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Multi-fractality in aeroelastic response as a precursor to flutter

J. Venkatramani [a], Vineeth Nair [b], R.I. Sujith [b], Sayan Gupta [a], Sunetra Sarkar [b,*]

[a] *Department of Applied Mechanics, Indian Institute of Technology Madras, Chennai 600036, India*
[b] *Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India*

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ABSTRACT

Wind tunnel tests on a NACA 0012 airfoil have been carried out to study the transition in aeroelastic response from an initial state characterised by low-amplitude aperiodic fluctuations to aeroelastic flutter when the system exhibits limit cycle oscillations. An analysis of the aeroelastic measurements reveals multi-fractal characteristics in the pre-flutter regime. This has not been studied in the literature. As the flow velocity approaches the flutter velocity from below, a gradual loss in multi-fractality is observed. Measures based on the generalised Hurst exponents are developed and are shown to have the potential to warn against impending aeroelastic flutter. The results of this study could be useful for health monitoring of aeroelastic structures.

1. Introduction

The dynamical behaviour of slender flexible structures in flows can be phenomenologically very rich due to the mutual interaction effects where the forces exerted by the fluid in the structure become dependent on the dynamics of the structure. In certain flow regimes, the coupling between the forces exerted by the fluid and the structure results in self-sustained oscillations or flutter [1] in the combined fluid–structure system. In the parlance of nonlinear dynamics, these oscillations represent limit cycle oscillations (LCO) that appear beyond the flutter onset velocity. As the flow velocity is increased further, the amplitude of the response oscillations increases. This behaviour is typical of supercritical nonlinearity and the flutter velocity represents the supercritical Hopf bifurcation point. In the subcritical variety, the transition to flutter is abrupt and is sensitive to perturbations and limit cycle oscillations can be encountered before the Hopf point. In the present study, we restrict our discussions only to the supercritical case.

Aero-elastic flutter is an undesirable phenomenon as the sustained oscillations post-flutter could lead to structural damage due to fatigue in metals and debonding or delamination in composites – either of which eventually leads to structural degradation and failure. From the perspective of health monitoring of aeroelastic structures, it is important to ensure that sustained limit cycle oscillations are avoided. Identification of the stability boundaries for such aeroelastic structures therefore constitutes a very important step in design and health monitoring. This has led to studies being devoted in the literature on methods for analysing the stability boundaries of such fluid–structure interaction problems. Analytical studies carried out in the literature are based on developing suitable mathematical models for the slender structure and the forces that arise due to the presence of the flow [2–7]. Here, the challenges lie in modelling the nonlinearities in the stiffness

* Corresponding author.
E-mail address: sunetra@iitm.ac.in (S. Sarkar).

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and damping properties of the structure [8,9] and developing expressions that approximate the fluid forces that act on the structure.

Alternative methods such as those based on monitoring the damping levels [6,10], have been one of the earliest tools used to estimate the flutter boundary. However, they become unsuitable in the presence of nonlinearity, measurement noise, interfering presence of different modes and in the case of abrupt transition to flutter. An alternative methodology for identification of flutter boundary is the Zimmermann–Weissenburger Methodology (ZWM) [11]. This methodology derives a flutter margin based on Routh's stability criterion and was applied to a two degree of freedom system with quasi-steady aerodynamics. Subsequently, the ZWM was applied to systems with higher degrees of freedom as well [12]. Using an analytical model, an online flutter prediction tool called flutterometer was developed [13]. For the sake of modelling errors and uncertainties, parts of the model were updated through a nonlinear iterative algorithm that generates a 'worst case flutter boundary'. Despite the technique being robust, the proposed stability margins were found to be conservative [14]. In order to predict nonlinear aeroelastic behaviour like LCO, an expert system was developed [15] and tested on short duration transient data acquired from both experiments and numerics. It was observed that the expert system could successfully predict behaviour like LCO's, diverging oscillations, etc. However, these methods were developed in the presence of free-play nonlinearity in pitch degree of freedom and is suggested that the effectiveness of the expert system depends upon an accurate estimation of the free-play parameters. Further, the suitability of this technique in the presence of other types of nonlinearities and wind gusts has not been explored.

