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Numerical procedure for the vibration analysis of arbitrarily constrained stiffened panels with openings

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ABSTRACT: *A simple and efficient vibration analysis procedure for stiffened panels with openings and arbitrary boundary conditions based on the assumed mode method is presented. Natural frequencies and modes are determined by solving an eigenvalue problem of a multi-degree-of-freedom system matrix equation derived by using Lagrange's equations of motion, where Mindlin theory is applied for plate and Timoshenko beam theory for stiffeners. The effect of stiffeners on vibration response is taken into account by adding their strain and kinetic energies to the corresponding plate energies whereas the strain and kinetic energies of openings are subtracted from the plate energies. Different stiffened panels with various opening shapes and dispositions for several combinations of boundary conditions are analyzed and the results show good agreement with those obtained by the finite element analysis. Hence, the proposed procedure is especially appropriate for use in the preliminary design stage of stiffened panels with openings.*

KEY WORDS: Stiffened panels; Openings; Vibration analysis; Energy approach; Arbitrary boundary conditions; Assumed mode method.

INTRODUCTION

Stiffened panels are primary design members in all fields of engineering: civil, mechanical, aerospace, naval, ocean, etc. Stiffening of a plate is done to increase its loading capacity and to prevent buckling (Sapountzakis and Mokos, 2008; Cho et al., 2014). Moreover, stiffened panels are often made with openings of different shapes and sizes to reduce structural weight and to provide passage ways. This is particularly emphasized in the case of ships and offshore structures where stiffened panels with oval openings can be found. At the same time, stiffening and plate openings significantly affect the dynamic properties of such structures.

The Finite Element Method (FEM) is nowadays an advanced and widespread numerical tool and gives a complete solution to the vibration analysis of stiffened panels with openings. However, the preparation of a model is a rather time-consuming task which makes its reasonable to be applied usually at the end of the detail design stage after all the structural members, their dimensions and boundary conditions have been completely defined. In this sense, at the preliminary design stage when the principal dimensions are being selected, it is useful to have some simplified method at hand.

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A short overview of methods for the vibration analysis of plates with openings is presented by Cho et al. (2013), where the advantages and drawbacks of different methods, for instance the finite difference method (Paramasivam, 1973; Aksu and Ali, 1976), the Rayleigh-Ritz (Kwak and Han, 2007) and the optimized Rayleigh-Ritz (Grossi et al., 1997) method, FEM (Monahan et al., 1970), etc., are discussed. Moreover, Kwak and Han (2007) presented an extensive literature survey on vibration analysis of rectangular plates with openings, with particular emphasis on the application of the Rayleigh-Ritz method. They proposed a Rayleigh-Ritz based method with different coordinate systems for a plate and opening with the particular aim to simplify the integration process in the determination of total energy. In the case of stiffened panels, there is extensive literature on the static analysis of stiffened panels using FEM, the element method or a combination of these methods, as discussed by Sapountzakis and Mokos (2008). However, to the authors' knowledge, there is a rather limited number of references to the dynamic analysis of stiffened panels. Generally, the most common methods applied to the vibration analysis of stiffened plates can be classified into closed-bound solutions, energy methods and other numerical methods (Samanta and Mukhopadhyay, 2004).

In the case of the vibration analysis of stiffened panels with openings, only a few references, based on the application of the finite element method, are available. Sivasubramonian et al. (1997) studied the effect of curvature and cut-outs on square panels with different boundary conditions applying the shell element having seven degrees of freedom per node. Sivasubramonian et al. (1999) also applied the same finite element to both stiffened and unstiffened plate with openings and presented comparative results. Recently, Srivastava (2012) applied the finite element method to the vibration analysis of stiffened panels with a single opening and different boundary conditions, under partial edge loading.

In order to provide a simple and efficient procedure, this paper presents the application of the assumed mode method to the problem of natural vibration analysis of stiffened plates with openings. Namely, the assumed mode method has already been successfully applied to the vibration analysis of solid plates (Chung et al., 1993; Kim et al., 2012), plates with openings (Cho et al., 2013) and stiffened panels (Cho et al., 2014). In that sense, its application to the dynamic analysis of stiffened panels with openings represents an extension, achieved by combining the former two approaches. The effect of stiffeners is taken into account by adding their strain and kinetic energy to the strain and kinetic energy of the plate, respectively. Similarly to this strain and kinetic energies of the openings are subtracted from the corresponding energies of plate, respectively. Illustrative numerical examples include an analysis of the natural vibrations of stiffened panels with different stiffening, opening types, sizes and various values of plate thickness. In addition, different combinations of boundary conditions are examined. A comparison of the results with those obtained by the FEM is also provided and commented on. The developed procedure based on the assumed mode method is shown to be very simple and fast and, from an engineering point of view, accurate enough. It is therefore recommended for practical use in the preliminary design phase of stiffened panel structures with openings.

OUTLINE OF MATHEMATICAL MODEL

A mathematical model for the vibration analysis of stiffened panels with openings actually represents a generalization of the procedures for the vibration analysis of thick plates with openings and stiffened panels, presented by Cho et al. (2013; 2014).

The Mindlin thick plate theory which takes shear influence and rotary inertia into account (Mindlin et al., 1956) is adopted in this mathematical model. The Mindlin theory operates with three general displacements, i.e. plate deflection w, and angles of cross-section rotation about the x and y axes, ψ_x and ψ_y, respectively. From the equilibrium of sectional forces (bending moments, torsional moments and shear forces) and inertia forces, the equations of motions yield:

$$\frac{\rho h^3}{12}\frac{\partial^2\psi_x}{\partial t^2} - D\left(\frac{\partial^2\psi_x}{\partial x^2} + \frac{1}{2}(1-\nu)\frac{\partial^2\psi_x}{\partial y^2} + \frac{1}{2}(1+\nu)\frac{\partial^2\psi_y}{\partial x\partial y}\right) - kGh\left(\frac{\partial w}{\partial x} - \psi_x\right) = 0 \tag{1}$$

$$\frac{\rho h^3}{12}\frac{\partial^2\psi_y}{\partial t^2} - D\left(\frac{\partial^2\psi_y}{\partial y^2} + \frac{1}{2}(1-\nu)\frac{\partial^2\psi_y}{\partial x^2} + \frac{1}{2}(1+\nu)\frac{\partial^2\psi_x}{\partial x\partial y}\right) - kGh\left(\frac{\partial w}{\partial y} - \psi_y\right) = 0 \tag{2}$$