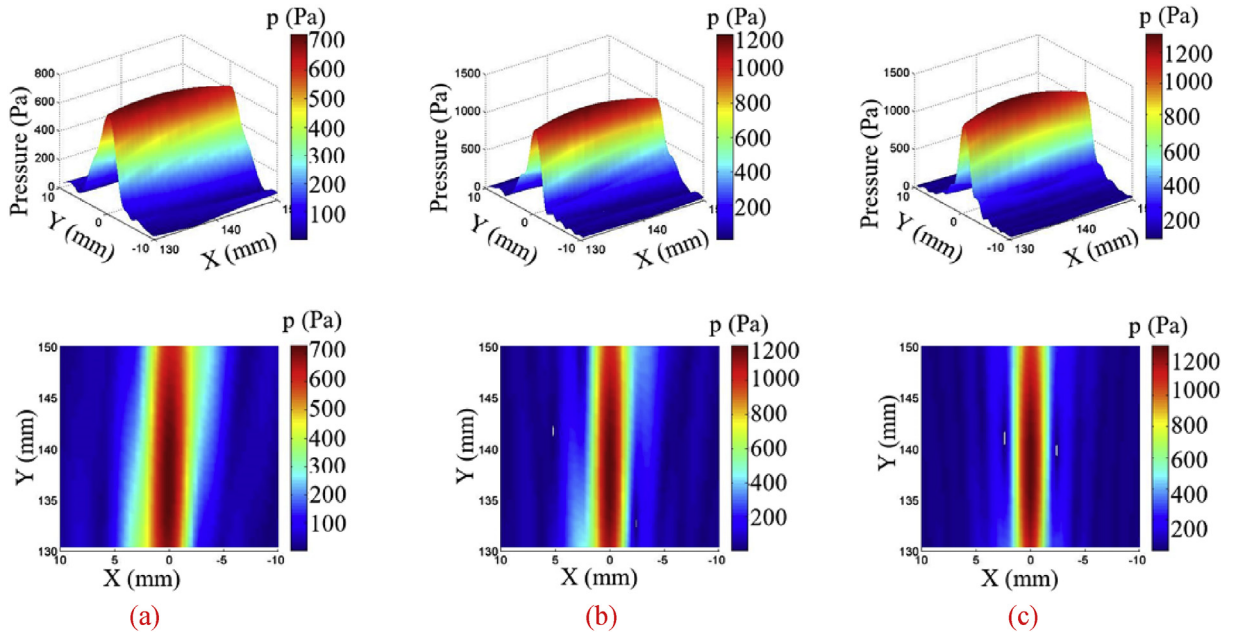


Fig. 17. Ultrasound pressure field in the plane P4 = 130–150 mm at (a) 325, (b) 362.5, and (c) 400 kHz.

A specific example of the performed measurements is shown in Fig. 20, where the radiation pressure field measured by the acoustic microphone at $\Delta f = 372$ Hz (i.e., the resonance frequency of the first mode of a test structure to be investigated in future test planned to validate this technique) is shown [55].

The results indicate that the radiation pressure field has a spot size of ~ 3 mm in diameter (the size of the focal spot is delimited by the area in which the ratio of pressure to the peak value is higher than 0.2), analogous to the dimension shown in the BEM simulation. In particular, it can be observed that the acoustic spot has a peak value of ~ 1.2 Pa and it is offset and located at (1.5, 0) mm when viewed from the front, rather than in the geometrical center. The offset can be attributed to a misalignment between the FUT and the measuring microphone.