Indeed, most studies on aeroelastic stability analysis were carried out under the assumptions of steady uniform flow. However, in real life conditions, the flow is seldom steady and is usually accompanied by fluctuations. These fluctuations could be either due to gust effects in the flows or due to turbulence, generated by the local flow conditions around the structure. The effect of fluctuations on the flow has significant influence on the structure response. For example, even in pre-flutter regimes, it has been shown that an impulsive gust loading in the flow can lead to transient growth in the structure response due to the transition of the system to higher stable branches in sub-critical bifurcating regimes [16]. Additionally, it has been observed that the dynamical system experiences sporadic bursts of oscillations prior to the onset of LCOs in the presence of fluctuating flows. These oscillations – termed as intermittent oscillations – have been reported in [17–21], but have not been investigated in detail. In a recent study [22], similar intermittent oscillations in airfoils have been observed in wind tunnel experiments. Detailed experimental studies carried out revealed that the sporadic bursts of oscillations that began to appear at pre-flutter flow speeds become more frequent and of longer durations as the flow speed approached the flutter velocity. The repeating patterns of these intermittent oscillations were visualised using recurrence plots and precursors were developed that enabled predicting the onset of flutter. It must be remarked here that the existing studies in the literature on methods for identifying the stability boundaries of an aeroelastic system could identify the instability regimes only after the system has already lost stability or is very close to it, and therefore are not precursors in a strict sense.

Development of precursors to instability in dynamical systems – that range from engineering applications to geophysical systems as well as biological processes – have been studied extensively in the literature. Approaches that involve analysing the response of dynamical systems in the frequency domain to estimate precursors have been carried out in [23,24]. The bandwidth of the dominant frequency of the filtered response of a dynamical system subjected to broad band noise was used as a measure of the instability in [23]. A similar technique was used in [24] where the width of the hysteresis zone obtained from the filtered response of a nonlinear geophysical system was used as a measure to quantify the instability. Similar approaches in either time or frequency domain have not been attempted in aeroelastic system to forewarn instability.

The focus of this paper is to investigate the small aperiodic oscillations that appear in the response of a NACA 0012 airfoil when subjected to fluctuating flows. Experiments are carried out in a low speed wind tunnel and the transition in the response dynamics is analysed as it changes from low amplitude aperiodic fluctuations to flutter as the mean flow speed is gradually increased. It is shown that the time histories of the response possess multi-fractal characteristics at flow speeds much lower than the flutter velocity. As the flow speed approaches the flutter velocity from below, the multi-fractality in the airfoil response gradually diminishes and eventually disappears with the onset of LCO. Measures based on quantifying the multi-fractality of the response are proposed that can be further developed to forewarn against an impending flutter.

This paper is organised as follows. A brief description on fractals and multi-fractality in time histories, and measures of quantifying the multi-fractality is presented in Section 2. Section 3 provides details of the wind tunnel experiments and the set-up. Investigations on the multi-fractality of the measured response are discussed in Section 4. Section 5 details the development of suitable measures that can serve as potential precursors to aeroelastic flutter. The effectiveness of these measures is validated through the numerical exercise presented in Section 6; discussions on the aeroelastic instability in the absence and presence of fluctuations are presented as well. The salient features of this study are summarised in Section 7. For the sake of completion, an appendix is provided which gives a brief description of the algorithm used for quantifying the multi-fractality in the measured time histories.

2. Multi-fractality

Fractal sets, which could represent infinitely complex patterns, a curve or a time history, exhibit self-similarity across different scales [25]. The dimension of a fractal set is a statistical measure that describes how densely the set occupies the

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