NONLINEAR STRUCTURAL DYNAMICS USING FE METHODS

Nonlinear Structural Dynamics Using FE Methods emphasizes fundamental mechanics principles and outlines a modern approach to understanding structural dynamics. The book will be useful to practicing engineers, giving them a richer understanding of their tools and thus accelerating learning on new problems. Independent workers will find access to advanced topics presented in an accessible manner. The book successfully tackles the challenge of how to present the fundamentals of structural dynamics and infuse it with finite-element (FE) methods. First, the author establishes and develops mechanics principles that are basic enough to form the foundations of FE methods. Second, the book presents specific computer procedures to implement FE methods so that general problems can be "solved" – that is, responses can be produced given the loads, initial conditions, and so on. Finally, the book introduces methods of analysis to leverage and expand the FE solutions.

James F. Doyle is a professor in the School of Aeronautics and Astronautics at Purdue University. His main area of research is experimental mechanics, wave propagation, and structural dynamics. Special emphasis is placed on solving inverse problems such as force and system-identification problems. He is a dedicated teacher and pedagogical innovator. He is a winner of the Frocht Award for Teaching and the Hetenyi Award for Research, both from the Society for Experimental Mechanics. This is his sixth book dealing with the mechanics of structures.

Nonlinear Structural Dynamics Using FE Methods

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For Linda,

who made this possible.

Thank you from my heart.

Contents

Notation

Roman letters:

a	radius, plate width
A	cross-sectional area
b, b_i	thickness, depth, plate length, body force
c_o	longitudinal wave speed, $\sqrt{E/\rho}$
c_P, c_S, c_R	primary $= \sqrt{E^*/\rho}$, secondary $= \sqrt{G/\rho}$, and Rayleigh wave speeds
$C, [\ C\ ]$	damping, damping matrix
D	plate flexural rigidity, $Eh^3/12(1-\nu^2)$
$\hat{e}_i$	unit vectors
$E, \hat{E}, E^*, \bar{E},$	Young's modulus, $E^* = E/(1-\nu^2)$, $\bar{E} = E^*h$
EI	beam flexural stiffness
E_{ij}	Lagrangian large-strain tensor
$F, \hat{F}, \bar{F}_o, F_i$	member axial force, element nodal force
$\mathcal{F}$	generalized nodal force
$g_i(x)$	element shape functions
$G, \hat{G}$	shear modulus, frequency-response function
h	beam or rod height, plate thickness
h_i	interpolation functions
i	complex $\sqrt{-1}$, counter
I	second moment of area, $I = bh^3/12$ for rectangle
J^o, J, J_e	Jacobian
J_n	Bessel functions of the first kind
k, k_1, k_2	wavenumbers
$K, [\ k\ ], [\ K\ ]$	stiffness, stiffness matrices
L	length
M, M_x	moment
$M, [\ m\ ], [\ M\ ]$	mass, mass matrices
$P(t), \hat{P}, \{P\}$	applied-force history
$\mathcal{P}$	generalized applied load
q, q_u, q_v, q_w	distributed load

r, R	radial coordinate, radius
r, s, t	isoparametric coordinates
$[\ R\ ]$	rotation matrix
t, t_i	time, traction vector
T	time window, period, temperature
$\mathcal{T}$	kinetic energy
$[\ T\ ]$	transformation matrix
$u(t)$	response; velocity, strain, etc.
u, v, w	displacements
$\mathcal{U}$	strain energy
V	member shear force, volume
$\mathcal{V}$	potential of conservative loads
W	beam width, Wronskein
$\mathcal{W}$	work
x^o, y^o, z^o	original rectilinear coordinates
x, y, z	deformed rectilinear coordinates

Greek letters:

α	coefficient of thermal expansion
δ	small quantity, variation
δ_{ij}	Kronecker delta
Δ	determinant, increment
ϵ, ϵ_{ij}	small quantity, strain
η	viscosity, damping, principal coordinate
θ	angular coordinate
λ	eigenvalue
μ	shear modulus, complex frequency
ν	Poisson's ratio
Π	total potential energy
ρ^o, ρ	mass density
σ, σ_{ij}	stress
ϕ	phase
ϕ_x, ϕ_y, ϕ_z	rotation
$\{\phi\}, [\ \Phi\ ]$	modal vector, matrix
ω	angular frequency
ω_o, ω_d	natural frequency, damped natural frequency
ξ	damping ratio

Special symbols:

∇^2	differential operator, $(\partial^2/\partial x^2) + (\partial^2/\partial y^2)$
$[\quad]$	square matrix, rectangular array
$\{\ \}$	vector, spectral amplitude
$\lceil\quad\rfloor$	diagonal matrix
$\bar{\ }$	(bar) local coordinates

$\hat{}$	(hat) vector, complex quantity
$\dot{}$	(dot) time derivative

Subscripts:

E, G, T	elastic, geometric, tangent (total) stiffness matrix
i, j, k	continuum tensor components
,	(comma) partial differentiation

Superscripts:

o	original configuration
$*$	complex conjugate
$'$	prime, derivative with respect to argument

Abbreviations:

BC, PBC	boundary condition, periodic BC
DoF, SDoF	degree of freedom, single DoF
DKT	discrete Kirchhoff triangular FE element
EoM	equation of motion
EVP	eigenvalue problem
FE	finite element
FFT	fast Fourier transform
FRF	frequency-response function
IC	initial condition
MRT	membrane with rotation triangular FE element
ODE	ordinary differential equation

Primary Examples of Notation Use

Discrete Systems:

$$\frac{\partial \mathcal{U}}{\partial u_I} - \mathcal{P}_I = 0 \qquad I = 1, 2, \ldots, N$$

where $\mathcal{U}$ is strain energy, u_I is generalized DoF, $\mathcal{P}_I$ is generalized force, N is total number of DoF, and I is the enumeration of DoF.

Continuum Systems:

$$\epsilon_{ij} = \frac{\partial u_i}{\partial x_j^o} \qquad i, j = 1, 2, 3$$

where ϵ_{ij} is strain tensor, u_i is Cartesian strain component, x_i^o is Cartesian position component, and i, j is Cartesian tensor component.

Atomic Systems:

$$P_i^\alpha = -\frac{\partial \mathcal{V}}{\partial u_i^\alpha} \qquad \alpha = 1, 2, \ldots, N, \quad i = 1, 2, 3$$

where P_i^α is Cartesian force component, $\mathcal{V}$ is load potential, u_i is Cartesian displacement, i is Cartesian tensor component, N is total number of atoms, and α is the enumeration of atoms.

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More information

Atomic EoM:

$$M^\alpha \frac{d^2 \hat{r}^\alpha}{dt^2} = \sum_{\beta \neq \alpha}^{N} \hat{P}^{\alpha\beta} \qquad \hat{r} = \sum_i^3 x_i \hat{e}_i = \text{vector}$$

where M^α is mass, $\hat{r}^\alpha$ is position vector, $\hat{P}^{\alpha\beta}$ is force vector on atom α due to atom β, and N is the total number of atoms.