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ACTIVE CONTROL OF PRESSURE FLUCTUATIONS DUE TO FLOW OVER HELMHOLTZ RESONATORS

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Grazing flows over Helmholtz resonators may result in self-sustained flow oscillations at the Helmholtz acoustic resonance frequency of the cavity system. The associated pressure fluctuations may be undesirable. Many solutions have been proposed to solve this problem including, for example, leading edge spoilers, trailing edge deflectors, and leading edge flow diffusers. Most of these control devices are "passive", i.e., they do not involve dynamic control systems. Active control methods, which do require dynamic controls, have been implemented with success for different cases of flow instabilities. Previous investigations of the control of flow-excited cavity resonance have used mainly one or more loudspeakers located within the cavity wall. In the present study, oscillated spoilers hinged near the leading edge of the cavity orifice were used. Experiments were performed using a cavity installed within the test section wall of a wind tunnel. A microphone located within the cavity was used as the feedback sensor. A loop shaping feedback control design methodology was used in order to ensure robust controller performance over varying flow conditions. Cavity pressure level attenuation of up to 20 dB was achieved around the critical velocity (i.e., the velocity for which the fundamental excitation frequency matches the Helmholtz resonance frequency of the cavity), relative to the level in the presence of the spoiler held stationary. The required actuation effort was small. The spoiler peak displacement was typically only 4% of the mean spoiler angle (approximately 1°). The control scheme was found to provide robust performance for transient operating conditions. Oscillated leading edge spoilers offer potential advantages over loudspeakers for cavity resonance control, including a reduced encumbrance (especially for low-frequency applications), and a reduced actuation effort.

1. INTRODUCTION

Grazing flows over open cavities often induce strong flow oscillations. Many instances of this phenomenon are reported in the literature, including gas oscillations in pipes with closed side-branches, flows over aircraft wheel wells, flow over open road vehicle windows and sunroofs, and many others [1–3]. The fundamental mechanism for the generation of flow-excited cavity resonance is well understood. The processes that lead to stable,

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sustained flow oscillations can be described as follows [3]:

1. The unstable shear layer across the cavity orifice periodically rolls up into discrete vortices.
2. These vortices are convected downstream at a speed of approximately one half the outer flow velocity, on average. The vortex core path is not straight. Vortices are often entrained into the cavity near the leading edge, and ejected further downstream.
3. The total net circulation of the flow over the cavity orifice fluctuates as the vortices are discharged past the downstream orifice edge.
4. The fluctuations in the total circulation strength for the flow region in the vicinity of the cavity orifice give rise to external pressure fluctuations, which excite acoustic modes within the cavity (or side branch resonator).
5. The acoustic pressure fluctuations inside the cavity, in turn, trigger discrete vortex shedding near the separation point at the upstream edge, synchronized with the nearly sinusoidal flow fluctuations. New vortices are initiated immediately after the moment where the cavity pressure is a minimum, and the air mass within the cavity orifice (treated as a lumped mass) is being displaced towards the interior of the cavity.

Flow-excited cavity resonance causes nearly sinusoidal cavity pressure fluctuations. The non-linear coupling between the acoustic response of the cavity and the vortical flow excitation can be modelled using a describing function theory [4]. Different acoustic modes may be coupled with different modes of the unstable shear flow, depending on the mean flow velocity and the cavity dimensions. In the present study, the fundamental (or "Helmholtz") resonance of a cavity system of small dimensions relative to the acoustic wavelength was considered.

These flow oscillations are undesirable in most engineering applications, since they can cause excessive vibration and/or radiated sound levels. Passive control methods have received considerable amount of attention since the early 1950s. Control devices include, for example, leading edge spoilers, leading edge air mass diffusers, trailing edge deflectors, and leading edge corrugations. Active control methods have been proposed more recently, following the increased availability of dynamic control systems. These normally involve a combination of actuators, feedback and/or error sensors, and feedforward or feedback control algorithms.

1.1. AIR-MASS INJECTION METHODS

Sarno and Franke [5] attempted the suppression of pressure fluctuations inside a cavity with an aspect ratio (defined as the orifice length divided by the cavity depth) of 2·0 for flow velocities corresponding to Mach numbers between 0·62 and 1·53 using steady and pulsating air injection. Two different leading edge flow diffuser angles (45° and parallel to the external flow) were used. Better suppression was achieved with 45° air injection. Pulsating air injection was found to have little effect beyond that of steady air injection. The pulsation frequency, however, was limited to 80 Hz which was well below the frequency of the flow oscillations, and no attempt was made to regulate the phase of the air–mass injection.

Vakili *et al.* [6] investigated steady air injection through various types of perforated plates placed upstream of a cavity with an aspect ratio of 4·33. The Mach number ranged between 0·5 and 1·8. The cavity pressure level was reduced by up to 27 dB in some cases. Although the terminology "active control" was employed, no attempt was made to dynamically regulate the flow injection rate.

Mandoza and Ahuja [7] studied the suppression of pressure fluctuations inside a rectangular cavity with an aspect ratio of 3·75 using steady mass injection through a thin slot located immediately upstream of the cavity leading edge, along its span. The Mach number ranged between 0·36 and 1·05. Reduction in sound pressure level up to 30 dB was achieved. Comparisons between the velocity profiles measured upstream of the cavity leading edge and over the cavity orifice with and without air injection revealed an increase in the boundary layer thickness in the former case. The ratio of the momentum thickness and the boundary layer thickness was also found to increase with the injection flow rate in another study by Voorhees and Bertin [8].

In general, it is believed that steady upstream air injection significantly alters the instability characteristics of the shear layer over the cavity orifice, and reduces the effectiveness of the feedback mechanism. Air injection methods have been applied mainly to shallow rectangular cavities. It was found to be successful over a wide range of Mach numbers in both the subsonic and the low supersonic regimes.

