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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

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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.

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* 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).

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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 imagining 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