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Dual cantilever flutter: Experimentally validated lumped parameter modeling and numerical characterization

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ABSTRACT

This paper presents an analytical and experimental investigation of a flow-induced vibration phenomenon referred to as dual cantilever flutter (DCF). The purpose of this research is to introduce the concept of DCF and to help isolate and understand key components that cause it. If unaccounted for, vibration produced by DCF has the potential to cause catastrophic structural damage or unwanted acoustic excitation. This paper includes experimentally validated lumped parameter analytical models for fluid coupling and fluid excitation between two adjacent cantilever beams surrounded by fluid. Results of a nondimensional analysis performed with the DCF model are also given.

1. Introduction

Perhaps the oldest and most common form of flow-induced vibration discussed in the literature is vortex-induced vibration (VIV) (Bearman, 1984; Williamson, 1996; Williamson and Govardhan, 2004; Williamson and Govardhan, 1997; Govardhan and Williamson, 2005; Williamson, 2003; Govardhan and Williamson, 2002; Sallet, 1973). The most common VIV occurs when a structure is placed in a flowing fluid such that vortices periodically shed from the structure sometimes forming the so-called Von Karman vortex street (Bearman, 1967; Wille, 1960). The rate or frequency at which these vortices shed is directly proportional to the fluid flow velocity and can be predicted accurately for simple structures over a large range of Reynolds numbers (Bearman, 1984; Williamson, 1996; Williamson and Govardhan, 2004; King, 1977). This periodic vortex shedding imposes periodic forces on the structure from which the vortices are shed. If the structure is sufficiently elastic, the periodic vortex shedding forces can cause the structure to vibrate at a frequency equal to the vortex shedding frequency. Large amplitude vibration can occur when the vortex shedding frequency approaches a natural frequency of the elastic structure (Bearman, 1984). Acoustic noise, unexpected fatigue, and ultimately catastrophic structural failure can occur from VIV; however, many have sought to harness these vibrations to harvest energy (Pobering et al., 2009; Gao et al., 2013; Hobbs and Hu, 2012; Pobering et al., 2009; Bernitsas et al., 2008; Akaydin et al., 2010).

Another form of well documented flow-induced vibration popular among those in the aerospace community is aeroelastic flutter (Weiliang and Dowell, 1991; Bryant et al., 2013; Dowell, 1970; Bisplinghoff et al., 1996). Flutter typically occurs with an elastic structure having both pitching (twist/torsion) and plunging (bending/translation) degrees of freedom. Aerodynamic loading on the structure can cause the pitch and plunge natural frequencies to coalesce with increased airspeed which leads to flutter and ultimately divergence and catastrophic structural failure (Bisplinghoff et al., 1996). Extensive effort is devoted to avoiding flutter in aircraft design for example; however, as with VIV many studies have

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investigated harvesting useful amounts of energy from flutter (Li et al., 2011; De Marqui and Erturk, 2013; McKinney and DeLaurier, 1981; Bryant and Garciaa, 2009; Dunnmon et al., 2011; Shimizu et al., 2008; Erturk et al., 2010; Tang et al., 2009).

1.1. The dual cantilever flutter concept

This paper presents a detailed study on a recently discovered form of flow-induced vibration that occurs with two identical adjacent cantilevers in cross-flow as illustrated in Fig. 1. This flow-induced vibration phenomenon is called dual cantilever flutter (DCF). It will be shown that DCF has characteristics similar to both VIV and flutter, yet is fundamentally unique. The DCF concept was originally introduced as a novel energy harvesting method by Hobeck et al. (2014). This earlier work focused on analytical and CFD entrainment models, and showed only experimental results for DCF dynamics without providing any model updating results or model parameters. The current research presents an experimentally validated model for predicting both entrainment and DCF dynamics. This paper builds on the initial investigation by providing all model parameters, discussing model updating results, defining functions for the fluid coupling parameters, discussing error analysis of the updated model, and including details of a nondimensional analysis performed with the final DCF model.

It was demonstrated in previous work by the authors that large arrays of cantilevers experience large amplitude persistent vibration when exposed to air flow at a certain and predictable velocity (Hobeck and Inman, 2012; Hobeck and Inman, 2013). The DCF flow-induced vibration phenomenon was first observed while performing wind tunnel experiments on these large arrays of cantilevers. Early observations of DCF occurred when only two cantilevers were placed side-by-side and positioned such that their faces were perpendicular to low velocity ($\sim$6 m/s) air flow. See Fig. 1 for a schematic of the DCF mechanism. Cantilever tip displacements are denoted in Fig. 1 as u_1 and u_2 for beam 1 and beam 2 respectively. At the appropriate combination of both gap distance (q) between the cantilevers and flow velocity (U), both cantilevers experienced large amplitude persistent vibration. It is assumed that the base structure to which the cantilevers are attached is rigid and that the only coupling between the beams is that of the fluid. Visual observations confirmed with time and frequency domain laser displacement measurements showed that during DCF the tip displacements of both cantilevers were consistently 180 degrees out-of-phase and displacements associated with the fundamental bending mode were orders of magnitude greater than those of higher modes.

Several series of experiments showed that the cantilevers began to oscillate at relatively small amplitudes where a slight increase of flow velocity initially caused a large increase in the amplitude of vibration. The velocity that caused this large amplitude state of vibration will be referred to as the *lock-in* velocity which is a term adopted from numerous studies on the topic of vortex-induced vibration. During DCF, vibration amplitude and frequency remain nearly constant even after increasing the flow velocity to more than twice the lock-in velocity. Because a large range of flow velocity is able to excite the cantilevers at or near resonance, there may be many cases were DCF-type excitation can cause structural fatigue, unwanted acoustic noise, and even catastrophic structural failure. In energy harvesting applications, this ability to excite the beams at or near resonance for a large velocity range is most desirable. For example: if an energy harvester is to be deployed

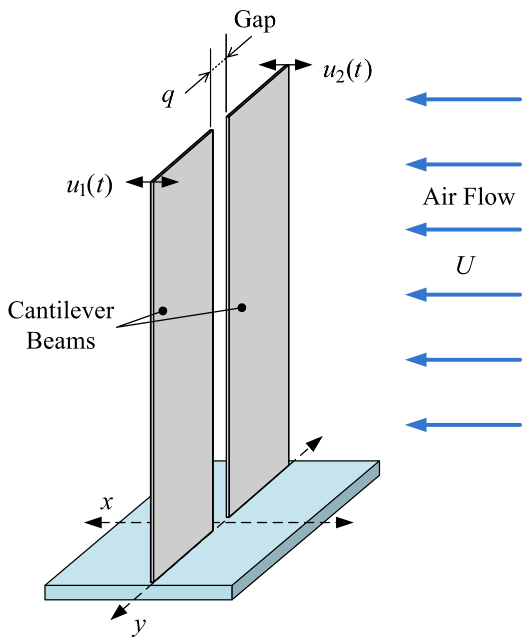

Fig. 1. A schematic used to illustrate critical components of the dual cantilever flutter mechanism showing identical cantilevered beams positioned side-by-side and oriented perpendicular to air flow (Hobeck et al., 2014).