1.2. ACTIVE CONTROL USING LOUDSPEAKERS

Ffowcs Williams and Huang [9] studied the active stabilization of compressor surge, which involved the control of the pressure fluctuations inside a Helmholtz resonator. In this case, the Helmholtz resonator was part of a system comprising a compressor, a plenum and a throttle connected in series. A loudspeaker was mounted flush with one plenum wall. The pressure signal measured inside the plenum was amplified, conditioned, and fed to the loudspeaker. The damping factor and the resonance frequency of the Helmholtz resonator were both altered by the active control system. Using a linearized analytical model of the system, the stability map denoting the stable operating range of the controller was plotted. The predictions compared favorably with the experimental results. It was shown that the system was stabilized when the loudspeaker increased the effective acoustic damping of the resonator.

The use of a loudspeaker within the wall of a side-branch resonator to control flow-induced resonance due to a grazing flow was investigated by Moser [10]. Reductions in sound pressure levels up to 40 dB were achieved. Nishimura and Fujita [11] used a loudspeaker placed at the end of a pipe side-branch resonator to control the self-excited flow oscillations in the pipe. They developed an active adaptive feedback control method, which was an improved version of feedforward control using the filtered-X-LMS algorithm. The non-model-based feedback control algorithm required only error signals, making the use of reference signals unnecessary. It was again believed that the loudspeaker acted as a sound-absorbing pipe termination, thus increasing the effective acoustic damping of the resonator. Small actuation efforts were reportedly required to prevent the growth of pressure oscillations into a large amplitude limit cycle.

The active control of impinging shear flows using the sound emissions of loudspeakers located near a flow nozzle was recently investigated by Ziada [12]. Reductions of the flow velocity fluctuations of jet-edge and jet-slot tones were reported for specific stability modes of the excitation. Feedback control methods were used, using a microphone near the jet as the feedback sensor. It was possible to achieve control of the first mode while simultaneously preventing the excitation of other stability modes of the jet.

While loudspeakers are often used to demonstrate the feasibility of stabilizing globally unstable flows, or flow-excited resonance, this type of actuator may not always be practical. At low frequencies, for example below 20 Hz, conventional loudspeakers are often unable to generate a sufficiently high pressure due to their limited radiation efficiency. Large

TABLE 1

Summary of recent publications on active control of flow-induced cavity resonance

References	Actuators	Control mode	Reduction	Comments
[15]	Leading-edge oscillating flap HFTG (high-frequency-tone-generator)	Open loop	30 dB	HFTG: placed a cylinder in the boundary layer at the leading edge of the cavity; shedding frequencies 10–30 kHz
[16]	Six-piece piezoelectric unimorph and bimorph as leading-edge spoiler	Open loop	18 dB (broadband) 25 dB (tonal)	Non-linear displacements observed. Additional bending and torsional modes at higher freqencies
[17]	Six-piece piezoelectric unimorph and bimorph as leading-edge spoiler	Closed loop	Around 20 dB	Less power consumed for closed-loop control than open-loop control; Control model and approach unclear
[20]	Leading-edge flap and pulsed fluidic injection	Open loop	Around 20 dB	Prelimenary work
[18]	Miniature Fluidic Oscillator	Open loop	10 dB	Used PSP to visualize pressure distribution
[21]	Leading-edge flap and pulsed fluidic injection	Closed loop	Up to 20 dB	Advantage of closed-loop scheme was not clear (e.g., energy consumption, etc.)
[19]	Two-piece piezoelectric unimorph as leading-edge spoiler	Closed loop	a few dB	Adaptive control. Tuned resonance of unimorph beam for the frequency to control ($d_{max} = 1{\cdot}85$ mm)
[22]	Unsteady bleed actuator	Closed loop	18 dB	Multiple acoustic mode suppression(3 BP filters, 8 Kulite transducers, 42 static pressure ports)
[23]	Piezoelectric unimorph and bimorph as leading-edge spoiler	Open loop	15 dB	Four pieces controlled separately
[24]	Pulsed fluidic actuator (up to 250 Hz) at leading edge	Open loop	First mode 15 dB Broadband 8 dB	$M = 1{\cdot}5$

diaphragms, and large coil displacements are required which can be a disadvantage in cases where space is at a premium. Consequently, there is a need for the development of flow manipulators that can be utilized over a wide frequency range as actuators for flow-excited resonant acoustic systems.

1.3. ACTIVE CONTROL USING OSCILLATED LEADING EDGE DEVICES

The organized flow structure convected behind oscillated spoilers and fences immersed in a turbulent boundary layer was studied for vehicle drag reduction and airfoil lift enhancement by Nelson *et al.* [13], and Miau *et al.* [14]. Oscillated spoilers and flaps have been used previously for the control of vortex shedding behind cylinders or the control of airfoil flutter. Sarno and Franke [5] attempted the use of an oscillated leading edge fence to control flow-induced pressure oscillations in cavities. Their apparatus, however, did not operate at a frequency comparable to that of the self-sustained flow oscillations.

Over the past five years, there has been a surge of interest for control methods utilizing leading edge flow manipulators. A number of these recent studies [15–24] are summarized in Table 1. Only a few investigations utilized closed-loop control methods in conjunction with flow manipulators at the leading edge of the orifice. Only one study, reference [21], utilized an oscillated spoiler in conjunction with closed-loop controls.

