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Numerical investigations on intermittency route to aeroelastic flutter

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Abstract

Recent wind tunnel studies have shown that an aeroelastic system, prior to losing stability through flutter, goes through a regime where the response is characterized by intermittent bursts of periodic oscillations. The focus of this study is to investigate the reasons for this intermittent behavior through a numerical model. The studies indicate that the intermittency is observed only when the flow is accompanied by small random fluctuations. A stochastic bifurcation analysis is carried out to gain an understanding for this phenomenological interesting behavior.

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Keywords: Intermittency; Aeroelastic flutter; Hopf bifurcation; Fluctuating flows.

1. Introduction

Classical aeroelastic flutter is a common dynamical instability that arises due to fluid-structure interaction effects in flexible aeroelastic structures, such as turbine blades and aircraft wings. The instability arises due to fluid-elastic coupling that leads to continuous transfer of energy from the flow to the structure [1], resulting in large amplitude, self-sustained oscillations [2, 3]. If the wind flow is smooth and undisturbed, aeroelastic flutter manifests via a Hopf-bifurcation phenomenon [2]. This implies that the system has a decaying motion below a critical flow velocity called the flutter speed, but exhibits self-sustained or limit cycle oscillations (LCO) above it. In reality, the flow is however always accompanied by fluctuations that could arise from numerous sources such as acoustic emissions, atmospheric conditions, flow separation and vortex break down leading to tail buffeting etc. In the presence of fluctuating flows, stability and bifurcations need alternative interpretations, as the aeroelastic system never decays even at flow speeds lower than the flutter speed. This implies that a single step transition from a fixed point response to a limit cycle response is insufficient to describe the instability of an airfoil subjected to fluctuating flows. Instead, the onset of instability or bifurcation can be defined in terms of an abrupt topological change that is manifested in terms of some response metric of the system.

In nonlinear dynamical systems, abrupt topological changes characterized through the phase portrait of the systems indicates changes in the dynamical behavior and are referred to as dynamical or D-bifurcations. The commonly

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used metric for identifying D-bifurcations is the largest Lyapunov exponent (LLE), which measures the average long term behavior of the response trajectories and a change in sign (from negative to positive) is indicative of loss of stability [4]. In systems exhibiting random oscillations, the joint probability density function (j-pdf) of the state variables is representative of the average time spent within a finite domain of the state space and any abrupt changes in the topology associated with the joint pdf is indicative of changes in the behavior of the system. This is referred to as phenomenological or P-bifurcations. In randomly vibrating nonlinear systems, D- and P- bifurcations may occur at different parameter regimes. Moreover, while D-bifurcations are abrupt and occur at particular values of the bifurcation parameter, changes in the topology of the pdf of the state variables is gradual and occurs over a range of the bifurcation parameter.

In the context of the intermittent behavior observed prior to aeroelastic flutter, a numerical study using a widely studied numerical model reveals that no intermittent behavior is observed when the flow is assumed to be uniform. Here, intermittency refers to the occurrence of a signal that irregularly alternates between regular phases and irregular bursts [5] and has been observed in several physical systems [6–12]. For a generic dynamical system, intermittency is analogous to fluctuations between two stable states for certain ranges of a control parameter in the system. Now, in sterile flows, the fluctuations between stable states do not arise unless there are perturbations that force the trajectories to move from the domain of attraction of one attractor to the other. This is possible only when the flow is accompanied by random fluctuations. Intermittent behavior in airfoils has been observed in a numerical study examining the dynamics of a structurally nonlinear pitch plunge airfoil model in the presence of randomly fluctuating flow [13]. At mean wind speeds much below the stochastic LCO behavior, bursts of periodic regimes were observed. The duration of the bursts increased with increase in the mean wind speed. This type of strange time domain behavior was referred to as on-off intermittency [14]. Similar observations (of intermittent bursts) were observed in the wind tunnel experiments under continuous flow disturbance [15]. Intermittent bursts were reported in a few other experimental studies, eg., in a bridge deck flutter [16] and in a delta wing [17]. In a recent wind tunnel experiment conducted under fluctuating wind flow [18], the route to aeroelastic flutter was observed to take place via an intermittent route. Though a stochastic bifurcation analysis examining the D- and P-bifurcations of an airfoil in randomly fluctuating flows has been carried out in [19], no efforts were undertaken to gain an understanding on the reasons of the observed intermittent behavior.

