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Dynamics of elastically connected double-functionally graded beam systems with different boundary conditions under action of a moving harmonic load

Mesut Şimşek [a,*], Sinan Cansız [b]

[a] Yildiz Technical University, Faculty of Civil Engineering, Department of Civil Engineering, Davutpaşa Campus, 34210 Esenler-Istanbul, Turkey
[b] Istanbul Aydin University, Faculty of Engineering-Architecture, Department of Civil Engineering, Florya Campus, 34295 Kucukcekmece-Istanbul, Turkey

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ABSTRACT

This paper studies the dynamic responses of an elastically connected double-functionally graded beam system (DFGBS) carrying a moving harmonic load at a constant speed by using Euler–Bernoulli beam theory. The two functionally graded (FG) beams are parallel and connected with each other continuously by elastic springs. Six elastically connected double-functionally graded beam systems (DFGBSs) having different boundary conditions are considered. The point constraints in the form of supports are assumed to be linear springs of large stiffness. It is assumed that the material properties follow a power-law variation through the thickness direction of the beams. The equations of motion are derived with the aid of Lagrange's equations. The unknown functions denoting the transverse deflections of DFGBS are expressed in polynomial form. Newmark method is employed to find the dynamic responses of DFGBS subjected to a concentrated moving harmonic load. The influences of the different material distribution, velocity of the moving harmonic load, forcing frequency, the rigidity of the elastic layer between the FG beams and the boundary conditions on the dynamic responses are discussed.

1. Introduction

The concept of functionally graded materials (FGMs) was first introduced in 1984 as ultrahigh temperature-resistant materials for aircrafts, space vehicles, nuclear and other engineering applications. Since then, FGMs have attracted much interest as heat-resistant materials. Functionally graded materials are heterogeneous composite materials, in which the material properties vary continuously from one interface to the other. This is achieved by gradually varying the volume fraction of the constituent materials. The continuity of the material properties reduces the influence of the presence of interfaces and avoids high interfacial stresses. The outcome of this is that this class of materials can survive environments with high-temperature gradients, while maintaining the desired structural integrity. Investigations on the dynamic characteristics of FG structures have been an area of intensive research over the last decade (see Refs. [1–23]).

The dynamic response of beam-type structures to moving loads has been well documented in hundreds of contributions during the past few decades, owing to their extensive use in many engineering applications, such as bridges, guideways, railroads, overhead cranes and gun-tubes. Under the action of a moving load or mass, a beam-type structure produces larger deflections and higher stresses than it does under an equivalent load applied statically. Such a structure is very important in engineering applications, especially in transportation system and in the design of machining process. Numerous previous studies have been reported in this field [24–40]. However, most of the published papers related to moving load problems are given for homogeneous beams, and research efforts devoted to vibration of FG beams under moving loads are very limited. For example, Yang et al. [41] studied free and forced vibrations of cracked FG beams subjected to an axial force and a moving load were investigated by using the modal expansion technique. Şimşek and Kocatürk [42] investigated the free and forced vibration characteristics of a FG Euler–Bernoulli beam under a moving harmonic load. Khalili et al. [43] employed the Rayleigh–Ritz method in space domain and a step-by-step differential quadrature method in time domain to study the transient response of FG beams induced by moving loads. Şimşek [44] examined dynamic deflections and stresses of an FG simply-supported beam subjected to a moving mass in the context of Euler–Bernoulli, Timoshenko and the third order shear deformation beam theories. Şimşek [45] performed the non-linear dynamic analysis of a functionally graded beam with immovable supports under a moving harmonic load. In a recent study, Yan et al. [46] studied the dynamic responses of FG Timoshenko beam with an open edge crack resting on an elastic foundation subjected to a transverse load moving at a constant speed.

A double-beam system, which consists of two parallel beams joined by innumerable coupling elastic springs and dashpots, have

* Corresponding author. Tel.: +90 2123835146; fax: +90 2123835102.
E-mail addresses: msimsek@yildiz.edu.tr, mesutsimsek@gmail.com (M. Şimşek).

