Journal of Fluids and Structures 61 (2016) 376–391

Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Precursors to flutter instability by an intermittency route: A model free approach

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ARTICLE INFO

Article history:
Received 10 September 2014
Accepted 23 November 2015
Available online 14 January 2016

Keywords:
Wind tunnel experiments
Intermittency
Recurrence
Aeroelastic flutter
Precursor to flutter

ABSTRACT

The aeroelastic response of a NACA 0012 airfoil in the flow regimes prior to flutter is investigated in a wind tunnel. We observe intermittent bursts of periodic oscillations in the pitch and plunge response, that appear in an irregular manner from a background of relatively lower amplitude aperiodic fluctuations. As the flow speed is increased, the intermittent bursts last longer in time until eventually transitioning to a fully developed periodic response, indicating the onset of flutter. The repeating patterns in the measured response are visualized using recurrence plots. We show that statistics of the recurrence states extracted from these plots can be used to develop model-free precursors that forewarn an impending transition to flutter, well before its onset.

1. Introduction

Aeroelastic flutter is an instability that occurs when the aerodynamic forces overcome the structural and inertial forces in slender flexible structures, such as aircraft wings, giving rise to large amplitude periodic oscillations. Classical flutter — also known as coupled-mode or bending–torsion flutter — involves a fluid–elastic coupling between the structural modes, wherein above a critical wind speed, energy is transferred from the flow to the structure (Fung, 1955). This energy transfer leads to self-sustaining limit cycle oscillations (LCO) that can cause either an abrupt structural failure due to overloading, or fatigue failure due to gradual accumulation of damage. It is therefore obvious that the onset of flutter poses a risk to the structure integrity, and consequently an important criterion in design and maintenance is that the operating conditions should not lead to flutter instability. Aeroelastic instabilities are not restricted to aircraft wings alone. The blades of modern wind turbines are also susceptible to aeroelastic flutter (Lobitz, 2004; Zhang and Huang, 2011). Understanding, predicting and preventing the onset of flutter has therefore remained a focal point of extensive research, especially in the past decades.

Stability characteristics and bifurcation behavior of aeroelastic systems having both structural and aerodynamic nonlinearities have been extensively investigated in the literature (Alighanbari and Price, 1996; Lee et al., 1999; Dowell and Tang, 2002; Sarkar and Bijl, 2008). Significant research effort has also been invested in identifying and modeling various types of nonlinearities (Abdelkefi et al., 2012). These studies were primarily aimed towards developing an understanding of the expected nonlinear aeroelastic response and its underlying physics. However, the high costs associated with structural failures and the expenditures incurred towards preventive maintenance, scheduling and retrofitting, there is a need to develop methodologies for identifying the onset of flutter.

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http://dx.doi.org/10.1016/j.jfluidstructs.2015.11.015
0889-9746/

Nomenclature

b	semi-chord of airfoil
c	chord length
d	embedding dimension
d_0	optimum embedding dimension
$E_1(d), E(d)$	measures used to compute d_0
$E_2(d)$	measure used to check for determinism in signals
f_s	under sampled frequency (Hz)
f_v	dominant frequency (Hz)
I_α	pitch moment of inertia kg m^2
k_y	stiffness in plunge (N/m)
k_α	stiffness in pitch (Nm/rad)
m_1	mass of the plunging frame (kg)
m_2	mass of the pitching mechanism (kg)
m_3	mass of the airfoil (kg)
m_y	total mass in plunge $(m_1+m_2+m_3)$(kg)
m_α	total mass in rotation (m_2+m_3)(kg)
S	static unbalance (kg m)
N	length of time series
U	wind flow speed (m/s)
y	plunge response (mm)
α	pitch response (deg)
ϵ	threshold for constructing recurrence plot
ζ_y	viscous damping ratio in plunge
ζ_α	viscous damping ratio in pitch
ω_y	natural frequency in plunge (Hz)
ω_α	natural frequency in pitch (Hz)
ϖ	ratio of plunge to pitch natural frequencies
r	radius of gyration
μ	nondimensional mass
V	nondimensional wind speed $(U/b\omega_\alpha)$
x_α	nondimensional distance between elastic axis and center of mass
a_h	nondimensional distance from the mid-chord to the elastic axis
τ	time delay for embedding
τ_{opt}	optimum time delay for embedding

Early studies devoted to the development of methodologies for identifying the flutter boundary focussed on estimating the damping in the fluid–structure interaction system (Kehoe, 1985; Cox et al., 2006). However, damping based approaches are unsuitable for structures with complex, nonlinear damping. The other traditional approach for flutter prediction is based on the estimation of dynamical stability. Zimmerman and Weissenburger (1964) proposed a methodology to derive a flutter margin based on Routh's stability criterion (Fung, 1955), which was applied to a two degree of freedom system under the assumption of quasi-steady aerodynamics. Later, the Zimmerman–Weissenburger Methodology (ZWM) was also applied in systems with higher degrees of freedom (Price and Lee, 1993). Recently, an extension of ZWM was presented by Poirel et al. (2005), using uncertainty quantification for a more reliable estimate of the modal parameters. Flutter margin prediction approach based on Jury's stability criterion for digitalized systems has been documented by Matsuzaki (2011). An on-line flutter prediction tool called flutterometer was developed by Lind and Brenner (2000) using an analytical model. To account for modeling errors and uncertainties, parts of the model were updated through a nonlinear iterative algorithm that generates a "worst case flutter boundary". Although this technique is robust, the stability margins tend to be quite conservative (Strganac and Platanitis, 2001).

The literature review reveals that the existing methodologies for predicting the flutter boundaries require the development of a mathematical model. Moreover, an accurate and early on-line prediction of the onset of flutter using measurements directly remain elusive. This study aims towards developing a methodology for identifying the flutter boundary directly from measurement data of the response of the system. The development of these precursors follows from time series analysis of the response measurements, where the onset of LCOs is presaged by a transitional intermittent state.

Studies on identifying precursors to undesirable states in other nonlinear systems are available in the literature. Precursors to instabilities have been obtained by forcing the dynamical system with broad band noise (Wiesenfeld, 1985; Surovyatkina, 2005). The noise gets selectively amplified at the instability frequency and the width of the dominant frequency is considered as an indicator of instability (Wiesenfeld, 1985). Further, Surovyatkina (2005) has shown for a nonlinear geophysical system that the width of the hysteresis zone gets reduced as the noise levels are increased. Both these studies were developed in the frequency domain. However, a frequency domain analysis might not always be sufficient to identify precursors as external stochastic forcing can change the dynamics qualitatively, as was shown for a thermoacoustic system by Jegadeesan and Sujith (2013).

The focus of the present study is to identify robust precursors to flutter instability through an intermittent state of response in an essentially model-free approach. This is done by studying the characteristics of the aeroelastic response at conditions prior to the onset of flutter. Experimental measures are obtained from wind tunnel tests. The responses are measured at regimes of both stable (no flutter) and unstable (flutter) operations by systematically increasing the mean flow velocity. The transition to instability happens through an intermittent regime which has a specific dynamical signature, based on which precursors to impending flutter are developed. As the precursors are developed based on the measured response, the technique is essentially model independent, the advantages of which are elaborated later in the paper.

The organization of the paper is as follows: a brief overview of intermittency and its appearance in other models and engineering systems is presented in Section 2. Section 3 describes the experimental setup and provides a primer on the computational techniques presented in the paper. Precursors to flutter are developed from the measured pitch and plunge response using recurrence quantification analysis in Section 4. The proposed developments are subsequently illustrated in