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Uncertain reduced-order modeling for unsteady aerodynamics with interval parameters and its application on robust flutter boundary prediction

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ABSTRACT

Computational fluid dynamics based unsteady aerodynamic reduced-order models can significantly improve the efficiency of transonic aeroelastic analysis. In this paper, the concept of the conventional model reduction method based on the system identification theory is extended to aerodynamic subsystems with the consideration of computational fluid dynamics-induced interval uncertainties in simulation to get the aerodynamic reduced-order model as uncertain as the original aerodynamic subsystem. The interval estimation of identified coefficients involved in the uncertain reduced-order model is obtained by utilizing the first-order interval perturbation method. The stability problem of the interval aeroelastic state-space model formulated based on the constructed uncertain aerodynamic reduced-order model is equivalently transformed into a standard interval eigenvalue problem associated with a real non-symmetric interval matrix in which the interval bounds of eigenvalues are evaluated by virtue of the first-order interval matrix perturbation algorithm. A new stability criterion for the interval aeroelastic state matrix is defined to predict the robust flutter boundary of the concerned uncertain aeroelastic system. Two numerical examples with respect to the uncertain aerodynamic ROM constructions and robust flutter boundary predictions of the two-dimensional Isogai wing and the three-dimensional AGARD 445.6 wing in transonic regime are implemented to assess the validity and accuracy of the presented approach. The obtained results are also compared with Monte Carlo simulation solutions as well as numerical and experimental results in the literatures indicating that the proposed method can provide a more robust and conservative prediction on the flutter boundary of an aeroelastic system compared with conventional deterministic aeroelastic analysis approaches.

1. Introduction

Classical aeroelasticity is the study dealing with the stability and response of elastic structures under the interaction of inertial forces, structural, and aerodynamic. Fluid–structure interaction effects are of paramount importance regarding the limits of the flight envelope and therefore strongly influence safety and efficiency requirements [1].

The issue of dynamic stability, which is commonly referred to as the flutter analysis, is an important branch in the field of aeroelasticity. The accurate prediction of unsteady aerodynamic forces is an essential foundation for flutter analysis. Due to the inherent superiority over the traditional linear potential flow theory for addressing distinct aerodynamic nonlinearities in the transonic flight regime or at a high angle of attack, the computational fluid dynamics (CFD) techniques have been widely used in aerodynamic calculations during the last several decades. However, in terms of efficiency, the high-fidelity CFD approach requires expensive computational costs associated with the meticulous descriptions of flow in both spatial and temporal dimensions, which limits its further applications in aeroelastic analysis, optimal design and control.

To alleviate the contradiction between the computational efficiency and predictive accuracy, increasing attention has been paid to the CFD-based reduced-order models (ROMs), which provide an alternate way to effectively model unsteady aerodynamic loads. The CFD-based ROM seeks to construct a simple mathematical representation model, which can capture the dominant behavior of the aerodynamic or aeroelastic system and can be convenient to

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Nomenclature

a	dimensionless distance of elastic axis behind midchord
$\mathbf{A}_{as}^{I}$	interval state matrix of uncertain aeroelastic model
$\mathbf{A}_i$	coefficient matrices of $\mathbf{f}(k-i)$
b	airfoil semichord
$\mathbf{B}_j$	coefficient matrices of $\boldsymbol{\xi}(k-j)$
$\mathbf{e}$	output error vector
E	Young's modulus
$\mathbf{f}$	system output (generalized aerodynamic coefficient) vector
$\mathbf{F}$	generalized aerodynamic force vector
G	shear modulus
$\mathbf{G}$	generalized structural damping matrix
h	plunge displacement of elastic axis
$J(\boldsymbol{\theta})$	criterion function with respect to $\boldsymbol{\theta}$
k	discrete time step
$\mathbf{K}$	generalized structural stiffness matrix
K_h	plunge spring constant
K_α	pitch spring constant
L	data length of system input and output
M	modal truncation order of structural subsystem
$\mathbf{M}$	generalized structural mass matrix
Ma	Mach number of freestream
na	output delay orders of aerodynamic model
nb	input delay orders of aerodynamic model
q	freestream dynamic pressure
q^*	critical dynamic pressure
r_α	dimensionless gyration radius of airfoil around stiffness center
t	real time
V_f^*	flutter speed index
$\mathbf{v}_i$	eigenvector associated with the ith eigenvalue of matrix
$\mathbf{v}_{im}$	imaginary part of the ith eigenvector
$\mathbf{v}_{ir}$	real part of the ith eigenvector
$\mathbf{x}_a$	state vector of aerodynamic state-space ROM
$\mathbf{x}_{as}$	state vector of aeroelastic state-space model
$\mathbf{x}_s$	state vector of structural state-space model
x_α	dimensionless distance of center of gravity behind stiffness center