The approach investigated in the present study consisted of using an oscillated leading edge spoiler to control the flow-excited resonance of a side-branch Helmholtz resonator. Installed near the leading edge of the orifice, oscillated spoilers may allow the phase of the discrete vortices shed over the orifice to be controlled. Oscillated spoilers may be driven such that the external pressure fluctuations associated with the convection of discrete vortices over the orifice are non-synchronized with acoustic pressure fluctuations inside the cavity to minimize the net power transferred from the mean flow to the acoustic flow oscillations. The spoiler imparts a fluctuating transverse velocity component to the flow grazing over the sensitive leading edge region, where the flow separates from the wall. Vortices are shed when the transverse displacement of flow particles near the leading edge relative to the position of the edge itself reaches a maximum (the positive transverse direction pointing outside the cavity). Control of the transverse edge position using the spoiler should thereby allow the phase of the vortex shedding process to be regulated.

Previous studies of active control of flow-induced cavity pressure oscillations have rarely addressed the issue of controller stability. Open-loop control methods cannot guarantee a consistent and stable performance when the system is operated in varying environments. Furthermore, the non-stationary and chaotic nature of flow-induced cavity pressure oscillations reduces the effectiveness of open-loop control systems. In this study, a robust controller design method employing microphone feedback was used. Similar robust feedback control technologies were applied for the control of flow-induced structural radiation of sound by Heatwole [25]. A robust frequency-domain controller design methodology was followed. The non-model-based controller design method takes advantage of the lightly damped plant dynamics, thereby requiring low controller DC gain, and low controller order.

2. CONTROLLER DESIGN METHODOLOGY

A single-input–single-output (SISO) controller was designed and implemented. Figure 1 shows a block diagram of the feedback controller system. The disturbance dynamics are

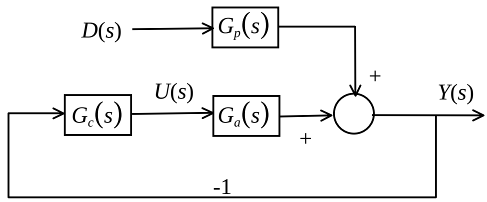

Figure 1. Block diagram of the feedback controller system.

characterized by the transfer function $G_p(s)$, which is the linearized response of the resonator as measured by the microphone to a pressure disturbance in the absence of feedback control. The transfer function $G_a(s)$ describes the actuation system dynamics from the input voltage to the control actuator to the output voltage of the microphone. The feedback controller transfer function is denoted as $G_c(s)$. The Laplace transform of the disturbance signal is $D(s)$ and that of the microphone signal is $Y(s)$.

The controller is designed via shaping the open-loop transfer $G_c(s)G_a(s)$ on a Nichols chart such that robust stability and performance are guaranteed. Classical frequency-domain design tools are used to realize the controller transfer function $G_c(s)$. The Nichols charts provides the required closed-loop information such as closed-loop sensitivity (robust performance) and complementary sensitivity (robust stability) based on the open-loop transfer function. The complementary sensitivity, $T(s)$, is the closed-loop transfer function given by

$$T(s) = \frac{L(s)}{1 + L(s)}, \tag{1}$$

where $L(s) = G_c(s)G_a(s)$ is the open-loop transfer function. Constant closed-loop transfer function magnitudes for a given complementary sensitivity magnitude form the so-called "M circles" on a Nichols chart.

The controller stability requirement can be expressed as an amplitude inequality on the complementary sensitivity using

$$\left| \frac{L(\mathrm{j}\omega)}{1 + L(\mathrm{j}\omega)} \right| \leqslant A. \tag{2}$$

This stability condition is more stringent than the Nyquist criterion and is typically used in the robust control literature [26]. The sensitivity transfer function $S(s)$ is defined as

$$S(s) = \frac{1}{1 + L(s)}. \tag{3}$$

Constant closed-loop transfer function magnitudes for given sensitivity magnitudes form "inverted M circles" on a Nichols chart. The closed-loop relation from Figure 1 is

$$\frac{Y(s)}{D(s)} = \frac{G_p(s)}{1 + G_c(s)G_a(s)} = S(s)G_p(s). \tag{4}$$

The objective of the control system is to obtain a sound pressure level reduction, i.e., reduce the transmission of the disturbance to the output. To realize this objective, the amplitude of the sensitivity transfer function should have a low gain (implying a large open-loop gain) at the frequency where a reduction in the sound pressure level is desired [26].