This paper focuses on carrying out a parametric study with a numerical model of an airfoil in flows accompanied by small random fluctuations, with the objective of gaining an understanding on the occurrence of intermittent behavior observed in pre-flutter regimes. The wind load acting on the airfoil is considered to be a simple canonical model having sinusoidal fluctuations with random frequencies in it.

2. Problem description

An airfoil subjected to both bending and torsion is modeled in 2D by considering a small representative panel along the axis and treating it as a rigid two dimensional flat plate. The bending and torsional stiffness are modeled through translational and torsional springs; see Fig 1 for a schematic. The plate has two degrees of freedom pitch and heave. The non-dimensional equations of motion describing the airfoil motion are expressed in Eqs. (1-2).

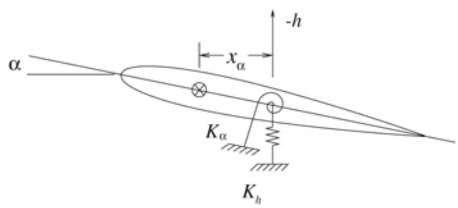

Fig. 1. Schematic of an airfoil

$$\epsilon'' + x_\alpha \alpha'' + 2\zeta_\epsilon \frac{\overline{\omega}}{U}\epsilon' + (\frac{\overline{\omega}}{U})^2(\epsilon + \beta_\epsilon \epsilon^3) = -\frac{1}{\pi\mu} C_L(\tau), \tag{1}$$

$$\frac{x_\alpha}{{r_\alpha}^2}\epsilon'' + \alpha'' + 2\frac{\zeta}{U}\alpha' + \frac{1}{U^2}(\alpha + \beta_\alpha\alpha^3) = \frac{2}{\pi\mu {r_\alpha}^2}C_M(\tau). \tag{2}$$

Here, $\epsilon = h/b$ is the non-dimensional heave displacement, α is the pitch angle, m is the total mass of the frame and airfoil per unit span, r_α is the radius of gyration about the elastic axis of the total pitching assembly, ζ_ϵ and ζ_α are the damping ratios in plunge and pitch respectively, β_ϵ is the heaving stiffness co-efficient, β_α is the pitching stiffness, $a_h b$ denotes the distance of the elastic axis from the mid chord and $x_\alpha b$ is the distance of the center of mass from the elastic axis. U or U_{nd} is the non-dimensional stream velocity given by $U = v/(b\omega_\alpha)$ $\overline{\omega} = (\omega_\epsilon/\omega_\alpha)$, where, ω_ϵ and ω_α are respectively the natural frequencies of the uncoupled plunging and pitching modes and $\tau = vt/b$ is the non-dimensional time. The non-homogeneous terms $C_L(\tau)$ and $C_M(\tau)$ represent the forcing terms and are usually represented as a set of coupled second order differential equations which are functions of α and ϵ and its expressions are available in [2] and given below in equations 3 and 4.

$$\begin{aligned} C_L(\tau) = {} & \pi(\xi'' - ah\alpha' + \alpha') + 2\pi[\alpha(0) + \xi'(0) + (0.5 - ah)\alpha'(0)\phi(\tau)] \\ & 2\pi \int_0^\tau \phi(\tau - \sigma)[\alpha''(\sigma) + \xi''(\sigma) + (0.5 - ah)\alpha''(\sigma)]d\sigma, \end{aligned} \tag{3}$$

$$\begin{aligned} C_M(\tau) = {} & \pi(0.5 + ah)[(\alpha(0) + \xi'(0) + (0.5 - ah)\alpha'(0))]\phi(\tau) \int_0^\tau \phi(\tau - \sigma) \\ & [\alpha'(\sigma) + \xi'(\sigma) + (0.5 - ah)\alpha''(\sigma)]d\sigma. \end{aligned} \tag{4}$$

