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总主编 顾诵芬

Reliability Analysis of Dynamic Systems: Efficient Probabilistic Methods and Aerospace Applications

动态系统可靠性分析：高效方法及航空航天应用（英文版）

Bin Wu
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内 容 提 要

本书针对动态系统的可靠性分析，阐述了一种新的优化技术，即针对低频率谐振动力载荷下的工程产品结构可靠性问题，使用综合的快速概率方法，也即“扰动算法＋蒙特卡洛方法”。在针对两个航空航天实际工程案例的应用中发现，运用此方法能快速准确地解决失效面高非线性、大量计算强度和动态系统高复杂度等原有概率方法的应用困难。本书的出版填补了国际上对高效快速概率方法的研究空白。

本书可供从事民用飞机结构可靠性安全性工程设计分析、试验、管理的技术人员和相关专业的研究生使用。

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出 版 说 明

科学技术是第一生产力。21 世纪，科学技术和生产力必将发生新的革命性突破。

为贯彻落实“科教兴国”和“科教兴市”战略，上海市科学技术委员会和上海市新闻出版局于 2000 年设立“上海科技专著出版资金”，资助优秀科技著作在上海出版。

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Dedication

To my family

Preface

Deterministic analysis approaches/tools have dominated the whole aerospace industry for many years. It has been widely accepted, however, that the relevant non-deterministic analysis methods, either probabilistic or possiblistic, will be eventually adopted to some extent in this area. This process has been very slow, partly due to the conservative nature of the industry and partly due to some difficulties in applying these methods, which are now being addressed by both academia and industry.

Within the last decade in the engineering field, possibilistic approaches have been widely studied and applied to the reliability analysis of dynamic systems. During this period, there has been a lack of research interest in delivering efficient probabilistic methods. This book presents a novel technique that applies probabilistic methods to reliability analysis of engineering systems under harmonic loads in the low-frequency range. The aim was to overcome certain problems of applying probabilistic methods. The problems that need to be overcome were the nonlinearity of the failure surface, the intensive computational cost, and the complexity of the dynamic system.

A perturbation analysis algorithm was developed based on a modal approximation model. Since the resonance cases are of most concern, the optimized model simplifies the complexity of the dynamic systems by only concentrating on the resonance dominating terms in the response element (expressed in terms of modal coordinates). This optimization and later newly defined parameters transform the original failure surface into an approximate but smooth and linear one. Finally, the statistical information of the new parameters can be derived from that of the original variables by solving only once the eigen problem on the mean values of the original variables. An efficient reliability method, such as FORM, can then be applied.

However, for a given 2D frame structure, the FORM method failed to accurately predict the probability of failure. The Monte Carlo simulation method was later adopted to replace the FORM method. The Monte Carlo simulations were only performed for the new random parameters that were obtained through one execution of an eigen solver. Thus the overall efficiency of this combined approach, i.e. perturbation approach plus Monte Carlo simulation method, is high. Both accuracy and efficiency were achieved when this combined approach was applied to the 2D structure, as well as to a complex 3D helicopter model. Finally the response surface method was employed to derive the statistical information of the stiffness matrix from that of the original property random variables.

Low modal overlap factor, responses near resonance, low statistical overlap and small changes in eigenvalues and Gaussian distribution of the original variables are the conditions required for this approach to work.

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My sincere thanks are firstly due to Professor Robin S. Langley, my supervisor during the years in Cambridge, for providing academic ideas, patient guidance and valuable support. The advice and help that I received from Sondipon Adhikari, Srikantha Phani, Andrew Grime, Rolf Lande, Brian Jujnovich, Simon Rutherford and other members in the Dynamics and Vibration Research Group will not be forgotten.

The support and information given freely and generously by researchers in the engineering domain outside Cambridge are acknowledged with much gratitude, in particular, Dr Qin Feng and Dr Jim Margetson, whose names should be mentioned.

My due thanks go to my colleagues at the Commercial Aircraft Corporation of China, Ltd (COMAC). Frequent discussion with Dr. Qian Guo, Shanghai Aircraft Design and Research Institute of COMAC, was technically very useful. Mr. Xiaojun Xue and Mr. Peng Wang deserve my special thanks for the information and expertise they provide on engineering reliability, aviation safety and airworthiness. I would like to express my sincere thanks to Mr. Qingwei Zhang, former Board Chairman of COMAC, Mr. Zhuanglong Jin, current Board Chairman of COMAC, Mr. Hua Yan, Director of HR department of COMAC, and Mr. Fuguang Qin, Director of Beijing Research Centre of COMAC, for their help and support of my research work.

I am very grateful to the Engineering and Physical Science Research Council (UK), QinetiQ, Queens' College Cambridge and COMAC for funding my research. I express my sincere gratitude to Shanghai Jiao Tong University Press and Elsevier Limited for publishing this book.

I would like to thank my parents, my brother and sister-in-law, for their eternal love, constant support and encouragement that are of great value to me to overcome many challenges and difficulties in life. My special thanks go to my wife, Dr. Jianxiang Cao, and my children, for their love and time. I am also grateful to my friends in Cambridge, London, Manchester, Beijing, Shanghai and Taibei for their advice and help that I received when needed.

Dr. Bin Wu
COMAC, China
March 2013

Nomenclature

ABBREVIATIONS

ACSR	Active control of structural response
AVS	Active vibration suppression
AVC	Active vibration control
BG	Bubnov–Galerkin
DOF	Degree of freedom
FE	Finite element(s)
FEA	Finite element analysis
FEM	Finite element method
FFEM	Fuzzy finite element method
FORM	First-order reliability method
FRF	Frequency response function
GOE	Gaussian orthogonal ensemble
HHC	Higher harmonic control
IBC	Individual blade control
jpdf	Joint probability density function
MC	Monte Carlo (simulation method)
MCS	Monte Carlo simulation (method)
pdf	Probability density function
PDE	Partial differential equation
RS	Response surface
RSM	Response surface method
SEA	Statistical energy analysis
SFE	Statistical finite element
SORM	Second-order reliability method
SRBM	Stochastic reduced basis method
TEF	Trailing edge flap

NOTATION AND SYMBOLS

M	Mass matrix
K	Stiffness matrix
A	Area
E	Modulus of elasticity (Young's modulus)
L	Length
β	Safety index
ρ	Property density
η	Loss damping factor
ω	Radian frequency/excitation frequency
f	Cyclic frequency (Hz)/excitation frequency

$[\Phi]$	Mass-normalized modal matrix
ϕ_j	jth column vector of mass-normalized modal matrix
ω_i	ith undamped natural frequency
$\{\psi_i\}$	ith mode shape
$P(\ )$	Probability
f_x	Pdf of random variable x
μ_x	Mean value of random variable x
σ_x	Standard deviation of random variable x
$E(x)$	Expected value of random variable x
$D(x)$	Variance of random variable x
$C_x(Cov_x)$	Covariance matrix of random variable x
C	Confidence level
α	Fuzzy confidence level
Φ	Standard normal distribution function

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