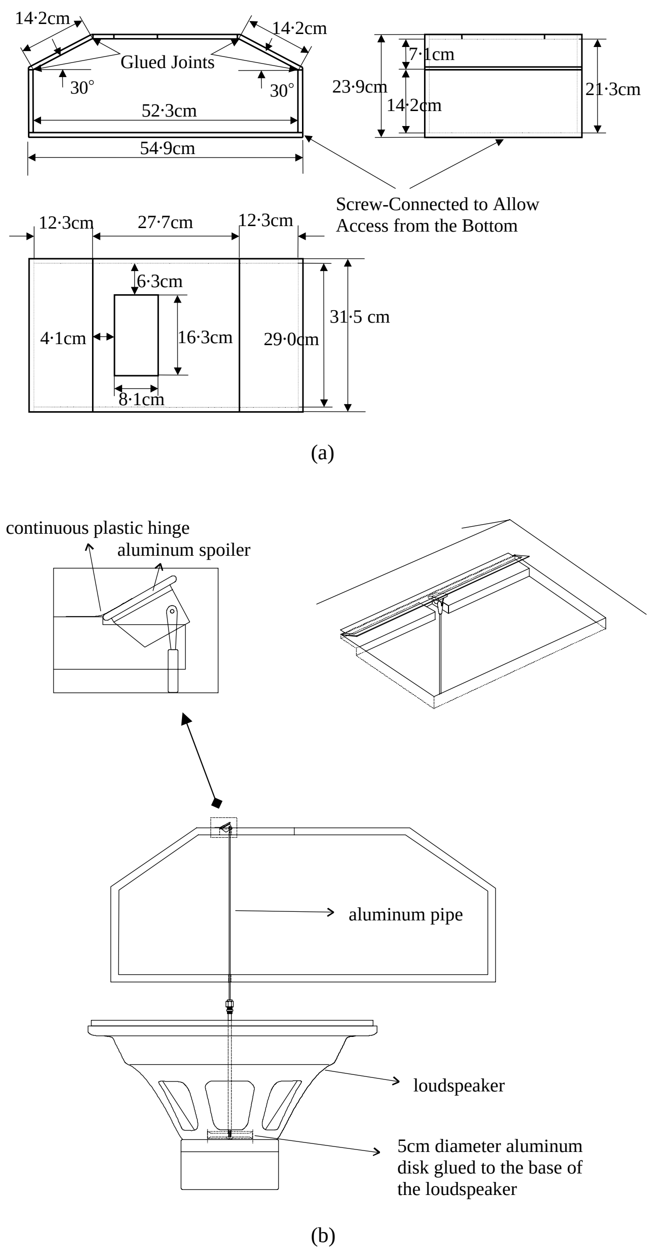

Figure 2. Sketches of the experimental apparatus: (a) cavity dimensions; (b) oscillated spoiler actuator.

3. EXPERIMENTAL APPARATUS AND INSTRUMENTATION

Experiments were performed to assess the effectiveness, or "authority," of leading edge oscillated spoiler actuators, and the performance of robust closed-loop feedback control schemes. The experimental apparatus consisted of an open cavity mounted within the test section floor of a low-speed wind tunnel [3]. The wind tunnel test section was rectangular, with rigid walls. The test section was 60·3 cm wide, 45·1 cm high, and 152 cm long. The open-loop wind tunnel featured noise reduction linings along the inlet turbulence management section and the diffuser. The maximum achievable flow velocity was about 160 km/h. Sketches of the cavity and the experimental apparatus are shown in Figures 2(a) and 2(b) respectively. The cavity used in the experimental study was made of 1·1 cm thick Plexiglas. The 1 mm thick rectangular (1 cm $\times$ 8 cm) aluminum spoiler was mounted flush with the top surface, near the upstream edge of the orifice. The spoiler was hinged to the cavity using a thin continuous plastic tape spanning the entire width of the spoiler and the orifice.

A 381 mm diameter loudspeaker was used to actuate the spoiler, as illustrated in Figure 2(a). The loudspeaker was located outside the wind tunnel test section and the cavity, and mounted on an isolated rectangular steel frame. This arrangement ensured minimal "flanking" sound transmission directly from the loudspeaker into the wind tunnel test section and/or the cavity. A Techron 5530 power amplifier capable of producing up to 120 W was used to drive the actuator. The maximum possible power input to the actuator was limited to 100 W. Note that most of the power input was dissipated as heat in the coil. An unknown fraction of the power input was needed to overcome the flow resistance of the spoiler. The peak coil displacement amplitude was about 1 mm at the frequency of interest (around 120 Hz). The input signal to the power amplifier was filtered using a Wavelet model 852 high-pass filter with a cut-off frequency of 30 Hz.

To fasten the speaker/spoiler connecting rod, the center of the loudspeaker cone was removed and replaced by a rigid 5 cm diameter hollow cylinder. The speaker/spoiler connecting rod was passed through a 5 mm diameter hole made in the bottom wall of the model cavity. The aluminum rod was attached to a 5 mm thick, 5 cm diameter aluminum disk fastened in the hollow cylinder at the center of the cone. A PCB-type 303A accelerometer attached to the aluminum disk was used to measure the vertical acceleration of the speaker coil. A PCB model 480D06 unit was used to power the accelerometer. The connecting rod length was adjustable, allowing the neutral spoiler angle to be varied.

The sound pressure inside the cavity was measured using a B&K-type 4291 microphone located 35·6 cm downstream from the front wall in the center of the cavity floor, in conjunction with a B&K-type 2609 measuring amplifier. The output signals from the microphone and the accelerometer were processed using a HP 35650 PC spectrum analyzer, which included a built-in function generator. Note that the sound pressure was nearly uniform in the cavity within the frequency range of interest.

4. CONTROLLER DESIGN

The block diagram of the flow-excited cavity system with an oscillated spoiler device actuated by a controller, $G_c(s)$, is depicted in Figure 1. In the block diagram, $G_a(s)$ represents the frequency response of the oscillated spoiler dynamics from the voltage input to the high-pass filter to the equivalent volume flow output, $q_{r,s}$, induced by the spoiler (see Figure 3). The transfer function, $G_p(s)$, denotes the frequency response of the interior pressure fluctuations, p_{cav}, as a function of the acoustic volume flow input, $q_{r,s}$. It includes a convection time delay as well as the frequency response of the cavity (acting as a Helmholtz resonator). In the robust feedback control scheme, the acoustic volume flow, $q_{r,c}$, resulting from the Helmholtz resonator response in a limit cycling loop, was treated as a disturbance coming from outside the closed-loop, as depicted in the block diagram. The open-loop transfer functions $G_a(s)G_p(s)$ were loop-shaped using appropriate selection of the controller transfer function $G_c(s)$. These are equivalent to the transfer functions measured between the signals fed into channels 2 and 1 (Ch2 and Ch1) of the data acquisition system, shown in Figure 3.

