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Deterministic and stochastic analyses of the lock-in phenomenon in vortex-induced vibrations

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ABSTRACT

The phenomenon of lock-in in vortex-induced vibrations of bluff bodies is studied from a phenomenological model perspective. The theoretical investigation includes asymptotic deterministic and stochastic analyses which are compared with experimental measurements and Monte-Carlo simulations. It is shown that, for the considered parameter space, the model can possess only a single or multiple (co-existing) synchronized solutions, where the stable synchronized solution is hardly affected by the turbulence-induced random fluctuations far from the bifurcation points. These results provide a relatively simple connection between experimental measurements and the model predictions, and they confirm the validity of the phenomenological model for vortex-induced vibrations problems that involve a turbulent wake.
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1. Introduction

Lock-in is perhaps the most important phenomenon associated with vortex-induced vibrations (VIV) of bluff (non-streamlined) bodies. It is defined by the matching of the frequency of the periodic wake vortex mode to the body oscillation frequency [1,2] and leads to high amplitude vibrations of the body. These large-amplitude vibrations are extremely important in the design of many engineering applications, such as offshore platforms [3], flexible bridges [4], aerostats [5], and energy harvesting [6].

The practical significance of VIV in general, and when the lock-in conditions are met in particular, has motivated numerous fundamental studies of this phenomenon; these studies typically consider, as a paradigm, an elastically tethered circular cylinder that is subjected to a time-dependent wake-induced force (for comprehensive reviews see Refs. [7–11]). The flow field in VIV problems is complex; it includes interactions between multiple shear layers [12], which can occur at a wide range of Reynolds numbers with either a laminar [13] or a turbulent [14] wake. Consequently, most theoretical studies have employed phenomenological wake-oscillators to model the wake-induced force. These phenomenological models were first suggested by Bishop and Hassan [15] and by Hartlen and Currie [16], and they have been widely explored and refined since. Many researchers [17–26] have highlighted the importance of such analytically tractable models and their ability to qualitatively explain some of the intricate underlying physics. In particular, these phenomenological models enabled a comprehensive analysis of the lock-in phenomenon from different perspectives, e.g., the half maximum amplitude threshold [22], eigenvalues analysis of the linearized system [27], and mutual synchronization of a pair of oscillators [28]. While these different studies suggested different

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criteria, it seems that all the different criteria agree with the definition of [1,2].

In its most simplified case, lock-in occurs in systems that can be modeled by an elastically tethered rigid circular cylinder with linear restoring forces and a single-degree of freedom (DOF) in the transverse direction, which is mutually and linearly coupled to a time dependent wake-induced force. The wake-induced force is usually modeled by a self-sustained nonlinear oscillator, often the van der Pol oscillator [22] or the Rayleigh oscillator [16]. These two oscillators are special cases of the more general Stuart-Landau oscillator [29], which is derived, with the aid of asymptotic methods, directly from the Navier-Stokes equations for VIV of circular cylinder at low Reynolds numbers [30,31]. Although the pair of seemingly simple coupled differential equations (i.e., the transverse DOF equation of motion and the wake-oscillator) has been the subject of intensive research, several questions remain open: (i) What kind of dynamical responses this pair of differential-equations can produce? (ii) How are these responses related to experimental measurements? (iii) Is the definition of lock-in made in Refs. [1,2] suitable for phenomenological models? And (iv) What is the influence of random fluctuations due to turbulence on the lock-in phenomenon?

The current study aims to answer these questions, and thereby to deepen our understanding of the lock-in phenomenon. To this end, an asymptotic analysis is applied on a phenomenological model and the analytical results are compared to the experimental measurements of Govardhan and Williamson [32], and to data obtained from Monte-Carlo simulations. The phenomenological model included the wake oscillator suggested by Facchinetti et al. [22] and it was augmented by a broadband additive noise, which models the turbulence-induced random fluctuations.

Section 2 of this paper presents the mathematical model and its relation to the physical quantities that are analyzed, and it provides a derivation of the slowly varying amplitudes and phase difference equations. Section 3 describes the deterministic analysis and compares it with experimental measurements. Section 4 describes the stochastic analysis and compares it to data from the Monte Carlo simulations. Section 5 summarizes the results and suggests potential future studies.

