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Experimental measurement of energy density in a vibrating plate and comparison with energy finite element analysis

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ABSTRACT

In this paper, a new method and formulation is presented for experimental measurement of energy density of high frequency vibrations of a plate. By use of the new proposed method and eight accelerometers, both kinetic and potential energy densities are measured. Also, a computer program is developed based on energy finite element method to evaluate the proposed method. For several points, the results of the developed experimental formulation are compared with those of the energy finite element analysis results. It is observed that, there is a good agreement between experimental results and analyses. Finally, another test setup with reduced accelerometer spacing was prepared and based on the comparison between kinetic and potential results, it is concluded that, the kinetic and potential counterparts of the energy density are equal in high frequency bands. Based on this conclusion, the measurement procedure was upgraded to an efficient and very simple one for high frequency ranges. According to the new test procedure, another experimental measurement was performed and the results had a good agreement with the EFEA results.

1. Introduction

At high frequency, where wavelengths are short, the response varies significantly as a function of location and frequency. The exact nature of this response is often not important and may disguise the general behavior of the structure. Therefore, in high frequency structural vibration analysis, approximate methods for predicting the response of the structure are often preferable to exact methods [1]. On the other hand, at high frequencies or for broadband analyses, exact solutions are computationally intensive. Also, exact solutions are very sensitive to structure details. Also, for many diagnostic and design purposes, especially in the preliminary design, knowing general behavior of the structure and a smoothed approximation of the response is often sufficient.

At high frequencies, conventional FEA methods require a very large number of elements in order to capture the high frequency characteristics of the structures, which results in very high computational costs. Statistical Energy Analysis (SEA) and Energy Finite Element Analysis (EFEA) are the two developed analysis methods for high frequency vibration analysis. In SEA, the system is partitioned into coupled "subsystems" of similar modes of vibration (longitudinal, shear, transverse,…) and the stored and exchanged energies in each subsystem are analyzed through a set of linear equations. The primary variable in SEA is the lumped averaged energy in each subsystem. A subsystem can be seen as a part or a physical element of

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the system (e.g. a beam, a plate or an acoustic cavity). In this method, energy is averaged over entire domain of each subsystem and there is no information about local variation of energy inside the subsystem.

Nowadays, EFEA has been investigated widely in academic researches to become a reliable tool for high frequency vibration analysis. This method uses the averaged energy density as the primary variable and also the energy intensity (flow) to form the governing differential equations of system energy. Energy intensity is proportional to the gradient of energy density. Energy density and intensity constitute a complete description of the energetic behavior of vibrating systems. The governing differential equation of energy of the system can be solved by finite element method. This method potentially can provide a practical approach to evaluate the structural response at high frequencies, which is difficult to reach with conventional finite element analysis because of the computational costs. It can capture the vibration behavior of the structure by using a significantly smaller number of elements compared to conventional FEA methods. Like SEA, EFEA predicts mechanical energy based on energy equilibrium equations but where SEA uses macro subsystems, EFEA uses finite elements for structural or acoustic subsystems. As a result, EFEA can predict the smooth spatial variation of the mechanical energy and the manipulation of local effects such as localized power inputs and local damping treatments is more straightforward.

Although the number of publications on applications of EFEA is growing, only few experimental investigations can be found on the validity, accuracy and robustness of this prediction tool [2].

As mentioned, EFEA is based on energy (power) flow equation in the structural/acoustic systems. Energy flow approximations were first proposed by Belov and Rybak [3] and Belov et al. [4]. In their investigations, assuming that energy from various waves is incoherent and can be superimposed, they developed simple heat equation analogies for energy flow in structures. Next, Nefske and Sung [5] developed a power flow finite element method based on these energy equations. In their research, the new method was developed as an alternative to SEA for high frequency vibration analysis. Wohlever [6] and Wohlever and Bernhard [7] investigated the thermal analogy to model mechanical power in structural systems. Energy density equations were derived from the classical displacement solutions for harmonically excited, hysteretically damped rods and beams. They also clarified approximations made and implication of the early studies of energy flow analysis. It is showed that these approximations are valid for space averages over a wavelength for bars and beams. They also imply these approximations are valid for frequency averages. Later, Bouthier and Bernhard [8–10] derived the equations of space- and time- averaged energy density and intensity in the far field and developed a set of equations that govern the space- and time- averaged energy density of plates, membranes and acoustic spaces. The equations were solved numerically and the results were validated with analytical solutions. Cho [11] solved coupling of the energy densities for various types of structures such as rods, beams, plates and acoustic cavities. In his work, he formulated EFEA system equations and calculated EFEA power transfer coefficients for coupled structures. Zhang [12] extended wave propagation approach to couple frequency analysis of finite cylindrical shells submerged in a dense acoustic medium and compared the results by numerical FEM/BEM analyses has been carried out.

There are few works on experimental investigation for high frequency vibration analysis. Most of these studies are focused on calculation and measurement of energy flow (intensity) of vibrational energy in structures. Pavic [13] discussed methods for measurement of structural wave intensities associated with various points in a wave field. He formulated methods of the measurement of structure born wave intensity for the cases of one- and two-dimensional wave propagation. Cross spectral density methods was presented by Verheij [14] to measure the structural power flow in beams and pipes. Pavic and Gavric [15] evaluated the structural intensity fields of a simply supported plate by using the finite element method. Normal mode summations and swept static solutions were employed for computation of structural intensity fields and identifying the source and the sink of the energy flow. The use of this modal superposition method was further extended as an experimental method by Gavric et al. [16]. Measurements were performed by using a test case consisted of two plates and the structural energy intensity was computed. In another work, Szwerc and Hambrich [17] developed a method for the simultaneous measurement of both longitudinal and flexural wave intensities in beams. They demonstrated that discontinuities in structures help to interchange large amounts of power between two wave types.

All previous works are concentrated to calculation of energy flow (intensity) in various types of structures by different methods. Further, there are some works which calculate energy density as the main parameter of the experiment. Nokhbatolfoghahai et al. [18] investigated experimental measurement of energy density in a beam and compared the results with those of EFEA. In their work, two methods were presented for measurement of energy density from low to high frequencies. Cho [11] calculated energy density of a light truck frame structure using EFEA and validate his calculation by experimental measurements. Unglenieks [19] implemented Cho's coupled energy flow approach into a generalized space frame finite element program and developed experimental procedures to measure the necessary parameters of the energy finite element model. Unglenieks' experimental techniques can be used to measure the intensity and energy density in a built-up structure. Bitsie [20] after implementation of structural-acoustic coupling relationship into EFEA verified his work by experimental test cases. Using structural and acoustical excitation sources, he verified EFEA energy density calculation of a flat aluminum plate adjacent to an acoustical enclosure by the experimental results. Wang et al. [21] used the transfer matrix method based on periodic structure theory to calculate transferred vibrational energy level in aircraft-like aluminum cylinder with periodic axial and circumferential stiffeners and obtained a good agreement with experimental data.

In this paper, a new formulation for extraction of energy density from experimental data is developed. An array of eight transducers with finite difference method is used to obtain energy density parameter from experimental data. Also, some considerations in the high frequency vibration measurement and analysis are explained. Finally, a comprehensive comparison between experimental measurements and EFEA calculations is presented and the results are discussed.