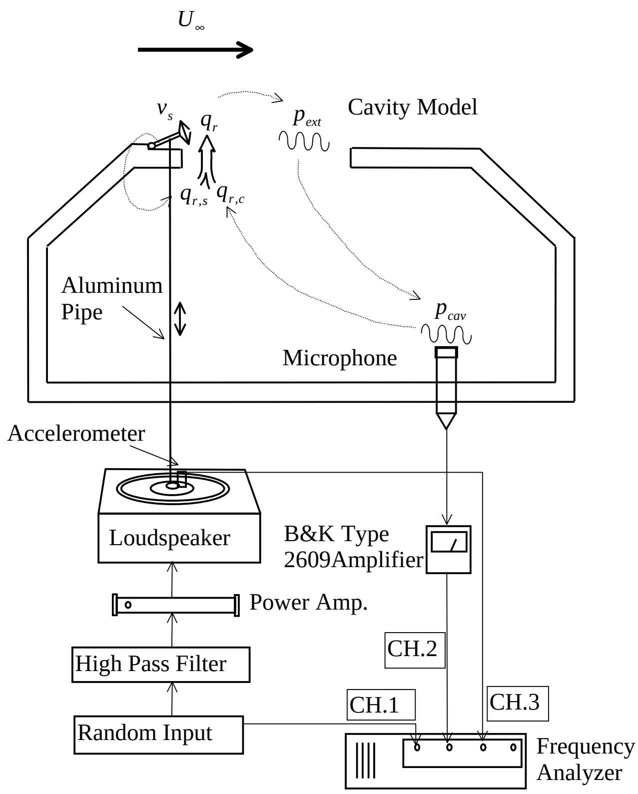

Figure 3. Apparatus used for the measurement of the open-loop transfer functions.

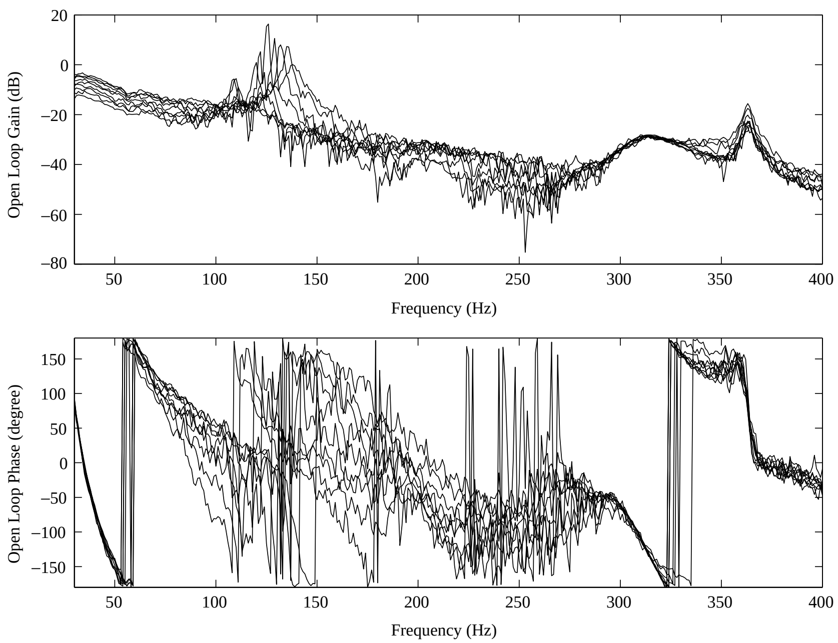

Figure 4. Bode plots of the measured system transfer functions for different flow velocities. Note that no legend is provided since the figure is intended only to show the range of gains and phases of the measured transfer functions.

To measure the open-loop transfer functions (OLTF's), a band-limited random signal of output level 1·01 V in the frequency range of 0–400 Hz was fed to the high-pass filter of the actuator system. The transfer functions between the voltage output of the microphone mounted inside the cavity and the random voltage input to the high-pass filter were measured for nine free stream flow velocities, U_∞: 14·8, 16·5, 18·2, 19·9, 21·6, 23·4, 25·1, 26·9, and 28·6 m/s. The lowest free stream flow velocity, 14·8 m/s, was found to be the onset velocity for the first mode of the self-excited oscillations. The highest velocity of 28·6 m/s was that at which the limit cycling mode was quenched [3]. The frequency response of the open-loop transfer functions was thus measured in the velocity region where the oscillations were strong, and control action was needed.

The Bode plots of the measured open-loop transfer functions are shown in Figure 4. The frequency distribution of the Bode plots magnitude was found similar to that of the auto-spectral density of the pressure fluctuations inside the cavity when the controller was turned off. Characteristically, the frequency at which the maximum amplitude of the open-loop transfer functions occurred changed gradually, exhibiting a 29 Hz increase as the free stream flow velocity was increased from 14·8 to 28·6 m/s [3]. The corresponding maximum amplitude also varied significantly, by 22 dB, over the range of free stream velocity considered. The phase varied by 162·5°. This variation is due to a change in the interactions between the fundamental acoustic mode of the cavity and the vortical flow excitation, rather than a change in the resonance frequency or quality factor of the cavity.

