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Review of Active Control of Flow-Induced Cavity Resonance

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Abstract

A review of active control of flow-induced cavity oscillations is presented. This paper 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.

1 Introduction

The complex nature of cavity resonance 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 upon 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 freestream speed before impinging near the trailing edge. The relevant dimensionless parameters are L/D, L/W and L/θ, as well as the flow parameters p_{rms}/q_{∞}, Re_{θ}, M_{∞}, and shape factor $H = \delta^{*}/\theta$, where q_{∞} is the freestream dynamic pressure and δ^{*} is the displacement thickness of the upstream boundary layer .

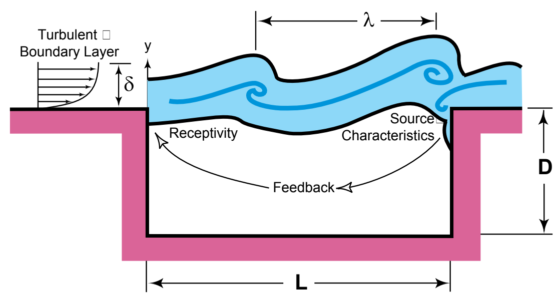

Fig. 1: Schematic illustrating flow-induced cavity resonance for an upstream turbulent boundary layer.

Cavity flows have been the subject of numerous studies since the 1950's.[1-3] Therefore, we cannot provide a comprehensive review of the subject in this short paper. The interested reader is referred to several excellent reviews.[4-10] In particular, the recent review by Colonius[10] provides a summary of numerical simulations and flow physics modeling, permitting us to largely ignore these relevant topics.

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[11] and over sunroofs and windows in automobiles.[12] The flow-acoustic coupling inherent in cavity resonance can produce a highly unsteady flowfield characterized by strong discrete tones and a large background or broadband level.

In aircraft bays, for example, dynamic loads in excess of 160 dB (re 20 μPa) are not uncommon. Such high dynamic loads can lead to structural fatigue of the cavity and its contents. In addition, the highly oscillatory flowfield generated by cavity flows

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can also 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 'smart' weapons that are lighter and more compact.[13]

The goal of this paper is to summarize recent activities in active control of flow-induced resonance of open cavities, 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. Due to space constraints (and perhaps ignorance), there are undoubtedly omissions. For this, we apologize.

The paper is organized as follows. Section 2 provides a brief overview of passive and open-loop suppression studies. While recent studies are emphasized, some classical results will be reviewed to place these new results in proper context. Sections 3, 4, and 5 describe actuators, flow sensors and measurements systems, and closed-loop control suppression and modeling/design approaches, respectively. Section 6 provides a summary and offers our perspective on outstanding issues and future directions.

2 Suppression of Cavity Oscillations

Flow Control Classifications

Techniques to suppress cavity oscillations can be classified in several ways. In this paper, we choose the classification shown in Fig. 2 to be consistent with terminology used in active noise and vibration control. Active control provides *external* energy (e.g., mechanical or electrical) input to the flow, while passive control techniques do not. Passive control of cavity oscillations has been successfully implemented via geometric modifications using, for example, rigid fixed fences, spoilers, ramps,[14,15] and a passive bleed system.[16] Note that some passive flow control devices extract energy from the flow itself and have been called active. Pertinent examples include unpowered or passive resonance tubes[13,17] and cylinders or rods placed in the boundary layer near the leading edge of the cavity.[18] These devices, described further in Section 3, are sometimes referred to as active because they provide an oscillatory input to the flow, but their effect cannot be adjusted without either changing the flow conditions or changing the device itself.

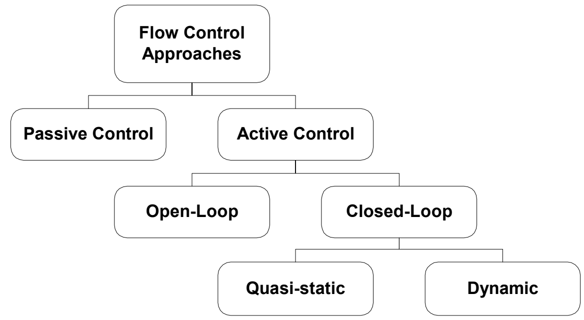

Fig. 2: Classification of flow control.

Active control is further divided into open- and closed-loop control. As shown in Fig. 3, by its very definition, closed-loop control implies a feedback loop, in which some flow quantity is directly sensed or estimated and fed back to modify the control signal.[19] Open loop corresponds to the case when there is no feedback loop.

A further classification of closed-loop cavity control is that of quasi-static vs. dynamic feedback control. The quasi-static case corresponds to slow tuning of an open-loop control approach and occurs when the time scales of feedback signal are large compared to the time scales of the plant (i.e., flow). As discussed in Section 5, this approach was successfully used by Shaw and Northcraft.[20] The usual dynamic compensation case corresponds to the situation when these time scales are commensurate. This can be implemented using an analog (see, for example, Williams et al.[21]) or "real-time" digital control systems.[22] In this context, "real time" refers to the situation in which the control signal is updated at the sampling rate of the data system.

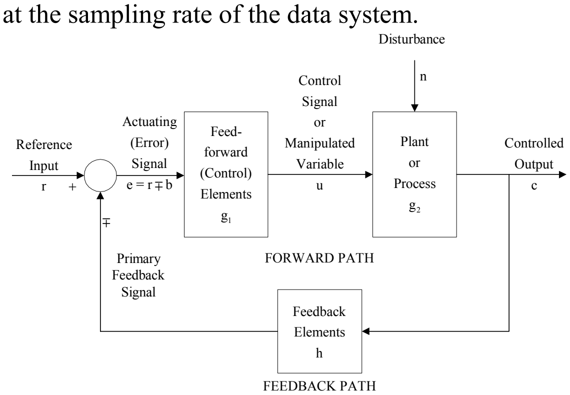

Fig. 3: Components of a feedback control system.[19]

Summary of Suppression Studies

Passive and Open-Loop Active Control

Table 1 in the Appendix provides a summary of selected passive and open-loop cavity suppression studies. Where possible, the cavity dimensions and flow conditions are summarized. The methods and key results are also included. The investigations are listed in chronological order for historical purposes.

Again, there are numerous other passive studies that have not been included because of space limitations and because these are summarized in the other reviews cited earlier. Some key points are discussed here.

Sarohia and Massier studied the efficacy of steady mass injection at the base or floor of two different axisymmetric cavity models for both laminar and turbulent boundary layers.[23] While base injection was effective at suppressing cavity tones, large mass flow rates were required - B_c = 5-15%. The mass flow rate parameter used by the authors is equivalent to that proposed later by Vakili and Gauthier[24] for rectangular cavities

$$B_c = \left(\frac{\rho_w V_w}{\rho_e V_e}\right)\frac{A_{inj}}{A_{cavity}} = \frac{\dot{m}}{\rho_e V_e A_{cavity}}. \qquad \{1\}$$

Sarno and Franke studied static and oscillating fences and also steady and pulsed injection (at 0º or 45º with respect to the freestream direction) at transonic speeds near the cavity leading edge.[25] Blowing coefficients B_c of up to 7% were used. While the static fences provided the best suppression, the bandwidth of the mechanical fences were limited to < 220 Hz, while the pulsed injection was < 80 Hz. These frequencies were at least an order of magnitude lower than the frequencies of the cavity tones and thereby constituted a quasi-static or low-frequency forcing. Nonetheless, they represented an important step in the evolution of active control of cavity oscillations.

Vakili and Gauthier[24] obtained significant attenuation with steady normal mass injection through variable-density porous plates upstream of the cavity leading edge at Mach 1.8 using $B_c \sim 4\%$. They attributed the attenuation to a thickening of the cavity shear layer and a corresponding alteration of its instability characteristics.

McGrath and Shaw subsequently studied mechanical oscillations of hinged flaps at frequencies up to 35 Hz over a range of subsonic and supersonic Mach numbers.[18] The static and oscillatory deflections were on the order of the boundary layer thickness δ and were shown to be effective despite their limited bandwidth.

McGrath and Shaw were the first to study the effect of a cylinder placed in the upstream subsonic boundary layer. Because of the well-known shedding characteristics of a circular cylinder of diameter d, $St = fd/U \approx 0.2$, over a wide Reynolds number range, this device was called a high-frequency tone generator (HFTG). The cylinder was capable of producing substantial reductions of both the cavity tones and the broadband level. The authors discussed the potential mechanism of the actuator: the interaction of the shed vortices with the shear layer instabilities. As will be discussed further below, however, there are other possible mechanisms, noted by other investigators, that may influence the suppression effectiveness of the cylinder.

