THE MATHEMATICAL MODELING OF FLUID STRUCTURE INTERACTIONS WITH STRUCTURAL BUCKLING

ANJU V. NAIR

Doctor of Philosophy

UNIVERSITI MALAYSIA PAHANG

SUPERVISOR'S DECLARATION

We hereby declare that We have checked the thesis and in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Doctor of Philosophy in Mathematics.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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DEDICATION

I dedicate this thesis to my parents, husband and my friends who had constantly encouraged and supported me in this long research journey.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

a	Radius of the circular plate
h	Thickness of the plate
N_r	Uniform radial edge compressive load per unit length
$N_{r_{cr}}$	Linear buckling load
$N_{r_{NL}}$	Total uniform radial edge compressive load per unit length
N_{r_T}	Uniform radial edge tensile load per unit length developed due to large lateral displacements
ΔT	Temperature rise from the stress free state
$\varepsilon_r, \varepsilon_\theta$	In-plane strains
ν	Poisson's ratio
U	Strain energy
r, θ	Radial and circumferential coordinates
W	Work done
χ_r, χ_θ	Curvatures
r_1, r_2	Internal and external radii
β	Orthotropic parameter
E_r, E_θ	Young's moduli in radial and circumferential directions
γ	Postbuckling load
b_0	Central (maximum)lateral displacement of the circular plate
u	Radial displacement
w	Lateral deflection
λ	Linear buckling load parameter
D	Plate flexural rigidity
α	Coefficient of linear thermal expansion
c	Ratio of radial tensile load parameter to critical buckling load parameter
F	Fluid domain

S_a	The surface between fluid and rigid wall
S_b	The surface between fluid and plate
S_∞	The surface at infinity
E	Young's modulus
ρ_p	Mass density of the circular plate
δ	AVMI factor
$\tilde{U}(r,\theta,z,t)$	Velocity potential
$\phi(r,z)$	Spatial distribution of the velocity potential
$f(t)$	Circular frequency of the plate with fluid
$\tilde{W}(r)$	Mode shape of the plate in contact with fluid
$W(r)$	Mode shape of the plate in air
f_a	Natural frequency of the plate
f_l	Natural frequency of the plate in contact with fluid
T_p^*	Reference kinetic energy of the plate
V_p	Maximum potential energy of the circular plate
T_l^*	Reference kinetic energy of the fluid due to motion of the plate
ω	Frequency in radians per second
∇^2	Laplace operator
Γ	NAVMI factor
ρ_l	Density of the fluid
h_0	Thickness of the centre of the plate
μ	Taper parameter of the varying curve
E_N	Residual
e_n	Derived coefficient
$\nabla\phi$	Gradient of ϕ
$\hat{n}$	Normal vector of the thickness curve
J_s	Bessel function of the first kind
r,θ,z	Radial, angular and axial coordinates
t	Time

LIST OF ABBREVIATIONS

FSI	Fluid structure interaction
AVMI factor	Added virtual mass incremental factor
NAVMI factor	Nondimensionalized added virtual mass incremental factor
FEM	Finite element method
CFD	Computational Fluid Dynamics
SMA	Shape Memory Alloy
ADINA	Automatic Dynamic Incremental Nonlinear Analysis
CAD	Computer – Aided Design
GMRES	Generalized Minimal Residual Method
LCO	Limit Cycle Oscillation
POD	Proper Orthogonal Decomposition

