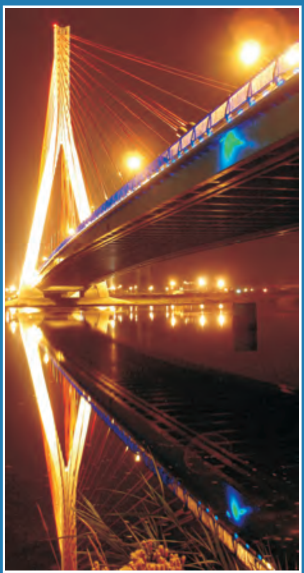
Krzysztof Wilde

modal diagnostics
of civil engineering structures



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Contents

List of symbols and abbreviations

Symbols

$\tilde{\phi}_n$ – experimental mode shapes
$\bar{m}_n$ – modal mass of the *n*-th mode
$\bar{k}_n$ – modal stiffness of the *n*-th mode
μ – complex value
λ – eigenvalue
ρ – mass density
$\mathbf{\Phi}$ – modal matrix
ω – natural circular frequency
α – real constant, angle of rotation of the control surface
β – real constant, angle of rotation of the control surface
$\mathbf{\Omega}$ – spectral matrix consisting of λ
$\mathbf{\Omega_d}$ – spectral matrix of discrete system
$\xi(t)$ – modal coordinate
$\mathbf{\Omega^2}$ – spectral matrix
ω_d – damped natural circular frequency
ϕ_{ij} – coefficients of the modal matrix
ξ_k – damping ratio of the *n*-th mode
$\mathbf{\Phi_L}$ – matrix of left eigenvectors
ϕ_n – eigenvector, mode shape
ϕ_{ai} – analytical mode shape
ϕ_{mi} – mode shape estimated from measurements
$\mathbf{\Phi_T}$ – matrix of right eigenvectors
$2b$ – width of the bridge deck with additional surfaces
$2b_c$ – width of the bridge deck
$\mathbf{a}$ – eigenvector of proportionally damped system, right eigenvector
$\mathbf{A}$ – system matrix in state space formulation, discrete system matrix
$A_{jk}(\omega)$ – accelerance, frequency response function
$\mathbf{b}$ – eigenvector of undamped system, left eigenvector
$\mathbf{B}$ – input matrix, discrete input matrix
B – width
$\mathbf{B}(s)$ – system matrix in Laplace domain
b_1, b_2 – width of the control surfaces
$\mathbf{C}$ – damping matrix, output matirx, discrete output matrix
c – damping coefficient of a single degree of freedom system
$\mathbf{D}$ – direct coupling matrix, discrete direct coupling matrix
D_1, D_2 – diameters
$D_{jk}(\omega)$ – dynamic stiffness, frequency response function
E – Young's modulus

$\mathbf{F}(t)$ – stochastic excitation
e_1, e_2 – control surface hinge location
e_{c1}, e_{c2} – control cable connection to the control surface
EI_k – stiffness of the *k*-th element
f – natural frequency
G_{FF} – autospectrum of force
G_{FX} – cross spectrum between response and force
G_{XF} – cross spectrum between force and response
G_{XX} – autospectrum of response
H – height
h – heaving motion of the bridge deck
$\mathbf{H}(\omega)$ – frequency response matrix
$\mathbf{H}(s)$ – transfer function matrix
$H(\omega)$ – frequency response function
H_1 – distance from a support to a defect along height
$H_1(\omega)$, $H_2(\omega)$ – estimators of frequency response function
$H_{jk}(\omega)$ – frequency response function, receptance
H_r – height of a defect
$\mathbf{I}$ – identity matrix
i – imaginary unit, integer number
$\mathbf{K}$ – stiffness matrix
k – integer number
L_1, L_2, L_3 – length of spans of a suspension bridge, damage location
L_r – length of a defect
$\mathbf{M}$ – mass matrix
m – mass of a single degree of freedom system, integer number
M_α, M_β, M_γ – aerodynamic moments generated on surfaces and bridge deck
$M_{jk}(\omega)$ – mechanical impedance, frequency response function
N – number of degrees of freedom, integer number
$\mathbf{p}(t)$ – vector of the external forces
$P(\omega)$ – Fourier transform of one-dimensional signal
$P_{jk}(\omega)$ – apparent mass, frequency response function
p_k – system poles
$\mathbf{R}_k$ – residue matrix
s – Laplace variable, scale parameter
T – natural period
t – time coordinate
t_k – scaling factor
U – wind velocity
$\mathbf{u}(t)$ – vector of displacements
$\mathbf{x}_1$, $\mathbf{x}_2$, $\mathbf{x}$ – system states
x_{c1}, x_{c2} – position of the control cables
$\mathbf{y}(t)$ – vector of output states
$Y_{jk}(\omega)$ – mobility, frequency response function
$\mathbf{x}_0$ – initial displacements
$\mathbf{u}_0$ – initial velocities
$\mathbf{R}_{xy}$ – cross correlation functions
$\mathbf{P}_\alpha$ – controllability matrix
$\mathbf{Q}_\beta$ – observability matrix
$\mathbf{H}(0)$, $\mathbf{H}(k-1)$ – Henkel matrix

