Composites for Vibro-Acoustics-A Review

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Abstract
In this paper literature review related to the vibro-acoustic behavior of composite panels carried out. A thorough survey that represents the effect of composite parameters such as fiber orientation, boundary conditions and fiber volume fraction on sound radiation is presented. A comparison is also presented for different fiber and matrix material combinations on the basis of their vibro-acoustic behavior. The study of vibro-acoustic cavity filled with air and at different cavity depth on the acoustic behavior of the composite panel is also debated. A survey of diverse analytical and numerical methods is also presented for the free and forced vibration analysis of a composite panel. The main concern of this paper is to present a study of sound radiation by a composite panel at different fiber-matrix material combinations along with fiber orientation and boundary conditions of the composite plate.
Keywords: composite panel, FEM, acoustic-cavity, mode shapes, natural frequency

Introduction

Composites are widely used in the manufacturing of aircrafts, spacecrafts, land vehicles and ships. The vibro-acoustic analysis of these structures plays a vital role in the design of these systems with regard to human health and living comfort. For this type of structure, it is required to couple solution that takes into account structural-acoustic interaction which is required for solutions. Many researchers are working in this field since 1960s and its vibro-acoustic analysis also been examined. Fig.1 shows the system geometry of the composite panel coupled with acoustic cavity. Many numerical techniques such as finite element method (FEM), boundary element method (BEM) or hybrid methods are introduced to study the solution of structures composed of complex geometries becomes possible.

Some researchers also solved fluid-structures interaction problems using FEM to represent both the structure and the fluid. In these leading works of the field, vibrating plates are made up of isotropic material. Composite materials are being used in most of the applications of their superior characteristics.

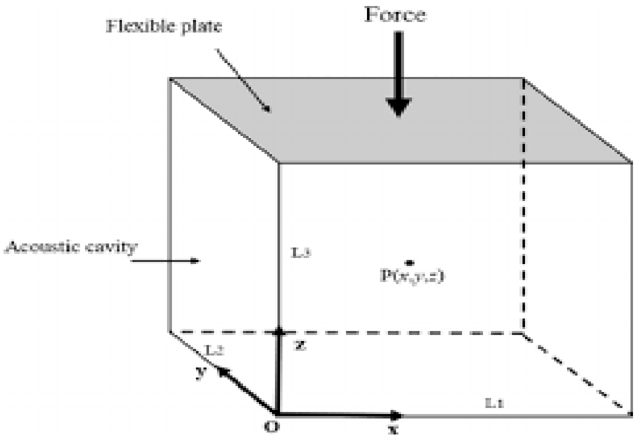

Fig.1: System Geometry

The studies of composite structures first have initiated with analyses of their mechanical and material properties. The studies include vibration and sound characteristics of various types of composites solved using different methods. The vibro-acoustics of composite wall and back cavity systems has not been extensively examined yet, though it is important for solutions in various applications. The composite plate with acoustic cabin is analysed many times by scientists on the basis of different ply angle, wall thickness, damping ratio on the boundary and interior acoustic pressure. Some scientists also presented the fundamental coupled frequencies of a plate cavity system with different composite material number of ply and ply angles obtained by FEM.

Saide et al., [1] presented the study of previous research by scientist and to include the extended higher order modes. The natural frequencies and modal characteristics of coupled composite plate-cavity system is also investigated due to the effect of coupling. This study is lead to be very helpful for the researchers working in this field. On the other hand, the coupling characteristics of isotropic and composite plate cavity system are also presented in this study.

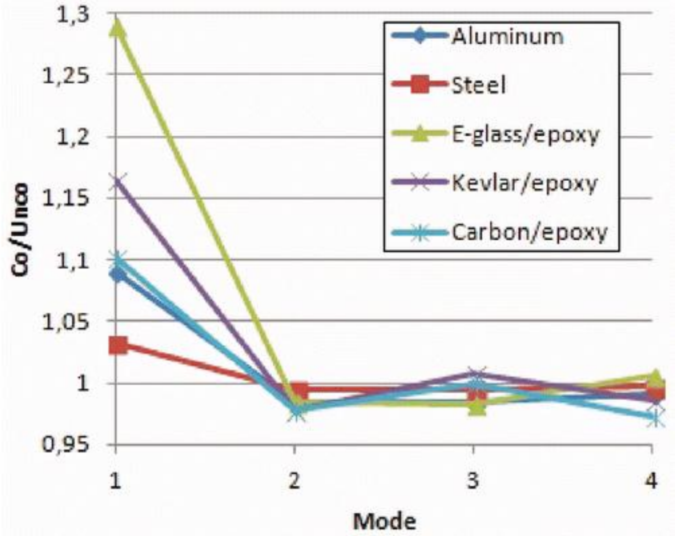

Fig.2: Comparison of the Coupled/Uncoupled frequency ratios for the first four modes of the plates with different materials [1].

