Journal of Fluids and Structures 57 (2015) 196–205

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Zeroth-order flutter prediction for cantilevered plates in supersonic flow

Marius-Corné Meijer [a,*], Laurent Dala [a,b]

[a] Department of Mechanical and Aeronautical Engineering, University of Pretoria, Pretoria 0028, South Africa
[b] CSIR, DPSS Aeronautic Systems, Pretoria 0001, South Africa

ARTICLE INFO

Article history:
Received 4 December 2014
Accepted 22 June 2015
Available online 17 July 2015

Keywords:
Zeroth-order
Flutter
Local piston theory
Shock-expansion
Cantilevered plate

ABSTRACT

An aeroelastic prediction framework in MATLAB with modularity in the quasi-steady aerodynamic methodology is developed. Local piston theory (LPT) is integrated with quasi-steady methods including shock-expansion theory and the Supersonic Hypersonic Arbitrary Body Program (SHABP) as a computationally inexpensive aerodynamic solver. Structural analysis is performed using bilinear Mindlin–Reissner quadrilateral plate elements. Strong coupling of the full-order system and linearization of the modal-order system are implemented. The methodology is validated against published experimental data in the literature and benchmarked against Euler computation in the Edge CFD code. The flutter dynamic pressure is predicted to be within 10% of the experimental value for 140 times lower computational cost compared to CFD. Good agreement in other cases is obtained with the industry-standard ZONA7 and ZONA7U codes.

1. Introduction

The modeling of multiphysics phenomena such aeroelasticity in the preliminary design of aerospace components is important in reducing the risk of the design not meeting requirements for structural integrity and safety. Typically, the prohibitive computational cost of multidisciplinary analysis results in such studies only being conducted in the detailed design phase. The reduction of the computational cost of aeroelastic prediction would allow for such analysis to be conducted earlier in the design cycle, and would allow for better filtering of concepts in the design space.

Modeling of the multiphysics problem is most broadly done through the use of segregated solvers—the equations for the structural dynamics and aerodynamic loading are solved separately. The exchange of data between the solvers is referred to as coupling. Strong coupling of the solvers refers to the practice of performing multiple iterations of data exchange between the solvers per time-step in the solution, in order to achieve dynamic equilibrium; weak coupling of the solvers disregards this subiteration, and only one exchange of data between solvers is performed per time-step. Early work in computational aeroelasticity (Rodden et al., 1962a,b) involved the use of monolithic solvers, in which the structural dynamics and aerodynamics are computed simultaneously. This work was associated with matrix (panel) methods. The aerodynamic models employed in such methods are typically applicable to both steady and unsteady flows. However, these aerodynamic models may also be exploited in segregated aeroelastic solvers, with coupling to a finite-element structural model; an example of this would be to use the Supersonic/Hypersonic Arbitrary Body Program (SHABP) code (Gentry et al., 1973)

* Corresponding author.
E-mail addresses: mariuscmeijer@gmail.com (M.-C. Meijer), ldala1@csir.co.za (L. Dala).

http://dx.doi.org/10.1016/j.jfluidstructs.2015.06.018
0889-9746/

(which is modular in the quasi-steady aerodynamic methods used) to provide the loading for a structural model derived from the finite-element method (FEM).

The advantage offered by the use of the aforementioned approximate aerodynamic methods is the significantly lower computational cost of the methods compared to high-fidelity aerodynamic analysis by computational fluid dynamics (CFD). The use of computationally inexpensive approximate methods in computational aeroelasticity continues (Yurkovich, 2003) alongside high-fidelity analysis involving the coupling of computational structural dynamics (CSD) and CFD solvers (Livne, 2003; McNamara and Friedmann, 2011). The ability of approximate methods to reproduce aerodynamic and aeroelastic trends for significantly lower computational cost (compared to CSD-CFD solutions) renders them valuable in guiding higher-fidelity analysis, and makes multidisciplinary design feasible in the preliminary design cycle.

To this end, the current work suggests a computationally inexpensive framework for flutter prediction through the use of approximate aerodynamic modeling. The framework offers modularity in the quasi-steady aerodynamic methods employed, using local piston theory to compute the unsteady aerodynamic contribution. This allows for consistent comparison of the merits of various approximate quasi-steady models for flutter analysis. The purpose of the work is thus to provide the designer with a method to rapidly model the aeroelastic response of a concept, in order to filter through the design space, and to provide the guiding “zeroth-order” solution upon which increasingly higher-fidelity analysis improves.

2. Modeling methodology

2.1. Structural dynamics

2.1.1. Structural model

A structural solver was developed in MATLAB as a core component of the computational framework. A finite-element structural model based on Mindlin-Reissner plate theory (Ferreira, 2009) was implemented for thin plates ($t/c \leq 0.1$) of trapezoidal planform. Bilinear quadrilateral plate elements with varying thickness were employed. The spanwise discretization of the planform was in this study restricted to producing successive chordwise sections that were parallel to the cantilevered root; no restriction was made on the chordwise discretization. The plate was modeled as having linear isotropic material properties.

2.1.2. Aeroelastic system

Two methods were adopted in incorporating the loading on the structural model from the aerodynamic solver: a modal representation with time-invariant linearized generalized aerodynamic forces (GAFs), and a strongly coupled full-order model.

In the linearized system, a truncated modal representation of the structure was used in linearizing the GAFs from the aerodynamic solver. The GAFs were computed once, about the trim condition, for small increments in modal displacements and velocities. The aeroelastic system is described by the following equation:

$$\mathbf{I}\ddot{\mathbf{q}} + \mathbf{D_s}\dot{\mathbf{q}} + \mathbf{\Omega_s}\mathbf{q} = \mathbf{D_a}\dot{\mathbf{q}} + \mathbf{\Omega_a}\mathbf{q} \tag{1}$$

where $\mathbf{I}$ is the identity matrix, $\mathbf{D_s}$ is the modal structural damping matrix, $\mathbf{D_a}$ is the aerodynamic damping matrix, $\mathbf{\Omega_s}$ is the matrix of structural modal frequencies, $\mathbf{\Omega_s}$ is the matrix of aerodynamic modal frequencies, $\mathbf{q}$ are the generalized coordinates, and dot notation denotes derivation with respect to time.

The resulting analysis resulted in a linear time-invariant aeroelastic system of truncated modal order. This allowed for the direct extraction of aeroelastic eigenvalues and for inexpensive computation of the time-history of system response. The aeroelastic modal parameters were used to calculate the Zimmerman–Weissenburger flutter margin as an indication of the stability trends. The two-mode characteristic equation of a continuous-time system has the following form (Dimitriadis, 2001):

$$G(\lambda) = \lambda^4 + A_1\lambda^3 + A_2\lambda^2 + A_3\lambda + A_4 \tag{2}$$

where $G(\lambda)$ is the characteristic polynomial of the continuous-time system and the λ are the eigenvalues of the system. The associated Zimmerman–Weissenburger flutter margin F_Z of the two modes is given (Dimitriadis, 2001) by

$$F_Z = A_2\left(\frac{A_1}{A_3}\right) - \left(\frac{A_1}{A_3}\right)^2 + A_0 \tag{3}$$

The strongly coupled aeroelastic system saw the full-order structural model used to compute the aerodynamic loading. Solution of the system response was obtained through direct integration of the full-order model, which is described by the following equation:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \tag{4}$$

where $\mathbf{M}$ is the structural mass matrix, $\mathbf{C}$ is the structural damping matrix, $\mathbf{K}$ is the structural stiffness matrix, $\mathbf{F}$ is the aerodynamic loading vector, and $\mathbf{x}$ is the displacement vector.