$\mathbf{S}$	–	matrix of singular values, sensitivity matrix
$\mathbf{U}$, $\mathbf{V}$	–	left and right matrix in singular matrix decomposition
$\mathbf{E}_r$, $\mathbf{E}_m$	–	transformation matrices
Δt	–	time increment
$\mathbf{w}_k$	–	input nose vector
$\mathbf{V}_k$	–	output nose vector
$\mathbf{K}_k$	–	Kalman filter gain
$\hat{\mathbf{x}}_k$	–	estimate of state $\mathbf{x}_k$
$\mathbf{e}_k$	–	estimation error in Kalman filter
$\psi(x)$	–	one-dimensional mother wavelet function
$\psi_{j,k}(x)$	–	family of discrete wavelets
$\psi_{u,s}(x)$	–	family of wavelets
$\psi^1(x,y)$	–	two-dimensional horizontal wavelet function
$\psi^2(x,y)$	–	two-dimensional vertical wavelet function
$\psi^3(x,y)$	–	two-dimensional diagonal wavelet function
$Wf(u,s)$	–	continuous wavelet transform of one-dimensional signal
$Wf(u,v,s)$	–	continuous wavelet transform of two-dimensional signal
M	–	number of neurons in hidden layer
$Mf(u,v,s)$	–	modulus wavelet transform of two-dimensional signal
θ_j	–	design parameter
$J(\delta\theta)$	–	penalty function
$\mathbf{W}_{\varepsilon\varepsilon}$, $\mathbf{W}_{\theta\theta}$	–	weighting matrices
$\mathbf{z}_a$	–	vector of analytical modal parameters
$\mathbf{z}_m$	–	vector of measured modal parameters
I_D	–	damage index
I_{EI}	–	relative stiffness change
I_{NMD}	–	index based on normalized modal difference
ν	–	Poisson ratio
h_{ij}	–	coefficients of frequency response matrix
ρ_{ijk}	–	peak value of the frequency response function
net	–	net function
o	–	output of neural network
P	–	number of patterns
R	–	number of neurons in input layer
w_{km}	–	weights of the neural network
$\mathbf{M}^e$	–	mass matrix of the finite element
$\mathbf{K}^e$	–	stiffness matrix of the finite element
$\mathbf{N}(x)$	–	matrix of shape functions
$\mathbf{K}_{ii}$	–	sub-block of stiffness matrix
$\mathbf{M}_{ii}$	–	sub-block of mass matrix
$\mathbf{T}_s$	–	transformation matrix
$Sf(u,\zeta)$	–	windowed Fourier transform of one-dimensional signal
$g_{u,\zeta}(t)$	–	window function

Abbreviations

adj	–	adjugate
det	–	determinant
$(.)^*$	–	complex conjugate
$(.)^T$	–	transpose

$\dot{u}$ – first derivative of u
$\ddot{u}$ – second derivative of u
CWT – continuous wavelet transform
DWT – discrete wavelet transform
FEM – finite element method
FRF – frequency response function
FT – Fourier transform
GPS – Global Positioning System
NDT – non-destructive testing
SHM – structural health monitoring
WFT – windowed Fourier transform
WT – wavelet transform
MAC – modal assurance criteria
MSF – modal scale factor
NMD – normalized modal difference
MSV – modal singular value
NCO – normalized cross orthogonality

Preface

The book presents a blend of information about the vibrational diagnostics in civil engineering structures, namely, elements of structural dynamics, experimental modal analysis, advanced signal processing and applied optimization theory. The book is oriented towards a practical application of the diagnostics based on measurements of the structure oscillations. Special attention is paid to the civil engineering structures and their experimental examples.