At the same time, Ahuja and his colleagues were investigating some other novel control strategies. For example, Mendoza and Ahuja studied the effect of a steady wall jet via a Coanda surface.[26] Although no mass flow measurements were obtained to document the suppression characteristics, upstream boundary layer profiles showed an increase in δ with blowing, thereby leading to the hypothesis that the suppression was due to a reduced shear layer growth rate.

Hsu and Ahuja[27] studied the effect of a trailing-edge array of Helmholtz resonators (i.e., commercial syringes) on cavity noise and obtained some suppression at lower Mach numbers. At intermediate Mach numbers, the resonators reduced the magnitude of the targeted tone, but new tones appeared at other frequencies – a phenomenon that has been observed by many researchers. At high Mach numbers, no suppression was obtained, but the authors believed that the reason was likely due to the difficulty in setting the small resonator volume accurately. This study is noteworthy for its attempt to control cavity oscillations in the vicinity of the acoustic source origin near the trailing edge impingement reason.

In 1997, Cattafesta et al. studied the use of a six-element piezoelectric flap array flush mounted at the leading edge of the cavity.[28] The bandwidth of the actuators was large enough (300 Hz) to provide forcing at frequencies comparable to that of the cavity tones. Open-loop sinusoidal forcing at a sufficient amplitude and appropriate detuned frequency was capable of suppressing the cavity tone. Shear layer velocity measurements indicated that the actuators seeded the shear layer with a disturbance that was large enough to prevent the growth of the natural cavity disturbances.

In 1998, Shaw continued his study of leading edge HFTGs, low frequency pulsed fluidic injection, and oscillating flaps.[29] While various diameter HFTGs mounted at a fixed height were shown to be effective, the suppression improved as the diameter was increased. However, the relative height of the cylinder in the boundary layer was not reported. Shaw also discusses two potential mechanisms of the HFTG: (1) high frequency forcing due to shedding, (2) reduced shear layer growth rates due to boundary layer thickening.

We have found that his pulsed blowing results were consistent with prior results – that B_c of a few percent were required to suppress the tones. However, no spectra were reported to assess the impact of blowing on the broadband. Interestingly, the tone amplitude continued to decrease as the pulse frequency of the injector reached its upper limit of 100 Hz. Furthermore, normal injection was shown to be superior to tangential blowing.

The oscillatory flap in Shaw's experiment, varied from 0-100 Hz, provided maximum suppression at 5 Hz and a monotonic improvement as the dynamic deflection angle increased to its upper limit, corresponding to a deflection of order δ. However, the increase in δ for a full-scale aircraft led Shaw to conclude that this approach (low frequency, large amplitude, open-loop forcing) was not feasible for a full-scale aircraft.

In 1999, three new approaches were reported. Fabris and Williams used unsteady bleed forcing to produce a broadband actuator capable of producing a complex input disturbance comprised of multiple frequency components.[30] They demonstrated that the shear layer was most receptive to horizontal forcing via shear layer velocity measurements.

Lamp and Chokani[31] used a rotary valve actuator to provide steady and/or oscillatory blowing upstream of the cavity leading edge at a particular pulsing frequency. Their actuator configuration emphasized three-dimensional effects and showed that oscillatory blowing can reduce tone amplitudes provided the forcing frequency is not a harmonic of the cavity resonance.

Raman et al. used novel miniature fluidic oscillators to suppress cavity oscillations.[32] These devices were capable of producing up to 3 kHz oscillations with mass flow rates of less than 0.12% of the main jet flow and produced significant tonal reductions. However, the mass flow rate and frequency of oscillations are coupled (in a predictable fashion).

Stanek reported on a series of larger-scale experiments in the UK over the past few years.[13,33,34] In the first experiment,[13] they investigated powered resonance tubes, protruding piezoceramic driven wedges, a cylindrical rod, and passive resonance tubes vs. a conventional spoiler. An interesting result was that the powered resonance tubes (see ref. 17 and Section 3) demonstrated significant tonal and broadband reduction when B_c ~ 1.6%. The success was termed a successful demonstration of high frequency forcing (at a frequency that is very large compared to that of the cavity tones). The authors hypothesized that the mechanism was an accelerated energy cascade from the largest to the smallest turbulent scales.[35]

A follow-on study[33] investigated powered and unpowered resonance tubes (in which the resonator tubes were blocked to prevent high frequency excitation), and microjets vs. various other devices. While the powered resonance tubes were redesigned to reduce their mass flow requirements, optimal suppression still required B_c ~ 0.6%. The unpowered resonance tubes consistently provided the best suppression, indicating that the primary suppression mechanism of these devices may not be high frequency forcing but the steady blowing component. The results also introduced microjet blowing and showed that vertical blowing is required for these devices to be successful in this application.

Furthermore, Stanek et al. [33] offered a new model for high frequency forcing. Simply stated, high frequency forcing alters the mean flow and, hence, its instability characteristics such that the growth of large scale disturbances is inhibited or prevented. This argument, while plausible, requires confirmation in the form of experiments and validated simulations to determine the mean velocity profile and subsequent shear layer growth characteristics for various high frequency devices.

Most recently, Stanek et al. investigated various aspects of the cylindrical rod in crossflow.[34] They studied the vertical position of the rod H/δ in the boundary layer, its relative size d/δ, installation issues, and end conditions. They recommended an optimal location as centered at the edge of the boundary layer and an optimal size of $d/\delta = 2/3$. They argued that their results conclusively demonstrate that the suppression is due to high frequency rod shedding. Again, while the cylinder clearly affects the mean flow and its stability characteristics, there are other important factors that cannot be ignored, including experimental evidence presented by Ukeiley et al.[36] and the numerical simulations of Arunajatesan et al.[37] that the cylinder lifts the shear layer and causes the impingement region to be altered. If the shear layer impingement location is altered, then the source strength is presumably affected.

One other mechanism, not yet discussed in the literature, is the possibility of rod or wire resonance. A cylinder in crossflow can vary in complexity from a resonating string in tension[38] to a pinned or clamped rod in tension or compression (that can sustain bending) depending on its diameter, length, material and boundary condition.[39] Sample calculations reveal fundamental resonance frequencies that can vary from several hundred Hz to several kHz, depending on the mounting configuration. If the wire/rod resonates due to the broadband excitation of the turbulent boundary layer or fluctuating pressure field, fluid/structure interaction effects, which have been ignored to date, may be significant.

There are a few other recent studies involving steady and/or pulsed blowing that have provided physical insight or have shown promising results. Bueno et al.[40] used an array of six fast-response (~3 ms) miniature jets mounted upstream of the leading edge to study the effects of normal injection on a Mach 2 cavity flow. They used instantaneous and ensemble-averaged pressure time histories and cross correlations to study the effects of single short and long cyclical pulses (50% duty cycle), the latter with relatively low forcing frequencies compared to that of the tones (50 or 80 Hz). They compared their pulsed results to steady blowing with B_c = 0.28%, 0.24%, 0.18%, and 0.16% at L/D =5, 6, 8, and 9, respectively, and concluded that continuous mass injection is more effective for suppression than pulsed blowing.

Ukeiley et al.[41] used an array of eight powered whistles mounted in the forward cavity wall. These devices essentially produce a high frequency tone superimposed on a steady jet. The jet is directed in the downstream direction but has a slight vertical velocity component. The authors studied the novel use of different injection gases (heated air, nitrogen, and helium) with and without the high frequency "whistle" component. Their best results were obtained using steady helium blowing (no high frequency component) with very low B_c = 0.09%. The suppression mechanism requires further study, but sample PIV images and cross correlations of pressure time histories suggest that the injection alters the impingement region and disrupts the acoustic feedback loop. Their results also highlight the need to rigorously study *isolated* high frequency forcing effects.

Most recently, Zhuang et al.[42] investigated the use of a vertically directed microjet array mounted upstream of the cavity leading edge. The microjets had a 400 μm diameter and produced sonic jets that interact with the upstream boundary layer. The authors show how, at Mach 2, an oblique shock is formed that deflects the shear layer and alters its trajectory and the resulting impingement region. Significant tonal and broadband suppression levels were achieved with B_c = 0.14%. Higher levels of B_c produced no additional improvement.

Collectively, the blowing results described above indicate that manually optimized steady blowing configurations with $B_c \le 0.1\%$ can be effective suppression devices. At subsonic speeds the primary mechanisms appear to be an alteration of the shear layer stability characteristics and the shear layer impingement location. While stability characteristics are also important at supersonic speeds, shock wave/boundary layer interactions at the upstream cavity edge and the ensuing shear layer trajectory alteration appear to be dominant factors.