Genovese et al., [2] explained a numerical and experimental study of the structural behavior and the vibro-acoustic response of an innovative composite rail vehicle car body roof. On the basis of structural and vibro-acoustic response the traditional metallic roof is compared with the new proposed solution in this paper. The vibration behaviour of the entire rail vehicle is changed due to the different stiffness and the different mass of the roof; therefore, the transmission loss is defined by the term vibro-acoustic analysis. The study results in the use of composite materials for making the sandwich structures because it provides good results in terms of weight, flexural stiffness and vibro-acoustic behaviour.

Sadri et al., [3] presented the first analytical model to investigate the vibro-acoustic behavior of sandwich structures coupled with an acoustic enclosure. The sandwich structure is coupled with an air cavity through a coupled boundary condition. Laplace domain and Durbin`s formula is used to predict the time responses of the free and forced vibro-acoustic responses of the system. The effect of parameters such as cavity depth, resilient layer stiffness, aspect ratio and thickness on the natural frequencies and the forced time and frequency responses of the mechanical system is predicted in this study.

Klaerner et al., [4] presented the sound radiation behavior in the surrounding fluid is determined by using the structural vibrations of continuous systems. Efficient numerical methods of vibration analysis such as mode-based steady state dynamic FE analysis are used to present the mathematical approaches. The energy balance in steady-state simulations is used to give the kinetic energy and thus, it is a very efficient but only qualitative measure. In addition to the previous work, the total power over frequency has been determined and applied as objective for a parameter study.

Sepahvand et al., [5] predicted the random fiber orientation by using random fields. The RFO is represented as random field by depending on spatial and random dimensions. The Karhunen-Love expansion is used to approximate the randomness in each orientation. The stochastic FEM formulation is used to develop the un-damped vibration of the FRC plates with RFO. The deterministic unknown coefficients of structural responses have to be estimated and any deterministic FEM model of the structure is used to perform the stochastic analysis.

Genc et al., [6] investigated the vibro-acoustic behaviors' of the luffa bio-composite on the basis of damping and elastic properties, sound absorption and transmission loss levels and evaluated its practical applications. The material for manufacturing the luffa composite is presented and the methods are also outlined. The impedance tube method is used to determine the acoustic absorption and transmission loss levels of sample luffa composites. By using experimental and theoretical modal data the damping and elastic properties of some sample luffa composites are also identified. The interface properties of the luffa fibres and matrix are examined using scanning electron microscope. All the results are evaluated and the potential of the use of luffa composites in practical applications is discussed.

Lee [7] and his research partners recently developed the multi-level residue harmonic balance method to solve nonlinear beam/plate problems. Only one set of nonlinear algebraic equations is generated in the zero-level solution procedure and it is the main advantage of this method. By solving a set of linear algebraic equations higher-level solutions to any desired degree of accuracy can be obtained. The number of nonlinear algebraic generated in the solutions processes in the proposed method is clearly much smaller than that in the classical harmonic method, showing that it is time saving and less complicated.

Mamtaz [8] and his research partners aims at finding the sound absorption response of natural fiber composites combined with granular materials. For the acoustic absorption purpose, the advancement from fibro-granular composites to natural fibro-granular composites is analysed in this review. In this review the physical parameters due to which the low frequency absorption in the materials is enhanced is also highlighted. The fibre diameter is reduced due to which the air flow resistivity of fibrous material get increases which in turns causes loss of sound energy through friction of sound waves with air molecules and thus improves low frequency sound absorption. The study analyses the limitations of natural fibre to achieve their acoustic absorption performance at a desired level.

Xie et al., [9] presented a unified method for modeling and predicting the vibro-acoustic features of 3D coupled structural-acoustic systems consisting of irregular acoustic enclosure with general wall impedances and an elastic plate subjected to arbitrary restrained boundaries. The structural and interior acoustical models are formulated by employing a modified variation method in conjunction with a multi-segment partitioning technique. According to the principle of compatibility and consistency, the displacement component of the thin plate and the sound pressure inside the acoustic domain are approximated in terms of 2D and 3D Chebyshev orthogonal polynomial, respectively. To reveal the beneficial abilities of the proposed method for the study of vibro-acoustic behaviour, a 3D coupled car-like model is finally examined and the present results are compared with those obtained by ANSYS.

