Journal of Fluids and Structures 82 (2018) 308–328

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

A novel unsteady aerodynamic Reduced-Order Modeling method for transonic aeroelastic optimization

Ziyi Wang [a], Weiwei Zhang [a,*], Xiaojing Wu [a], Kongjin Chen [b]

[a] School of Aeronautics, Northwestern Polytechnical University, China
[b] HONGDU Aviation Industry Group Co., Ltd., Aviation Industry Corporation of China, China

HIGHLIGHTS

- A Reduced-Order Modeling method for transonic aeroelastic optimization is proposed.
- Number of basis modes can be largely reduced by Principal Component Analysis.
- Efficiency of optimization is two orders of magnitudes higher than previous ROMs.

ARTICLE INFO

Article history:
Received 21 August 2017
Received in revised form 26 June 2018
Accepted 5 July 2018

Keywords:
Optimization
Aeroelasticity
Unsteady aerodynamics
Reduced-order modeling
Transonic flow
Flutter

ABSTRACT

In aircraft design, structural optimization concerning transonic aeroelastic issues is computationally impractical, due to a great number of aeroelastic analyses are required in iterative process. Reduced-Order Model (ROM) method is convenient for transonic aeroelastic analyses; however, current ROMs are not reusable during iteration, hence the time consumption is still too high. To solve the problem, this study proposes an improved ROM suitable for Arbitrary Mode Shapes (ROM-AMS), which is reusable in iterative process. By adopting Principal Component Analysis, ROM-AMS method significantly reduces the number of basis mode shapes, while improves the accuracy of flutter analysis. In an optimization case, the weight of a cropped delta wing is reduced by 28.46%, and the efficiency is 900 times higher than that of traditional ROM approaches, which demonstrates the feasibility of this method in aeroelastic optimization.
© 2018 Elsevier Ltd. All rights reserved.

1. Introduction

In the field of aerospace, optimization is carried out to obtain a subtle design with minimized weight or achieve other objectives, meanwhile subject to some constraints such as safety. Of interest here is structural optimization concerning transonic flutter issues. Flutter is dynamic instability of aeroelastic system, therefore flight speed of an aircraft must be lower than its critical flutter velocity (flutter boundary). In flutter analysis, it is the calculation of unsteady aerodynamic responses that consumes most computational resources, thus a rapid and reliable aerodynamic calculation method is of most importance for iterative process.

At present, two kinds of approaches are applied to calculate the aerodynamic force in iterative problems—Traditional AeroElasticity (TAE) and Computational AeroElasticity (CAE) (Beran et al., 2017). TAE provides a rapid aerodynamic force prediction using lower-fidelity aerodynamic tools. For example, Doublet Lattice Method (DLM) (Jutte et al., 2014; Werter and De Breuker, 2016; Wan et al., 2003; De Leon et al., 2012), strip theory (Georgiou et al., 2014; Weisshaar, 1981) and ONERA

* Corresponding author.
E-mail address: aeroelastic@nwpu.edu.cn (W. Zhang).

https://doi.org/10.1016/j.jfluidstructs.2018.07.001
0889-9746/© 2018 Elsevier Ltd. All rights reserved.

stall model (Stanford and Beran, 2013a) were applied to aeroelastic optimization in subsonic regime, while piston theory was frequently used in supersonic and hypersonic regimes for optimization and Reliability-Based Design Optimization (RBDO) (Stanford and Beran, 2013b, 2012). However, the drawback of TAE is its low fidelity in transonic regime. As a remedy, Prandtl–Glauert correction factor was incorporated in TAE method (Mallik et al., 2013), but it is still invalid when Mach number (*Ma*) is approaching 1.

Many aircrafts, such as large commercial jets and fighters, need to cruise in transonic regime, in which flow nonlinearity cannot be correctly captured by TAE. What is worse, due to the flow nonlinearity like shock wave movement and flow compressibility, aircrafts in transonic regime could undergo a dangerous reduction of flutter boundary, namely the "transonic dip". Therefore, it is critical to accurately calculate the unsteady aerodynamic force in transonic regime. With the development of Computational Fluid Dynamics (CFD), CAE has become an appealing method in transonic regime and was applied to design optimization concerning static-state aeroelastic problems (Barcelos and Maute, 2008). To obtain flutter velocity, traditional CAE based analysis should be casted at many trial freestream velocities until critical velocity is found, which is computational impractical for iterative process, as a result, CAE method is mainly used for post verification at present (Schuster et al., 2003; Yurkovich, 2003). To ease the problem, the flutter analysis can be treated as an eigenvalue problem by using Schur method, since flutter is actually Hopf-Bifurcation (Badcock and Woodgate, 2008). This approach was utilized in Uncertainty Qualification (UQ) (Marques et al., 2010b) and UQ based optimization (Marques and Badcock, 2012), in which iterative process is also involved. Additionally, Chen and Stanford proposed a novel field-panel method which was conductive to transonic aeroelastic optimization (Chen et al., 2004; Stanford et al., 2015). Firstly, full-order simulation was carried out to obtain a background steady flow. Linearization of the steady background flow was then carried out for a range of reduced frequencies and interpolated onto a flat-plate wing mesh with a field panel scheme (Stanford et al., 2015). Above process produces Aerodynamic Influence Coefficients (AIC) governing the relationship between pressure and downwash at a set of reduced frequencies. The AIC is independent of the variation of structural parameters, therefore it is reusable during structural optimization.