The measured open-loop transfer functions were then plotted on an extended Nichols chart for purposes of controller design. The open-loop transfer functions were loop-shaped to meet design specifications regarding controller stability and reduction in sound pressure level. The open-loop transfer function measured for $U_\infty = 26{\cdot}9$ m/s is shown as an example in Figure 5. One dominant peak occurs around the fundamental Helmholtz resonance frequency of the cavity. The gain of higher order acoustic modes of the cavity rapidly decreases with frequency. Within the frequency range considered, between 0 and 400 Hz, the Helmholtz resonance occurred near 120 Hz. The next acoustic mode occurred at 352 Hz. The controller bandwidth was 400 Hz, as detailed below. The range of phase lags of the

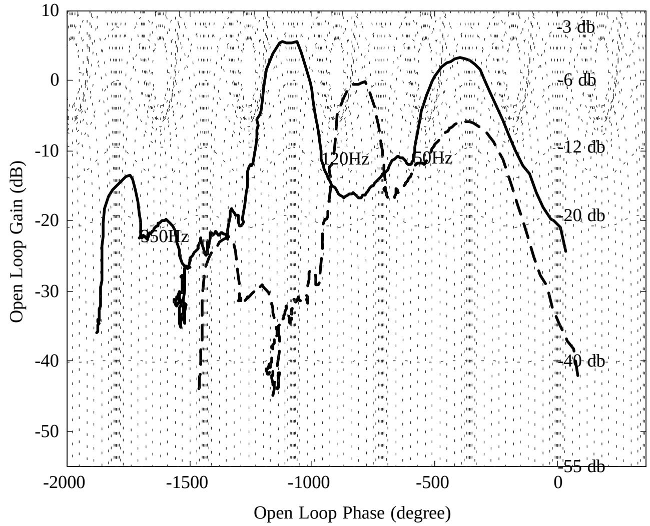

Figure 5. Extended Nichols chart of the open-loop transfer function for a flow velocity of $U_\infty = 26{\cdot}9$ m/s: - - - -, OLTF; ——, loop-shaped OLTF.

measured open-loop transfer functions was from 0 to $-2000°$. This phase is associated with the convection time delay of vortices included in the open-loop transfer function.

As mentioned earlier, larger open-loop transfer function gains are required for closed-loop performance. For phase values that are multiples of $-180°$, the open-loop transfer function gain should be lower than unity to ensure controller stability, thereby satisfying the Nyquist encirclement condition. Finally, control effort can be limited by ensuring that the open-loop transfer functions are not contained within the 6 dB M circle bounds enclosing the Nyquist stability points. These performance and stability requirements can be simultaneously achieved by ensuring that high-gain regions due to resonance fall between Nyquist stability points on Nichols charts.

The measured open-loop transfer functions (for the nine different free stream flow velocities) were thus shaped. The shaped open-loop transfer function for the open-loop transfer function measured at $U_\infty = 26{\cdot}9$ m/s is plotted as a solid line in Figure 5. The high-gain region around the Helmholtz resonance frequency was placed between the two Nyquist points and the open-loop transfer function gain was increased to achieve more attenuation. However, variability in the phase in the low-frequency high-gain region (approximately 50 Hz for 26·9 m/s) made it difficult to place the open-loop transfer function between two consecutive Nyquist stability points for all cases. A controller comprising complex zeros was, therefore, used to reduce the frequency range of this high-gain region. In particular, a complex lead compensator which was composed of a pair of complex zeros at $f = 42$ Hz, $\zeta = 0{\cdot}15$, and a pair of complex poles at $f = 40$ Hz, $\zeta = 0{\cdot}9$ were used. A pair of complex poles at $f = 100$ Hz, $\zeta = 0{\cdot}7$ and a pair of non-minimum phase complex zeros at $f = 125$ Hz, $\zeta = 0{\cdot}3$ were used to add phase lag so that the frequency region of large gain associated with the fundamental mode (around $f = 120$ Hz) is centered between the two stability points. To roll off the gain of the controller at high frequencies, two additional poles were added at $f = 400$ Hz. The resulting controller was a sixth order controller with a DC gain of 19 dB. The controller transfer function, $G_c(s)$, was given by the following expression:

$$G_c(s) = \frac{9[s^2/(2\pi 42)^2 + 2(0{\cdot}15s)/(2\pi 42) + 1]\;[s^2/(2\pi 125)^2 - 2(0{\cdot}3s)/(2\pi 1252) + 1]}{[s^2/(2\pi 40)^2 + 2(0{\cdot}9s)(2\pi 40) + 1]\;[s^2/(2\pi 100)^2 + 2(0{\cdot}7s)/(2\pi 100) + 1]\;[s/(2\pi 400) + 1]^2}. \tag{5}$$

The controller was implemented using MATLAB® Simulink Real Time Workshop, with a 4000 Hz sampling rate and Euler's integration method.

5. RESULTS

The cavity pressure spectral densities with and without active control are shown in Figures 6(a) and 6(b) for two different mean stream flow velocities. The neutral spoiler angle was approximately 35°. Acoustic pressure attenuation up to 20 dB was achieved. Note that the stationary spoiler itself caused the cavity pressure level to be reduced by 10 dB relative to the no-spoiler configuration. When the spoiler was actuated using the microphone feedback, additional noise reduction was achieved for all flow velocities. From the recorded acceleration signals, it was estimated that the amplitude of the spoiler tip displacement was <1 mm. The frequency of the flow oscillations measured over a range of constant outer flow velocities is shown in Figure 7(a). The frequency was estimated from the cavity pressure spectra, such as those shown in Figure 6. It can be noted that the intervention of the controller caused an increase in the frequency of the flow oscillations as shown in