It is interesting that when all of the available blowing data is expressed using the blowing coefficient definition of Vakili and Gauthier,[24] one finds that the evolution of steady blowing techniques has reduced effective (not necessarily optimal) B_c from O(10%) by two orders of magnitude down to O(0.1%). Note that the definition of B_c accounts for the cavity area but does not directly incorporate the scaling effects of the boundary layer thickness. This has important implications for full-scale applications and is addressed further in Section 3.

In comparison, low frequency forcing does not appear to be very attractive when the actuator bandwidth is insufficient in comparison to the frequencies of the cavity tones. This is discussed further in Sections 3 and 5.

High frequency excitation, whether it is passive or active, appears promising for both tonal and broadband suppression. However, the responsible mechanisms require further study. There is ample evidence that high frequency forcing alters the mean flow. As a result, the shear layer stability characteristics are altered and, in some cases, the trajectory of the shear layer is modified. When the impingement location is altered, the strength of the acoustic source is reduced and the broadband noise level decreases. We will show in Section 5 that, to date, closed-loop control produces comparatively little change in the mean flow properties and, as such, has only been shown to be effective for tonal control.

3 Actuators

In general actuators for cavity tone control are devices that act to disrupt the acoustic resonance mechanism. Actuators may be a component of a closed-loop control system or act independently in an open-loop or passive mode. One is normally interested in attenuating the narrow band Rossiter modes, but in some cases the broadband noise level is reduced as well.[18] Examples of actuators, their strengths and weaknesses, and the issues associated with their application will be discussed in this section.

Passive Actuators

Passive actuators attenuate tones by changing the characteristics of the shear flow over the cavity. Passive actuators require the fewest moving parts and tend to be the least expensive and least complicated devices. However, they often do not work well at off-design conditions.[43] Passive actuators disrupt the resonance through one of at least three mechanisms:

1) the trajectory of the mean shear layer is changed such that the reattachment point is shifted downstream of the cavity edge,[36,37,40]
2) the stability characteristics are modified by the change in the shear layer (velocity profiles or gas properties),[10,41] so that the resonant modes are not amplified, and
3) the spanwise coherence of the shear layer and corresponding Rossiter mode is disrupted.[37]

Examples of passive actuators include leading edge ramps,[25] spoilers,[44] fences,[36] steady gas injection,[24] or contouring of the trailing edge of the cavity.[14] Spoilers and fences are commonly installed on production aircraft to reduce the resonant tones in weapons bays and deploy when the bay doors open. The fences act to increase the shear layer thickness, which shifts the most unstable shear layer frequencies to lower values. Spoilers and ramps deflect the mean separation streamline higher into the flow so that reattachment occurs downstream of the cavity edge. This weakens the feedback acoustic wave and the resulting strength of the Rossiter mode.

Similarly rods placed in the upstream boundary layer will produce a mean wake (momentum deficit) that modifies the mean shear layer development.[34,36,37] Ukeiley et al.[36] studied both rods and variable height fences, and found the effect of the device on the *mean gradient* of the shear layer to be important in determining the level of attenuation.

Active Open-Loop Actuators

Actuators that add energy to the flow are defined as active control devices. The term "open loop" emphasizes that a feedback signal is not used to control the actuator output. Examples include oscillating electromechanical[25,44,45] and piezoelectric flaps,[28,46,47,48] steady blowing,[25,40,49,50] and pulsed blowing,[20,29,51] voice-coil drivers,[52,53] powered resonance tubes,[13,17,54,55] and fluidic oscillating jets.[32] All of these open-loop actuators have demonstrated control of cavity resonance at subsonic flow conditions, but only the powered resonance tube and the steady and pulsed jets have been successful at supersonic freestream conditions.

It is important to recognize that a mean component of forcing is associated with most unsteady actuators. Even in the case of actuators that have no net mass addition, such as voice coils, and synthetic jets, there will be a net momentum flux associated with the second-order streaming effect.[56] Streaming is the steady, secondary flow component resulting from the quadratic nonlinear interaction of the unsteady flow components. Whether this effect is significant or not depends on the amplitude of the oscillations. Actuators with a nonzero mass addition such as pulsed jets, siren valves, powered resonance tubes, fluidics, and whistles will have first-order mean flow components with disturbance magnitudes that are comparable to or exceed the amplitude of the unsteady component. It is often a challenge to the actuator designer to maintain, for example, velocity fluctuation amplitudes at the same order of magnitude as the mean flow as the frequency increases. Because these devices have a strong mean component, it is often difficult to separate which effect is responsible for the flow control.

As suggested by Stanek et al.,[13] actuators can be further categorized into low-frequency excitation and high-frequency excitation ("hifex"). Hifex corresponds to forcing an order of magnitude larger than the frequencies of the resonant tones, while low-frequency excitation corresponds to frequencies that are the same order of magnitude or less. Sarno and Franke[25] proposed the concept of forcing the shear layer at a frequency different from the Rossiter mode as a way to suppress resonance. Because their actuators were limited to frequencies an order of magnitude lower than the first Rossiter mode, the results did not provide convincing evidence that the low-frequency forcing approach could be effective. By using a piezoelectric flap, Cattafesta et al.[28] were the first to clearly demonstrate that forcing the shear layer to oscillate at a frequency different from the Rossiter modes would result in noise attenuation. Provided the excitation frequency was not in a narrow band near a Rossiter mode, the piezoelectric flaps were able to attenuate the mode by exciting shear layer instabilities incommensurate with the Rossiter resonance mechanism. The effectiveness of this approach at higher Mach numbers remains an open question. Wider bandwidth open-loop actuators (voice-coil type) are being used by Debiasi and Samimy to further explore the low frequency concept.[57]

Actuation at frequencies an order-of-magnitude larger than the Rossiter modes can also lead to suppression of the cavity tones via hifex. In particular, the technique pioneered by McGrath and Shaw[18] and revisited by others has suppressed tones at supersonic flow conditions. One hifex hypothesis[13] argues that energy addition to the shear layer at length scales much smaller than the coherent shear layer vortices will directly increase dissipation and accelerates the turbulent energy cascade. An alternate hypothesis proposed by Stanek et al.[33] argues that hifex results in a *deceleration* of the turbulent energy cascade.

Note that hifex can be achieved via active control (with powered whistles[41,58] and powered resonant tubes) or passive control with rods mounted in the upstream boundary layer (due to passive high frequency vortex shedding). A typical hifex experiment will produce disturbances in the range of 5 kHz or higher in order to suppress tones in the 500 Hz range or lower. The physics of the hifex effect are difficult to sort out because all hifex actuators realized to date also have a substantial effect on the mean flow that can influence the shear layer development and the acoustic source. This effect using rods in crossflow has been demonstrated by Ukeiley et al.[36] and Arunajatesan et al.[37] Note that Rizzetta and Visbal[59] have shown, via large eddy simulations in a Mach 1.19 cavity, that pure high-frequency forcing can suppress cavity oscillations. But such a device has yet to be realized.

Irrespective of the type used, active open-loop actuators are attractive because of their relative simplicity and ability to be activated when needed. However, Shaw & Northcraft[20] demonstrated the sensitivity of the control effect to forcing frequency and changing flow conditions. Open-loop actuators, like passive actuators, must be optimized for each flow condition. Furthermore, Cattafesta et al.[28] demonstrated with piezoelectric actuators that an order-of-magnitude higher power is required to drive the actuators compared to closed-loop systems. Similar power penalties with other open-loop actuators are expected.

Active Closed-Loop Actuators

Actuators for closed-loop control form part of a system that includes at least one flow state sensor and a feedback control algorithm. This approach is the most expensive in terms of hardware and complexity, but it offers the greatest adaptability to changing flow conditions and potentially the lowest power consumption. A summary of some actuators used in closed-loop cavity control experiments are listed in Table 2.

Closed-loop actuators for active control of cavity oscillations also fall into two types. What we call a "Type A" actuator is a device with sufficient bandwidth that is capable of producing, at any instant in time, a control input consisting of several frequencies, each with their own amplitude and phase. This type of actuator has a time response commensurate with the time scales of the cavity flow dynamics so that it can be used in a dynamic feedback compensation scheme. A "Type B" actuator is also a broadband device but produces a control signal of prescribed amplitude and *primarily* one frequency (and perhaps its harmonics) at any instant in time. The actuator frequency can change on a time scale that is large compared to the time scales of the cavity flow dynamics. Shaw and Northcraft successfully used this approach with a rotary valve, pulsed blowing actuator.[20] At any instant in time, the rotor spins at a particular rotation rate (rpm) and the supply pressure has a certain value. These can both be changed via, for example, control voltage to a dc motor and servo valve, but the slow time response of this actuator precludes a rapid change in the actuator output.