For ease of understanding the effects of the random fluctuations of the flow on the behavior of the system, the deterministic flow was superimposed with a small sinusoidal component whose frequency of oscillation was assumed to be random. This is a simple artifice as a random process can be spectrally represented as a superposition of a large number of sinusoids. Thus, the flow speed U, is expressed as,

$$U = \frac{U_m}{b\omega_\alpha}(1 + \sigma(\sin(\omega_r t)), \tag{5}$$

where, U_m is the dimensional mean wind speed in m/s, σ indicates the amplitude of the fluctuating component and ω_r is the frequency of the sinusoid, adjusted such that, $\omega_r = \omega_1 + \kappa R$, Here, κ is a constant and R is a number that varies at each time instant and has uniform distribution in $[0, 1]$. This model is developed such that random perturbations are added in time to a dominant frequency component in the assumed sinusoidal form. Thus, perturbations of various time scales (about a dominant frequency) are continuously injected to the mean wind flow and is used as an input to equations 1 and 2. One can refer to [18] for more details on the gust model formulation. The physical parameters used in the numerical calculations are those relevant to the experimental setup presented in [18].

3. Results and discussions

First, Eqs (1-4) were numerically integrated using a fourth order Runge-Kutta algorithm and the deterministic onset of flutter was identified by obtaining a Hopf bifurcation plot(see Figure 2). Accordingly, the onset of flutter was noticed to be at approximately $U = 7.5$ m/s. Next, the sinusoidal fluctuations were considered in the wind loads. Note that the presence of fluctuating components in the wind field result in changes in the form of the equations of motion which are obtained by non-dimensionalizing with respect to the mean wind speed.

The system behavior is studied by systematically increasing the mean wind speed in small incremental steps of 0.2 m/s. In Eqs 5, the intensity of fluctuations, namely σ play a key role in the dynamics of the response. In Figure 3, the time history of the pitch and plunge responses at a mean wind speed of 4 m/s is shown. The time response is observed to comprise of low-amplitude fluctuations about zero. The corresponding joint pdf of the response and its instantaneous time derivative is unimodal, having mean amplitude close to zero and is indicative of the mean amplitude of the fluctuations of the trajectories about the origin; see Figure 4. Clearly, the origin is an attractor in the state space.

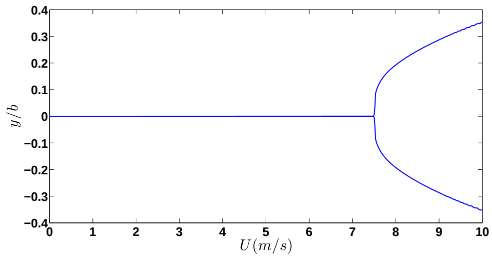

Fig. 2. Bifurcation diagram of the response as a function of U.

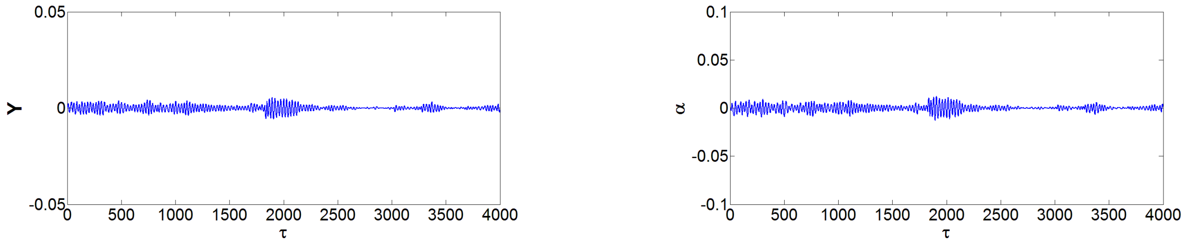

Fig. 3. Time histories of the heave and pitch response respectively for U_m = 4 m/s.