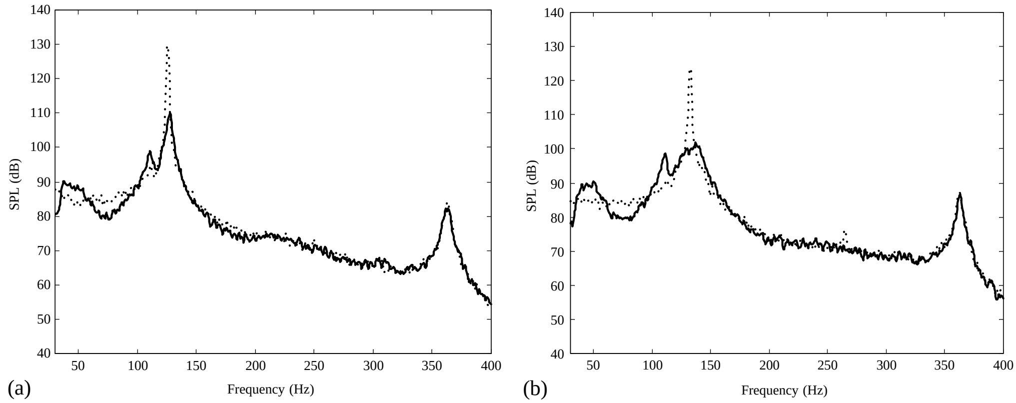

Figure 6. Cavity pressure spectral density level: ·····, without active control; ——, with active control; (a) $U_\infty = 21{\cdot}7$ m/s; (b) $U_\infty = 31{\cdot}9$ m/s.

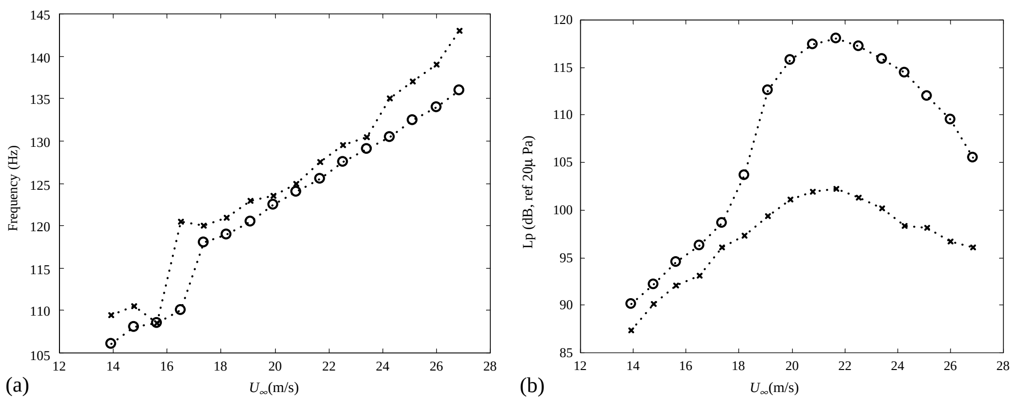

Figure 7. (a) Frequency, and (b) amplitude of the cavity pressure oscillations: ○····○····○, without active control; ×···×···×, with active control.

Figure 7(a). The critical velocity was around 21·5 m/s in this case. A noticeable jump in frequency occurred as the velocity reached, and then exceeded the value of around 16 m/s for both cases of with and without control.

It is believed that strong standing waves were excited within the closed wind tunnel test section at a speed around $U_\infty = 16$ m/s. A longitudinal acoustic mode of the wind tunnel test section was detected with resonance frequency near 115 Hz. As the excitation frequency approached the resonance frequency of this longitudinal acoustic mode, the flow oscillations may have locked on the external acoustic pressure within the test section rather than the flow oscillations within the cavity. The interactions between standing waves and cavity response, however, were believed to be minimal for flow velocities exceeding 16·5 m/s. The spectral level within a one-third octave band centered at the oscillation frequencies is shown with and without control in Figure 7(b). Significant attenuation was achieved over most of the velocity range.

The transient performance of the control scheme was investigated by letting the wind tunnel fan "coast down" such that the flow velocity decreased from 23 m/s to 0 in a period of approximately 8 s. The instantaneous cavity pressure without control over that period is shown in Figure 8. When the coast-down test was repeated with controller on, the

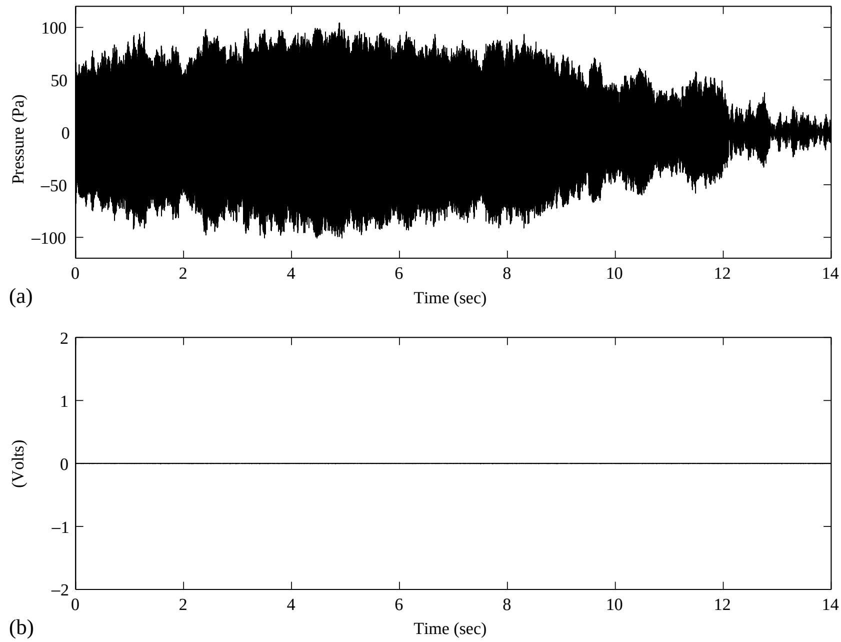

Figure 8. Results of coast-down test with no active control: (a) cavity pressure; (b) controller output voltage.