The majority of closed-loop flow control experiments summarized in Table 2 use Type A actuators.[28,53,60-65] Note that the bandwidth of the actuator must be large enough in order to suppress more than one Rossiter mode. The bandwidth of the actuator plays a crucial role through the "area rule" in determining the closed-loop system response. More details will be given in Section 5, but an actuator with too narrow a bandwidth will leak energy into undesirable neighboring modes.[63] For this reason, it is important to know the actuator transfer function when designing a closed loop control algorithm. Techniques to accomplish this for piezoelectric flaps and synthetic jets are described, for example, in Ref. 46 and 66, respectively.

Initially the closed-loop actuator must have enough power to produce a disturbance that exceeds the receptivity-induced perturbation at the upstream end of the cavity. After the system responds to the actuation, the actuator power requirements decrease with the decreasing tone amplitudes. Cattafesta et al.[28] demonstrated the initial high amplitude piezoelectric actuator output reduced by an order-of-magnitude after control was established.

To date there has not been a demonstration of closed-loop control (Type A) at supersonic speeds. Shaw and Northcraft[20] demonstrated both open-loop and Type B closed-loop control were capable of controlling the tones and reducing the broadband noise levels with pulsed-fluidic injection at supersonic speeds. The challenge associated with closed-loop control is to achieve similar noise reductions with an order of magnitude less input power by using Type A closed-loop control. Actuators with large amplitudes, high bandwidth, and fast time response are required, which raises the issue of actuator scaling. Shaw[67] studied the mean mass flow rate requirements for a pulsed injection system directed perpendicular to the freestream and determined that the steady momentum coefficient $C_\mu = \dot{m}U_{jet}/\left(q_\infty W\delta\right)$ scaled two sets of data at Mach 0.95 with frequencies ranging from 100 Hz to 600 Hz and widely varying δ and q_∞. Note that the area in the denominator of the scaling parameter is the width of the cavity multiplied by the boundary layer thickness at the leading edge of the cavity. This scaling parameter was used successfully for weapons bay cavity flow control in the flight test of an F-111.[68]

For the purposes of Type A flow control actuation with piezoelectric flaps or with zero-net-mass actuators like the synthetic jet, the momentum coefficient will need to include the fluctuating component of velocity. Experiments at IIT with pulsed-blowing jets for separation control on airfoils have shown that an oscillatory momentum coefficient is the correct scaling parameter, and we expect a similar parameter, $c_\mu = \rho_{jet} u_{rms}^2 A_{jet} / (q_\infty W \delta)$, to apply to the cavity as well. Since $q_\infty = 0.5 \gamma p M_\infty^2$, the dynamic pressure will increase by a factor of nine as the Mach number goes from 0.5 to 1.5. This implies that the actuator rms velocity fluctuation level will need to increase by a factor of 3 to be effective at supersonic conditions.

Finally, we note the reported discrepancy for the optimal injection angle. As summarized in Table 1, Shaw[29] has found vertical injection is superior for pulsed blowing at low frequencies, while Williams et al.[21] and Kegerise et al.[65] find horizontal injection is superior for Type A synthetic jet actuators. Stanek et al.[33] have found that steady microjets have only been effective in vertical injection configurations. The reason for this observed discrepancy is unclear.

4 Sensors and Flow Measurements

Since the aim of most cavity control experiments is to reduce the pressure fluctuations, unsteady pressure sensors are commonly used in laboratory control applications. Lou et al.[69] used microphones to measure (and control) the flow induced pressure oscillations in an impinging jet. By far the most common sensors used to examine these flows are miniature, high frequency response transducers, such as those made by Kulite, Endevco, PCB, and microphones, such as from Brüel & Kjær.

These transducers are usually flush-mounted on one of the cavity surfaces, generally the floor and/or the leading and trailing surfaces. Alternatively, they are placed in the flowfield or tunnel walls near the cavity to measure the acoustic field. The small size, linearity (output voltage linearly proportional to input pressure), their flat-frequency response over a large frequency range, and their high dynamic range (ratio of maximum-to-minimum detectable pressure) make them an excellent tool for characterizing the cavity dynamics. Such transducers have been used to examine subsonic,[70] supersonic,[42] and hypersonic[71] cavity flows. They have been used in small scale, laboratory facilities and in larger commercial testing facilities.[33,69]

In order to better understand the global flow behavior, one must look beyond the surface pressure or acoustic field. The dynamics of cavity flows have been examined using a number of other diagnostic tools. For example, relatively low Mach number cavity flows have also been examined using constant-temperature hot wire anemometry. Shear layer profiles (mean and fluctuating) and, in some cases, instability growth rates have been obtained. Examples can be found in Mendoza and Ahuja,[26] Hsu and Ahuja,[27] Cattafesta et al.,[28] Garg and Cattafesta,[72] Kegerise,[73] and Williams et al. at IIT.[21,30,62,70,74]

Hot wire anemometry becomes increasingly problematic in high speed flows due to wire breakage and compressibility effects.[75] Consequently other techniques have been used. Vakili et al.[76] used a multi-hole probe to obtain upstream boundary layer profiles as a function of mass injection. Kegerise et al.[73,77] and Garg and Cattafesta[72] characterized the spatio-temporal behavior of high-speed, subsonic, cavity flows using a combination of fluctuating pressure measurements and phase-conditioned measurements of the density field inside the cavity using a non-intrusive schlieren instrument. The quantitative schlieren technique (and hot wires) were used to study nonlinear mode interactions and mode switching.[78,21] Zhuang et al.[42] also used a combination of schlieren and shadowgraph methods along with unsteady surface pressure measurements to study supersonic cavity flows. Such data provide invaluable information regarding the spatio-temporal nature of the events that dominate the cavity dynamics and can provide insight of nonlinear interactions and model switching.

Similarly, Forestier et al.[79] have studied transonic (Mach 0.8) flow over deep cavities ($L/D \sim 0.4$) using high-speed schlieren photography to visually examine the periodic component of the cavity shear layer oscillations. In addition, they obtained phase-locked laser Doppler velocimetry measurements to examine the evolution of periodic and spatially coherent structures (or vortices) extracted from the velocity-field data. Murray and Elliott[80] have used schlieren photography and planar laser imaging of supersonic cavity flows (1.8 to 3.5) to study the characteristics of cavity shear layer structures.

Some investigators have used particle image velocimetry with varying degrees of success to study high speed cavity flows.[41,42,81] Most of the difficulties are associated with proper seeding of the cavity flow. Zhuang et al.[42] have obtained velocity and vorticity-fields in a supersonic flow and have examined the effects of microjet control.

With regards to safe separation of stores from military aircraft,[82] one wishes to predict the trajectory, based on a simple measurement, such as the fluctuating pressures inside the cavity. To accomplish this, correlations between the measurements made inside the cavity to store separation characteristics are required. Such a database can be created through captive trajectory tests where forces and moments on the store are measured simultaneously with the unsteady pressures inside the cavity. Another approach is the use of sensors, such as accelerometers, gyros, and inclinometers, which measure the pertinent store trajectory parameters. Stores embedded with such sensors combined with telemetry data systems can then be used to obtain correlate simultaneous store trajectory and the pressure signals.

5 Closed-Loop Control Methodologies

The studies described in Section 2 suppressed cavity noise using open-loop techniques. Here, we discuss several studies using closed-loop control, which incorporates some type of feedback from a sensor placed in the flow. One way to use this feedback is to tune an inherently open-loop approach, for instance by slowly modulating the frequency of open-loop forcing to achieve the best suppression. A different way uses dynamic feedback at the timescale of the unsteadiness, and can have even more beneficial effects, as very low-power control is possible.

Open-loop control cannot alter the dynamics of a system (e.g., stabilize an instability) except by exciting nonlinearities (e.g., by modifying the mean flow). This implies a large power requirement, either as power explicitly supplied to an actuator, or as a drag penalty. By contrast, closed-loop control can *linearly* stabilize a system (i.e., with “infinitesimal” actuation), and furthermore it can reduce the amplification of external disturbances, such as boundary layer turbulence or external acoustic waves. In addition, adaptive techniques may be used to tune the controller’s behavior in real time.

Quasi-Static Controllers

The first closed-loop strategies were modifications of open-loop strategies. We categorize these strategies as quasi-static, because in these approaches, the time scales by which feedback acts are much slower than the time scales of the flow. In perhaps the first known closed-loop cavity control experiments, Gharib[83] used periodically-forced strip heaters to excite Tollmien-Schlichting waves in the boundary layer upstream of a cavity. By feeding back a velocity measurement from a downstream location in the cavity, and phase-locking the sinusoidal forcing to this measurement, they obtained a 40% reduction in velocity fluctuations.