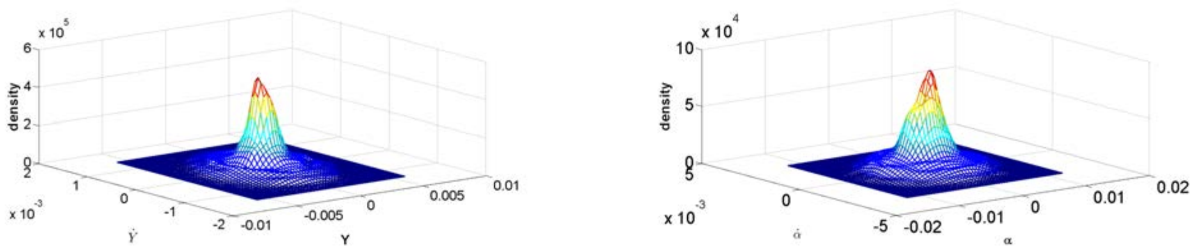

Fig. 4. Joint probability density function of the heave and pitch response respectively for U_m = 4 m/s.

As Um is increased to 5.2 m/s, the time histories of pitch and plunge response shown in Figure 5, reveal bursts of periodic oscillations amidst low-amplitude fluctuations. The corresponding joint pdf of the response and its time derivative reveal the birth of a weak attractor an LCO around the origin; see Figure 6.

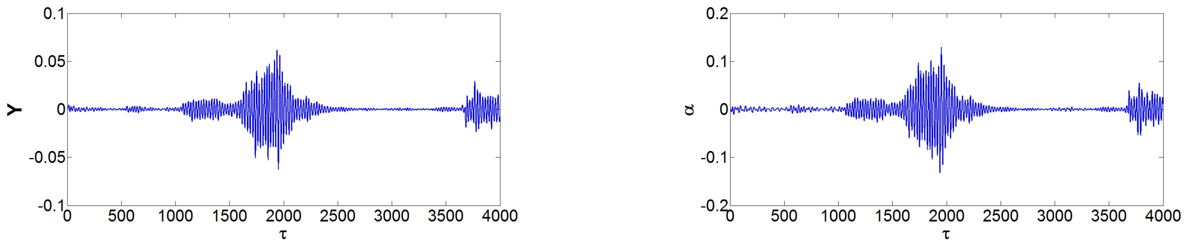

Fig. 5. Time histories of the heave and pitch response respectively for U_m = 5.2 m/s

Thus, the periodic bursts of oscillations could be triggered by the trajectories being forced out of the domain of attraction of the attractor at the origin to the domain of attraction of the weak LCO attractor.

Next, as Um is increased to 6 m/s, it can be seen from Figure 7, that the occurrence of high-amplitude periodic bursts increases. An inspection of the joint pdfs shown in Figure 8 reveals that the attractor at the origin is weakening

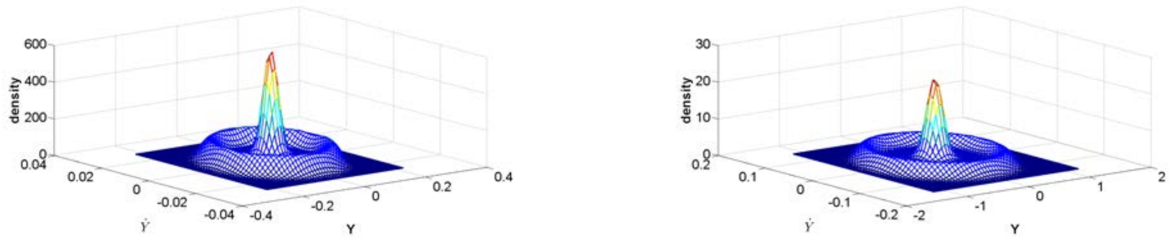

Fig. 6. Joint probability density function of the heave and pitch response respectively for U_m = 5.2 m/s

while the LCO attractor is gaining in strength. This structure of the joint pdf indicates that the system oscillates between two stable regimes.

