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First passage time as an analysis tool in experimental wind engineering

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ABSTRACT

The first passage time is the time required for a system to evolve from an initial configuration to a certain target state. This concept is of high interest for the study of transient regimes which are widely represented in wind engineering. Although the concept has been widely studied from theoretical and numerical standpoints, there are very few practical or experimental applications where the results are seen from this angle. This work is a first attempt at bringing first passage times of stochastic systems into wind engineering by suggesting the use of a first passage time map as a standard analysis tool in experimental wind engineering. The wind tunnel data related to the spinning dynamics of a rotating square cylinder in turbulent flow is processed under the frame suggested by a theoretical model for a simple linear oscillator. A specific algorithm is developed for the determination of the average first passage time as a function of initial and target conditions based on the experimental measurements. It is shown that the simple theoretical model is able to capture the different regimes of the experimental setup, so that an equivalent linear Mathieu oscillator, presenting the same evolution of energy, from a first passage time point of view, was identified. This experimental investigation provides a first link between an analytical but simplified result and a more complex reality.

1. Introduction

The first passage time is the time required for a system, leaving a known initial configuration, to reach a certain state for the first time. In deterministic dynamics this concept is central in the description of transient regimes, for instance to estimate the time required for a deterministic system to reach its steady-state, under a stationary excitation (Chopra, 2007). The first passage time has attracted much more attention in a stochastic context, in which numerous theoretical approaches to its estimation and description have been developed (Grigoriu, 2002; Lin and Cai, 2004; Preumont, 1994; Schuss, 2010; Bolotin, 1984; Stratonovitch, Silverman). Although the concept has been widely studied from theoretical and numerical standpoints, there are very few practical or experimental applications where the results are seen from the angle of first passage times. This seems paradoxical for slightly damped and randomly excited structures, such as those which are studied in wind engineering today. Indeed, slightly damped systems have long memory times and require a lot of time before a steady regime can be reached. Because they spend most of their time in transient regimes, it is important to focus on a transient representation of their response. Among others, first passage times are one way to do this.

Some examples of the possible application of first passage times in wind engineering are the following ones. First, dispersion of pollutant releases is the object of massive experimental and numerical research. Reliable and accurate results are obtained through costly high-resolution developments or experimental testing such as field measurements (Barad, 1958; Stathopoulos et al., 2004), atmospheric boundary layer flow simulations (Stathopoulos et al., 2004; Halitsky, 1963; Huber and Snyder, 1982; Li and Meroney, 1983; Meroney, 2004) or computational fluid dynamics (Meroney, 2004, 2016; Gousseau et al., 2011; Tominaga and Stathopoulos, 2013, 2016; Di Sabatino et al., 2013). A bridge deck flutter instability in turbulent flow (Andrianne and de Ville de Goyet, 2016) is another problem in which first passage times are of outmost concern. Another example concerns tower cranes that are left free to rotate as a weathervane in a turbulent wind velocity field. The increasing number of recorded accidents due to high wind and partly to the autorotation (Mok, 2008) aroused the curiosity of the scientific community. Out-of-service wind velocities criteria are proposed by (Eden et al., 1983; Sun et al., 2009) while the stochastic response under turbulent wind conditions was the object of experimental testing assessing the risk of autorotation of the crane in a given environment (Voisin, 2003; Voisin et al., 2004; Eden et al., 1981, 1983). In all these applications, the

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question of first passage time is typically central and offers an alternative answer to the risk assessment with a good understanding of the influence of problem parameters of a system/structure's transient response. In particular it tackles questions such as the time it takes for a pollutant to reach a given concentration at a given place, the time required before stochastic instability occurs, the time it takes for a crane to exhibit large amplitude oscillations, or complete autorotations. The large number of potential applications in wind engineering encourages the development of reliable tools for the understanding and prediction of systems in transient regimes.

We restrict the current study to linear oscillations around an equilibrium point. In a single degree-of-freedom case, a very general model of a linear system, which is also suitable to capture many features of the aeroelastic loading, is composed of inertial, viscous and restoring forces, as well as a forcing and, possibly, a parametric excitation. The stochastic analysis of such systems has been widely studied. In particular, by analogy with a pendulum subjected to a support motion, the stochastic stability of a simple oscillator has already been studied under deterministic or stochastic excitations (Gitterman, 2010a, 2010b; Alevras et al., 2013; Yurchenko et al., 2013). The separatrix between stable and unstable zones is studied in (Bishop and Clifford, 1996; Clifford and Bishop, 1994; Garira and Bishop, 2003; Xu and Wiercigroch, 2006) while (Mallick and Marcq, 2004) provides an asymptotic solution for the probability density function of the energy. Beside, the analysis of non-stationary problems can be done in several different ways, (i) either through Monte Carlo simulations (Kloeden and Platen, 1992; Primožič, 2011; Giles, 2008; Vanvinckenroye and Denoël, 2015) providing for instance the time evolution of the joint probability density function in transient and, eventually, stationary regimes, (ii) either through a more theoretical context, where the state-variable probability density function and the first passage time are obtained as the solutions of the Fokker-Planck-Kolmogorov and generalized Pontryagin equations. These equations can be solved numerically through a path integration method (Kougioumtzoglou and Spanos, 2014a), the perturbation method (Canor et al., 2016), the smooth particle hydrodynamics method (Canor and Denoël, 2013), high dimensional finite elements (Náprstek and Král, 2014, 2017), or other approximate techniques. Comparisons of approached and numerical solutions for the first passage times and the associated, so-called, survival probability, are widely available (Kougioumtzoglou and Spanos, 2014b; Spanos and Kougioumtzoglou, 2014a, 2014b; Palleschi and Torquati, 1989).