Shaw and Northcraft[20] also used feedback to modulate a sinusoidal forcing function. They measured the sound pressure level (SPL) in a bandpass-filtered pressure signal and then used an iterative search algorithm to adjust the frequency and amplitude of a pulsed jet actuator and achieved a significant suppression of the tones, along with some suppression of broadband noise. Debiasi and Samimy[57] are also pursuing an adaptive learning approach, in which open-loop forcing is applied at a particular frequency, and this frequency is automatically adjusted by a learning algorithm to obtain the best suppression.

Dynamic Controllers

As described in Section 2, the class of closed-loop control we call dynamic controllers use feedback at the timescale of the unsteady motion of the fluid. This is type of control is most amenable to techniques from classical and modern control theory, and has some distinct advantages over modulated open-loop techniques, as discussed at the beginning of this section.

Nearly all of the dynamic closed-loop cavity control studies to date have used linear control techniques. While this might seem restrictive, it is actually reasonable to expect that linear controllers would perform well. The reasons for this are twofold. First, recent experiments have indicated that in some regimes, purely linear mechanisms can describe even finite-amplitude oscillations of the cavity.[63] Second, even in regimes in which nonlinearities play a role in the naturally oscillating cavity, one hopes that in the controlled cavity, oscillations will be small, and thus linear models will remain valid.

Models

Most linear control approaches rely on an accurate model of the system to be controlled. In this setting, the cavity flow is viewed as an input-output system, where the input is, for instance, the voltage signal supplied to the actuator, and the output is a sensor measurement. There may be multiple sensors, or even multiple actuators, in which case the input and/or output are vectors. Many different modeling techniques have been used in recent years, either based on flow physics or empirically identified directly from an experiment, and we describe some of these techniques below.

<u>System Identification</u>

Several studies have determined a model for the cavity flow empirically, using some form of frequency response experiment. The general approach is to force the actuator at a range of frequencies, measure the response from the sensor, and then either determine an empirical transfer function from spectra, or use an adaptive algorithm to tune coefficients in a filter such that the output from the filter matches the data as closely as possible. In the first case, the model takes the form of frequency-response data, which may be expressed as a curve on a Bode or Nyquist plot. In the second case, the model takes the form of a rational transfer function, either discrete-time or continuous-time, whose coefficients are known. Many tools for control design (e.g., LQR/LQG, to be discussed later) depend on such a model, but for classical techniques such as loopshaping, a curve on a Bode plot is sufficient.

The first approach was used by Mongeau et al.,[60,61] in which they determined open-loop transfer functions for low-speed flow past a Helmholtz resonator at several different flow velocities.

A similar approach was used by Rowley et al.,[53] who obtained an empirical transfer function for a compressible cavity flow. An important difference in this work was that a manually-tuned controller was used to stabilize the oscillations prior to performing the frequency response experiment. The frequency-response experiment was performed on the stabilized system, and then the effect of the known controller was inverted out. The reason for this is that a frequency response experiment makes sense only for stable linear systems. If the system is unstable, with the amplitude of oscillation limited by nonlinearities, then it is not clear how to interpret the results of the frequency response experiment.

Several system-identification techniques have been used to determine models in the form of rational transfer functions, or state-space representations. Most of these involved frequency response experiments on the uncontrolled cavity, and as mentioned above, if the linearized system is indeed unstable, and the oscillations are self-sustained then the meaning of such experiments is not clear.

Kestens and Nicoud[84] used a filtered-X least mean square (LMS) algorithm to determine a model for a 2D Navier-Stokes simulation of a forced cavity flow. The model was determined with no flow, so effects such as shear-layer convection and amplification would not be captured by such a system identification.

Cattafesta et al.[28] performed a frequency-response experiment on the oscillating cavity, using a least-squares method to identify the parameters in a discrete-time transfer function, and then an eigensystem realization algorithm to convert this to state-space form. Cabell et al.[64] used a similar approach and obtained models of very high order (150-200 states). In these experiments, low coherence was observed between input and measured signals in the system identification experiment, so long time records (10 seconds) were collected. Controllers designed from these models yielded reasonably good suppression, and models predicted general trends observed in the experiments. Cattafesta et al.[22] also used an adaptive algorithm which could be used either offline, or with a feedback controller in place, in which case it also served as an adaptive controller, tuning controller coefficients to minimize the output. Such closed-loop system identification avoids the problem of doing a frequency response experiment on an unstable system, mentioned earlier.

Kegerise et al.[65] and Pillarisetti and Cattafesta[85] have used various adaptive algorithms to tune coefficients in linear and nonlinear discrete-time models for the cavity. Kegerise et al. compared finite impulse-response (FIR) and infinite impulse response (IIR) filters and found that IIR filters were necessary to capture the dynamics well, as one expects since FIR filters cannot represent resonances or instabilities.

Physics-Based Models

The system identification procedures described above treat the cavity as a black box, and models are obtained by observing the response to forcing. In this section, we review models based solely on the physics of the flow. Of course, the models in the previous section will also contain flow physics, but the models in this section are obtained exclusively by studying the flow physics. The advantage of this approach is that it can give insight into the mechanisms of cavity oscillations that might not be apparent otherwise. In addition, one may obtain scaling laws which determine how the models vary as a parameter such as Mach number or cavity length is varied.

POD/Galerkin Models. The governing equations for fluids are the Navier-Stokes equations, so in a sense a very accurate model of cavity flows is already known. However, tools for control analysis and design do not apply to nonlinear partial differential equations. So in order to use these techniques, it is desirable to approximate the Navier-Stokes equations by a finite-dimensional system. An increasingly popular method for obtaining such low-dimensional models is the method of Proper Orthogonal Decomposition (POD) and Galerkin projection. In this method, data from simulations or experiments is used to determine a finite-dimensional subspace which contains the “most important” features of the flow (based on energy). The Navier-Stokes equations are then projected onto this subspace to obtain a low-dimensional model. For a thorough review of this method, see Holmes et al.[86]

POD/Galerkin models for 2D flow past a cavity were computed by Rowley,[87,88] and POD modes were also computed by Ukeiley.[89] The standard method for incompressible flows was modified for compressible flows, in which the thermodynamic variables become important. It was found that vector-valued POD modes worked better than scalar-valued POD modes, but to use vector-valued modes, one must choose an inner product that appropriately weights the thermodynamic (e.g. density) and kinematic variables (e.g. velocity). See Rowley[90] for a thorough description of the method for compressible flows.

While these models capture the open-loop dynamics well, including all nonlinearities, it is difficult to include the effects of actuation, and we are not aware of any studies which have included actuation in POD models of the cavity flow.

Rossiter-Type Models. In contrast to POD models, in which the full Navier-Stokes equations are simplified, another approach is to model different components of the Rossiter mechanism, and connect these together, building more complex models from simple models of the individual components. Cain et al.[91] used a nonlinear model for shear layer amplification, coupled with models for acoustic scattering and receptivity, to predict amplitudes of cavity oscillations. Their procedure was iterative, and provided an estimate for steady-state amplitude, but was not time-accurate. Nonetheless, it represented a significant improvement over the Rossiter model[3] and the improved Tam and Block model[92].

Rowley et al.[53] used purely linear models for the various components, including shear-layer amplification, and obtained time-accurate models in the form of transfer functions. The model suggested an alternative mechanism for cavity oscillations: while the conventional view is that the oscillations are self-sustained, an alternative view is that the cavity could act as a lightly damped oscillator that amplifies noise at resonant frequencies. In this case, the oscillations are not self-sustaining. The linear models obtained in this paper explained some peak-splitting effects observed in experiments, and implied some fundamental performance limits, discussed later.

Clearly, the models described above provide physical insight but are not sufficiently accurate to design a control system. Recently, Kerschen and Tumin[93] described a theoretical model of cavity resonance that shows great promise for physics-based cavity control design. The model combines a propagation model based on a finite-thickness shear layer with scattering models for the leading and trailing edge regions of the cavity using an exact Wiener-Hopf technique. The model predicts the cavity resonance frequencies without any empirical constants and also provides the temporal growth rate of each mode.

Control Algorithms

Here, we focus on dynamic control algorithms, in which the feedback is at the timescale of the unsteadiness. The simplest control strategies do not require a model, and the parameters of the controller are tuned manually. Williams et al.[21] used such a strategy, in which a pressure signal was bandpass filtered about the frequency of a cavity tone, and a phase shifter was manually tuned until the oscillations were suppressed. Several bandpass filters were used in parallel to achieve suppression of multiple modes, and a similar approach was used by Kegerise et al.[65] to suppress multiple modes.

