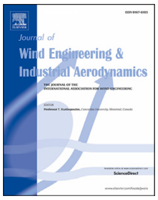
Journal of Wind Engineering & Industrial Aerodynamics 174 (2018) 281–295

Contents lists available at ScienceDirect

Journal of Wind Engineering & Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia



Aerodynamic damping model in vortex-induced vibrations for wind engineering applications

Francesca Lupi [a,*], Hans-Jürgen Niemann [b], Rüdiger Höffer [a]

[a] *Ruhr-Universität Bochum, Faculty of Civil and Environmental Engineering, Institute for Wind Engineering and Flow Mechanics, Universitätsstraße 150, 44801 Bochum, Germany*

[b] *Niemann & Partner Ingenieurgesellschaft, Universitätsstraße 142, 44799 Bochum, Germany*

ARTICLE INFO

Keywords:
Vortex-induced vibrations
Van der Pol and Rayleigh oscillators
Aerodynamic damping
Circular cylinders
Vickery spectral method

ABSTRACT

The paper addresses the modelling of aeroelastic forces in vortex-induced vibrations (VIV) and aims to provide a suitable model to predict cross-wind oscillations of circular structures. The Van der Pol and Rayleigh oscillators – non-linear physical systems, which attain limit cycles under self-induced vibrations – are often applied in literature to describe the aeroelastic force. Among VIV models, the paper focuses on the model developed by Vickery and Basu (1983). In the paper, the quadrature component of the force as a function of the oscillation amplitude in lock-in is investigated through forced-vibration wind tunnel experiments on a circular cylinder. In presence of aeroelastic interaction, the positive quadrature component corresponds to energy transferred to the structure, which then acts as negative aerodynamic damping. The experiments reveal an amplitude-dependent behaviour of the aerodynamic damping with positive curvature. The experimental curve can be applied as modification of the Vickery and Basu model and used to predict the oscillation of circular structures under vortex-excitation. In the paper, it is applied to the response of a cantilever beam. The prediction is validated through free-vibration wind tunnel experiments. The consistency of results is promising.

1. Introduction

The paper addresses the modelling of aeroelastic forces in vortex-induced vibrations (VIV) of circular structures and aims to provide a suitable model to predict cross-wind oscillations of circular structures.

The aeroelastic interaction consists in lock-in of the vortex-shedding load to the natural vibration of the structure, not only in the resonant condition, rather for a range of velocities that depends on the mass-damping parameter, where the Strouhal law is violated. The fluid-structure interaction acts as source of energy and originates aeroelastic vibrations.

The physical process of VIV is accurately described in the reviews from Berger and Wille (1972), Parkinson (1989), Sarpkaya (2004), Williamson and Govardhan (2008). An interesting description of the modes of vortex formation depending on the mass-damping parameter is reported in Williamson and Roshko (1988), Khalak and Williamson (1999) and Govardhan and Williamson (2000). An investigation about the correlation between motion time histories and aerodynamic integral forces calculated from pressure measurements is presented in Zasso et al. (2008).

Several VIV models are investigated in literature. They can be divided in two classes: the first class comprises the so-called 1-degree-of-freedom models, based on the equation of motion of the structure, where the aeroelastic force generally has a component in phase with the motion (aerodynamic stiffness) and a non-linear component in quadrature with the motion (aerodynamic damping). The concept goes back to Scruton (1963) and is then applied by Scanlan (1981), Vickery and Basu (1983a, b), Simiu and Scanlan (1986), Ehsan and Scanlan (1990), Goswami et al. (1993), Larsen (1995), Hansen (2013), Yanguo Sun et al. (2014). In addition to them, VIV can be modelled as force-driven vibrations due to a longer correlation length in the 1-dof model developed by Ruscheweyh (1986) or spectral load modification in Flaga (1997) and Arunachalam and Lakshmanan (2015).