Lee et al., [10] investigated the two physical models which contain two or more flexible panels and it is coupled with an internal air cavity. The internal panel surface is experiencing internal acoustic pressure forces within the cavity and causes the structural acoustic coupling effect and thus, panel vibration amplitudes are responsible for acoustic pressure forces. The acoustic pressure forces and the nonlinear panel responses are calculated by wave equation and Von Karman large deflection panel equation respectively. The nonlinear structural acoustic coupled governing equations of the enclosure problems are solved by using multi-level residue harmonic balance method. The effect of cavity size, vibration amplitude and excitation magnitude are examined and the transmission loss and nonlinear vibration results which are generated from two modelling techniques are compared in this study.

Li et al., [11] presented the analytical solution of the buckling and vibro-acoustic responses for fully clamped composite laminated plate in thermal environment. By applying CLT the natural frequencies, modal shapes and the analytical solutions of the buckling temperatures are firstly obtained. Then the presented theory is extended to the more accurate method of FOSDT. Finally, the vibration and acoustic responses are analysed. To validate the accuracy of the theory numerical simulations are also carried out. The influence of the temperature on the laminated plate is discussed in depth. Some conclusions related to results are also presented.

Cherif et al., [12] investigated the vibro-acoustic parameters such as wave-number, modal density, and radiation efficiency and compared it with the predictions of the general laminate model (GLM). The analysis is performed in the frequency range of 100Hz to 5 KHz. Pair of aircraft type panel are used in this validation, one is thin panel representing a trim panel or another one is thick panel representing a floor or skin panel. Both are of a honeycomb core construction. The presented experimental validation study is generic and can be used as a benchmark to validate the accuracy of other analytical or numerical models for sandwich-composite panels.

Sepahvand et al., [13] examined the vibro-acoustic response of laminated composite plates with uncertain elastic parameters by implementing generalized polynomial chaos (GPC) method. By impact of uncertainty in elastic modulus and shear modulus the radiated acoustic power and the natural frequencies of the rectangular composite laminated composite plates is investigated. The truncated GPC expansion is used to approximate the uncertain parameters with predefined orthogonal random basis. The natural frequencies are estimated by the stochastic non-intrusive collocation method which in turns used to solve the stochastic governing equations numerically. The random equivalent radiated power density at each mode is estimated by using a stochastic FEM at a set of random collocation points and GPC expansion.

Shahraeeni et al., [14] analyzed analytically the free and forced vibration of a piezoelectric laminated plate which is coupled with an acoustic cavity. This method provides a way to differentiate between the electromechanical and the acoustical properties of rectangular acoustic cavities coupled with piezoelectric laminates. This method helps in studying the vibratory behaviour in time domain.

Sadri et al., [15] examined that there is no analytical solution is developed to describe the effects of mode number, excitation frequency and vehicle parameters on the structure – borne inside rail vehicle. In the present study the noise generated inside the rail vehicle due to the random excitation of rail irregularities is predicted. For this purpose, vehicle is modelled by an acoustic enclosure with a randomly excited flexible floor. Track parameters and surface irregularity are the uncertainty due to which random vibration occurs in rail vehicles. The Galerkin-Laplace transform technique is used to predict the interior noise of the rail vehicle. The effect of parameters such as train speed, rail quality on the time and frequency response of the system is examined.

Li et al., [16] investigated the effect of harmonic force in a high temperature environment on the vibro-acoustic response of the sandwich panels constituted of orthotropic materials. The piecewise low order shear deformation theory is used to analyse the free vibration of the sandwich panels with the in-plane forces induced by thermal effects and the Rayleigh integral is applied to derive the sound pressure distribution. The accuracy of the analytical solution is validated by employing numerical simulation. Finally, the influences caused by the high temperature environment on the sandwich panels are deeply discussed.

Chandra et al., [17] evaluated the vibro-acoustic behavior of a three-layer supported sandwich plate with functionally graded (FG) core and metal-ceramic face-sheets. The first order shear deformation theory is used to estimate the structural model and the elemental radiator approach is used to analyse the acoustic behaviour of the system. The effect of graded core thickness and grading index on the vibration and acoustic properties is also presented. The benefits of having a sandwich configuration compared to an FG plate are discussed.