2. Model formulation

The dynamical system considered in this study is illustrated in Fig. 1. It includes a rigid circular cylinder of diameter D and length ℓ. The cylinder is constrained to vibrate transversely (along the y axis) and is affected by linear restoring forces, produced by a spring with stiffness k and an equivalent dashpot with a constant $c = c_s + c_f$ where c_s is the structural damping and c_f is the fluid-added damping. The oscillatory wake-induced force, represented by the variable $q(t)$, resulting from a uniform stationary flow of free stream velocity U_∞ (along the x axis). Following Facchinetti et al. [22], the dynamical system is modeled by

$$\ddot{y}_d + (2\zeta_s\Omega_s + \gamma\Omega_f/\mu)\dot{y}_d + \Omega_s^2 y_d = S/m, \tag{1}$$

$$\ddot{q} + \varepsilon\Omega_f(q^2 - 1)\dot{q} + \Omega_f^2 q = F, \tag{2}$$

where the overdots denote derivatives with respect to time (t), y_d is the dimensional cylinder transverse displacement, ζ_s is the structural damping ratio (associated with c_s), $\Omega_s = \sqrt{k/(m_s + m_f)}$ is the structural natural frequency (m_s - structure mass, m_f - fluid added mass, and $m = m_s + m_f$), γ is a stall parameter [21] (associated with the fluid-added damping c_f), $\Omega_f = 2\pi \mathrm{St} U_\infty/D$ is the vortex-shedding frequency (St - is the Strouhal number), $\mu = (m_s + m_f)/\rho\ell D^2$ is a reduced-mass parameter (ρ - is the density of the fluid), $S = \rho U_\infty^2 \ell D C_L/2$ is the hydrodynamic force, $q = 2C_L/C_{L_0}$ is the dimensionless wake variable (C_{L_0}- is the magnitude of the reference lift coefficient that is observed on a fixed structure subjected to vortex shedding, which is usually taken as $C_{L_0} = 0.3$ in a large range of Reynolds numbers [22]), ε is the van der Pol parameter, and F models the back-action of the structure on the wake and the presence of noise due to turbulence.

While the functional form for the coupling between the fluid and the structure equation of motion (i.e., $S = \rho U_\infty^2 \ell D C_L(t)/2$ with $C_L(t) = C_{L_0} q(t)/2$ being the instantaneous lift coefficient) is well defined, the functional form of the coupling between the structure and the wake-oscillator equation, in the absence or presence of turbulence (i.e., F), is not known. Many attempts were made to model the back-action of the structure on the wake, e.g., [16,18,20,22,33]. Facchinetti et al. [22] examined three different types of structure back-action, namely Ay, $A\dot{y}$, and $A\ddot{y}$. They found that the acceleration back-action, $A\ddot{y}$, is the most suitable choice and captures many different phenomena associated with VIV. Nevertheless, as shown at Section 3 below, this acceleration back-action yields a poor estimation for the structure amplitude (see Fig. 2). Since our analysis is concerned mainly with the frequency lock-in phenomenon, which defines the region of internal resonance between the structure and the wake, we implicitly assume that the acceleration back-action yields a good representation of the phase (or, equivalently, the frequency) dynamics despite its poor estimation of the amplitude dynamics (see Eqs. (8)-(10) for the amplitudes and phase difference equations). This assumption can be justified by the fact that, regardless of the type of a considered $n : m$ internal resonance of non-conservative system (e.g., 1:1, 1:2, 1:3, 2:3) and its normal form, which dramatically changes the amplitude dynamics, the phase difference, $\phi = m\theta_1 - n\theta_2$, will always be locked (i.e., $\dot{\phi} = 0$) at the internal resonance conditions [34]. In other words, in the vicinity of the phase-locked solution ($\dot{\phi} = 0$), the phase difference dynamics can be mapped onto an isochron [35] regardless of the amplitude dynamics.

There is a large body of studies on the effects of turbulence in VIV, including experimental investigations of high turbulence level imposed by surface roughness [36–39], 2D and 3D numerical simulations of turbulent flows [14,40–42], and the recent theoretical investigation of VIV with a noisy mean flow [43]. With regard to the presence of turbulence in the wake, we note

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