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a great importance in many fields of civil and mechanical engineering. Recently, the double-beam system has been used as a new vibration absorber to control the vibration of a beam-type structure. Such a system for vibration isolation is called as a continuous dynamic vibration absorber (CDVA) [47] or dynamic absorbing beam system (DABS) [48]. A dynamic absorbing beam system (DABS) consists of a main beam, a dynamic absorbing beam and uniformly distributed-connecting springs and dampers between the main and dynamic absorbing beam [48]. The dynamic absorbing beam and viscoelastic layer between the beams are designed in order to reduce the vibration experienced by the main beam. The double-beam system is used to model floating-slab tracks, which are widely used to control vibration from underground trains [49]. In a system of the floating-slab tracks, an upper beam accounts for the rail and a lower beam corresponds to the floating slab. Railpads between the upper and the lower beams are represented by a continuous layer of springs and dashpots. In this context, Shamalta and Metrikine [50] investigated the steady-state dynamic response of an embedded railway track to a moving train. The model for the track consists of a flexible plate performing vertical vibrations, two beams that are connected to the plate by continuous viscoelastic elements and an elastic foundation that supports the plate. Further, elastically connected concentric beams are able to capture to mechanical behavior of multi-walled carbon nanotubes in nanomechanics. The elastic layers provide a linear model for inter-atomic Van der Waals forces [51]. Because of the great practical importance in the fields of aerospace, civil and mechanical engineering, the different problems associated with the free and forced vibration analysis of the elastically connected parallel-beam systems have been investigated by several researchers. For instance, free vibration analysis of two parallel simply supported beams continuously joined by a Winkler elastic layer was presented by Oniszczuk [47]. Seelig and Hoppmann [52] studied free vibration of a system of n elastically connected parallel beams with various boundary conditions. In [52], frequencies obtained from theoretical analysis were compared with those obtained from experiment. It was concluded that for the lower modes, at least up to the eighth, the agreement between the theory and experiment was very good. Kessel [53] derived the resonance conditions for an elastically connected simply-supported double-beam system in which one of the members is subjected to a moving point load that oscillates longitudinally along the beam about a fixed point along the length of one of the beams. Rao [54] examined free flexural vibration of elastically connected Timoshenko beams considering the effects of the shear deformation and the rotary inertia. Chonan [55] studied the dynamical behavior of two identical beams connected with a set of independent springs subjected to an impulsive load by using Laplace transformations. Vu et al. [56] presented an exact method for solving the vibration of a double-beam system subject to harmonic excitation. Oniszczuk [57] investigated undamped forced transverse vibrations of an elastically connected complex simply supported double-beam system. The problem was formulated and solved in the case of simply supported beams. The classical modal expansion method was applied to ascertain dynamic responses of beams due to arbitrarily distributed continuous loads. Several cases of particularly interesting excitation loadings were investigated. The dynamic response for a simply supported homogeneous isotropic double-beam system subject to a moving constant load was investigated by Abu-Hilal [58]. Zhang et al. [59] studied the free vibration and buckling of an elastically connected simply-supported double-beam system under compressive axial loading on the basis of the Bernoulli–Euler beam theory. Based on Bernoulli–Euler beam theory, the effect of compressive axial load on the properties of forced transverse vibration of an elastically connected double-beam system was investigated by Zhang et al. [60]. In this study, two different loading conditions, uniformly distributed harmonic load and a concentrated harmonic force applied at the midspan of the beam, were taken into account. Jun and Hongxing [61] developed an exact dynamic stiffness method for predicting the free vibration characteristics of a three-beam system, which is composed of three non-identical uniform beams of equal length connected by innumerable coupling springs and dashpots. On the basis of Timoshenko beam theory, Jun et al. [62] established an exact dynamic stiffness matrix for an elastically connected three-beam system, which is composed of three parallel beams of uniform properties with uniformly distributed-connecting springs among them. Ariaei et al. [63] investigated the dynamic behavior of n parallel identical elastically connected Timoshenko beam subjected to a moving load with constant magnitude. In this study, in order to decouple the governing equations, each beam was divided into $m + 1$ segments, which are separated by m intermediate connections. It leads to discontinuities at each spring location in shear force proportional to vertical displacement. In a recent study, Şimşek [64] have presented an analytical method for the forced vibration of an elastically connected double-carbon nanotube system (DCNTS) carrying a moving nanoparticle based on the nonlocal elasticity theory. A novel state-space form for studying transverse vibrations of double-beam systems, made of two outer elastic beams continuously joined by an inner viscoelastic layer, has been presented by Palmeri and Adhikari [65].

The above review clearly indicates that the majority of the aforementioned works on the elastically connected beams are related to the free vibration analysis of beams made of homogeneous material properties. Further, the works [53,57,58,63,64] related to the forced vibration of double-beam systems subjected to moving loads were limited to the particular cases of identical beams with simply-supported boundary conditions, homogeneous material properties. Also, in these works, the moving load is not harmonic, namely it is a moving load with constant magnitude. Because, the title problem with arbitrary boundary conditions and forcing functions is difficult to solve. Under certain conditions, the problem becomes tractable. Also, closed-form solutions for the forced response of damped double-beam systems can be obtained under specialized cases. The present formulation is very useful to analyze double or multiple-beam system with arbitrary forcing function and arbitrary boundary conditions including elastic support, multiple-beam system whose elements are made of different material composition, those with variable cross-section etc. The dynamic responses of the elastically connected functionally graded double-beam system (DFGBS) with the different boundary conditions of the two parallel beams to a moving harmonic load are not available in the open literature.

Therefore, based on the above discussion there is a strong encouragement to gain an understanding of the entire subject of vibration complex beam system and the mathematical modeling of such phenomena. This paper focuses on the dynamic behavior of DFGBS subjected to a moving harmonic load at a constant speed based on Euler–Bernoulli beam theory. The two parallel functionally graded (FG) beams are connected with each other continuously by elastic springs. Six elastically connected double-functionally graded beam systems (DFGBSs) having different boundary conditions, which are combination of pinned, clamped and free end supports, are considered. The point constraints of the supports are modeled as linear springs of very large stiffness. These linear springs of sufficiently large stiffness will ensure that the points where the springs attached will remain stationary during the transverse deformation of the beam. Material properties of the beams vary continuously in the thickness direction according to the power-law form. The equations of motion are derived with the aid of Lagrange's equations. The unknown functions denoting the transverse deflections of DFGBS are expressed in polynomial form.