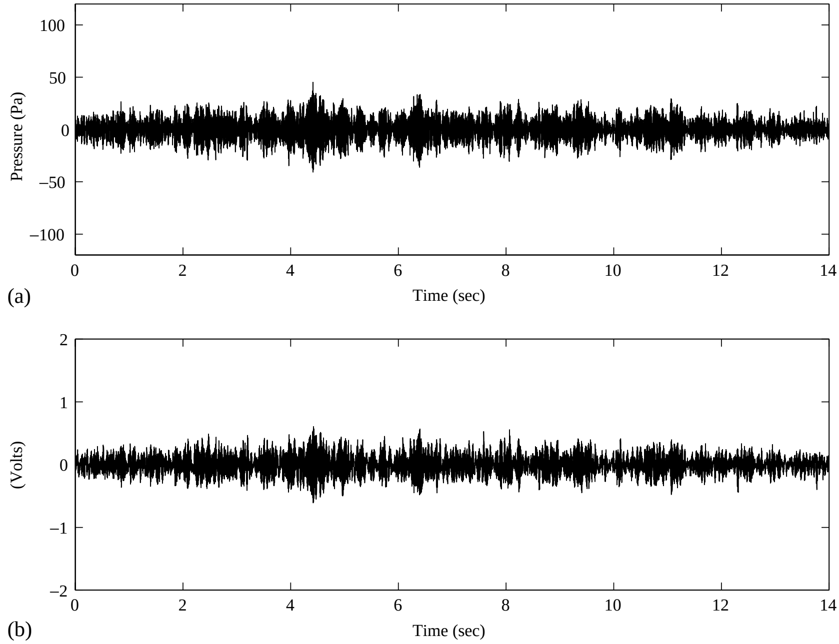

Figure 9. Results of coast-down test with active control: (a) cavity pressure; (b) controller output voltage.

controller tracked the changes in the excitation frequency and amplitude well as shown in Figure 9. Robust stability and performance was obtained over the entire range of flow velocities.

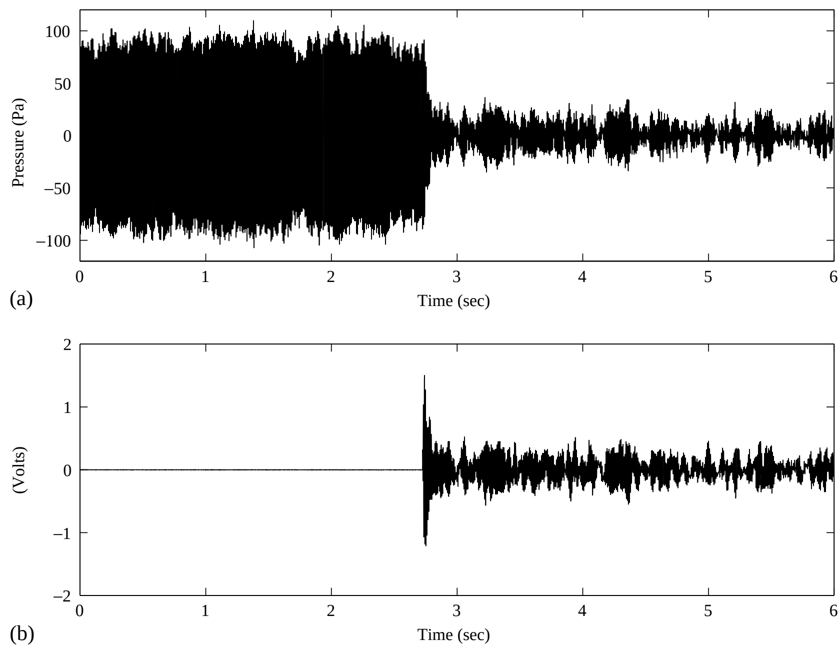

Figure 10. Transient response of the controller abruptly turned on: (a) cavity pressure; (b) controller output voltage.

The transient response was investigated further by abruptly turning the controller on, while the flow velocity was maintained constant at 21·6 m/s. Although relatively larger control efforts were required immediately after the controller was turned on (for about 0·1 s or 12 acoustic cycles), the controller quickly reached a steady state and remained stable as shown in Figure 10.

6. CONCLUSIONS

It was found that the flow excitation of a side-branch Helmholtz resonator may be significantly reduced using actuated leading edge spoilers. Active robust feedback control design methodologies allowed stable and robust controller performance to be achieved over a wide range of flow velocities. The performance of active systems was superior to that of many passive methods considered in a previous study of the same cavity system [27]. The actuation effort required was small. Reduction of the cavity pressure level up to 20 dB was achieved over a significant range of flow velocities. These results suggest that a similar active control device could be successfully implemented to control buffeting in applications such as road vehicles with open sunroofs or windows. Stationary spoilers are already in use in many sunroof systems. The addition of a feedback controller and a suitable actuator may allow the active control of the pressure oscillations in the passenger compartment for varying wind conditions and vehicle velocity.

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APPENDIX A: NOMENCLATURE

A	amplitude limit
$D(s)$	Laplace transform of disturbance
f	frequency (Hz)
$G_a(s)$	actuator transfer function
$G_c(s)$	feedback controller transfer function
$G_p(s)$	plant gain function
p_{cav}	cavity pressure (Pa)
p_{ext}	excitation pressure (Pa)
q_r	resonator flow (m^3/s)
$q_{r,c}$	resonator flow due to acoustic response of resonator (m^3/s)
$q_{r,s}$	resonator flow associated with spoiler displacement (m^3/s)
s	Laplace variable
$S(s)$	sensitivity transfer function
$T(s)$	complementary sensitivity transfer function
$U(s)$	input transfer function
U_∞	free stream flow velocity (m/s)
v_s	spoiler velocity (m/s)
$Y(s)$	Laplace transform of output
ω	angular frequency (rad/s)
ζ	damping ratio