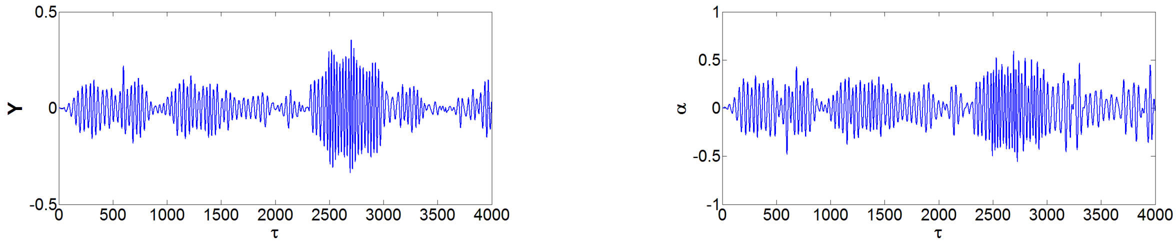

Fig. 7. Time histories of the heave and pitch response respectively for U_m = 6 m/s

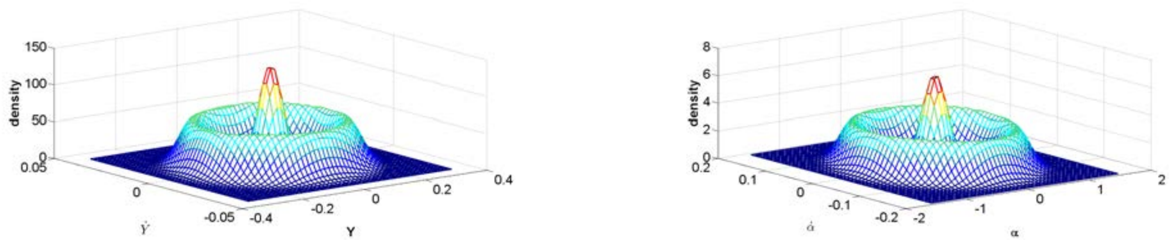

Fig. 8. Joint probability density function of the heave and pitch response respectively for U_m = 6 m/s.

Further, increasing U_m to 7.2 m/s, shows well developed LCO in the time histories; see Figure 9. An inspection of the joint pdfs shown in Figure 10 reveal that the attractor at the origin has been destroyed and only the LCO attractor exists. This explains the absence of intermittent behavior at this flow regime. The contour plots obtained from the joint pdfs for the various flow regimes and shown in Figure 11 reveal these features clearly. The width of the regions defined by the contour plots reveal the relative strength of the two attractors. Note that the changes in the topological structure of the pdf initiate for flow speed approximately 4 m/s, while a change in the sign of the LLE occurs only much later. This indicates that even though P-bifurcations have initiated, the system was essentially stable as the attractor at the center was still in existence, even though it was gradually weakening. The onset of instability is accompanied by the destruction of the attractor at the origin.

4. Conclusion

In this study, a numerical response analysis for a nonlinear airfoil was carried out to understand the intermittency route to flutter. While in an undisturbed flow, the transition to flutter instability happens via a Hopf bifurcation, it is observed that in a scenario involving fluctuating flows, an intermediate state of intermittent oscillations exists before the onset of flutter. Unlike in deterministic systems, the bifurcations in stochastic systems can be characterized by

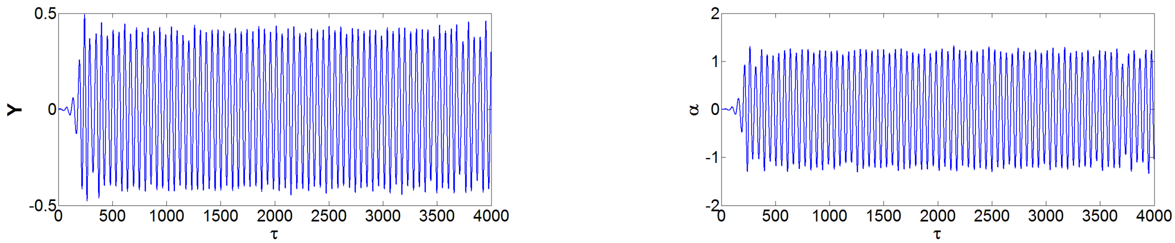

Fig. 9. Time histories of the heave and pitch response respectively for U_m = 7.2 m/s