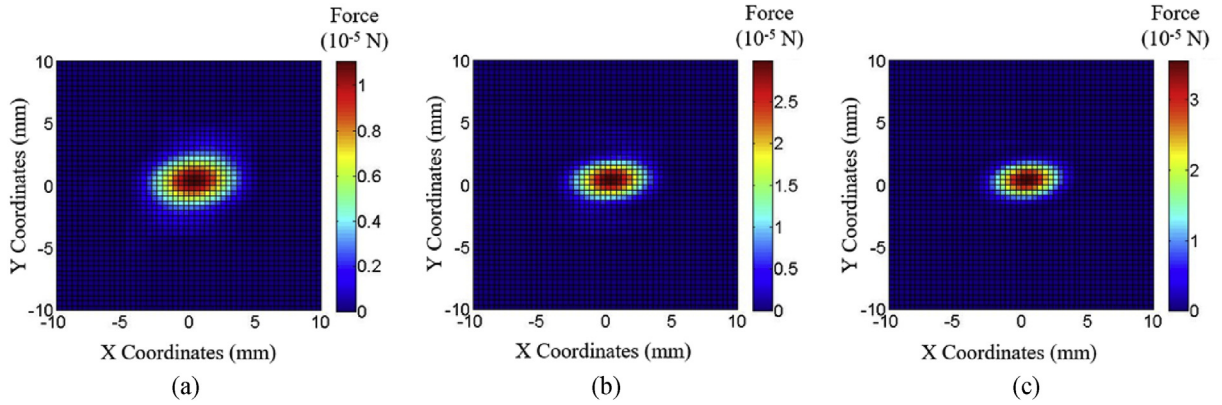


Fig. 18. Quantification of ultrasound radiation force $F_{\Delta f}(r, t)$ acting on a test article 140 mm away from the FUT for three frequencies: (a) 325 kHz, (b) 362.5 kHz, and (c) 400 kHz.

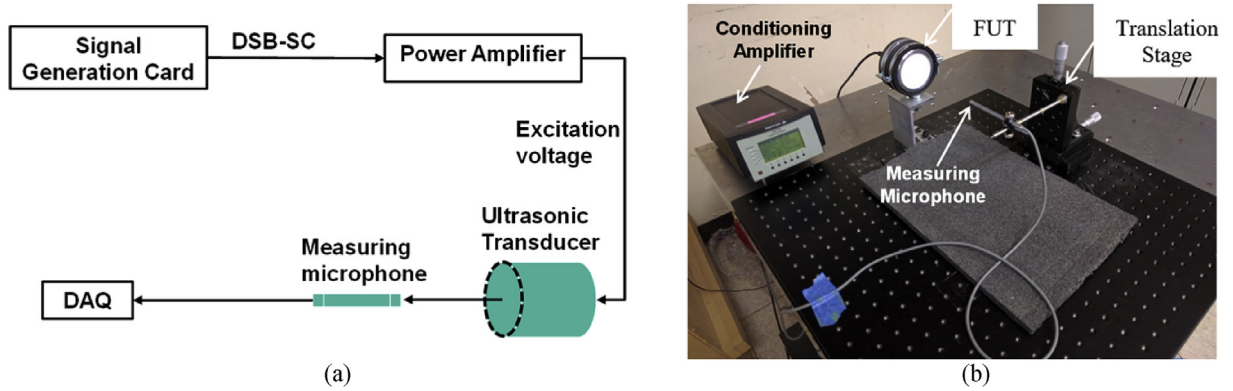


Fig. 19. Radiation pressure mapping using acoustic microphone: (a) Schematic diagram, (b) experimental setup.

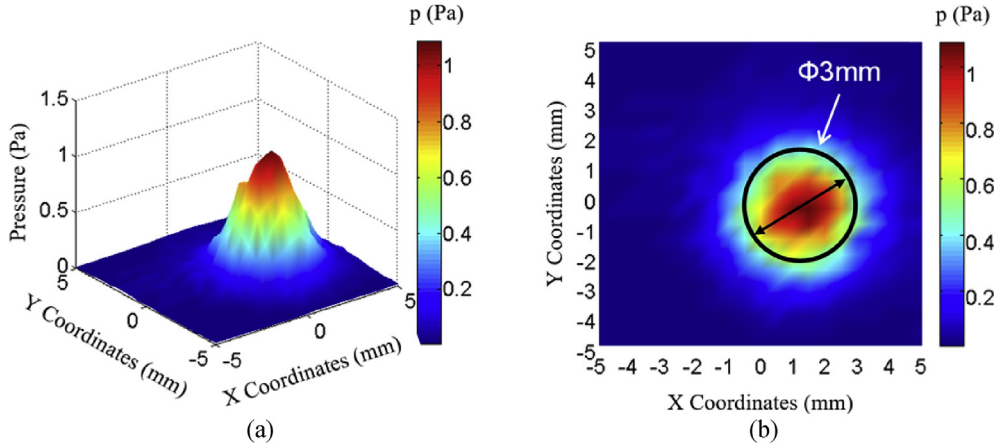


Fig. 20. Radiation pressure field at $\Delta f = 372$ Hz in the focal plane. (a) Isometric view; (b): Front view.

