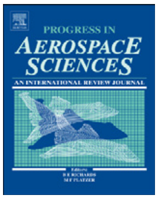
Progress in Aerospace Sciences 44 (2008) 479–502

Contents lists available at ScienceDirect

Progress in Aerospace Sciences

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



Active control of flow-induced cavity oscillations

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ARTICLE INFO

Available online 11 September 2008

Keywords:
Active flow control
Cavity oscillations
Cavity resonance
Flow-induced oscillations
Actuators
Feedback control

ABSTRACT

A review of active control of flow-induced cavity oscillations is motivated by two factors. First, the search for solutions to the practical problem of suppressing oscillations caused by flow over open cavities has generated significant interest in this area. Second, cavity oscillation control serves as a model problem in the growing multidisciplinary field of flow control. As such, we attempt to summarize recent activities in this area, with emphasis on experimental implementation of open- and closed-loop control approaches. In addition to describing successes, failures, and outstanding issues relevant to cavity oscillations, we highlight the characteristics of the various actuators, flow sensing and measurement, and control methodologies employed to date in order to emphasize the choices, challenges, and potential of flow control in this and other applications, such as impact on store trajectory.

Contents

1. Introduction

Flow over cavities has received a great deal of interest over the last several years because of practical and academic interests

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doi:10.1016/j.paerosci.2008.07.002

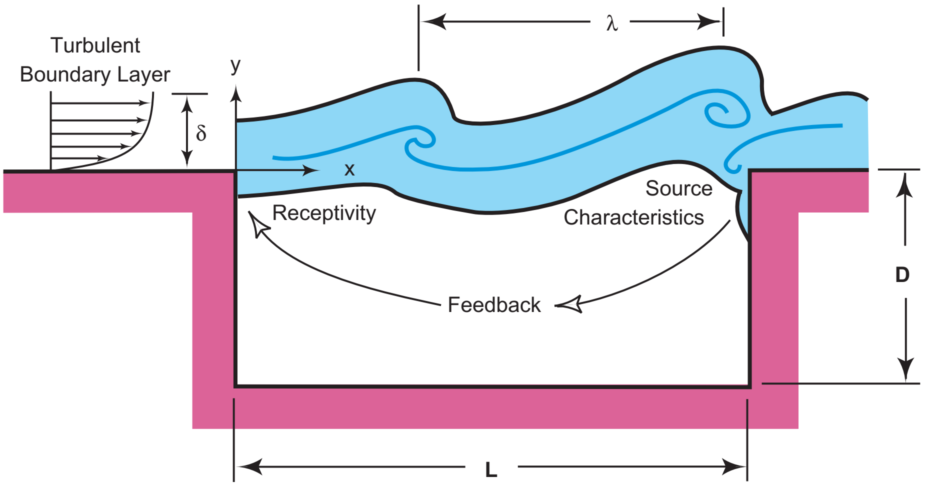

Fig. 1. Schematic illustrating flow-induced cavity resonance for an upstream turbulent boundary layer.

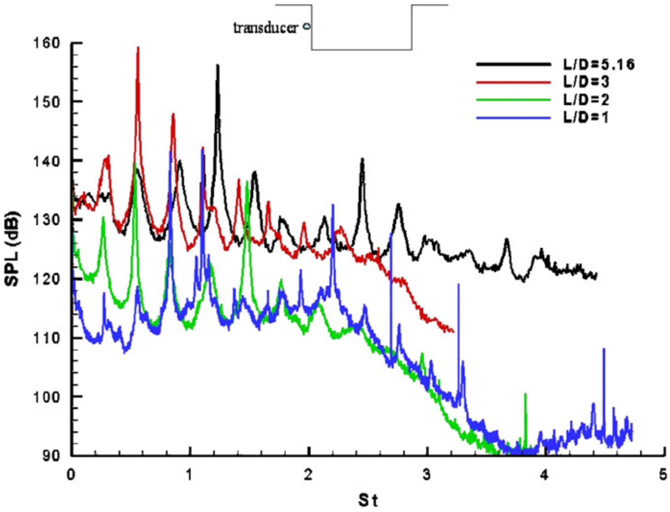

Fig. 2. Pressure spectra for different L/D cavities at $M_{\infty}=2$. Unsteady pressure spectra measured using a transducer located at the upstream wall, as shown in the inset (from Zhuang et al. [1]). The dimensionless frequency is the Strouhal number $St=fL/U_{\infty}$.

