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Physical mechanism of intermittency route to aeroelastic flutter

J. Venkatramani [a], S. Krishna Kumar [a], Sunetra Sarkar [b,*], Sayan Gupta [a]

[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*

HIGHLIGHTS

- The role of time scales of flow fluctuations on aeroelastic response is studied.
- Long time scale fluctuations give rise to “on–off” type intermittency.
- Fluctuations with short time scales lead to “burst” type intermittency.
- The role of unsteady wake effects on “burst” intermittency is demonstrated.
- Measures from time series analysis used to quantify different dynamical responses.

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ABSTRACT

Intermittency has been observed in the response of aeroelastic systems in the presence of flow fluctuations. This study focuses on developing an understanding of the physical mechanisms that lead to intermittency in such systems. Specifically, the role of time scales of the input flow fluctuations is investigated. Numerical investigations reveal that flow fluctuations with predominantly long time scales in the pre-flutter regime lead to “on–off” type intermittency. On the other hand, rapid fluctuations constituting of small time scales lead to another qualitatively different intermittency, which is referred to in this paper as “burst” type intermittency. It is further shown that the unsteady wake effects play a crucial role in the burst type intermittency. Measures derived from time series analysis of the aeroelastic response are proposed to identify the different dynamical states quantitatively.

1. Introduction

Intermittency is a phenomenon that is commonly observed in nonlinear dynamical systems when their response characteristics alternate between qualitatively distinct behavioral states (Schuster and Just, 2006). Typically, systems exhibit intermittent behavior in parameter regimes in the neighborhood of the stability boundaries. The nature of the intermittency observed in dynamical systems depend on the nature of the equations of motion and the dynamical stability characteristics associated with the system across the stability boundaries. For example, dynamical systems that transgress from periodic behavior to chaotic state exhibit intermittencies that are classified as Types I–III (Pomeau and Manneville, 1980). Type-I intermittency is typically observed in systems in the neighborhood of saddle–node bifurcations, Type-II is classified as the intermittent response behavior in the vicinity of a Hopf bifurcation and Type-III intermittency arises in systems in the neighborhood of reverse period doubling bifurcation (Hilborn, 2000). Other forms of intermittency have also been identified

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* Corresponding author.
E-mail address: sunetra.sarkar@gmail.com (S. Sarkar).

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Nomenclature

α	Non-dimensional pitch displacement of airfoil
ϵ	Non-dimensional plunge displacement of airfoil
$x_\alpha b$	Distance between elastic axis and center of gravity
$a_h b$	Distance between elastic axis and midchord
r_α	Radius of gyration of airfoil about elastic axis
ζ_α	Viscous damping ratio in pitch
ζ_ϵ	Viscous damping ratio in plunge
β_ϵ	Coefficient of cubic nonlinearity in plunge
ϖ	Ratio of plunge to pitch natural frequencies
μ	Non-dimensional mass
U	Non-dimensional free stream velocity
U_m	Non-dimensional mean free-stream velocity
U_e	Mean free-stream velocity (m/s)
σ	Intensity of fluctuation
ω_r	Time perturbed frequency
ω_1	Frequency of the sinusoidal fluctuation
κ	Constant scalar value and is of $\mathcal{O}(\omega_1)$
R	Uniformly distributed random number in [0-1]
λ_i	Eigenvalues of the correlation function of random process
$u_i(x)$	Eigenvectors of the correlation function of random process
$\eta_i(\theta)$	Mutually uncorrelated random variables $\mathcal{N}(0, 1)$
τ	Non-dimensional time
Ω	Sample space
ξ	Set of events
P	Probability measure on (Ω, ξ)

in the literature. In–out intermittency (Covas et al., 2001) occurs during switching between a transversely stable and a transversely unstable invariant in a manifold. Crisis induced intermittency (Grebogi et al., 1987) arises due to 'attractor-merging' or 'attractor-widening' and has been observed in Ikeda map, forced damped pendulum, forced double well Duffing oscillator and also in logistic maps when three bands of a chaotic attractor merge together and form a single chaotic attractor at a specific bifurcation parameter value (Hilborn, 2000). Type-X intermittency (Price and Mullin, 1991) has been experimentally encountered in a variant of Taylor–Couette flow. Type-V intermittency (Bauer et al., 1992) is associated with discontinuous maps and occurs when an attractor loses stability due to its collision with a point of discontinuity. "On–off" intermittency is observed when the bifurcation parameter of the dynamical system has random temporal variations (Platt et al., 1993). Of these, the last type of intermittency is of interest in the context of this paper.

"On–off" intermittency is usually observed in dynamical systems when the bifurcation parameter has aperiodic temporal variations, the origin of which lies in physical mechanisms that are often unmodeled and referred to as noise; consequently, this is also referred to as noise-induced intermittency (Platt et al., 1993; Bottiglieri and Godano, 2007; Cabrera and Milton, 2004). The response time histories exhibiting "on–off" intermittency is characterized by the presence of two distinct qualitative behavioral states in the time history: a rest state marked by absence of any oscillations and a state of periodic oscillations that intersperse the rest states. Explanations for the "on–off" intermittency have been presented using the concepts of dynamical stability theory (Platt et al., 1993; Hammer et al., 1994). For a system that undergoes Hopf bifurcation, addition of irregular temporal fluctuations in its bifurcation parameter (say, γ) about its critical value γ_{cr} drives the system back and forth from the fixed point regime to the oscillatory regime. When $\gamma > \gamma_{cr}$ for a sufficiently long duration of time, the system exhibits periodic oscillations. This is defined as the "on" state. Subsequently, if $\gamma < \gamma_{cr}$ for a sufficient duration, the oscillations decay and attain the rest state characterized as the "off" state. This cycle repeating at irregular intervals leads to the "on–off" intermittency behavior.

For aeroelastic systems, the bifurcation parameter is usually taken to be the uniform flow speed U. In realistic situations, the uniform flow is usually superimposed with small fluctuations which implies that in the governing equations of motion it appears as a time varying quantity $U \equiv U(\tau)$. These fluctuations in the input flow are the main instigator for intermittency in the aeroelastic response (Venkatramani et al., 2016, 2017). Similar observations were also made by Poirel (2001) while numerically investigating the dynamics of a structurally nonlinear pitch–plunge aeroelastic system in the presence of a randomly fluctuating flow. Even when the mean wind was much below the flutter onset (the onset of limit cycle oscillations (LCOs)), the presence of flow fluctuations resulted in irregularly occurring windows of periodic-looking oscillations which the author referred to as "on–off" intermittency state. These intermittent oscillations were observed experimentally as well by Poirel et al. (2008) when bluff bodies were placed ahead of the wing in a wind tunnel. Intermittency was experimentally observed in other types of aeroelastic systems as well; for e.g., in bridge deck flutter (Andrianne and Dimitriadis, 2011) and