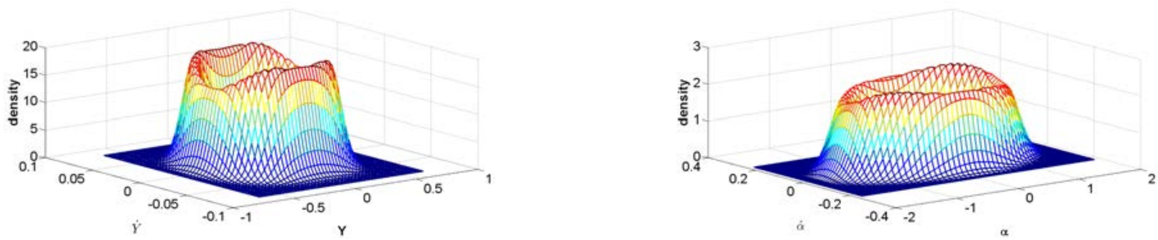

Fig. 10. Joint probability density function of the heave and pitch response respectively for U_m = 7.2 m/s

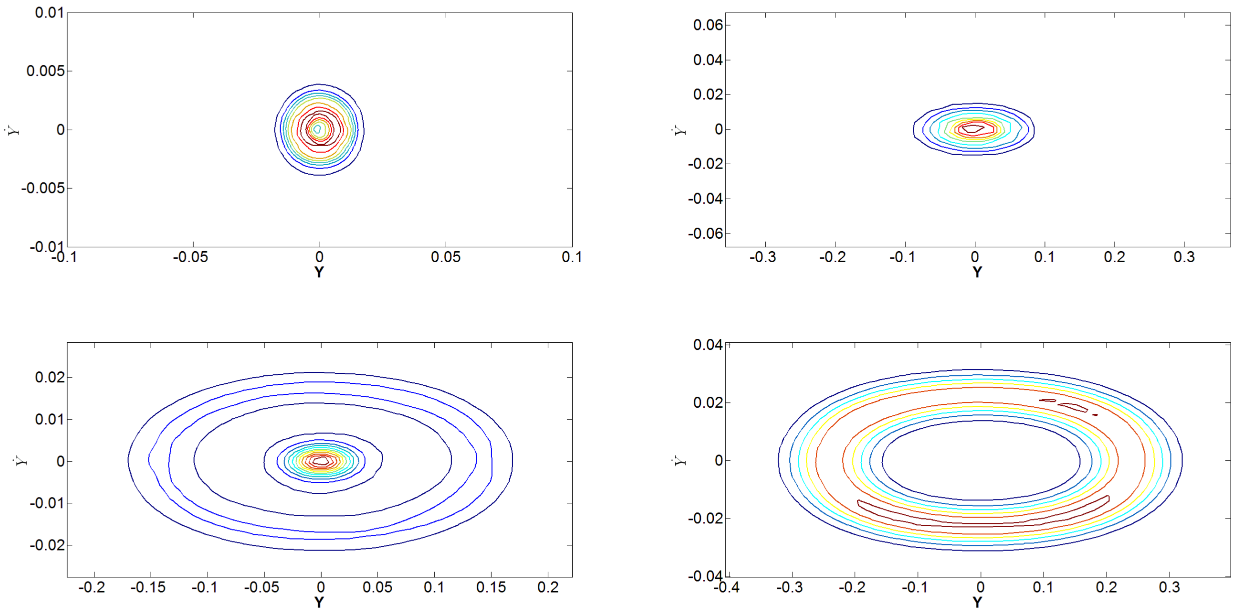

Fig. 11. Contour plot of the heave response and its instantaneous derivative for U_m = 4 m/s, U_m = 5.2 m/s (top row), U_m = 6 m/s and U_m = 7.2 m/s (bottom row) respectively.

topological changes in the structures of the j-pdf, termed as P-bifurcations. Indeed, the transition from intermittent oscillations to fully developed limit cycles could be captured by the topological changes in the joint-pdf and pdf of the energy envelope. While the qualitative changes in the joint pdfs in our numerical study highlights a P-bifurcation taking place in the dynamics, more studies are required to be carried out to quantitatively characterize P-type bifurcations in an aeroelastic system and identify regimes that could demarcate it from D-type bifurcations.

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