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Analysis of FG-CNT reinforced composite conical panel subjected to moving load using Ritz method

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ABSTRACT

Forced vibration response of a conical panel subjected to the action of a moving load is investigated in the current research. Panel is made from a carbon nanotube (CNT) reinforced composite where the CNTs as reinforcements are distributed either uniformly or functionally graded across the panel thickness. Panel is formulated using the first order shear deformation shell theory and the Donnell kinematic assumptions. It is subjected to a moving load whose path and velocity are both arbitrary. The properties of the composite media are estimated according to a refined rule of mixtures approach. The governing equations of motion of the shell are obtained according to the Ritz method where the shape functions are obtained according to the Gram-Schmidt process. The developed equations with the aid of Ritz method are transformed into time-dependent ordinary differential equations whose solution is traced in time by means of the Newmark time marching scheme. Numerical results are provided to explore the influences of semi-vertex and opening angles of the cone, geometrical parameters and also CNT characteristics of the shell. It is shown that, dynamic deflection of the shell decreases significantly with the introduction of FG-X pattern of CNTs. Furthermore, enrichment of the matrix with more CNTs alleviates the dynamic deflection of the conical shell.

1. Introduction

A novel class of composites knows as functionally graded carbon nanotube reinforced composites (FG-CNTRC) have attracted increasing attention in the past years. In this type of composites, a polymeric or metallic matrix is reinforced with carbon nanotubes. Distribution of reinforcements in the matrix is dictated according to a nonuniform distribution profile. As a result, FG-CNTRCs have the advantages of FGMs and CNTs together. The fascinating thermal and electrical properties of CNTs indicated the extraordinary features of beams, plates and shells made of FG-CNTRC. An overview of the works done on the property evaluation and structural response of FG-CNTRCs is performed by Liew et al. [1].

Shen [2] was the first who exhibited that, when CNTs are inserted into the matrix according to a functionally graded pattern, the bending response of a rectangular plate may be enhanced significantly. Shen showed that, via a specific functionally graded pattern of CNTs across the plate thickness, the bending moments within a rectangular plate induced due to the uniform lateral pressure may be alleviated significantly. This research attracted the attention of other investigators to examine the structural response of beams, plates and shells in various geometries made of FG-CNTRCs. An overview of the works on the dynamic response of FG-CNTRC flat and curved panels is provided in the subsequent review.

Based on the two step perturbation technique, suitable for simply supported plates in flexure, Wang and Shen [3,4] investigated the nonlinear and linear free vibration characteristics of FG-CNTRC plates and also sandwich plates with a hard core and FG-CNTRC face sheets. In the mentioned researches, different effects such as interaction of a two parameter elastic foundation and uniform temperature rise are also included. The developed solution method may be used for both the axially free to move and axially movable plates. Based on the first order shear deformation plate theory with Mindlin assumptions and the standard finite elements formulation, Zhu et al. [5] performed an investigation on the free vibration characteristics of FG-CNTRC plates. Different types of boundary conditions such as completely clamped and complete simply-supported are analysed in the mentioned research. Unlike the two dimensional plate theory formulations, Yas et al. [6] performed and investigation on the free vibration characteristics of FG-CNTRC thick cylindrical panels using the three dimensional theory of elasticity. In this research, panels which are completely simply supported on four edges are analysed. Using the Navier solution method, the three dimensional equations are reduced to ordinary differential equations whose solution is deduced by means of the generalised differential quadratures. Employing a higher order shear deformation plate theory, Natarajan et al. [7] discussed the free vibration of FG-

