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Study of non-linear dynamic behavior of open cracked functionally graded Timoshenko beam under forced excitation using harmonic balance method in conjunction with an iterative technique

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The nonlinear modeling and subsequent dynamic analysis of cracked Timoshenko beams with functionally graded material (FGM) properties is investigated for the first time using harmonic balance method followed by an iterative technique. Crack is assumed to be open throughout. During modeling, nonlinear strain–displacement relation is considered. Rotational spring model is adopted in order to model the open cracks. Energy formulations are established using Timoshenko beam theory. Nonlinear governing differential equations of motion are derived using Lagrange's equation. In order to incorporate the influence of higher order harmonics, harmonic balance method is employed. This reduces the governing differential equations into nonlinear set of algebraic equations. These equations are solved using two different iterative techniques. Methodology is computationally easier and efficient as well. This is observed that although assumption of simple harmonic motion (SHM) simplifies the problem, it yields to erroneous results at higher amplitude of motion. However, accuracy of the solution is improved considerably when the contribution of higher order harmonic terms are considered in the analysis. Results are compared with the available results, which confirm the validity of the methodology. Subsequent to that a parametric study on influence of forcing term, material indices and crack parameters on large amplitude vibration of Timoshenko beams is performed for two different boundary conditions.

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1. Introduction

The beam-like structures in engineering applications are very often subjected to dynamic loadings causing large amplitude motion. Vibration analysis of such systems has drawn attention of researchers due to its non-linear strain-displacement nature, which alters the dynamic response from the linear response, inducing jump phenomenon, amplitude dependence of frequencies [1]. Numerous methods based on analytical, semi analytical and numerical techniques have been proposed addressing the nonlinearities on forced and free vibration problem for beam-like structures. Perturbation methods such as multiple time scale, multi dimensional Lindstedt Poincare method are used in order to obtain transient as well as steady-state response of such systems [2]. Lau and Cheung [3] in 1981 proposed an amplitude incremental variational method

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named as incremental harmonic balance method to get a steady-state solution for weak as well as strong nonlinearities. Subsequently, Lau et al. [4] clubbed multiple time scale and incremental harmonic balance method in order to obtain aperiodic solution. Ewing and Mirsafian [5] proposed an analytical model to study the forced vibration response of two beams joined with nonlinear rotational joint using harmonic balance method. Fung and Chen [6] studied free and forced vibration of Euler-Bernoulli beam in contact with a cylindrical foundation. Governing nonlinear ordinary differential equations are derived and are solved using Runge–Kutta algorithm. Succeeding to previous work, Azrar et al. [7] used the spectral analysis, Lagrange's equation and harmonic balance method in order to study large amplitude forced vibration problem of beams for different excitation pattern. Luongo et al. [8] proposed a unified approach to study the planer forced vibration of shear indeformable beams with or without axial constraints. Response curves and stability analysis is reported by deducing a single nonlinear differential equation and subsequently solving it by multiple time scale method. A very interesting and detailed study on transition of hardening and softening behaviours of nonlinear free vibration of thin and thick beams based on asymptotic analysis are reported by Lenci et al. [9]. Authors have explored various aspects of transition of hardening and softening behaviours depending upon various axial constraints and slenderness. Later Lenci and Rega [10] extended the work for axial transversal coupling and reported that how nonlinear free vibration behaviour changes from hardening to softening and vice versa by inclusion of axial oscillation compared to uncoupled motion. In their later study, Clementi et al. [11] compared two different approximate methods, one based on analytical approach obtained by asymptotic development method, another on numerical method using finite element method for various aspect of hardening and softening behaviour of nonlinear free vibration of beams for different axial boundary conditions and slenderness. Ribeiro [12] used shooting, Newton and p-version, hierarchical finite element methods to find out geometric nonlinear forced vibration of beams and plates.

Functionally graded materials (FGM) have been the area of interest for researchers in recent times as such material behaves tremendously well at adverse operating conditions in many engineering sectors such as space vehicles, aerospace, automotive, biomedical, optics, electronics, and military applications. Therefore it becomes necessary to study the forced vibration response of such materials under their typical application. Xiang and Yang [13] used Timoshenko beam theory in order to formulate free and forced vibration problem of a laminated FGM beam of variable thickness in thermal influence. Thermo-elastic equilibrium equations and dynamic equations are solved numerically. Simsek and Kocaturk [14] studied free and forced vibration under concentrated moving harmonic load of Euler–Bernoulli beam where material property varies continuously in thickness direction following exponential and power law. Azadi [15] used finite element method to find out free and forced vibration response of a temperature dependent FGM beam.

A flaw in structures such as cracks alters the dynamic response of a structure by inducing a change in the local stiffness [16]. Chondros et al. [17] proposed a continuous cracked beam vibration theory. Effects of such crack on linear as well as nonlinear free vibration response for isotropic and FGM beams are well explained by various authors [18-23]. Panigrahi and Pohit [18] studied the free vibration problem for a cracked FGM beam using Ritz method followed by an iterative technique. Some of the researchers focused on the study of forced vibration response of such damaged beams. Khiem and Lien [24] proposed a methodology based on dynamic stiffness matrix method in order to determine forced vibration response of multiple cracked beams. Radhakrishnan [25] studied response of a cracked cantilever beam to free and forced vibrations. Loutridis et al. [26] simulated the forced vibration of the beams with breathing crack by simplifying the beam as a spring mass model. Sadettin [27] analyzed free and forced vibration response of single and double cracked isotropic beam. Wu [28] proposed an iterative method in order to analyze forced vibration response of a damaged beam with breathing crack. Yan and Yang [29] and Yang et al. [30] proposed an analytical method for forced vibration problem of an FGM cracked beam with a transverse load moving longitudinally and an axial compressive load. Simsek [31] used implicit integration method in order to study the forced vibration response with moving harmonic load for a FG beam. Gupta et al. [32] proposed a method to solve cubic nonlinearity vibration problem by modifying nonlinear terms.

Considering the advance features of FGM beams, it becomes essential to assess health condition of this kind of structures under different operating conditions. It is evident from the literature review that a very few work have been devoted on forced vibrational response of cracked FGM beam most of the works have focused on small amplitude of motion only. It is found that various aspects considering different crack positions and load positions for such problems are yet to be explored. In addition to that there must be an approach to study these effects following a relatively accurate method. Most of the available literatures considered a simple harmonic motion for the analysis purpose, which gives a reasonable solution. However, accuracy needs to be improved considering the influence of the higher harmonics as well. In the present work an attempt is made to capture the influence of various parameters mentioned above with the improved level of accuracy by proposing an easier and computationally efficient method to capture large amplitude forced vibration response of a cracked beam having FGM properties. The method uses harmonic balance method in conjunction with an iterative technique. The analysis is carried out using two different iterative techniques, namely, direct substitution method and multidimensional Broyden's algorithm. It is also found that considering simple harmonic motion assumption, the problem is simplified. However, for large amplitude vibration, simple harmonic assumption yields to erroneous results. In order to improve the accuracy of the results, harmonic balance method is adopted. It is observed that with higher number of harmonic terms, accuracy of results improves to a considerable extent. Subsequently, this methodology is followed to obtain the influence of crack depth, material indices and different loadings on the frequency–amplitude response and nonlinear mode shapes of an FGM beam under two different boundary conditions clamped-clamped(C–C) and clamped-free(C–F).

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