Koruk et al., [18] presented the sound absorption and transmission loss properties of luffa fibers and composites. The results are evaluated and the acoustic performances of the luffa materials are highlighted.

Gyani et al., [19] presented a comparison of analytical and numerical model of a composite material comprising a host medium embedded with cylindrical scatters in a 2D periodic configuration. The effective approximation method is used to predict the analytical model, whereby the composite material is modelled as a homogeneous visco-elastic material, determined by the inclusions in the composite. A finite element model of the sonic crystal array using commercial software COMSOL multi-physics is also developed. The acoustic performance of the sonic crystal obtained analytically and numerically is compared.

Djojodihardjo et al., [20] presented the application of BE-FE fluid structure interaction on a structure interaction. On a structure subject to acoustic load and to elaborate FE formulation of the computational scheme for unified approach on acoustic-aero-elastic interaction as developed earlier.

Larbi et al., [21] investigated the vibro-acoustic analysis of double wall sandwich panel with visco-elastic core. In the first part of the paper, a variation principle involving structural displacement and acoustic pressure in the fluid cavity is used to derive a non-symmetric finite element formulation of double wall sandwich panels with visco-elastic core. As a next step, the sound transmission through double wall is investigated. The second part of the paper is devoted to the development of an efficient finite element sandwich plate. In the last part, numerical examples are presented in order to validate and analyse results computed from the proposed formulations.

Sarigul et al., [22] investigated the vibro-acoustic response of thin composite plates backed by air containing cavity were performed by using finite element method (FEM). The effects of type of composite material, ply angle and number of ply on the coupled system natural frequencies were examined. A regression analysis was carried out in order to put forward the mathematical relation between these variables.

Sadri et al., [23] presented the study of nonlinear differential equation of a plate backed by an air cavity using analytical method. The results are affected by the coupling between the modes of the system. It is shown that in addition to the cavity-plate coupling, nonlinear coupling between the mode's shapes should be taken into account. Variation iteration method (VIM) is employed to solve the nonlinear equations of the system. Nonlinear natural frequencies are also determined by the use of the harmonic balance approach. Results are compared in time and frequency domains. Sensitivity of the frequency-amplitude relationship with respect to different parameters is then examined in a parametric study.

Chronopolous et al., [24] employed 2D wave finite element method (WFEM) in order to compute the sound transmission loss (STL) of thick layered structures by accounting for their symmetric and anti-symmetric wave motion. Anisotropic, multi-layered panels can be accurately modelled using this generic approach for a broadband frequency range. The resonant transmission coefficient of the panels is directly expressed in relation to the statistical energy analysis (SEA) quantities. A way for computing the reverberant field sound transmission loss (STL) of the structures directly derived by their SEA properties is also exhibited. The results are successfully compared to experimental measurement encountered in the open bibliography.

Sadri et al., [25] presented first time the nonlinear harmonic vibration of a plate-cavity system analytically and solved. Von-Karman theory is used for formulating large amplitude oscillation of the plate. By use of multiple scales method the frequency responses are analytically derived for such a coupled system. Main harmonics as well as the super-harmonics are derived in primary and secondary resonance conditions and also in the case of combinational resonance circumstances. A parametric study is then carried out and the effect of different parameters on the frequency responses is evaluated. Methodology, formulation and closed-form results can be employed by prospect researchers in extending the idea for large amplitude vibration of an air-cavity system.

Kam et al., [26] investigated the vibro-acoustics especially the sound pressure level (SPL) curves of elastically restrained shear deformable stiffened orthotropic plates are studied via both theoretical and experimental approaches. The Rayleigh-Ritz method together with the first Rayleigh integrals is used to study the vibro-acoustic behaviours and construct the SPL curve of elastically restrained shear deformable stiffened orthotropic plates. The accuracy of the experimental results obtained in this paper.

Vivolo et al., [27] presented an experimental-numerical approach to tackle the vibro-acoustic characterization of composite sandwich structures. Experimental modal analysis and acoustic insertion loss tests are carried out in order to verify the structural and acoustic numerical models of a given sandwich panel. The vibro-acoustic test rig is shown to be valuable support for the design of composite structures.

