Mechanical Systems and Signal Processing 52-53 (2015) 465–494

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

An optimal modeling of multidimensional wave digital filtering network for free vibration analysis of symmetrically laminated composite FSDT plates

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ARTICLE INFO

Article history:
Received 24 October 2013
Received in revised form
27 June 2014
Accepted 4 July 2014
Available online 28 July 2014

Keywords:
Laminated composite plate
MDWDF network
Courant–Friedrichs–Levy stability
Free vibration analysis
Augmented Lagrangian genetic algorithm
Nonlinear programming problem

ABSTRACT

The technique of multidimensional wave digital filtering (MDWDF) that builds on traveling wave formulation of lumped electrical elements, is successfully implemented on the study of dynamic responses of symmetrically laminated composite plate based on the first order shear deformation theory. The philosophy applied for the first time in this laminate mechanics relies on integration of certain principles involving modeling and simulation, circuit theory, and MD digital signal processing to provide a great variety of outstanding features. Especially benefited by the conservation of passivity gives rise to a nonlinear programming problem (NLP) for the issue of numerical stability of a MD discrete system. Adopting the augmented Lagrangian genetic algorithm, an effective optimization technique for rapidly achieving solution spaces of NLP models, numerical stability of the MDWDF network is well received at all time by the satisfaction of the Courant–Friedrichs–Levy stability criterion with the least restriction. In particular, optimum of the NLP has led to the optimality of the network in terms of effectively and accurately predicting the desired fundamental frequency, and thus to give an insight into the robustness of the network by looking at the distribution of system energies. To further explore the application of the optimum network, more numerical examples are engaged in efforts to achieve a qualitative understanding of the behavior of the laminar system. These are carried out by investigating various effects based on different stacking sequences, stiffness and span-to-thickness ratios, mode shapes and boundary conditions. Results are scrupulously validated by cross referencing with early published works, which show that the present method is in excellent agreement with other numerical and analytical methods.

1. Introduction

Advanced composite materials in structural components are finding increasingly use in aerospace structures, marine vehicles, automotive parts, and many other applications that have led to extensive research activities in the field of composite materials. This is because of their advantages in the higher stiffness-to-weight and strength-to-weight ratios, which provide designers an added flexibility to tailor the elastic characteristics of a structure without changing its physical dimensions. In some cases, the change takes the form of shifting one or several of the natural frequencies of a structure.

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http://dx.doi.org/10.1016/j.ymssp.2014.07.001
0888-3270/

In other cases, it is desired in a given mode shape or deflection. For example, composite and sandwich constructions are used in the fuselage, wings and tails of modern airplanes to obtain a resistant material with high loading capacity and low weight. Furthermore, superstructure and radar enclosure of naval ships are often built using sandwich structures; elements of buildings are constructed using sandwich elements to provide thermal insulation and structural efficiency [1–3].

Surely, the most widely used composite structures are laminates, which consist of many parallel layers fiber-reinforced composite plates, e.g. a graphite/epoxy-reinforced (or glass-reinforced) polymer composite laminate. By bonding together of these materials, the geometry of laminate can generally achieve more desirable structural properties in the mechanics and better performance than conventional materials. Due to the inherently complex mechanical behavior of laminated composite plates with the existence of different kinds of couplings between extension, shear, bending and twisting, it is often necessitated to require complex mathematical models in order to understand their dynamic responses.

As the field continues to grow in academia and industry, so the need to perform accurate, yet efficient analysis will remain high. Therefore, the future calls not only for increased understanding and more accurate modeling of composite materials but also for fresh ideas and approaches in how to predict the dynamic behaviors of the laminate. Moreover, it is equally essential to investigate how the resultant simulation models can provide an efficient, effective and most importantly economic process to speed-up the solution of the composite plate system when is compared with conventional approaches such as the commonly used finite elements.

The most popular kind of models for the system of laminate mechanics can be represented by sets of linear and/or nonlinear partial differential equations (PDEs) with properly imposed initial and boundary conditions. In most cases of complex vibration-influenced design, the equations cannot be solved analytically and so numerical approaches are sought. As far as the practical interest is concerned, it is, therefore, desirable to numerically analyze the dynamic behaviors of such PDE systems as cheaply and rapidly as possible, especially when dealing with complicated boundary conditions.

The initial and boundary values PDE systems have attracted many interests with numerical solver, e.g. finite difference (FD) [4–6], finite element (FE) [7–11], differential quadrature (DQ) [12,13], Rayleigh–Ritz [14,15], Galerkin [16], pseudo-spectral [17], Runge-Kutta [18], radial basis functions (RBFs) [6,17,19,20], and mesh-free [21]. These methods, however, have respective drawbacks in that they may be too complex mathematically for routine engineering analysis, be relatively easy to be used but only limited to some special cases, need initial trial functions, or require large amounts of computational effort and consequently high cost.

For instance, in a physical domain, despite reasonably approximate solutions desired at only a few specific points, conventional methods, e.g. FDs and FEs require a large number of grid points storage in order to get results even at or around a point of interest with acceptable accuracy. Consequently, the requirements for excessive CPU runtime and storage consumption are often unnecessarily large in such cases. Other techniques like DQ and Rayleigh–Ritz based methods, although require less computational effort as compared with FDs and FEs methods, they, however, need one to scrupulously select initial trial functions for satisfying boundary conditions prior to the consideration of the problems. Generally, the ways of selection for initial functions are not an easy task in practice.

Apart from those common drawbacks, another major concern of applying the conventional methods to the vibrational analysis of the laminated plate system is to encounter with large-scale matrices that require an extra effort and efficient transposition. More specifically, as the task usually turns out towards solving a large-scale eigenproblem whereby the eigenvalues provide the natural frequencies of the system, while each corresponding eigenvector represents the mode shapes of the system [22–24]. In most cases, the large-scale eigenvalue problem can be quite cumbersome not only for problems with many degrees of freedom requiring excessive CPU runtime and memory consumption but also imposing arbitrarily difficulty to solve. This adversity can essentially make any algorithm fail, especially when is dealing with the inverse of non-symmetric matrices [25].

A remarkable alternative approach named multidimensional wave digital filtering (MDWDF) [26–28], while is built on the same class of FDs with properties of the traveling wave formulation of lumped electrical elements [27] to achieve the solution of PDE systems, has gained a lot of interest in recent year. As is heavily involved with principles of modeling and simulation, circuit theory and MD digital signal processing, the MDWDF method natively provides a great variety of outstanding features [27], which make the concept better off to other conventional numerical techniques e.g. FDs and FEs.

Some of these features concern not only the conservation of passivity and stability [29,30], but also a suppression of parasitic oscillations and low round-off noise [31], a great level of computational parallelism [32,33], and full local inter-connectivity with the second-order accuracy [28]. We note that in a physical system, passivity is a result of energy conservation, and low round-off noise characteristics together with suppression of parasitic oscillation has essentially led to high accuracy of the algorithm proposed. Furthermore, massive parallelism combined with local inter-connectivity is inherent in nature when is performing the time step updates.

Using digital filtering techniques to model differential equations can go back to a paper by Rabenstein [34]. Since then, a great deal of researches has been conducted, both developing the theory and looking at particular applications. Research areas include conducting plates [28], acoustic and water waves phenomena [35,29,36], Maxwell's equations [28], membrane and plate bending dynamics in strength of materials [36], and many other contributions. Generally, this approach can be applied to causal and passive physical systems with finite propagation speed, i.e. PDE systems of hyperbolic type. Other types of system such as elliptic and parabolic PDEs can be dealt with too, which needs some modifications to the equations.