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Synthesis of nonlinear frequency responses with experimentally extracted nonlinear modes

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ABSTRACT

Determining frequency response curves is a common task in the vibration analysis of nonlinear systems. Measuring nonlinear frequency responses is often challenging and time consuming due to, e.g., coexisting stable or unstable vibration responses and structure-exciter-interaction. The aim of the current paper is to develop a method for the synthesis of nonlinear frequency responses near an isolated resonance, based on data that can be easily and automatically obtained experimentally. The proposed purely experimental approach relies on (a) a standard linear modal analysis carried out at low vibration levels and (b) a phase-controlled tracking of the backbone curve of the considered forced resonance. From (b), the natural frequency and vibrational deflection shape are directly obtained as a function of the vibration level. Moreover, a damping measure can be extracted by power considerations or from the linear modal analysis. In accordance with the single nonlinear mode assumption, the near-resonant frequency response can then be synthesized using this data. The method is applied to a benchmark structure consisting of a cantilevered beam attached to a leaf spring undergoing large deflections. The results are compared with direct measurements of the frequency response. The proposed approach is fast, robust and provides a good estimate for the frequency response. It is also found that direct frequency response measurement is less robust due to bifurcations and using a sine sweep excitation with a conventional force controller leads to underestimation of maximum vibration response.

1. Introduction

1.1. Motivation

In many mechanical systems, the forces acting on a structure depend in a nonlinear way on the generalized coordinates describing the motion of the structure. Examples include geometrical nonlinearity due to large deformation or deflections, nonlinear material deformation behavior, contact interactions and multi-physical interactions. Nonlinearity can significantly influence the dynamical behavior. One major difference to linear systems is that nonlinearity leads to a dependence of characteristic vibration features such as resonance frequencies, damping measures and vibrational deflection shapes, on the

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Nomenclature

Matrices and vectors

$\mathbf{M}, \mathbf{D}, \mathbf{K}$	mass, damping, stiffness matrix
$\boldsymbol{\Psi}$	eigenvector matrix
$\boldsymbol{\Phi}$	normalized eigenvector matrix
$\mathbf{I}$	identity matrix
$\boldsymbol{v}$	Fourier coefficient of velocity
$\boldsymbol{x}$	displacement
$\boldsymbol{\psi}$	eigenvector
$\boldsymbol{\phi}$	normalized eigenvector
$\boldsymbol{f}$	force vector

Scalars

h	frequency response function
t, T	time, period time
ω, Ω	circular frequency, forcing frequency
δ	modal damping
P	active power
γ	fundamental harmonic content
a	response spectrum
ω_0	modal frequency
q	modal amplitude
m	modal mass
i	imaginary unit

Operators

$\dot{()}, \ddot{()}$	first, second time derivative
Re	real part
diag	diagonal matrix
$\mathcal{F}$	Fourier transform
$()^{\mathrm{T}}, ()^{\mathrm{H}}$	transpose, hermitian of a matrix
$\hat{()}$	amplitude dependent quantity
$()^{+}$	(generalized) inverse matrix

Sub- and superscripts

n	number of harmonic
k	index of linear mode
A	acceleration
l, pl, nl	linear, projected linear, nonlinear
diss, mod	dissipative, modal
p, i	excitation, response point
j	index of nonlinear mode
F	force
exp	experimental
ref, exc	reference, excitation

Abbreviations

FRF	frequency response function
RMS	root mean square
PI	proportional-integral
EMA	linear experimental modal analysis
PLL	phase-locked-loop
MIF	mode indicator function

vibration level. Moreover, inherently nonlinear phenomena, such as bifurcations and the co-existence of multiple stable or unstable vibration limit states (attractors) lead to fundamental differences to linear systems.

It is frequently postulated that nonlinear vibration behavior plays already an important role in many engineering applications and the technical relevance will further increase in the future. This can be attributed to technological trends such as