While manual tuning can work reasonably well, often new tones are produced; furthermore, tuning the parameters is usually difficult, especially when multiple modes were present. More predictable design methodologies are available if one has a model of the system. For instance, Mongeau et al.[60,61] used a classical loopshaping technique to design a control law for the flow past a Helmholtz resonator. Given a plant model $P(s)$, then with a controller given by $C(s)$, one may design the loop gain $L(s)=P(s)C(s)$ such that the closed-loop system has some desired properties (such as good disturbance rejection over a certain frequency range). One then determines $C(s)$ by inverting the plant: $C(s)=L(s)/P(s)$. If the plant model has right-half-plane zeros or poles, then in order to avoid right-half plane (RHP) pole-zero cancellation, one must place certain restrictions on $L(s)$, which can be cumbersome (see Doyle, Francis, and Tannenbaum[94] for more details).

Modern control tools provide systematic ways of designing controllers, given an adequate model.[95] Cattafesta et al.[28] used two such methods, pole-placement and LQG, to suppress the oscillations with an order of magnitude less input power than open-loop techniques. Cabell et al.[64] also used an LQG regulator, with a frequency-dependent weighting on the control effort. For both pole-placement and LQG, one begins with a model of the system in state-space form

$$\begin{aligned} x_{k+1} &= Ax_k + Bu_k \\ y_k &= Cx_k + Du_k, \end{aligned} \qquad \{2\}$$

where u_k is the input (actuator voltage) at time $t_k = k\Delta t$, and y_k is the corresponding output (sensor measurement). Here x_k is the state vector, and $A, B, C,$ and D are matrices of appropriate dimension. If one chooses a feedback law

$$u_k = Kx_k, \qquad \{3\}$$

where K is a matrix of gains, then the closed-loop system becomes

$$x_{k+1} = (A + BK)x_k$$
$$y_k = (C + DK)x_k. \qquad \{4\}$$

A basic fact from control theory is that if the realization is controllable, the matrix K may be chosen to place the eigenvalues of $A + BK$ at any desired locations. Thus, even if the original system is unstable (i.e., the eigenvalues of A lie outside the unit circle), K can be chosen such that the closed-loop system is stable, and in fact such that the response decays arbitrarily quickly. The tradeoff in control design is to choose K to achieve a balance between fast response (good), and large values of the gains (bad), which require large actuator power, and amplify sensor noise.

An optimal way of achieving this balance between fast response and large gains is to use a Linear Quadratic Regulator (LQR),[96] which chooses K to minimize a cost function

$$J = \sum_{k=0}^{\infty} \left(x_k^T Q x_k + u_k^T R u_k \right), \qquad \{5\}$$

where Q and R are symmetric, positive-definite matrices. These matrices are the parameters in the control design, and by choosing different matrices we choose how to balance good performance against the cost of control. One determines the value of the gain matrix K that minimizes this cost function by solving a quadratic matrix equation (an algebraic Riccati equation), and there are common routines to do this.

In order to use these techniques, one of course needs to know the state x_k, which usually is not directly available. In order to obtain the state, one typically designs an observer to estimate the state, for instance by solving an equation

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k + L\left(C\hat{x}_k + Du_k - y_k\right), \qquad \{6\}$$

where $\hat{x}_k$ is the state estimate at time t_k, and L is a matrix of observer gains. One may choose these observer gains such that the estimate is guaranteed to converge to the actual state (as long as the realization is observable). Again, there is a tradeoff between fast convergence and large amplification of sensor noise, and an optimal way of balancing these tradeoffs uses a procedure that precisely parallels LQR. Such an optimal observer is called a Kalman filter, and when a Kalman filter is combined with state feedback using LQR, the resulting controller is called an LQG regulator (Linear Quadratic Gaussian).

Note that all of these techniques (pole placement, LQR, and observer design) rely on an adequate model of the system, in the form of the matrices $A, B, C,$ and D.

Adaptive control techniques are also used, in which parameters in a controller are updated real-time, in order to drive the sensor measurements to zero. Such controllers were used by Kestens and Nicoud[84] and Cattafesta et al.[22]

Fundamental Limits on Achievable Performance

Though closed-loop controllers have provided reasonably good suppression, they often produce some adverse effects, such as an increase in noise at other frequencies. For instance, if the gain of a controller is increased too much, a peak-splitting phenomenon may be observed (Rowley et al.[63] and Cabell et al.[64]), in which the main resonant peak splits into two peaks on either side of the original frequency. Because of some fundamental limitations of feedback control, to some extent such adverse effects are unavoidable, though they may be minimized by a sensible controller design.

In the feedback loop shown in Fig. 3, if the plant is denoted $P(s)$ and the controller by $C(s)$, where $s = i\omega$, then the transfer function from an external disturbance to the output is given by

$$\frac{P(s)}{1 + P(s)C(s)} = S(s)P(s), \qquad \{7\}$$

where $S = 1/(1 + PC)$ is the *sensitivity function*. Since the transfer function from disturbances to output for the open-loop system (no control) is simply $P(s)$, the sensitivity function measures how feedback alters the effect of disturbances. One of the goals of feedback design is to decrease the amplification of disturbances, so we would like to make $|S(i\omega)| < 1$ for all frequencies $\omega \in \Re$. Unfortunately, this is never possible, due to Bode's integral formula, which states that if the relative degree of the loop gain is at least 2 (that is, the degree of the denominator of $P(s)C(s)$ is at least 2 greater than the degree of the numerator, which is virtually always true in practice), then

$$\int_0^{\infty} \log|S(i\omega)| d\omega = \pi(\log e) \sum_i \mathrm{Re}(p_i) \qquad \{8\}$$

where p_i denotes the right-half-plane poles of $P(s)C(s)$. For instance, if the plant is stable (i.e., the right-hand side of the equation is zero), then in a log-linear plot of $|S(i\omega)|$, the area of attenuation $(|S(i\omega)| < 1)$ must be balanced by an equal area of amplification $(|S(i\omega)| > 1)$, in which the closed-loop system amplifies disturbances even more than open-loop. If the plant is unstable, the area of amplification must be larger than the area of attenuation. Of course, all of this attenuation and amplification must occur within the bandwidth of the controller, since $\left|S(i\omega)\right| = 1$ when the actuation goes to zero. Hence, narrow bandwidth controllers or actuators will have severe limitations: if one desires good performance at one frequency, one will pay a penalty of bad performance at other frequencies within the passband. Wider bandwidth actuators will not have such severe limitations, since the area of amplification may be spread out over a large frequency range.

6. Summary and Future Directions

This paper has provided a review of active control of cavity resonance. Due to space limitations, emphasis has been placed on experimental investigations of open- and closed-loop suppression techniques. We conclude with the following observations/recommendations.

First, while the suppression of cavity resonance is an important problem of practical interest, the search for a solution to this problem combined with budgetary, time, and scientific constraints often limits flow-physics experiments. Where possible, boundary layer and shear layer measurements (of the mean and fluctuating components) should be conducted for the baseline and controlled cases. In addition the interaction of the actuator with the flow should be characterized. Beyond improving our understanding of cavity oscillations, these data will provide the basis for future comparison and scaling results. It will also permit the evaluation of critical issues, for example, isolated high frequency excitation effects.

Furthermore, several active open-loop and passive schemes have demonstrated the ability to reduce the broadband levels, while closed-loop control does not appear to modify the mean flow significantly. Evidence suggests that broadband suppression implies a modification of the mean flow.

While the closed-loop results have been promising, only passive and active open-loop methods have been successful at supersonic speeds. It is conceivable that a hybrid scheme consisting of some combination may be effective. For closed-loop control to have an even greater impact, several things must occur. First, improved physical dynamic models, like that of Kerschen and Tumin,[93] are required that can determine the tonal frequencies and their amplitudes as well as the broadband level. These models must ultimately be able to incorporate actuator dynamics. Second, better "Type A" (discussed in Section 3) actuators are required that have high output, large bandwidth, and fast time response such that multi-mode tonal (and perhaps broadband) closed-loop control at supersonic speeds is possible. Third, it is our opinion that researchers in the field of flow control must accept, if not embrace, the role of multiple disciplines (e.g., fluid dynamics, control theory, and transducers). Only in this manner can active flow control achieve its full potential.

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Table 1: Summary of Selected Passive and Open-Loop Cavity Suppression Studies.