Using Eq. (5), the force distribution in the focal plane of the FUT can be calculated from the results shown in Fig. 20. The radiation force distribution is shown in Fig. 21, where it is possible to observe that its maximum intensity is equal to 2.5×10^{-5} N, similar to the value calculated using the BEM and shown in Fig. 18b.

5. Conclusions

Ultrasonic non-contact excitation of structures for experimental modal analysis would avoid some of the issues such as mass-loading and coupling effects that characterize traditionally used methods, and it would make possible for high-

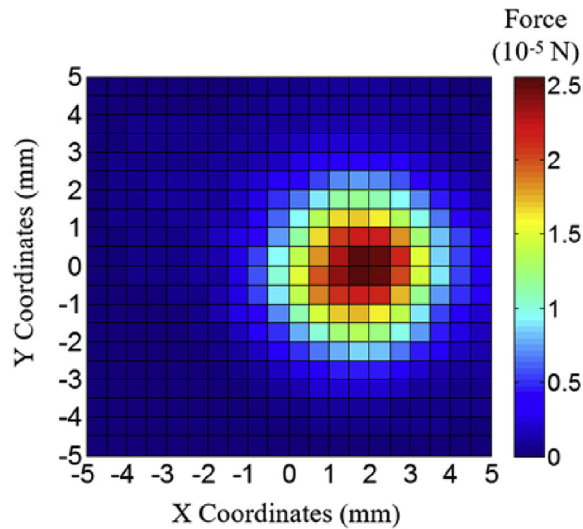


Fig. 21. Ultrasound radiation force distribution obtained from the radiation pressure field shown in Fig. 20.

frequency excitation (i.e., above 40 kHz) on small-sized structures. In this research, a focused air-coupled ultrasonic transducer is quantified and evaluated for achieving structural excitation and performing a modal analysis. Having a good understanding of the force applied is essential to assess its Frequency Response Function and calculate the structures' true dynamic characteristics and modal parameters of interest (e.g., natural frequencies, mode shapes, damping, etc.). The study includes the evaluation of the force imparted by the transducer on the test object. In this paper, the airborne acoustic pressure field generated by a focused ultrasound transducer (FUT) is characterized both experimentally and numerically and used for calculating the acoustic radiation force generated on a test article. Since experimentation has suggested that the FUT's location and size of the focal point have frequency dependency, the acoustic pressure field generated by the transducer in the lower frequency range (i.e. 50–80 kHz) has been experimentally mapped with an acoustic microphone and compared with that calculated by an acoustic BEM model based on the Rayleigh Integral. The model, using the distributed surface vibration of the transducer, has then been used to simulate the radiated sound pressure field with excitation in a high-frequency range (i.e., 300–400 kHz). As operated at those frequencies, the transducer has been found to have an acoustic spot diameter of ~3 mm, an extended focal region (i.e., more than 20 mm in length) where the pressure is substantially uniform and higher than 1000 Pa. The proposed method was also shown to be accurate in predicting the direct acoustic force generated by the FUT as it is excited using a double sideband suppressed carrier amplitude modulation (DSB-SC AM) signal, a method that allows using ultrasound frequency carrier signals to excite the dynamic response of a structure in the frequency range of interest for modal analysis. The measured velocity FRFs of a FUT is used in combination with a boundary-element model to predict pressure distributions of a FUT, and that data was used to determine the input force acting on an excited structure.

Future work will focus on using the theoretically quantified and experimentally verified focused ultrasound radiation force for modal testing and exciting target test structures. Since frequencies of interest for structural dynamics applications have a frequency bandwidth from tens of Hertz to up to 100 kHz, the effect of the higher frequencies modulated signals has to be investigated as well. Starting at a frequency of ~50 kHz, the effects of a parametric array in the radiation force have to be taken into account in the developed boundary element method model. Those effects were not found to be a factor in the research performed, but cannot be excluded entirely under other signal generation conditions. Therefore, further studies in this direction need to be implemented. The knowledge gained about the characteristics of the force imparted to the structure will be used for acquiring FRFs to obtain modal parameters including structural resonance frequencies, damping, and mode shapes. Using the proposed approach, it should be possible to use the quantified input force, apply excitation without loading the structure, and perform excitation over a broad frequency range by merely sweeping the difference frequency of the AM signal to the ultrasound transducer.

