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Investigations on precursor measures for aeroelastic flutter

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ABSTRACT

Wind tunnel experiments carried out on a pitch-plunge aeroelastic system in the presence of fluctuating flows reveal that flutter instability is presaged by a regime of intermittency. It is observed that as the flow speed gradually increases towards the flutter speed, there appears intermittent bursts of periodic oscillations which become more frequent as the wind speed increases and eventually the dynamics transition into fully developed limit cycle oscillations, marking the onset of flutter. The signature from these intermittent oscillations are exploited to develop measures that forewarn a transition to flutter and can serve as precursors. This study investigates a suite of measures that are obtained directly from the time history of measurements and are hence model independent. The dependence of these precursors on the size of the measured data set and the time required for their computation is investigated. These measures can be useful in structural health monitoring of aeroelastic structures.

1. Introduction

The interaction of flows with flexible airfoil like structures can give rise to instabilities like aeroelastic flutter. The onset of flutter instability is marked by the appearance of self-sustained, limit cycle oscillations (LCOs) via a supercritical Hopf-bifurcation [1]. The sustained high amplitude oscillations in the post flutter regime can lead to structural damage due to accumulation of fatigue, which in turn leads to a loss of structural integrity and failure. A key step in aeroelastic design considerations is to ensure that flutter is avoided in normal operating conditions. Identifying the onset of aeroelastic flutter is therefore crucial in the design and health monitoring of aeroelastic structures.

Most studies in the literature on identifying aeroelastic flutter relies on developing an accurate mathematical model for the fluid structure interaction problem and carrying out a numerical or analytical study to identify the flutter boundary [1–6]. The challenge in these studies lie in identifying and modelling the nonlinearities in the stiffnesses and damping associated with system [7]. The studies reported in Refs. [5,8] estimate the damping levels in the aeroelastic system to predict the onset of flutter instability. However, this technique becomes unsuitable in the presence of nonlinearities, measurement noise and in cases involving abrupt transitions to flutter. Using dynamic stability criteria, the Zimmermann-Weissenburger Methodology (ZWM) [9] was also developed to identify flutter boundaries for a two-degree of freedom airfoil. Later, the ZWM was extended to higher degrees of freedom [10]. The ZWM methodology used a simpler quasi-steady aerodynamics model rather than a more rigorous unsteady aerodynamics formulation. A toolbox called expert system was developed in Ref. [11] to predict LCOs and was tested on response data obtained from both wind tunnel and numerical experiments. The toolbox could successfully predict impending LCOs. However, the methodology was developed in the presence of free-play nonlinearity. The effectiveness

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of this methodology in generic cases with other nonlinearities has not been addressed.

The accuracy of these methods in identifying flutter depends, in turn, on the accuracy of the mathematical modelling of the physical system. In reality, this is a difficult task especially when one needs to incorporate the effect of nonlinearities and uncertainties into the mathematical model. In a fluid-structure interaction problem, nonlinearities can arise from large structural deformations or from the flow-separation. The sources of uncertainties could be due to fluctuating flows or from inadequately modelled structural and fluid parameters. Moreover, for a structure that is already in use, fatigue and other ageing effects lead to changes in the structural parameters, which in turn lead to changes in the stability boundaries. Thus, in structural health monitoring applications, the ageing effects need to be accurately incorporated into the mathematical model. This would require a solution of the inverse problem at periodic intervals and updating of the mathematical model. An alternative methodology for identifying flutter would be through time series analysis of measurement data. Any quantitative analysis for identifying aeroelastic flutter directly from measurement data bypasses the requirement, and in turn the associated difficulties in developing accurate mathematical models for the system. Issues related to changing of the stability boundaries due to ageing effects is directly manifested through the time history measurements of the response and the need for periodic updating of the mathematical model is bypassed. Thus, time series based studies for identifying aeroelastic flutter are essentially model independent approaches.

Such model free approaches to developing precursors to aeroelastic flutter has been investigated recently by the present authors [12,13]. In these studies, the authors experimentally investigated the dynamic behavior of an aeroelastic system in a wind tunnel when the mean flow is accompanied by irregular fluctuations. The motivation for considering irregularly fluctuating flow lies in the fact that in field situations, the flow is invariably accompanied by fluctuations due to the wake effects of adjoining structures or components. In the presence of irregularly fluctuating flow, it was shown that the transition to flutter is distinctly different from the case when flow is uniform and devoid of any disturbances. Unlike the latter case where flutter occurs through a supercritical Hopf bifurcation as the mean flow speed is gradually increased, the presence of fluctuations lead to an intermittent behavior that presages the limit cycle oscillations. The intermittent behavior is characterized by the presence of bursts of large amplitude periodic oscillations amidst small amplitude irregular fluctuations. The occurrence of these bursts become more frequent as the mean flow speed approaches the flutter speed from below and eventually transitions to well developed LCOs. Investigations on the physics associated with this intermittency [14] reveal that it is induced by the flow fluctuations, the correlation length scales of which play an important role in dictating the type of intermittency.

Quantifying the occurrence of these intermittent bursts of large amplitude periodic oscillations using recurrence quantification techniques led to the development of precursor measures to forewarn an impending aeroelastic flutter [12]. The pre-flutter aeroelastic response was observed to possess a multifractal signature and as the system approached the vicinity of flutter instability, the signature lost its multifractal characteristics. This loss in multifractality was quantified using measures like Hurst exponent and led to the development of another precursor for an impending flutter instability [13]. Both these precursor measures were robust in forewarning an impending transition. However, these measures were largely dependent on ancillary procedures that resulted in a dependence on the length of measured aeroelastic response and is computationally intensive as well. The high computational cost places restrictions in the use of these measures for online health monitoring. There is therefore a need for developing precursor measures that work efficiently even for smaller data sets and requires minimal computational effort for their estimation.

The present study aims at identifying a suite of model-free measures that are practically viable and can be used as early warning signals to an impending flutter instability. This is carried out by investigating the underlying dynamical signature of the aeroelastic response prior to the onset of flutter instability. The aeroelastic response measurements are obtained from wind tunnel tests, where the flow is designed to have irregular fluctuations superimposed on a mean flow speed. The responses are measured at regimes of both pre-flutter and post-flutter conditions by systematically increasing the mean flow speed. Measures like Approximate entropy, Sample entropy and the Lempel-Ziv complexity are used to capture the changes in response dynamics as the system moves to post flutter regime. The measures from Refs. [12,13], namely, Hurst exponents and recurrence plot based measures are also presented here for the sake of completeness and to aid in discussing the relative merits of the newly proposed measures. The effectiveness of these measures are analyzed by studying their dependence on the length of measured time signal and the computational time required to estimate these measures. To gain confidence on the efficacy of the identified precursor measures, the measures have been subsequently applied to synthetic data generated from a numerical model, where the flutter speed can be analytically determined as well.

The rest of this paper is organized as follows: Section 2 provides a description of the wind tunnel experiments. Section 3 presents the suite of precursor measures discussed in the paper. These precursor measures are applied on the experimentally observed data and the corresponding results are presented in Section 4. The viability and relative merits of these precursor measures are investigated in Section 5. Section 6 presents the behavior of these precursor measures on synthetically obtained data from a numerical model and serves as a validation exercise. Finally, the paper concludes with Section 7 where the key findings that emerge from this study are summarized.