STUDY	***CONDITIONS***	***METHOD***	***COMMENTS***
Sarohia and Massier (1977)	•2 axisymmetric cavity models • L/D =0-1.5 • M_∞ =0-0.5 •Laminar and turbulent BL	•steady injection at base of the cavity B_c ~5-15%	•Large mass flow rates were required to stabilize cavity oscillations
Sarno and Franke (1994)	• L/D =2, L/W =6.4 at M_∞ =0.6, 0.7, 0.9, 1.1, 1.3, and 1.5 •Calculated δ =0.048 in. (at • M_∞ =1.53) to 0.062 in. (at M_∞ =0.62)	•Static and oscillating mechanical fences (<220 Hz) •steady and pulsed flow injection (<80 Hz) at either 0º or 45º w.r.t. freestream at leading edge • B_c up to 7%	•Insufficient actuator bandwidth •Low frequency forcing ineffective •Significant 3D effects possible
Vakili and Gauthier (1994)	• $L/D = L/W = 2.54$, $M_\infty = 1.8$, • $\mathrm{Re}_\delta = 3.68\times10^5$	•Obtained significant attenuation with steady mass injection through porous plates upstream of cavity leading edge $B_c \sim 4\%$	•Proposed blowing coefficient $B_c = \left(\frac{\rho_w V_w}{\rho_e V_e}\right)\frac{A_{inj}}{A_{cavity}} = \frac{\dot{m}}{\rho_\infty U_\infty A_{cavity}}$ •Attenuation attributed to thickening of cavity shear layer to alter its instability characteristics
McGrath and Shaw (1996)	• L/D = 2.56, 3.73, 6.83 • $\mathrm{Re}/ft = 2.0\times10^6$ • δ =0.13 in. at $M_\infty = 0.85$	•Mechanical oscillations of hinged flap up to 35 Hz at M_∞ = 0.6, 0.8, 1.5, 1.89 •Static and oscillatory deflections of up to 1 δ •Cylinder (d =0.062 in) placed in upstream cavity BL at M_∞ = 0.6, 0.8 →Called high frequency tone generator HFTG •Based on shedding concept $St = fd/U = 0.2$ for $\mathrm{Re}_d = 10^3\text{-}10^5$	•Oscillating flaps show effective reduction of tones at subsonic and supersonic flow conditions •Limited bandwidth of actuator •HFTG shows effective reduction of tones and broadband •Proposed mechanism is the interaction of shed vortices with shear layer instabilities •Resonance effects?
Mendoza and Ahuja (1996)	• $L/D = 3.75$, $L/W = 0.47$ • M_∞ = 0.36, 0.44, 0.55, 0.9, and 1.05 • δ =0.057, 0.059, 0.062 in. at M_∞ = 0.36, 0.44, 0.55, respectively	•Studied effects of steady wall jet on cavity noise (normal via 0.2 mm slot and upstream via a ¼ in. radius of curvature Coanda surface 0.5625 in. upstream of cavity leading edge) •Proposed δ/L > 0.07 for elimination of cavity tones	•Upstream BL profiles showed an increase in δ with upstream blowing from Coanda surface •Hypothesized that suppression is due to reduced shear layer growth rate •No injected mass flow measurements provided
Hsu and Ahuja (1996)	• $L/D = 2.5$, $L/W = 0.47$ • M_∞ = 0.34, 0.53, and 0.9	•Studied effect of trailing-edge array of Helmholtz resonators (commercial syringes) on cavity noise	•No effect of resonators when in their closed position •Significant reductions observed at low Mach numbers, but new tones can appear •Negligible suppression at M=0.9 •Reason may be due to difficulty in accurately setting correct volume of all resonators
Cattafesta et al. (1997)	• L/D =0.5, L/W =0.5, U_∞=40 m/s, $\mathrm{Re}_\theta = 4750$, $L/\theta = 81$ • L/D =2.0, L/W =2.0, U_∞=45 m/s, $\mathrm{Re}_\theta = 5210$, $L/\theta = 328$	•Used piezoelectric flaps flush mounted at the leading edge of the cavity to suppress low-speed cavity oscillations	•OL forcing at detuned frequency suppresses oscillations •Shear-layer meas. w/ & w/o control Also CL results
Shaw (1998)	• L/D = ~6.5, $L/W = 3.67$ • M_∞ = 0.6, 0.85, 0.95, 1.05 • δ ~ 0.38 in. • $\mathrm{Re}/ft = 2.0\times10^6$	•Studied leading edge oscillating flaps, pulsed fluidic actuation, and HFTG using 1/16, 1/8, and 3/16 in. diameter cylindrical rods located at a height of 0.3 in	•Discussed possible mechanisms of HFTG (mode competition, shear layer instability) •Low freq., notched flaps effective when oscillating flap reaches BL edge •Showed normal injection (B_c <4.5%) superior to tangential
Fabris and Williams (1999)	• $L/D = 4$, $L/W = 0.49$ • M_∞ = 0.15, 0.23 (θ =3.1 mm)	•Unsteady bleed forcing (second mode) through a 12.7 mm slot located 12.7 mm ahead of cavity leading edge via speakers	•Shear layer receptive to unsteady bleed forcing

Lamp and Chokani (1999)	• $L/D = 4$, $L/W = 3$ • $M_\infty = 0.15, 0.23$, • $\mathrm{Re}/m = 5.9\times10^6$	•Used rotary valve actuator to provide steady and/or oscillatory blowing 0.1 in. upstream of cavity at frequencies up to 750 Hz •Used $\langle c_\mu \rangle = \frac{\rho u_{rms}^2 A_j}{q A_r}$ up to 0.16% where A_r = cavity front wall area (2 in. by 1.5 in) up to 0.16%	•Configuration emphasized 3D effects •Showed that oscillatory blowing can reduce tone amplitude significantly (up to 10 dB) provided frequency of forcing is not a harmonic of the cavity resonance, but new tones appear at the forcing frequency
Raman et al. (1999)	• $L/D = 6$, $L/W = 1.7$ • M_∞ = 0.4-0.7 •Jet cavity configuration	•Used upstream miniature fluidic oscillators to suppress cavity oscillations via sine, square, and triangular waveforms up to 3 kHz with mass flow rates of only 0.12% of main jet flow	•Comparable steady injection and upstream acoustic excitation do not suppress the cavity resonance •Hypothesized that periodic sweeping motion in spanwise direction destroys the spanwise coherence of shear layer
Stanek et al. (2000)	• $L/D = L/W = 5$ • M_∞ = 0.4, 0.6, 0.85, 0.95, 1.19, 1.35 •calculated δ =10.5 mm @ $M_\infty = 0.6$, $\mathrm{Re}/m = 11\times10^6$	•Investigated powered resonance tubes, protruding piezoceramic driven wedges, a cylindrical rod, and passive resonance tubes vs. conventional 1 δ spoiler	•Successful hifex forcing claimed for powered resonance tube at B_c = 1.6% •Hypothesize that mechanism is “accelerated energy cascade”
Bueno et al. (2002)	• $M_\infty = 2$, δ = 0.53 in, • $\mathrm{Re}/m = 3.0\times10^7$ • L/D =5, 6, 8, 9, $W/D = 3$	•Six fast-response (~3 ms) jets used to study effects of upstream pulsed and steady mass injection via a staggered configuration •Studied single short duration (1-2 ms) and long duration (50% duty cycle of forcing frequency of 50 or 80 Hz) pulses	• B_c = 0.28%, 0.24%, 0.18%, and 0.16% at L/D =5, 6, 8, 9, respectively, for continuous injection with all 6 valves •Found that continuous mass injection was more effective than pulsed injection in suppressing tones and overall noise level
Ukeiley et al. (2002)	•At M_∞ = 0.6, 0.75, δ = 0.1, 0.08 in., $\mathrm{Re}/ft = 11,\ 15\times10^6$, respectively, L/D = 5.6, 9, • $W/D = 2$ •At M_∞ = 0.8 & 1.4, $\mathrm{Re}/ft = 9.6\times10^6$, cavity dimensions doubled	•Used leading edge fence and 0.03 in. diameter cylindrical rod at various locations in BL for suppression	•Shear layer profiles suggest that rod works by “lifting” the shear layer and also by altering the mean shear
Stanek et al. (2002)	•Similar conditions as in Stanek et al. (2000)	•Investigated powered and unpowered resonance tubes, microjets vs. various other devices •Attempted to reduce mass flow requirements of mass flow devices	•Proposed that hifex forcing alters the mean flow and its inviscid stability characteristics such that the growth of large-scale disturbances is prevented •Provides evidence that substantial amount of suppression in powered resonance tubes may be due to steady blowing effects (optimal B_c ~ 0.6%)
Stanek et al. (2003)	•Similar conditions as in Stanek et al. (2000)	•Investigated cylindrical rod in crossflow •Investigated endcaps and fences	•Recommended optimal location is rod center at BL edge, optimal diameter is $2\delta/3$ •Concluded that acoustic suppression is due to high frequency rod shedding
Ukeiley et al. (2003)	•Similar conditions as in Ukeiley et al. (2002)	•Investigated powered whistles (8) to superimpose hifex perturbations on ~horizontal steady blowing at the leading edge w/ heated air, nitrogen (28 kHz) and helium (78 kHz)	•Used B_c up to 0.4% but best results (factor of ~2-4 reduction in aft wall OASPL) were with lowest steady Helium injection rate (B_c ~ 0.09%) •Suppression mechanism unclear; limited PIV images and cross correlation data suggest injection alters impingement region and disrupts acoustic feedback loop
Zhuang et al. (2003)	• $M_\infty = 2$, $L/D = 5.1$, $L/W = 5.8$, $\mathrm{Re}_L = 2.8\times10^6$	•Investigated 400 μm diam. microjet array (12) with vertical injection	•Found B_c < 0.14% provides large tonal and OASPL reductions •Saturation noted as B_c increased

Table 2: Summary of Selected Actuators used for Closed-Loop Control.