Acknowledgments

This work was funded by the NSF Civil, Mechanical and Manufacturing Innovation (CMMI) Grant Nos. 1266019 and 1300591 entitled "Collaborative Research: Enabling Non-contact Structural Dynamic Identification with Focused Ultrasound Radiation Force". Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the particular funding agency.

Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.jsv.2018.06.028>.

References

- [1] P. Avitabile, Experimental modal analysis, *Sound Vib.* 35 (1) (2001) 20–31.
- [2] D. Cloutier, P. Avitabile, R. Bono, M. Peres, Shaker/stinger effects on measured frequency response functions, in: *Proceedings of the XXVII International Modal Analysis Conference*, 9–12 February, Orlando, FL, 2009.
- [3] T.M. Huber, N.M. Beaver, J.R. Helps, Noncontact modal excitation of a classical guitar using ultrasound radiation force, *Exp. Tech.* 37 (4) (2013) 38–46.
- [4] E. Jampole, N. Spurgeon, T. Avant, K. Farinholt, Characterization of bio-inspired synthetic hair cell sensors, in: R. Allemang, J. De Clerck, C. Niezrecki, J. Blough (Eds.), *Topics in Modal Analysis II*, vol. 6, Springer, New York, 2013, pp. 137–152.
- [5] R.L. Clark, C.R. Fuller, A.L. Wicks, Characterization of multiple piezoelectric actuators for structural excitation, *J. Acoust. Soc. Am.* 90 (1) (1991) 346–357.
- [6] V. Giurgiutiu, A.N. Zagrai, Embedded self-sensing piezoelectric active sensors for on-line structural identification, *Trans. Am. Soc. Mech. Eng. J. Vib. Acoust.* 124 (1) (2002) 116–125.
- [7] Y.F. Xu, W.D. Zhu, Operational modal analysis of a rectangular plate using noncontact acoustic excitation, in: E.B. Zimmerman (Ed.), *Rotating Machinery, Structural Health Monitoring, Shock and Vibration*, vol. 5, Springer, New York, 2011, pp. 359–374.
- [8] Y.F. Xu, W.D. Zhu, Operational modal analysis of a rectangular plate using non-contact excitation and measurement, *J. Sound Vib.* 332 (20) (2013) 4927–4939.
- [9] M. Fatemi, J.F. Greenleaf, Vibro-acoustography: an imaging modality based on ultrasound-stimulated acoustic emission, *Proc. Natl. Acad. Sci. Unit. States Am.* 96 (12) (1999) 6603–6608.
- [10] M.W. Urban, M. Fatemi, J.F. Greenleaf, Modulation of ultrasound to produce multifrequency radiation force a, *J. Acoust. Soc. Am.* 127 (3) (2010) 1228–1238.
- [11] T.M. Huber, S.M. Batalden, W.J. Doebl, Measurement of vibration resulting from non-contact ultrasound radiation force, in: M. Mains (Ed.), *Topics in Modal Analysis*, vol. 10, Springer, New York, 2015, pp. 87–92.
- [12] S. Maruvada, G.R. Harris, B.A. Herman, R.L. King, Acoustic power calibration of high-intensity focused ultrasound transducers using a radiation force technique, *J. Acoust. Soc. Am.* 121 (3) (2007) 1434–1439.
- [13] Y. Zhou, Acoustic power measurement of high-intensity focused ultrasound transducer using a pressure sensor, *Med. Eng. Phys.* 37 (3) (2015) 335–340.
- [14] P.L. Marston, Shape oscillation and static deformation of drops and bubbles driven by modulated radiation stresses—Theory, *J. Acoust. Soc. Am.* 67 (1) (1980) 15–26.
- [15] S. Zhao, J. Wallaschek, A standing wave acoustic levitation system for large planar objects, *Arch. Appl. Mech.* 81 (2) (2011) 123–139.
- [16] C. Chen, J. Wang, B. Jia, F. Li, Design of a noncontact spherical bearing based on near-field acoustic levitation, *J. Intell. Mater. Syst. Struct.* 25 (6) (2014) 755–767.
- [17] S. Chen, M. Fatemi, J.F. Greenleaf, Remote measurement of material properties from radiation force induced vibration of an embedded sphere, *J. Acoust. Soc. Am.* 112 (3) (2002) 884–889.
- [18] A. Alizad, D. Whaley, J.F. Greenleaf, M. Fatemi, Critical issues in breast imaging by vibro-acoustography, *Ultrasonics* 44 (2006) e217–e220.
- [19] M. Fatemi, J.F. Greenleaf, Ultrasound-stimulated vibro-acoustic spectroscopy, *Science* 280 (5360) (1998) 82–85.
- [20] F.G. Mitri, P. Trompette, J.Y. Chapelon, Detection of object resonances by vibro-acoustography and numerical vibrational mode identification, *J. Acoust. Soc. Am.* 114 (5) (2003) 2648–2653.