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CNTRC plates which are simply supported all around. In this investigation, a finite element procedure is developed to establish the eigenvalue problem and obtain the natural frequencies. This research confirms the fact that volume fraction of CNTs and distribution pattern of CNTs greatly affect the frequencies of the plate. To obtain the free vibration characteristics of composite laminated plates composed of FG-CNTRC lamina in an arbitrary quadrilateral shape, Malekzadeh and Zarei [8] developed a two dimensional generalised differential quadrature method. This research may be used for laminated plates with arbitrary lay-ups and number of layers of FG-CNTRC. Free vibration characteristics of cylindrical panels [9], skew plates [10] and triangular plates [11] are studied by Zhang et al. [9–11]. In the mentioned works the discreted form of the governing equations is obtained using the element free methods. The developed solution method may be used for arbitrary combinations of free, simply supported and clamped boundary conditions. In other two studies, Zhang et al. [12,13], also analysed the free vibration characteristics of plates with elastically restrained edge supports and also plates with two parallel edges simply supported and the two others arbitrary (Lévy plates). The effect of elastic foundation on the natural frequencies of rectangular plates is analysed by Zhang et al. [14]. For composite laminated plates comprising of FG-CNTRC lamina, Lei et al. [15] performed an investigation to analyse the effect of lay-up, number of layers and characteristic of CNTs on free vibration characteristics. Free vibration features of cylindrical panels under the action of rotation is investigated by Lei et al. [16]. Malekzadeh and Heydarpour [17] performed an investigation on free vibration characteristics of three layered plates where either the face sheets or the core are made of FG-CNTRC. The developed solution method is suitable only for plates with all edges simply supported. A hybrid layerwise-Navier solution method is developed to establish the eigenvalue problem. Free vibration characteristics of rectangular plates integrated with piezoelectric layers in analysed by Kiani [18]. In the mentioned work, the motion equations of the plate and the two electrostatic Maxwell equations for each of the piezoelectric layers are discreted using the conventional Ritz formulation. In this research, both the open circuit and closed circuit conditions are taken into considerations. For FG-CNTRC plates containing a centric rectangular hole, Mirzaei and Kiani [19] obtained the frequencies and discussed the effects of CNT volume fraction and CNT dispersion profile on the frequencies of the plate. It is concluded that, flexural vibrations are highly affected by the CNT dispersion profile where the in-plane frequencies are approximately independent of the CNT dispersion profile. Based on the Ritz method, where the shape functions are estimated according to the Chebyshev polynomials, Mirzaei and Kiani [20] obtained the free vibrations of shallow cylindrical panels made of FG-CNTRC. The developed solution method is suitable for panels with arbitrary combinations of boundary conditions such as free, clamped, shear diaphragm and simply supported. Kiani [21] performed an investigation on the free vibration response of FG-CNTRC skew plates with arbitrary combinations of boundary conditions. The governing equations of the plate are transformed from a rectangular coordinate system to an oblique one. Such transformation makes it easier to apply the boundary conditions of the skew plate directly. Free vibration characteristic of conical panels made of FG-CNTRC is investigated Jooybar et al. [22]. This research also takes into account the effect of uniform temperature elevation and material properties of the media are assumed to be temperature dependent. Critical buckling temperatures of the panel also may be obtained as the temperature level which results in zero natural frequency of the panel. Based on the conventional Ritz formulation, where the shape functions are estimated with the aid of the Gram-Schmidt process, Kiani [23] obtained the natural frequencies and the mode shapes of spherical shallow shells. The developed solution method may be used for arbitrary combinations of boundary conditions for the panel. The effect of intermediate point supports or those located on boundary conditions on the natural frequencies and mode shapes of the plate are investigated by Kiani [24] using an energy based method. The effect of point supports is implemented into the Hamilton principle with the aid of Lagrangian multipliers technique. Recently, Mehar et al. [25] performed an investigation on the large amplitude vibration behaviour of singly curved or doubly curved shallow shells made of FG-CNTRC in thermal environment. A finite elements solution method is developed using a higher order shear deformation shell theory.

Literature on the subject of free vibration characteristics of FG-CNTRC flat and curved paned is wealth enough as the above survey reveals. Meanwhile in comparison to free vibration, less attention is devoted to forced vibration. The force vibration response of rectangular plates with consideration of von Kármán strains is investigated by Wang and Shen [26]. In this research, a two step perturbation technique is developed to establish the dynamic motion equations of the plate with large displacements and small strains. The developed formulation captures the effect of elastic foundation and thermal environment, however is suitable only for plates which are simply supported all around. The linear response of FG-CNTRC rectangular plates subjected to uniform or nonuniform sudden dynamic loads is studies by Lei et al. [27] using a mesh free method. Thomas and Roy [28] applied an eight-noded shell element to the motion equations of a doubly curved FG-CNTRC panel. Attention is devoted to damping and settle times of the dynamic response of the doubly curved panel. The response of a rectangular plate subjected to the action of a moving load is studied by Malekzadeh et al. [29]. The solution method is based on the finite elements formulation. Also Malekzadeh and Dehbozorgi [30] performed a throughout investigation on the dynamic response of a skew plate made of FG-CNTRC materials subjected to the lateral low velocity impact of a single mass. Recently, Kiani [31] analysed the response of cylindrical panels subjected to the action of a moving load. It is shown that, the dynamic deflections of the shell alleviate significantly with the enrichment of matrix with more CNT or through introduction of a proper functionally graded pattern of CNTs. Zarei et al. [32] analysed the dynamic response of rectangular plates subjected to the action of multiple impacts using the conventional Ritz method where the shape functions are chosen as simple polynomials. For more works on the mechanics of carbon nanotube reinforced composite and functionally graded plates one may refer to [33–59].

The above literature review indicates that the dynamic response of plates and shells made of FG-CNTRC has been the subject of a limited number of researches. Also, the dynamic response of FG-CNTRC plates and shells under the action of a moving load is studied only for flat plates and cylindrical panels. As the above literature survey accepts and according to the best of the present author knowledge, the dynamic behaviour of a conical panel under the action of a single moving load is not reported yet. Present study deals with the dynamic response of the conical panel made of FG-CNTRC. Panel is subjected to a single moving load which passes through the panel surface with arbitrary velocity and arbitrary path. The mechanical properties of the panel are estimated according to a refined rule of mixtures approach. The discreted motion equations of the panel are obtained via the Ritz method where the shape functions are constructed by means of the simple polynomials. The time dependent motion equations are solved via the β-Newmark time marching scheme. Results are given to explore the geometrical characteristic of the shell and also CNT properties on the temporal evolution of displacement. It is shown that, deflection of the panel decreases significantly with the introduction of CNTs through a proper functionally graded pattern.

2. Basic formulation

Consider a circular conical panel made of FG-CNTRC of thickness h, end radii $R_1 < R_2$, slanted length L, subtended angle θ_0 and vertex half angle α. The meridional, circumferential, and normal directions of the shell are denoted by x, θ, and z, respectively. The adopted coordinates system (x, θ, z), geometric characteristics, and sign convention of the cone are depicted in Fig. 1.