The second class comprises the so-called coupled or wake oscillator models, where the wake of the cylinder is a self-excited and self-limited oscillator, whose state variable (e.g. the lift force) is described by a non-linear equation, usually of the Van der Pol or Rayleigh type. The wake oscillator is coupled to the structure oscillator through a force term that can be proportional to the displacement, velocity or acceleration. The concept was first proposed by Bishop and Hassan (1964) and then

---

[*] Corresponding author.
E-mail address: francesca.lupi@rub.de (F. Lupi).

https://doi.org/10.1016/j.jweia.2018.01.006
Received 10 February 2017; Received in revised form 24 November 2017; Accepted 7 January 2018

Table 1
Test-case: cantilever beam with circular cross-section.

Diameter	d	50	*mm*
Slenderness ratio	h/d	15.5	-
Natural frequency	f_1	20.020	*Hz*
Modal mass	M_1	0.063	*kg*
Equivalent mass	m_{eq}	0.232	*kg/m*
Log. Decrement of damping	δ_s	0.019	-
Turbulence intensity	I_v	0.045	-
Strouhal number	St	0.185	-
Scruton number	Sc	2.806	-
Reynolds number	Re	1.804E+04	-

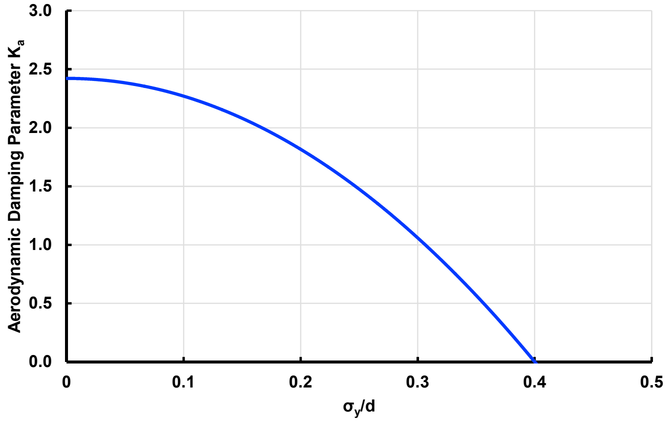


Fig. 1. Aerodynamic damping parameter K_a proposed by Vickery and Basu (1983a,b), Basu and Vickery (1983). Application to the test case in Table 1 ($K_a = 2.422$ for $\sigma_y/d = 0$, in accordance with Commentaries for Steel Chimney Code, 2011, equation C3.3.25).

developed by Hartlen and Currie (1970), Skop and Griffin (1973, 1975), Griffin (1980), Griffin and Koopmann (1977), Griffin et al. (1973), Iwan and Blevins (1974), Landl (1975), Tamura and Matsui (1980), Dowell (1981), Benaroya and Lepore (1983), Billah (1989), Blevins (1990), Krenk and Nielsen (1999), Plaschko (2000), Skop and Luo (2001), Facchinetti et al. (2004), Farshidianfar and Zangeneh (2010), Ogink and Metrikine (2010) and others.

A common feature among the majority of these models is the application of the Van der Pol equation (or, equivalently, the Rayleigh equation), either to model the aeroelastic force within the equation of motion of the cylinder in case of 1-dof models, or within the governing wake equation in case of coupled wake oscillator models. The Van der Pol oscillator is a classic example of non-linear system, which attains a limit cycle under self-induced vibrations (Magnus et al., 2013). Thus, it offered a theoretical background to model the self-limiting character of the aeroelastic interaction in vortex-induced vibrations. A discussion about this issue is addressed in section 2.