- [21] X. Zhang, M. Zeraati, R.R. Kinnick, J.F. Greenleaf, M. Fatemi, Vibration mode imaging, *IEEE Trans. Med. Imag.* 26 (6) (2007) 843–852.
- [22] A.J. Livett, E.W. Emery, S. Leeman, Acoustic radiation pressure, *J. Sound Vib.* 76 (1) (1981) 1–11.
- [23] B.T. Chu, R.E. Apfel, Acoustic radiation pressure produced by a beam of sound, *J. Acoust. Soc. Am.* 72 (6) (1982) 1673–1687.
- [24] P.J. Westervelt, The theory of steady forces caused by sound waves, *J. Acoust. Soc. Am.* 23 (3) (1951) 312–315.
- [25] S. Chen, G.T. Silva, R.R. Kinnick, J.F. Greenleaf, M. Fatemi, Measurement of dynamic and static radiation force on a sphere, *Phys. Rev. E* 71 (5) (2005), 056618.
- [26] A.A. Doinikov, Theory of acoustic radiation pressure for actual fluids, *Phys. Rev. E* 54 (6) (1996) 6297.
- [27] G.T. Silva, S. Chen, J.F. Greenleaf, M. Fatemi, Dynamic ultrasound radiation force in fluids, *Phys. Rev. E* 71 (5) (2005), 056617.
- [28] F.E. Borgnis, Acoustic radiation pressure of plane compressional waves, *Rev. Mod. Phys.* 25 (3) (1953) 653.
- [29] J.A. Rooney, W.L. Nyborg, Acoustic radiation pressure in a traveling plane wave, *Am. J. Phys.* 40 (12) (1972) 1825–1830.
- [30] Z.Y. Hong, W. Zhai, N. Yan, B. Wei, Measurement and simulation of acoustic radiation force on a planar reflector, *J. Acoust. Soc. Am.* 135 (5) (2014) 2553–2558.
- [31] K.Y. Jhang, Nonlinear ultrasonic techniques for nondestructive assessment of micro damage in material: a review, *Int. J. Precis. Eng. Manuf.* 10 (1) (2009) 123–135.
- [32] K. Nightingale, Acoustic radiation force impulse (ARFI) imaging: a review, *Curr. Med. Imag. Rev.* 7 (4) (2011) 328–339.
- [33] B.J. Schwarz, M.H. Richardson, Introduction to operating deflection shapes, *CSI Reliability Week* 10 (1999) 121–126, Orlando, FL.
- [34] T.M. Huber, M. Fatemi, R. Kinnick, J.F. Greenleaf, Noncontact modal analysis of a pipe organ reed using airborne ultrasound stimulated vibrometry, *J. Acoust. Soc. Am.* 119 (4) (2006) 2476–2482.
- [35] T.M. Huber, D. Calhoun, M. Fatemi, R.R. Kinnick, J.F. Greenleaf, Noncontact modal testing of hard-drive suspensions using ultrasound radiation force, *J. Acoust. Soc. Am.* 118 (3) (2005) 1928.
- [36] T.M. Huber, B.C. Abell, D.C. Mellema, M. Spletzer, A. Raman, Mode-selective noncontact excitation of microcantilevers and microcantilever arrays in air using the ultrasound radiation force, *Appl. Phys. Lett.* 97 (21) (2010), 214101.
- [37] H. Olsen, H. Wergeland, P.J. Westervelt, Acoustic radiation force, *J. Acoust. Soc. Am.* 30 (7) (1958) 633–634.
- [38] G.T. Silva, S. Chen, L.P. Viana, Parametric amplification of the dynamic radiation force of acoustic waves in fluids, *Phys. Rev. Lett.* 96 (23) (2006), 234301.
- [39] G.T. Silva, Dynamic radiation force of acoustic waves on solid elastic spheres, *Phys. Rev. E* 74 (2) (2006), 026609.
- [40] S. Chen, M. Fatemi, R. Kinnick, J.F. Greenleaf, Comparison of stress field forming methods for vibro-acoustography, *IEEE Trans. Ultrason. Ferroelectrics Freq. Contr.* 51 (3) (2004) 313–321.
- [41] E.C. Elegbe, M.G. Menon, S.A. McAleavey, Comparison of two methods for the generation of spatially modulated ultrasound radiation force, *IEEE Trans. Ultrason. Ferroelectrics Freq. Contr.* 58 (7) (2011) 1344–1354.
- [42] M.W. Urban, G.T. Silva, M. Fatemi, J.F. Greenleaf, Multifrequency vibro-acoustography, *IEEE Trans. Med. Imag.* 25 (10) (2006) 1284–1295.
- [43] G.T. Silva, M.W. Urban, M. Fatemi, Multifrequency radiation force of acoustic waves in fluids, *Phys. D Nonlinear Phenom.* 232 (1) (2007) 48–53.
- [44] A.P. Sarvazyan, O.V. Rudenko, S.D. Swanson, J.B. Fowlkes, S.Y. Emelianov, Shear wave elasticity imaging: a new ultrasonic technology of medical diagnostics, *Ultrasound Med. Biol.* 24 (9) (1998) 1419–1435.
- [45] F.G. Mitri, J.F. Greenleaf, M. Fatemi, Chirp imaging vibro-acoustography for removing the ultrasound standing wave artifact, *IEEE Trans. Med. Imag.* 24 (10) (2005) 1249–1255.
- [46] Y. Hu, D. Zhang, H. Zheng, X. Gong, Chirp excitation technique to enhance microbubble displacement induced by ultrasound radiation force, *J. Acoust. Soc. Am.* 125 (3) (1999) 1410–1415.