Atalla et al., [28] presented the modeling of the vibration and acoustic response of panels with attached sound packages, using both analytical and numerical methods. Special attention is developed to the modelling of various types of porous materials (rigid, limp, porous, elastic) in various mounting conditions (single wall and double wall) together with the calculation of various vibro-acoustic indicators (vibration response, radiated power, transmission loss, added damping, air-borne insertion loss, structure-borne insertion loss…) under various excitations (acoustical, mechanical and turbulent boundary layer). In particular, examples illustrating the practicality and usefulness of these methods are presented in this paper.

Omrani et al., [29] presented a brief survey of the state of the art on the analytical and experimental investigations on the acoustic absorption effects due to perforated plates and boards. A new appropriate analytical homogenized model of impedance is developed in this paper. More adapted for a composite structure with a honeycomb core covered by two micro-perforated thin shell panels. The numerical results delivered analytical model are compared to the measured results using the Kundt tube.

Dhandole and Modak., [30] reviewed a brief summary of the various numerical and experimental approaches used for predicting the low frequency sound field or noise. The numerical tools such as finite element method or boundary element method have been studied.

Samyal et al., [31] studied the modal analysis of the composite panel at different fibre orientation and at different boundary conditions. The mode shapes and natural frequency at each individual condition are examined.

Conclusion

This work summarized and contained review of major development in various analytical, numerical and experimental methods for predicting the vibro-acoustic analysis of a plate cavity system. The vibro-acoustic analysis of different structures such as single wall and double wall sandwich panels is carried out. A review of application of acoustic cavity to problems of vehicles interior noise is also included. The most widely used approach for the prediction of vibro-acoustic response is finite element method or boundary element method. Though the boundary element method is quite effective for exterior problems but losses one of its advantages when it comes to identifying the acoustic modal characteristics of a cavity. Vibro-acoustic modal analysis is an experimental tool that has also been used to analyse the acoustic behaviour of cavities. Experimental approach is very time consuming and uneconomical to use in an environment when evaluation of the various design alternatives is to be made. That's why there must be development of analytical approach to predict the vibro-acoustic response which will overcome the drawbacks of the experimental approach.

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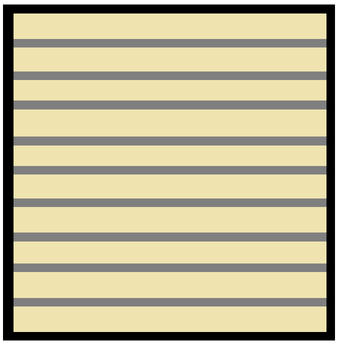

Fig.3: Composite panel at different 0˚ fibre orientation [31]

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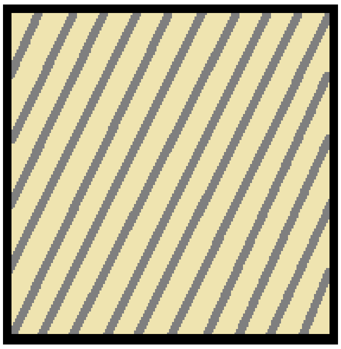

Fig.3: Composite panel at different 60˚ fibre orientation [31]

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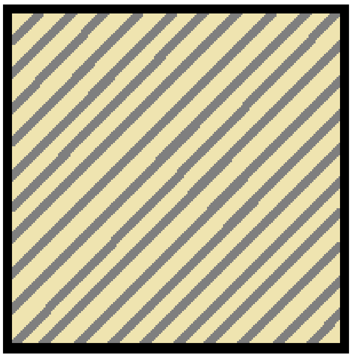

Fig.3: Composite panel at different 45˚ fibre orientation [31]

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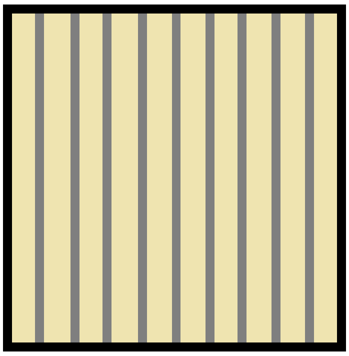

Fig.3: Composite panel at different 90˚ fibre orientation [31]

In addition, the details of formation of both the acoustic and coupled vibro-acoustic problems are presented in the review. Updating of numerical models for acoustic and vibro-acoustic applications is proposed as a suitable strategy to further improve the accuracy of vibro-acoustic predictions. The main objective of this work is to review the major developments in the field of vibro-acoustic analysis. This work serves as starting point that not only give details of approaches for vibro-acoustic analysis but also the effect of different parameters on the vibro-acoustic response of the system.

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