Among all the aforementioned VIV models, the paper focuses on the Vickery & Basu model (1983a,b; Basu and Vickery, 1983) because it is the basis of a code method used worldwide in many building codes for the design of circular structures prone to vortex excitation (see, e.g. Eurocode, 2010, CICIND, 2010, Commentaries for Steel Chimney Code, 2011). Its peculiarity is the application of the aeroelastic interaction within the theory of random vibrations. This is because the lift force on a structure is not a pure harmonic function, but it has a spectral density centred on the vortex shedding frequency and a bandwidth that depends on the turbulence of the incoming flow. Therefore, the Vickery & Basu model is also known as Spectral Method: the resonant response of the structure is calculated in the frequency domain and the aeroelastic effect is included in the negative aerodynamic damping.

Another approach to the modelling of the aeroelastic interaction can be found, for example, in the Ehsan & Scanlan model (Simiu and Scanlan, 1986; Ehsan and Scanlan, 1990). It focuses on large oscillations, where the vortex shedding lift can be neglected in comparison to the motion-induced force. Consequently, the limit cycle can be calculated from energy considerations and corresponds to the zero-damping amplitude. This approach is confirmed by Zasso et al. (2008), whose experiments show that - in case of very low mass-damping parameters - a pronounced in-phase component of the lift force is accompanied by a very small quadrature component, meaning a phase shift, i.e. a damping, that approaches zero.

As pointed out since Hartlen and Currie (1970), a criterion which specifies in detail the exact nature of the aerodynamic damping force in VIV is not known. Generally, the simple form derived from the self-excited and self-limited Van der Pol and Rayleigh oscillators is used. Vickery and Basu (1983a,b), Basu and Vickery (1983) try to give a physical justification to the application of the Rayleigh equation by referring to Marris (1964), who found an analogy between the Magnus effect on a rotating cylinder (Swanson, 1961) and the lift force produced by the non-symmetric boundary layer separation in case of cross-wind vibrations. Vickery & Basu simplified the non-linear Marris formulation in view of practical applications and developed a model to predict the cross-wind oscillation of a stack (Vickery and Basu, 1983b). This method is recommended in many international codes for the design of circular structures (e.g. Eurocode, 2010). However, the predictions of the Vickery model often result extremely conservative and not realistic for most of design cases.

The paper investigates the quadrature component of the force as a

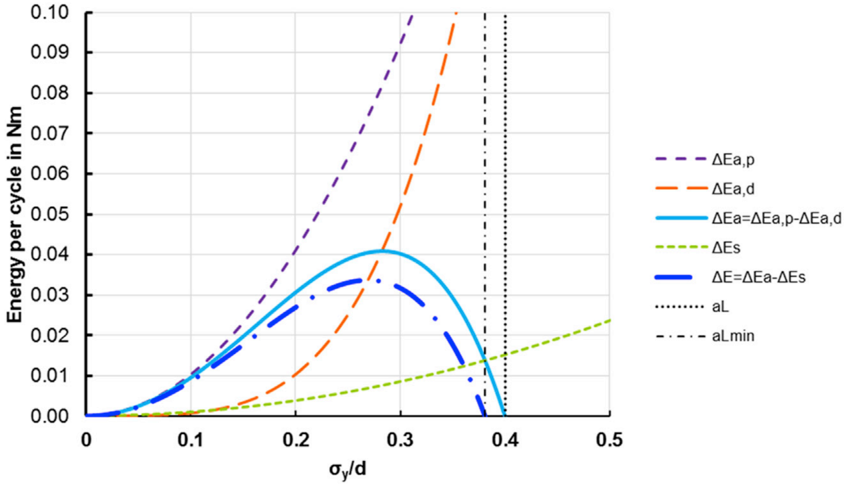


Fig. 2. Energy diagram for equations (3) and (14) applied to the test case in Table 1. ΔE_a = aeroelastic energy per cycle, given by the difference between energy produced ($\Delta E_{a,p}$) and energy dissipated ($\Delta E_{a,d}$); ΔE_s = structural dissipation of energy due to structural damping; ΔE = net energy per cycle. a_L and a_{Lmin} = non-dimensional limit cycles for equations (3) and (14), respectively.