associated with controlling such flows. The problem of accurate prediction and control over a wide range of flow conditions is not solved. The need to accurately model the disparate scales of acoustic and vortical disturbances driving the oscillations is a difficult task for fluid dynamicists and aeroacousticians, while control theorists are challenged by the multiple competing modes of oscillation that must be controlled to achieve suppression. These and a number of other issues have established flow-induced cavity oscillations as a canonical problem in flow control.

The nature of flow-induced oscillations in an open cavity is illustrated in Fig. 1. A boundary layer of thickness δ and momentum thickness θ separates at the upstream edge of the cavity of length L, depth D, and width W. The resulting shear layer develops based on its initial conditions (imposed by the upstream boundary layer and cavity acoustic field) and the instability characteristics of the mean shear-layer profile. The shear layer spans the length of the cavity and ultimately reattaches near the trailing edge of the cavity in an "open" cavity flow. The reattachment region acts as the primary acoustic source. Acoustic waves travel inside the cavity (and outside for subsonic flow), towards the cavity leading edge. The incident acoustic waves force the shear layer, setting the initial amplitude and phase of the instability waves through a receptivity process. These instabilities grow to form large-scale vortical structures that convect downstream at a fraction of the free stream speed before impinging near the trailing edge.

The overall process produces resonant frequencies, which are referred to as *cavity tones*. Fig. 2 illustrates representative, unsteady pressure spectra (dB re 20 μPa) at Mach 2 for a range of cavity length/depth L/D ratios [1]. The spectra are dominated by high-amplitude, discrete-frequency tones and large broadband levels. In many cases, multiple tones are observed, and these are often accompanied by their harmonics. In the context of cavity flows, the flow–acoustic coupling which leads to resonance is commonly called the *Rossiter mechanism* [2], although a similar phenomenological model was proposed for the edge-tone problem more than a decade earlier by Powell [3]. The relevant dimensionless parameters are L/D, L/W, and L/θ, as well as the flow parameters $p_{\mathrm{rms}}/q_{\infty}$, Reynolds number Re_{θ}, Mach number M_{∞}, and shape factor $H=\delta^{*}/\theta$, where p_{rms} is the rms pressure fluctuation, q_{∞} is the free stream dynamic pressure, and δ^{*} and θ are the displacement and momentum thicknesses, respectively, of the upstream boundary layer.

Cavity flows have been the subject of numerous studies since the 1950s [4,5], and we do not attempt to provide a comprehensive review of the subject here. The interested reader is referred to several reviews spanning three decades of research [6–14]. In particular, the review by Colonius [12] provides a summary of numerical simulations and flow-physics modeling, permitting us to largely ignore these relevant topics.

Control of grazing flow over cavities is pertinent to a wide range of real-world applications, ranging from landing-gear and weapons bays in aircraft to flow in gas transport systems [15], over sunroofs and windows in automobiles [16], and in instrument or telescope bays [17]. The high dynamic loads illustrated in Fig. 2 are generally present in all of these applications and can lead to structural fatigue of the cavity and its contents or, in the case of compressible flow, aero-optic distortion [18]. In addition, the highly oscillatory flow field generated by cavity flows can adversely affect the safe departure and accurate delivery of munitions stored in the weapons bay. This problem has become more acute with the recent emphasis on store separation of "smart" weapons that are lighter and more compact [19].

Although the overall goal of control is usually to reduce the flow unsteadiness in some form, the specific objective of what