However, aforementioned Schur method is still a "trial and error" process, and requires significant modifications to existing codes (Yao and Marques, 2017). Instead, unsteady aerodynamic Reduced-Order Models (Dowell and Hall, 2001; Lucia et al., 2004; Raveh, 2005) were applied to model nonlinear aerodynamic response. Existing ROMs can be summarized into two categories: the Proper Orthogonal Decomposition (POD)-Galerkin/Dynamic Mode Decomposition (DMD) (Bourguet et al., 2009, 2011; Rowley et al., 2009; Schmid, 2010) method, and the system identification method (such as Volterra series Milanese and Marzocca, 2009 and Auto Regressive with eXogenous input model, ARX). At present, system identification based ROMs have been extensively applied to aeroelastic problems, for instance, flutter analysis at high angle of attack (Zhang and Ye, 2007), frequency lock-in in transonic buffeting flow (Gao et al., 2017b), vortex-induced vibrations at low Reynolds numbers (Zhang et al., 2015b), transonic Limit Cycle Oscillation (LCO) prediction (Zhang et al., 2012; Mannarino and Mantegazza, 2014), control law design for active flutter suppression (Chen et al., 2012), active control of transonic buffet flow (Gao et al., 2017a). However, in structural optimization, ROM must be reusable when design variables are altered. One solution to the problem is Parametric Reduced-Order Modeling (PROM) (Liu et al., 2014; Kou and Zhang, 2017; Winter and Breitsamter, 2016): firstly, an offline sampling is conducted in parameter space; then, full-order analyses are carried out for each sample to collect training data; finally, a PROM robust in the parameter space is generated. The current PROM is just a model of few flow parameters (such as Mach number), for structural optimization where the number of parameters is larger, the time consumption of full-order analyses is high. Instead of PROM, some researchers found that ROM in itself has generalization ability for variation of structural parameters. For example, nonlinear ROM is robust to structural variation of an airfoil (Zhang et al., 2016), while Song and Wang found that ROM could adapt to the changes of modal mass and modal frequency (Song et al., 2011; Wang et al., 2008).

The problem is, above ROMs are just valid for Prescribed Mode Shapes (such ROM is referred as ROM-PMS). Marques demonstrated that neglecting the variation of mode shapes in structure-changeable cases would lead to misleading results (Marques et al., 2010a). To solve the problem, Zhang developed a ROM suitable for arbitrary mode shapes (ROM-AMS) (Zhang et al., 2015a). Firstly, a set of Radial Basis Functions (RBFs) are selected as basis mode shapes to linearly fit the physical mode shapes. Then, different from traditional ROMs, ROM-AMS was constructed in basis mode coordinate. Once converted to real modal coordinate, ROM-AMS can replace CFD solver in aeroelastic analyses. For various structures with same aerodynamic shape and flow condition, ROM-AMS is reusable and robust to the variation of both modal frequencies and mode shapes. Only one round execution of CFD is required in structural optimization. Under the same framework, Winter proposed another ROM-AMS where Chebyshev polynomials were selected as basis mode shapes, which can capture the global features of physical mode shapes (Winter et al., 2017).

However, in Zhang and Winter's work, the number of required basis mode shapes is relatively large. Take ARX model as an example, with same delay order, the number of parameters to be identified is square of basis modes. Subsequently, excessive number of basis modes will significantly prolong the duration of training and modeling. At the same time, fewer basis modes will enlarge the deviation of flutter prediction. So there is a tradeoff between model simplicity and fitting accuracy. To make the tradeoff easier, PCA basis (Smith, 2002) is adopted as the basis mode shapes in this paper. It has been confirmed that only a small number of basis modes can reach desirable accuracy. In the end, ROM-AMS is applied in transonic aeroelastic design optimization for the first time. To verify the effectiveness of PCA basis, the variation of mode shapes in the optimization case is relatively large.

Download English Version:

https://daneshyari.com/en/article/11003992

Download Persian Version:

https://daneshyari.com/article/11003992

Daneshyari.com