- [47] A.L. Baggio, H.A. Kamimura, J.H. Lopes, A.A. Carneiro, G.T. Silva, Parametric array signal in confocal vibro-acoustography, *Appl. Acoust.* 126 (2017) 143–148.
- [48] D. Blackstock, *Fundamentals of Physical Acoustics*, John Wiley & Sons, New York, 2000, pp. 441–442.
- [49] S. Chen, C. Niezrecki, P. Avitabile, Experimental mapping of the acoustic field generated by ultrasonic transducers, in: J. De Clerck, S. David (Eds.), *Rotating Machinery, Hybrid Test Methods, Vibro-acoustics & Laser Vibrometry*, vol. 8, Springer, New York, 2015, pp. 243–254.
- [50] S. Chen, C. Niezrecki, P. Avitabile, N. Wu, X. Wang, Numerical simulation and dual experimental mapping of acoustic field generated by ultrasonic transducers, in: *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, 2016, pp. 849–856, 252(2) Providence, RI.
- [51] Non-contact Ultrasound (NCU), Phenomenally High-efficiency Transducers – 50kHz to >50MHz, Available online: <http://www.ultrangroup.com/Transducers/Catalogs/NCU.pdf>. (Accessed 31 July 2017).
- [52] PCB378C01, ICP Microphone System, Available online: <https://www.pcb.com/products.aspx?m=378C01>. (Accessed 31 July 2017).
- [53] PSV-400, Scanning Vibrometer, 1-D and 3-D Vibration Measurement, Imaging and Analysis, Available online: http://www.dbkes.com.tr/brosur/psv_400.pdf. (Accessed 31 July 2017).
- [54] S. Chen, A. Sabato, C. Niezrecki, P. Avitabile, Modeling and experimental mapping of the ultrasound pressure field generated from focused ultrasonic transducers using fiber optic acoustic sensors, in: *Proceedings of the 5th Joint Meeting of the Acoustical Society of America and Acoustical Society of Japan*, 28 November – 2 December 2016. Honolulu, HI.
- [55] P. Logan, T. Dardeno, P. Avitabile, Validation of time and frequency domain methods for calibration of non-contacting force excitation, in: S. Evro Wee (Ed.), *Sensors and Instrumentation*, vol. 5, Springer, New York, 2016, pp. 61–69.