Explicit solutions of the Fokker-Planck-Kolmogorov and Pontryagin equations are available in some limited cases only (Chunbiao and Bohou, 2000; Schuss, 2010; Risken, 1996). The stochastic averaging method used in (Vanvinckenroye and Denoël, 2017a, 2017b) to solve the generalized Pontryagin equation provides an approximate but closed-form solution for a single-degree-of-freedom system submitted to broadband parametric and forced excitations. This generic model can be used to describe a wide range of physical problems, such as the behaviour of a tower crane under wind excitation (Vanvinckenroye and Denoël, 2016), the deflection of a cable submitted to an axial oscillation of an anchorage (de Sa Caetano and Engineering, 2007) or ship capsizing and rolling motion (Moshchuk et al., 1995a; Troesch et al., 1992). Although being too simple to capture the full complexity of realistic problems such as those related to colored excitations, non-linearities (Moshchuk et al., 1995b) or multi-degrees-of-freedom structures, it is conjectured that this model can be fitted or adjusted to many (more complex) wind engineering problems. This paper serves as a demonstration, with the particular application of a crane oscillating in a turbulent flow.

While first passage times have been thoroughly studied in many aspects of numerical and theoretical modeling, it is surprising that experimental investigations are very limited. It appears that the only experimental investigations are in the field of applied physics (Roberts and Yousri, 1978; Spano et al., 1989), and usually aim at comparing experimental observations and approached analytical solutions. These applications in other fields of science and engineering suggest that it is a mistake to ignore the first passage time representation of transient signals. Following this motivation, we have decided to process wind tunnel data within the framework of first passage time and to compare the results with the simple theoretical model discussed before. As shown next, results are concluding and suggests the use of first passage time maps as a complementary technique to usual analysis tools (Gurley et al., 1997). This is to the authors' knowledge a first attempt at bringing first passage times of stochastic systems into engineering.

2. A mathematical model of a tower crane

The dynamics of a crane spinning in a turbulent velocity field can be modeled with a governing equation of the type:

$$I\ddot{\theta} + C\dot{\theta} = M_w \tag{1}$$

where $\theta(t)$ is the angular position of the crane jib in a horizontal plane and $M_w(t)$ is the aerodynamic load resulting from the wind flow. Considering that the rotation of the crane is associated with slower timescales than those of the wind flow along a characteristic length of the crane (say its diameter), the quasi-steady assumption (Dyrbye and Hansen, 1997) is considered. The aerodynamic torque is therefore expressed by

$$M_w = \frac{1}{2}\rho_{air} C_M H B^2 ||\boldsymbol{v}_{rel}||^2 \tag{2}$$

as a function of the air density ρ_{air}, the moment coefficient C_M, the circumscribed dimensions of the lattice cross section $H \times B$ (height × span) and the relative wind velocity $\boldsymbol{v}_{rel}$.

There is no angle-proportional term (no stiffness) in the rotative equilibrium (1), since the spinning crane is assumed to be ideally balanced. If the wind was uniform and steady, without turbulence, the crane would find an equilibrium position in the mean direction of the wind; in other words, the stiffness in the problem comes from the aerodynamic loading $M_w(t)$. In this paper, we are concerned with small amplitude rotations of the crane, which also partly justifies a linearized version of the inertial and internal forces in the governing equation, therefore simply modeled by the rotative inertia I and viscosity C.

In the horizontal plane of the crane, the wind velocity is characterized by its mean component U and its fluctuating components u and w respectively parallel and perpendicular to the wind direction (see Fig. 2 (c)), which are stochastic processes characterized by their power spectral densities $\mathcal{S}_u(\omega)$ and $\mathcal{S}_w(\omega)$. For small incidences, the moment coefficient can be linearized too so that $C_M(\alpha) = \frac{\partial C_M}{\partial \alpha}|_{\alpha=0}\alpha$ with α the relative angle between the crane and the instantaneous wind velocity vector. The relative velocity entering in (2) is given by:

$$\boldsymbol{v}_{rel} = (U + u, w) - \left(-r\dot{\theta}\sin\theta, r\dot{\theta}\cos\theta\right). \tag{3}$$

with r the abscissa of the aerodynamic focus along the jib, i.e. the point at which the moment coefficient does not vary with the lift coefficient (Dyrbye and Hansen, 1997). In this model we subscribe to the common assumption that u and w are small compared to U, although they might affect higher order statistics (Dyrbye and Hansen, 1997); also we assume that rotations are small around the equilibrium configuration, i.e. $\theta \ll 1$ and that the rotative velocity of the crane, of order $B\dot{\theta}$ is also small compared to U. The squared norm of the relative velocity and the apparent angle of attack are therefore expressed as

$$||\boldsymbol{v}_{rel}||^2 = U^2 + 2Uu \quad \text{and} \quad \alpha = \theta - \frac{w - r\dot{\theta}}{U} \tag{4}$$

which is identical to usual assumptions for wings (Fung, 2002) and bridge decks (Claudio and Carlotta, 2004; Carlotta and Claudio, 2006).

Respectively grouping together rigidity and damping terms, equation