Journal of Fluids and Structures 82 (2018) 651–671

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

A novel approach for flutter prediction of pitch–plunge airfoils using an efficient one-shot method

Hang Li *, Kivanc Ekici

Department of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee, Knoxville, TN 37996, United States

ARTICLE INFO

Article history:
Received 14 March 2018
Received in revised form 1 June 2018
Accepted 22 August 2018

Keywords:
One-shot method
Aeroelasticity
Flutter
Limit cycle oscillations
Harmonic balance method
Frequency search

ABSTRACT

In this work, the one-shot method previously developed for the solution of limit cycle oscillation problems is extended to predict flutter boundaries of aeroelastic systems. In essence, the one-shot method determines the aeroelastic response of wings and airfoils in a tightly-coupled fashion where both aerodynamic and structural dynamic problems are solved simultaneously using harmonic balance. This approach is superior to the frequency-based techniques previously reported in the literature such that it eliminates the need to sweep over a range of frequencies to determine flutter conditions. For each Mach number of interest, the values of flutter frequency and flutter velocity are determined as part of a single aeroelastic run. A method for identifying appropriate initial conditions is also presented. It is shown that the flutter onset point for given flow conditions can be accurately identified by prescribing a very small pitch amplitude treating flutter prediction as a response problem instead of the classical stability problem. Using this technique, three two-degree-of-freedom aeroelastic models, including a flat plate, the NACA 64A010 airfoil and the supercritical NLR 7301 airfoil, are studied under different flow conditions ranging from low-speed, inviscid flow to transonic, viscous, turbulent flow. The results are verified against reference results from the literature. In addition, two other established flutter methods are implemented in this work for verification purposes, and the efficiency and robustness of the one-shot method are investigated.

1. Introduction

Accurate prediction of flutter boundaries for air vehicles is crucial to ensure the safety of flight operations. In practice, flutter prediction methods can be broadly classified in three categories regardless of the specific type of techniques used to model the fluid and the structural fields. The first category is based on the physical property of flutter onset phenomenon. Methods that fall in this category continuously sweep over possible flutter conditions (such as the frequency and the freestream velocity) using an aeroelastic solver, and observe how oscillations evolve following an initial disturbance. The flutter point is obtained when the oscillation sustains its amplitude, i.e., when the total damping of the system vanishes (Geuzaine et al., 2003; Woodgate et al., 2005; McNamara and Friedmann, 2007; Kachra and Nadarajah, 2008; Mundis and Mavriplis, 2013) or when the excitation force required to sustain the oscillation becomes zero (Fung, 1969). Note that this type of flutter prediction needs multiple runs of the aeroelastic solver in order to bracket a single flutter onset point which may be computationally expensive.

* Corresponding author.
E-mail addresses: hli70@vols.utk.edu (H. Li), ekici@utk.edu (K. Ekici).

https://doi.org/10.1016/j.jfluidstructs.2018.08.012
0889-9746/

Nomenclature

b, c	Half-chord and chord length, respectively
C_l, C_m	Lift coefficient and moment coefficient about the elastic axis, respectively
C_p	Pressure coefficient, $C_p = (p - p_\infty)/q_\infty$
$\boldsymbol{E}$, $\boldsymbol{E}^{-1}$	Discrete Fourier and inverse Fourier transformation matrices, respectively
e	Position of elastic axis behind leading edge in unit of chord length c
$\boldsymbol{F}$, $\boldsymbol{G}$	Flux vectors in x and y directions, respectively
$\mathcal{F}$	Assembly of flutter governing equations
fi	Flutter index, $fi = 2\tilde{V}_f/\sqrt{\mu}$
$\boldsymbol{f}$	Vector of aerodynamic forces
H	Total enthalpy
h	Enthalpy or plunge displacement
I_α	Second moment of inertia of airfoil about the elastic axis
K_h	Plunge stiffness of airfoil
K_α	Torsional stiffness of airfoil about the elastic axis
$\boldsymbol{K}$, $\boldsymbol{M}$, $\boldsymbol{T}$	Stiffness, mass and damping matrices, respectively
m	Mass of aeroelastic model
M_∞	Free-stream Mach number
N	Number of harmonics
p, p_∞	Local and free-stream pressure
$\boldsymbol{Q}$	Conservation variables of fluid equation
$\hat{\boldsymbol{Q}}_{c_n}$, $\hat{\boldsymbol{Q}}_{s_n}$	Fourier coefficients of conservation variables
q_∞	Free-stream dynamic pressure, $q_\infty = \rho_\infty U_\infty^2/2$
r_α	Radius of gyration of airfoil about the elastic axis, $r_\alpha^2 = I_\alpha/(mb^2)$
Re_∞	Free stream Reynolds number
$\mathcal{R}_f$, $\mathcal{R}_s$	Residuals of fluid and structure governing equations, respectively
$\boldsymbol{S}$	Source vector of fluid equation
S_α	First moment of inertia of airfoil about the elastic axis
T_h, T_α	Plunge and torsional damping of airfoil, respectively
S_t	Source term for the Spalart Allmaras turbulence model
$\boldsymbol{S}$	Source vector of fluid equation
t	Physical time
u, v	Cartesian velocity components
U_∞	Free-stream velocity
$\tilde{V}$	Reduced velocity, $\tilde{V} = U_\infty/(\omega_\alpha c)$
x, y	Cartesian coordinates
x_α	Airfoil static unbalance, $x_\alpha = S_\alpha/(mb)$
Z	Figure-of-merit for reduced frequency and reduced velocity search
α	Pitch displacement
γ	Ratio of specific heats
ζ_h	Plunge coordinate damping coefficient, $\zeta_h = T_h/(2m\omega_h)$
ζ_α	Pitch coordinate damping coefficient, $\zeta_\alpha = T_\alpha/(2I_\alpha\omega_\alpha)$
$\boldsymbol{\eta}$	Vector of dependent structure variables
μ	Mass ratio, $\mu = m/(\pi\rho_\infty b^2)$
μ_l, μ_t	Laminar and eddy viscosities, respectively
$\tilde{\nu}$	Working variable of the turbulence model
ρ_∞	Free-stream density
τ_f, τ_s	Pseudo-time for fluid and structure solvers, respectively
ϕ_α, ϕ_h	Phase of pitching and plunging oscillations, respectively
ω	Frequency
$\tilde{\omega}$	Reduced frequency based on airfoil chord length, $\tilde{\omega} = \omega c/U_\infty$
ω_α, ω_h	Uncoupled natural frequencies of pitching and plunging about the elastic axis

Superscripts and accents

$*$	Variable in sub-time levels
$\hat{}$	Fourier coefficients
$\dot{}$	Dimensional time derivative
$'$	Non-dimensional time derivative