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ABSTRAK

Plat membulat adalah salah satu anggota utama struktur kejuruteraan yang digunakan dalam industri aeroangkasa dan pembinaan. Plat membulat biasanya dibahagikan kepada pelbagai jenis seperti ortotrop dan isotrop kerana jenis ciri-ciri bahannya. Masalah lengkok pada plat membulat yang disebabkan oleh perubahan suhu dan interaksi dengan bendalir merupakan salah satu penyelidikan yang hebat. Tesis ini bertujuan untuk memaparkan perumusan matematik dan penyelesaian berangka untuk mengkaji tindak balas realistik plat membulat ortotrop tertakluk kepada beban terma serta analisis getaran bagi plat membulat isotrop dan ortotrop yang bersentuhan dengan bendalir. Kerja penyelidikan terkini membincangkan teknik baharu perumusan matematik dalam menangani isu-isu pascalengkungan serta masalah interaksi struktur bendalir pada anggota struktur yang terlibat. Ia terdiri daripada empat masalah penyelidikan yang mana dua daripadanya mengkaji tindak balas pascalengkungan plat membulat dengan sifat bahan ortotrop dan dua yang seterusnya melibatkan permasalahan interaksi struktur bendalir ortotrop dan isotrop plat membulat. Masalah penyelidikan pertama menganalisis kesan pelbagai fungsi penghampiran bagi alihan sisi, serta untuk menilai beban tegangan jejari. Beban lengkok linear dinilai menggunakan perkiraan von Kármán dan dengan menggunakan nilai beban lengkok linear dan beban lebihan jejari, kekuatan pascalengkungan bagi plat ortotrop membulat dikira untuk kedua dua syarat sempadan yang disokong mudah dan terkapit. Perumusan matematik bagi masalah pertama menganggap bahawa alihan jejari adalah sifar. Masalah penyelidikan awal ini kemudian dikemukakan semula sebagai masalah penyelidikan kedua untuk meningkatkan ketepatan hasil dalam menganggarkan perilaku terma pascalengkungan plat membulat ortotrop. Hasil daripada siasatan ini adalah dalam ketepatan kejuruteraan (4.02% untuk syarat sempadan disokong mudah dan 3.67% untuk syarat sempadan terkapit) berbanding dengan kaedah unsur terhingga. Pemeriksaan semula menentukan alihan jejari dengan memilih fungsi alihan sisi teraku. Oleh itu, masalah kedua menentukan beban terma pascalengkungan plat ortotrop membulat dengan menambahkan purata bersepadu. Peratusan ralat dikurangkan kepada 1.13% untuk syarat sempadan yang disokong mudah dan 1.77% untuk syarat sempadan terkapit. Masalah penyelidikan ketiga dan keempat menentukan kelakuan getaran plat membulat isotrop dan ortotrop berhubungan dengan bendalir.Frekuensi semula jadi dan bentuk mod ragam yang sepadan dengan plat di udara dinilai dengan menggunakan penghampiran Galerkin. Anggaran berangka bagi faktor *jisim maya tokokan tambahan tak berdimensi* (NAVMI) dinilai dalam kes ketebalan seragam dan tidak seragam menggunakan perisian MAPLE. Didapati bahawa faktor NAVMI menurun dengan peningkatan dalam urutan nombor mod (n = 1, 2 dan 3). Selain itu, faktor NAVMI untuk mod yang lebih tinggi (n = 3) adalah lebih kecil daripada mod yang lebih rendah (n = 1). Berdasarkan hasil bahagi Rayleigh, frekuensi semula jadi plat yang bersentuhan dengan bendalir dinilai dengan mengira faktor *jisim maya tokokan tambahan* (AVMI) untuk syarat sempadan yang disokong mudah dan terkapit. Perumusan menentukan bahawa frekuensi semula jadi dari kedua-dua plat membulat yang bersentuhan dengan bendalir bertambah dengan peningkatan bilangan mod. Keputusan berangka yang diperoleh dari perumusan terkini akan membantu para jurutera untuk merekabentuk anggota struktur berhubungan dengan bendalir yang lebih selamat dan lebih berekonomi.

ABSTRACT

Circular plates are one of the main engineering structural members used in aerospace and construction industries. The circular plates are usually divided into different types such as orthotropic and isotropic owing to their type of material property. The buckling problem of these circular plates due to the temperature changes and its interaction with fluid are one of the great research interests. The thesis aims to present the mathematical formulations and numerical solutions to study the realistic response of orthotropic circular plates subjected to thermal loads as well as the vibration analysis of isotropic and orthotropic circular plates which comes in contact with fluid. The present research work discusses a new approach of mathematical formulations to tackle the postbuckling issues as well as fluid structure interaction problems of these structural members. It consists of four research problems, as two deals with postbuckling response of circular plates with orthotropic material properties and the other two dealing with the fluid structure interaction problems of orthotropic and isotropic circular plates. The first research problem analyses the effect of various approximate functions for the lateral displacement, as well as to evaluate the radial tensile load. The linear buckling load is evaluated using von Kármán approximations and hence by applying the values of linear buckling load and radial edge load, the thermal postbuckling strength of orthotropic circular plates are calculated for both simply supported and clamped boundary conditions. The mathematical formulation of the first problem assumes that the radial displacement is zero. This initial research problem is further reinvestigated as the second research problem to improve the accuracy of results in predicting the thermal postbuckling behavior of orthotropic circular plates. The results from these investigations are within the engineering accuracy (4.02 % for simply supported and 3.67 % for clamped boundary conditions) compared with the finite element method. The reinvestigation determines the radial displacement by selecting an admissible lateral displacement function. Therefore, the second problem determines the thermal postbuckling load of orthotropic circular plate by adding the integrated average. The error percentage is reduced to 1.13 % and 1.77 % for simply supported and clamped conditions, respectively. The third and fourth research problems determine vibration behavior of isotropic and orthotropic circular plates in contact with fluid, respectively. The natural frequencies and corresponding mode shape of the plates in air are evaluated by using Galerkin approximation. The numerical estimation of nondimensionalized added virtual mass incremental (NAVMI) factor is evaluated in uniform and nonuniform thickness cases using MAPLE software. It is found that the NAVMI factor decreases, with an increase in the order of mode number (n = 1, 2 and 3). Moreover, the NAVMI factor for a higher mode (n = 3) is smaller than for a lower mode (n = 1). Based on Rayleigh quotient, the natural frequencies of the plate in contact with fluid are evaluated by calculating the added virtual mass incremental (AVMI) factor for simply supported and clamped boundary conditions. The formulation determines that the natural frequencies of both the circular plates in contact with fluid increases with an increase in number of modes. The numerical results obtained from the present formulation will help the engineers to design safer and more economical structural members in contact with fluid.

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