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Aerodynamic damping of sidewall bounded oscillating cantilevers

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ABSTRACT

As a result of their simplicity, low power consumption, and relative ease of implementation, oscillating cantilevers have been investigated for use in multiple applications. However, the in situ operation in many cases, requires oscillating near one or more solid walls. When the separation distance between the vibrating cantilever and the solid wall becomes small, damping from the surrounding fluid is increased, which in turn can increase the power required to maintain certain operational performance characteristics (e.g., vibration amplitude). This increase in damping is a well-studied phenomenon for certain configurations (e.g., microcantilevers in Atomic Force Microscopy, or AFM), but is largely unexplored for a cantilever sweeping across a solid wall, which has direct impact for many macro-based applications including electronics cooling and propulsion. In this paper, we experimentally investigate the aerodynamic damping as a function of the gap between two sidewalls parallel to the oscillating motion of the cantilever. Multiple voltage and frequency inputs are considered in addition to the magnitude of the wall to cantilever gap. Experiments performed across a range of operating conditions reveal that decreasing the distance between the walls and the oscillating cantilever can increase the aerodynamic damping as much as 5 times that of the isolated (i.e., without sidewalls) operation. The resonance frequency is also shown to decrease when the gap spacing is extremely small, suggesting the added mass of the fluid is also sensitive to this variable. However, this change is much smaller (~0.5%) compared to the change typically observed in damping. The findings in the paper help to quantify the overall effect of solid enclosure walls on the performance of an oscillating cantilever, which will better enable the designer to achieve the maximum operational effectiveness. The experimental findings also suggest viscous damping with sidewalls could be predicted from first principles in a similar manner to well accepted analytical models of a cantilever vibrating above a solid surface.

1. Introduction

Oscillating cantilevers are simple mechanisms that have many applications ranging from atomic force microscopy (AFM) (Binnig et al., 1986) to biological sensors (Gupta et al., 2006) to energy harvesting (Aureli et al., 2010b) and electronics

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Nomenclature

A	Oscillation amplitude
A_{max}	maximum amplitude of a single frequency sweep
c	effective structural damping coefficient of the cantilever
c_a	aerodynamic damping coefficient
D	cantilever width
F_o	effective force on the beam from the piezoelectric element
I	input current to the piezoelectric fan
k	effective beam stiffness
KC	Keulegan–Carpenter number
L	total length of the fan blade
L_b	length of exposed portion (i.e., not covered by piezoelectric patch) of fan blade
L_p	length of the piezoelectric patch
m	effective mass of the cantilever
m_a	mass of the air
t_b	thickness of the Mylar blade
t_p	thickness of the piezoelectric patch
Q	structural quality factor
Q_a	aerodynamic quality factor
Q_{air}	quality factor in air (combined structural and aerodynamic effects)
Q_{iso}	isolated quality factor in air (i.e., when no sidewalls are affecting the fan)
V	input voltage to the piezoelectric fan
β	frequency parameter for oscillating flows
γ	dimensionless gap between edge of cantilever and sidewall
δ	distance between the wall and side edge of the cantilever
ν	kinematic viscosity of the fluid
ζ	structural damping ratio
ζ_{air}	damping ratio in air
ω	oscillation frequency of fan excitation signal
ω_n	structural natural frequency of the fan
$\omega_{n,air}$	natural frequency in air

cooling (Acikalin et al., 2004, 2007; Kimber and Garimella, 2009; Wait et al., 2007; Yoo et al., 2000). Their simple structure and straightforward operating requirements make them effective low power solutions with desirable fatigue life characteristics. Although the motion of a cantilever has been a well-understood concept for centuries, the complexity increases many fold when it becomes essential to quantify the coupling between structure and fluid. This is the case for most useful applications (including each of those mentioned above), and as a result, a great deal of literature exists on the topic of cantilevers oscillating within a fluid, but is primarily focused on microscale cantilevers. Perhaps the primary motivation for the vast amount of literature on this topic is the AFM cantilever (Binnig et al., 1986), where the oscillatory motion is employed to quantify certain properties of the surface below the cantilever. For further information on microscale applications, the reader is directed to the seminal work by Sader (1998), who developed an analytical model for the frequency response of an AFM cantilever oscillating in a viscous fluid. This analytical model accounts for the hydrodynamic forces as well as quantifying the quality factor. For the scenario when the microscale beam is vibrating near a solid substrate, many additional studies have been conducted. Green and Sader (2005a) used a boundary integral formulation based on the analysis done by Tuck (1969) to develop analytical models, and found that the impact of the solid surface is very limited unless the separation distance between the cantilever and the surface is less than the width of the cantilever. This and a related study by the same authors (Green and Sader, 2005b), reveal that the surface interaction with the cantilever mainly impacts the viscous dissipation and plays a relatively minor role in changing the inertial load (i.e., added mass) seen by the beam.

Other significant contributions to the field of fluid forces present for micro-sized cantilevers include Cho et al. (1994), who investigated the validity of different 2D viscous damping models for laterally oscillating microstructures. They found that a Stokes type fluid motion assumption yields a more accurate quality factor when compared to a Couette type fluid motion. Yum et al. (2004) experimentally determined that the damping ratio increases as a result of decreasing cantilever scale. Findings in the well-explored microscale applications provide a basis from which the macro-scale can be considered, however the magnitude and source of non-negligible forces in macro-sized applications are markedly different.

Unlike the fluid forces in microscale studies, the viscous damping caused by the surrounding fluid for macrosized beams is highly dependent on the oscillation amplitude in a non-linear fashion. Modeling of this fluid–structure interaction on this scale includes the high impact study by Jones (2003), where he developed a 2-D theoretical framework designed to predict the flow of an inviscid fluid around a thin oscillating cross section. He was able to capture the flow separation and subsequent vortex formation as the rectangular cross section oscillates in a fluid. Bidkar et al. (2009) continued the work of Jones by integrating this 2-D model along the entire length of a cantilever operating in the fundamental vibration mode. Experiments were also conducted using Mylar and stainless steel cantilever materials, and good agreement was found between predicted and experimentally measured values. As expected, theory predicts that a decrease in aerodynamic damping will lead to an increase in oscillation amplitude. Subsequent studies have extended this analysis by removing the limitation imposed by Jones (2003) and Bidkar et al. (2009), each of which is restricted to inviscid flow. Aureli et al. (2012) expressed the fluid–structure interaction with a complex hydrodynamic function which accounts for behavior expected for small vibration amplitudes, but also includes non-linear terms which are amplitude and frequency dependent. This analysis greatly extends the range of applicability for 2-D flows. Facci and Porfiri (2013) have since extend this work to accommodate three dimensional attributes with a particular emphasis on the thrust production. The result over the past decade has been

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