Mechanical Systems and Signal Processing 106 (2018) 367–394

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Static bending deflection and free vibration analysis of moderate thick symmetric laminated plates using multidimensional wave digital filters

Chien-Hsun Tseng

Department of Information Engineering, Kun Shan University, 71013, Taiwan

ARTICLE INFO

Article history:
Received 13 October 2015
Received in revised form 14 August 2017
Accepted 29 December 2017

Keywords:
Laminated composite plate
MDWDF network
Courant-Friedrichs-Levy criterion
Static and free vibration analysis
First-order shear deformation theory
Optimum shear correction factor

ABSTRACT

This paper aims to develop a multidimensional wave digital filtering network for predicting static and dynamic behaviors of composite laminate based on the FSDT. The resultant network is, thus, an integrated platform that can perform not only the free vibration but also the bending deflection of moderate thick symmetric laminated plates with low plate side-to-thickness ratios ($<=20$). Safeguarded by the Courant-Friedrichs-Levy stability condition with the least restriction in terms of optimization technique, the present method offers numerically high accuracy, stability and efficiency to proceed a wide range of modulus ratios for the FSDT laminated plates. Instead of using a constant shear correction factor (SCF) with a limited numerical accuracy for the bending deflection, an optimum SCF is particularly sought by looking for a minimum ratio of change in the transverse shear energy. This way, it can predict as good results in terms of accuracy for certain cases of bending deflection. Extensive simulation results carried out for the prediction of maximum bending deflection have demonstratively proven that the present method outperforms those based on the higher-order shear deformation and layerwise plate theories. To the best of our knowledge, this is the first work that shows an optimal selection of SCF can significantly increase the accuracy of FSDT-based laminates especially compared to the higher order theory disclaiming any correction. The highest accuracy of overall solution is compared to the 3D elasticity equilibrium one.

1. Introduction

In the past decades, composite material plays a key role in many fields of engineering applications such as aerospace, automotive, submarines, sport and health instrument applications [1,2] due to its desire properties, e.g. low specific density, high stiffness and strength-to-weight ratios, long fatigue life, etc. As applications continuously grow, the field of researches in academia and industry are often necessitated and desirable to look into better solutions fundamentally. It includes not only more accurate modeling of composite material but also fresh ideas and practical approaches for predicting the dynamic behaviors of the laminate in an efficient and effective manner.

Several laminate theories have been applied to the analysis of composite laminates in the past where a critical review of more recent works can be found in [43] with laminated theories and selective numerical methods developed. These theories primarily involving stress and/or displacement were presented to overcome various issues and explain behaviors of

E-mail address: jason.tseng.taiwan@gmail.com

https://doi.org/10.1016/j.ymssp.2017.12.044
0888-3270/

composite material more accurately for certain types of problems [3]. The classical laminated plate theory (CLPT) [21], a displacement-based theory with the Kirchhoff hypothesis, was the earlier approach adopted to analyze deformations of composite plates. Because of this assumption, the CLPT provides acceptable results only for thin isotropic plates but for thick plates it often yields under prediction of deflection and over prediction of natural frequency as well as bulking loads.

Since then, considerable efforts have gone into developing better methods to gain more accurate prediction of the composite plate static and dynamic gross response as well as for plates with being relatively thick i.e. the plate side-to-thickness ratios < 20. In general, these methods can be classified as 3D elasticity equilibrium equations [27], layerwise plate theories (LWPTs) [27,41], zigzag theories (ZZTs) [29], higher-order shear deformation plate theories (HSDTs) [43,49,50] and the first-order shear deformation theory (FSDT) [45]. Among these methods, the FSDT (or simply named the Mindlin-type theory) is by far the most popular analytical technique. The FSDT allows the computation of inter-laminar shear stresses through constitutive equations more simpler rather than costly deriving them through the equilibrium equations. Furthermore, it helps reduce the 3D coordinates elasticity model to a 2D one, while assuming linear combinations of the thickness through the entire laminate and undetermined functions of position in the reference surface.

Since the FSDT accounts only for a constant transverse shear stresses with respect to the thickness coordinate, a specific constant shear correction factor (SCF) must be added to the transverse shear forces so that the inter-laminar stresses can match those derived from the equilibrium equations. As is defined by energy considerations, the SCF plays a key role to compensate for the discrepancy through the laminate thickness between the constant stress state predicted by the FSDT and the actual one varying at least quadratically through each layer thickness [27]. The works [27,44] are typical of study using the FSDT, while others [20,42] are in an attempt to overcome some of the deficiencies of this theory (mainly because of the need for the SCF). Eventually, more accurate prediction is gained by carrying more terms in the series expansion of the displacements. In other words, a higher order (in the thickness coordinate) shear deformation theory is used.

Compared with the Mindlin FSDT-type, the HSDT-type based on the expansion of the displacement field can represent the kinematics better and yield more accurate inter-lamina stress distributions without the need for a SCF. In principle, it is possible to expand the displacement field in terms of the thickness coordinate up to any desired degree. However, the disadvantage of the HSDT approaches is that these theories involve considerably more computational effort as the number of unknowns in the model quickly becomes large, e.g. 7 unknowns in [46], 9 unknowns in [47], and 11 unknowns in [48]. Furthermore, it becomes difficult to prescribe boundary conditions for these additional terms as not coincided with the physics of the model [49]. In general, the higher order approaches make sense in theory to offer good predictions. As their equations of motion involving higher-order stress resultants are much more complicated than those of FSDT, they are, however, difficult to interpret physically and incur higher computational complexity. An overall comparison of laminated theories based on the displacement hypothesis was reviewed and investigated in [43,50].

Following from our previous attempts [14,16], we have successfully employed a multidimensional wave digital filtering (MDWDF) network for the free vibration analysis of symmetric laminated plates. The technique [7–9] basically involves principles of modeling and simulation, circuit theory and MD digital signal processing, to achieve solutions of PDE systems efficiently and effectively. A schematic flow diagram towards modeling and implementing a general MDWDF network can be viewed in Fig. 1. In particular, by adopting a Kirchhoff paradigm one can find a suitable MD lumped electrical network combined with MD inductors [7], which serve as a passage from a well-conditioned mechanical system to a passive electronic equivalent circuit. The synthesized design with its proper analogy using the standard circuit elements is a lumped network named by multidimensional Kirchhoff circuit (MDKC). Behaviors of MDKC are entirely equivalent to those of the mechanical governing equations described by sets of linear/or nonlinear time-dependent PDEs. From this lumped network, the

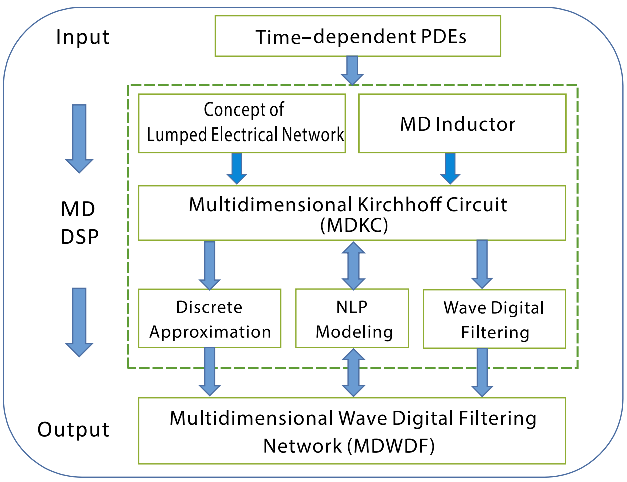

Fig. 1. A schematic flow diagram towards modeling a general MDWDF network.