There are many books discussing the problems of modal experimental analysis. The most comprehensive one, to the best of the author's knowledge, is the work by Maia and Silva (1997) entitled "Theoretical and Experimental Modal Analysis". In this book the theory on modal testing methods, modal identification techniques, Finite Element (FE) model updating and nonlinear modal analysis is systematically analyzed. However, the number of the examples on modal analysis on real objects is small. A detailed study on updating the Finite Element models is given by Friswell and Mottershead (1995) in the book "Finite Element Model Updating in Structural Dynamics". The Authors carefully explain the advantages and disadvantages of the direct and iterative methods of dynamic system coefficients updating. The examples are mostly based on the numerically determined input data. The third book that is often cited in the presented work, is "Application of Wavelet Analysis in Damage Detection and Localization" (Rucka and Wilde 2007). In this study a relatively new idea of using the wavelet analysis of damage detection from static and dynamic responses of the structures is discussed.

The aim of this book is to present a state-of-the-art knowledge on modal diagnostics with a special attention on its real application in civil engineering structures. Therefore, the experimental techniques leading to estimations of the structure natural frequencies and mode shapes are discussed in detail. Several examples are given from the author's engineering experience. All of the presented techniques are tested on the data obtained from the experimental studies in the Laboratory of Department of Structural Mechanics and Bridge Structures, Gdansk University of Technology, Poland. One example of mode shape extraction is based on the existing composite bridge, located near Gdańsk. The ambient vibration identifications, not mentioned in the above books, are also formulated and experimentally tested.

The theoretical knowledge on structure dynamics is omitted since many books and papers are available on this topic. Only the derivation of mode shapes for systems with no damping, a proportional damping matrix and arbitrary viscous damping are discussed in detail. For reasons of priority given in the book to the practical aspects, all the structural models are linear. It is assumed that the obtained equations of motion are describing the oscillations of a civil engineering structure around its equilibrium position. Only very small vibration amplitudes are considered. In the case of civil engineering structures the range of frequencies of interest is very low in comparison to the structures in aeronautical or mechanical engineering.

In this book a use of three types of damage detection methods on the experimental modal parameters are studied. To the best of the author's knowledge, there are relatively few publications that refer to the efficiency of damage location on data obtained from the in situ measurements. The first type damage detection methods presented in this book are techniques based on the wavelet analysis. The wavelet analysis, under consideration, do not need any theoretical models of the structure nor information on undamaged structure. Only the experimental mode shapes of structure in the current state are needed. This method belongs to a group of methods that search the crack location from the derivatives of the mode shapes. The wavelets act as a differentiating operator, and therefore, have all the constrains of this type of methods. The method is effective in detecting only relatively large cracks.

The second direction in modal diagnostics, followed in this book, is Finite Element model updating. In this case the mathematical model of the structure dynamics is necessary. It is also necessary to conduct the measurements of the damaged and undamaged structure. Only the updating that uses the reference data can give the correct and practically useful information. There are many papers on updating based on natural frequencies. In this book the updating using both frequencies and experimental mode shapes is discussed. The effective iterative algorithm is searched.

The third type of the modal diagnostics is the proposition of a combination of an artificial neural network with diagnostic data obtained from simple ambient tests and detailed forced vibration tests. In both cases the experimental frequencies and these mode shapes are used as the network input. The proposed strategy assumes a multilevel approach in the sense that cheap ambient tests, that can be easily performed on an existing structure, are conducted to detect the presence of the damage. In doubtful cases about the integrity of the structure, some forced dynamic testes are suggested. Both levels of the structure diagnostics are facilitated by a neural network. This part of the book is rather a presentation of a concept than a systematic study on the neural expert system.