Greek

α	pitch displacement
$\boldsymbol{\Gamma}_{\boldsymbol{\theta}}$	feasible set of identified coefficients
$\boldsymbol{\Gamma}_{\lambda}$	feasible set of eigenvalues
δ	perturbation variable
Δ	radius of interval
$\boldsymbol{\theta}$	coefficient set of the aerodynamic ROM to be identified
$\hat{\boldsymbol{\theta}}$	estimation of identified coefficients
λ_i	the ith eigenvalue of matrix
λ_{im}	imaginary part of the ith eigenvalue of matrix
λ_{ir}	real part of the ith eigenvalue of matrix
μ	mass ratio
ν	Poisson's ratio
$\boldsymbol{\xi}$	system input (generalized structural displacement) vector
ρ	density
ω_h	uncoupled natural frequency of airfoil in plunge
ω_α	uncoupled natural frequency of airfoil in pitch

Abbreviations

ARMA	autoregressive moving average
ARX	autoregressive model with exogenous input
CFD	computational fluid dynamics
LB	lower bound
LTI	linear time invariant
MCS	Monte Carlo simulation
NV	nominal value
POD	proper orthogonal decomposition
ROM(s)	reduced-order model(s)
ROM-DAR	reduced-order modeling suitable for deterministic aerodynamic responses
ROM-UAR	reduced-order modeling suitable for uncertain aerodynamic responses
UB	upper bound

use in the conceptual design, control and data-driven systems [2]. According to different modeling ideas, the methodologies to reduce the order of an aerodynamic model can be subdivided broadly into two main categories: one is based on the proper orthogonal decomposition (POD) approach [3] and the other on the system identification technology, mainly including autoregressive moving average (ARMA) models [4], linear state-space models [5], Volterra series models [6] and neural networked models [7]. Typically, most of the current proposed CFD-based ROMs, such as first-order POD methods, ARMA models, linear state-space models and first-order Volterra series models, are dynamic linear models constructed under the assumption of small-amplitude vibrations, which can accurately predict mildly nonlinear responses and are suitable for a wide range of flight conditions. These aerodynamic ROMs have been extensively applied to the analysis or design of transonic flutter [8], limit cycle oscillation [9], gust response [10], aeroservoelasticity [11], aerothermoelasticity [12] and transonic flutter suppression with control delay [13] with respect to simple airfoils, three-dimensional wings and even complete aircrafts in both frequency and time domain through the years. Most of the existing aerodynamic ROMs are generally linear or weakly-nonlinear models. The latest developments in the field of aerodynamic model reduction especially nonlinear model reduction is discussed by Marques et al. [14] Among the nonlinear ROMs, the nonlinear model projection is used to the reduction of nonlinear aerodynamic models for gust response prediction allowing a systematic investigation of the influence of a large number of gust shapes without regenerating the ROM [15]. The investigation on the accuracy of prediction and incurred computational cost of ROMs based on indicial functions, Volterra theory using nonlinear kernels, radial basis functions and a surrogate-based recurrence framework for X-31 aircraft pitching motions indicates that these ROMs can produce accurate predictions for a wide range of motions in transonic regime with a limited number of time-accurate CFD simulations [16]. While maintaining a high level of accuracy, the preceding aerodynamic model reduction methods can expedite the computational efficiency by 1 to 2 orders of magnitude compared with full CFD simulations, and demonstrate a huge potential for the analysis and design of aeroelasticity.

Generally, conventional aeroelasticity investigations are performed under the assumption of complete determinacy of systems. As a practical matter, real aeroelastic systems are inevitably confronted with multiple sources of uncertainty arising from 1) modeling-induced uncertainties due to simplifying assumptions, modal truncation, errors in boundary conditions and unmodeled dynamics, 2) numerical uncertainties generated by diversity in

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