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Vibration isolation design for periodically stiffened shells by the wave finite element method

Jie Hong [a, b], Xueqing He [a], Dayi Zhang [a, *], Bing Zhang [c], Yanhong Ma [a, b]

[a] School of Energy and Power Engineering, Beihang University, Beijing, 100191, PR China
[b] Collaborative Innovation Center of Advanced Aero-Engine, Beihang University, Beijing, 100083, PR China
[c] Rolls Royce Composites University Technology Centre (UTC), Bristol Composites Institute (ACCIS), University of Bristol, Queen's Building, University Walk, Bristol, BS8 1TR, UK

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ABSTRACT

Periodically stiffened shell structures are widely used due to their excellent specific strength, in particular for aeronautical and astronautical components. This paper presents an improved Wave Finite Element Method (FEM) that can be employed to predict the band-gap characteristics of stiffened shell structures efficiently. An aero-engine casing, which is a typical periodically stiffened shell structure, was employed to verify the validation and efficiency of the Wave FEM. Good agreement has been found between the Wave FEM and the classical FEM for different boundary conditions. One effective wave selection method based on the Wave FEM has thus been put forward to filter the radial modes of a shell structure. Furthermore, an optimisation strategy by the combination of the Wave FEM and genetic algorithm was presented for periodically stiffened shell structures. The optimal out-of-plane band gap and the mass of the whole structure can be achieved by the optimisation strategy under an aerodynamic load. Results also indicate that geometric parameters of stiffeners can be properly selected that the out-of-plane vibration attenuates significantly in the frequency band of interest. This study can provide valuable references for designing the band gaps of vibration isolation.

1. Introduction

Thin shell structures have been widely used to reduce weight for modern mechanical systems, in particular for aeronautical and astronautical components Stiffeners are usually employed to improve the mechanical behaviour of thin shell structures, via forming a higher specific-strength structure, however, a stiffened shell structure is still susceptible to vibration. It is always difficult to suppress vibration due to natural modes inherent to the structure, in particular in the high frequency range. In engineering applications, the intense resonance may occur due to vibration and lead to severe hazards to machines [1–3].

In recent decades, a considerable amount of studies have been reported on the vibration control of periodic structures based on their band-gap properties. Due to the spatial periodicity, a “filtering” phenomenon arises in periodic structures, where vibration waves can propagate freely in pass bands, but attenuate sharply in band gaps [4]. In the open literature,

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[*] Corresponding author.
E-mail address: dayi@buaa.edu.cn (D. Zhang).

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Nomenclature

K	Blade number
k_x	Wavenumber in x direction
k_y	Wavenumber in y direction
k_α	Wavenumber in α direction
$\mathbf{k}$	Wave vector
$\Delta\alpha$	circumferential dimension for unit cell of the cylinder model
Δy	Axial dimension for unit cell of the cylinder model
λ	Propagation constant
ω	Angular frequency
Ω	Nondimensional frequency
L	Length of the structure
Γ	Kinetic energy
t_c	Thickness of the shell
t_{s1}	Width of the circumferential stiffeners
t_{s1}	Width of the axial stiffeners
h_{s1}	Height of the circumferential stiffeners
h_{s2}	Height of the axial stiffeners
R	Radius of the shell
$\mathbf{q}$	Vector for Nodal displacement
$\mathbf{F}$	Vector for Nodal force
$\mathbf{K}$	Stiffness matrix
$\mathbf{M}$	Mass matrix
K	Vibration energy proportion of different directions

characterisation of vibration band gaps in periodic structures, including beams, grids [5], plates [6] and laminated shells [7] has been examined. The vibration characteristics of free modes for a periodically stiffened shell structure with different configurations have also been investigated in Ref. [8]. Mead and his collaborators [9–11] studied different configurations of stiffeners, e.g. circumferential, axial and orthogonal stiffeners. The band-gap characteristic was plotted by the 3D phase constant surface which is the embryo of the 2D dispersion curve used nowadays. Considering the limitation of the early-stage mathematical calculation method and the oversimplification given to a real structure, more accurate methods and models were put forward later to improve the prediction accuracy. The Wave FEM was proposed in Refs. [7,12,13] that was capable of predicting the wave motion in a two-dimensional periodic structure with acceptable accuracy and negligible computational cost. However, only the boundary curvature of the structure was considered in the original Wave FEM, which limits the prediction accuracy on vibration modes. Thus, improvements are imperative for the application of the Wave FEM to more complicated structures, e.g. a periodically stiffened shell, which is studied in this paper.

The open-literature studies mentioned above aid in understanding the periodicity of shell structures from various points of view, however, little attention has been paid to the effect of excitation direction on vibration response, which is significant in engineering applications. For instance, the casing of an aero-engine, which normally features a thin stiffened shell structure, mainly undertakes radial aerodynamic loads due to the rotation of fan blades [14], thus usually showing the radial vibration with a high amplitude. The radial aero dynamical load always features a high frequency with an order of K times as large as the rotation speed, where K refers to the number of blades near to the casing. Moreover, it is quite difficult to get the global band-gap characteristics for the stiffened shell, which implies that specific or local band gaps may need to be defined. Mead [11] figured out that the bending mode band gaps may exist, which provided a strategy to classify the band gaps by directions. Bennet and Accorsi [15] made some attempts by placing capital letters above each pass band to indicate the directions of maximum displacements (radial, axial or tangential). However, the judgement criterion is rather subjective and only suitable for qualitative insight, and the influence of the curvature was also neglected. This means that a quantitative and objective method is required to select the out-of-plane wave modes. Thus, a mode selection approach based on vibration energies associated with different modes is proposed and validated in this paper.

One objective of this article is to propose an improved Wave FEM which can auto-select the mode shapes of interest, thus providing a reference for the practical application of the vibration isolation design for a stiffened shell structure. The out-of-plane mode shapes and high-frequency aero dynamical load in Engineering are of interest, e.g. from 2500 Hz to 4000 Hz. The improved Wave FEM is presented and the optimisation design based on the Genetic algorithm (GA) is adopted, leading to a fan casing with minimum weight and desired band-gap characteristics. Section 2 reviews the relevant wave concepts. Section