Study	Conditions	Method of Actuation	Control Approach	Power Requirement	Comments
Shaw and Northcraft (1999)	• M_∞ = 0.6-1.05 • L/D = 6.46, L/W = 3.67	•Pulsed fluidic at leading edge, 90o w.r.t. flow •frequency < 650 Hz	•Type B •Mass flow and frequency adjusted based on rms levels within 3 frequency bands		
Cattafesta, et al. (1997)	• U_∞ =40m/s, L/D = 0.5, L/W = 0.5, Re_θ=4750, L/θ=81 • U_∞ =45m/s, L/D = 2.0, L/W = 2.0, Re_θ=5210, L/θ=328 •W=12", D = 6",12"	•Unimorph piezoelectric flaps at leading edge •f_{typ}≈300Hz •23μm/V @ 300 Hz	•Type A		•Comparison of open-loop voltage and closed-loop voltage requirements
Cattafesta, et al. (1999)	• M_∞ = 0.4 – 1.35 • L/D = 5	•Piezoelectric flaps at cavity leading edge •f_{res}≈475Hz •2.5μm/V @ 500 Hz •1.875mm max displacement	•Type A •Adaptive disturbance rejection controller using ARMARKOV sys.ID		•Feedback signal is pressure near leading edge of cavity
Mongeau, et al. (1999)	• U_∞ =14 – 29 m/s •Partially closed cavity, 1/5 scale car model	•Oscillating spoiler hinged at leading edge of cavity opening •Voicecoil driver •1 mm max displacement @ 120 Hz	•Type A •Loop shaping of open loop transfer functions measured on system components	< 100 W	•Digital control using Simulink© Real-Time Workshop
Williams, et al.(2000) Rowley & Williams(2003)	• M_∞ = 0.25 = 0.55 • L/D = 5	•Zero-net-mass flow oscillations through leading edge slot, 0^o w.r.t. flow •two 500 W, 8"dia. Speakers •f_{typ}≈340Hz	•Type A •Model based control with 2nd order bandpass filters	0.33W – 53W depending on control	•Feedback signal from cavity floor at x/L = 0.8, 0.875
Ziada (2002)	• M_∞ = 0.3 • L/D = 2.5, 4 •L = 127mm, 203mm •D = 50.8mm •W = 76mm	•Synthetic jet through leading edge slot, 45^o w.r.t. flow •Two 50W, 100mm dia. Speakers	•Type A •Time delay and gain applied to feedback signal		
Kegerise(2003, private communication)	• M_∞ =.275 • L/D =5	•Bimorph piezoelectric •0.25 μm/V •f_{nat}=1200Hz	•Type A •ARMARKOV	1 W	

Table 3: Summary of Selected Closed-Loop Cavity Suppression Studies.

STUDY	CONDITIONS	METHOD	COMMENTS
Gharib (1987)	• U_∞ = 22 cm/s, Re_D = 24,000, laminar BL H = 2.5, Re_θ = 95 • L/θ = 66, 77, 82	•Strip heater used to excite TS waves via Joulean heating	•Feeback control using manual gain and phase adjustment reduced rms fluctuations by factor of 2
Cattafesta et al. (1997)	• L/D =0.5, L/W =0.5, U_∞ = 40 m/s, $L/\theta = 81$ • L/D =2.0, L/W =2.0, U_∞ = 45 m/s, $L/\theta = 328$	•Used piezoelectric flaps mounted at the leading edge of the cavity to suppress low-speed cavity oscillations •Used LQG and pole-placement feedback control designs	•CL control suppressed oscillations w/ order-of-magnitude less input actuator power •Shear-layer meas. w/ & w/o control show no effect on mean flow
Mongeau et al. (1998) and Kook et al. (2002)	• U_∞ = 15-29 m/s flow over a Helmholtz resonator	•Used active spoiler driven via a moving coil loudspeaker (up to ~1 mm or less that 1º) •Used robust loop shaping algorithm	•Significant attenuation achieved with small actuation effort •Robust performance for transient operating conditions
Kestens and Nicoud (1998)	•Laminar BL with Re_δ = 1000 and L/D =2 for M_∞ = 0.2	•2D NS simulations •Used off-line system identification for system transfer function model •Used filtered-X algorithm	•Demonstrated suppression only in vicinity of microphone •No effect on flow (active noise control not active flow control)
Cattafesta et al. (1999)	• $L/D = L/W = 5$ • M_∞ = 0.4, 0.6, 0.85 •Calculated δ =10.5 mm @ M_∞ = 0.6, $\mathrm{Re}/m = 11\times10^6$	•Used piezoelectric flaps flush at the leading edge of the cavity •Used adaptive disturbance rejection algorithm & system identification	•Demonstrated successful single-tone suppression at M_∞ = 0.74 in $L/D = 4$, L/W = 3 small scale test but negligible suppression in larger-scale wind tunnel tests
Shaw and Northcraft (1999)	• L/D = 6.46, L/W = 3.67 • M_∞ = 0.6, 0.85, 0.95, 1.05	•Tested pulsed fluidic injection at the cavity leading edge using closed loop control via rotary valve •Quasi-steady tuning of open-loop fixed frequency forcing based on bandpass filtered rms pressure signal	•Controller optimizes injection mass flow rate and frequency •Suppression of tones demonstrated but new tones appear at excitation frequency
Williams et al. (Jan. 2000)	• L/D = 2,4, or 5, L/W = 1.33 • M_∞ = 0.2 to 0.55, δ =3.18 to 2.41 cm and θ =0.30 to 0.26 cm	•Used zero net mass flux unsteady bleed actuator to suppress or enhance individual resonant cavity modes •Used analog output feedback	•Experiments showed 0º forcing was better than 45º or 90º (vertical) •Multiple mode suppression at M_∞ = 0.48 •Studied nonlinear mode interactions
Williams et al. (June 2000)	•Similar conditions as above •BL data: at M_∞ = 0.2 to 0.55, δ =3.18 to 2.41 cm and θ =0.30 to 0.26 cm	•Used zero net mass flux unsteady bleed actuator used to suppress or enhance individual resonant modes •Used analog output feedback control circuit	•Found single mode resonance can occur if cavity mode coincides with Rossiter mode •at Mach 0.35, input power from 6.3 W (suppressed oscillations) to max of 53 W •Could suppress or enhance tones
Williams and Morrow (June 2001)	•Similar to above • L/D = 5, L/W = 1.33 • M_∞ = 0.25 to 0.55,	•Used a commercial adaptive digital controller from Arbor Scientific as a follow-on to earlier work •Used filtered-X LMS algorithm	•Comparable results for single mode analog controller suppression but unable to suppress multiple modes simultaneously •Suggested need for adaptive plant model
Williams et al. (2002) & Rowley et al. (2002)	•Similar to above • L/D = 5, L/W = 1.33 • M_∞ = 0.34,	•Companion papers to study model based control of cavity oscillations •Experiments used feedback control to suppress the mode and then perform frequency response exp. •Feedback controller is 2nd-order Butterworth filter with different bandwidths, gain, and time delay	•Cavity can exhibit limit-cycle behavior or act like a stable noise amplifier •Discussed peak splitting via Nyquist analysis, fundamental performance limitations of feedback control using area rule
Cabell et al. (2002)	• M_∞ = 0.275, 0.4, and 0.6 • L/D = 5, L/W = 3 s at M_∞ = 0.275, δ ~ 5-6 mm	•Application of discrete-time, linear quadratic control design methods to the cavity tone problem •Used ERA to obtain state-space model via system identification •Piezo synthetic jet actuator at leading edge directed parallel to freestream	•System model required ~150-200 states •Control order reduced to ~60 states using balance realization truncation •Frequency shaping technique used to restrict controller frequency range •Peaking and peak splitting observed – features explained via linear models
Kegerise et al. (2002)	• M_∞ = 0.275, 0.4, and 0.6 • L/D = 5, L/W = 3 s at M_∞ = 0.275, δ ~ 5-6 mm	•Used piezoceramic bimorph flap actuator to suppress multiple cavity tones using output feedback control •Assessed IIR- and FIR-based system identification plant models	•Demonstrated multiple mode •Found required actuator tip motion for suppression varied from 6-17 wall units •FIR model not suitable for plant model, IIR model required