Closed-Loop Control of Linear Supersonic Cavity Tones

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Experiments in a supersonic wind tunnel studied the behavior of acoustic tones introduced by open-loop forcing, and the ability of a closed-loop controller to suppress acoustic tones. The performance of pulsed-blowing and zero-net-mass actuators was documented. By independent changes in the wind tunnel static pressure and actuator supply pressure, we showed that the amplitude of disturbances input from the actuator is proportional to the pressure difference across the actuator, and scaled with the freestream dynamic pressure. The cavity used in this experiment at $M = 1.86$ responded linearly to the disturbance input from the actuators. Acoustic tone amplitudes in the cavity were linearly proportional to actuator input, and nonlinear interactions between different acoustic modes (such as the formation of combination modes) were not observed. Given that the system responded linearly to open-loop forcing and the amplitude of disturbances from the actuator exceeds background disturbance levels, then closed-loop control of the Rossiter tones should be feasible using standard linear control design tools. A simple gain-phase adjustable feedback controller is used to demonstrate linear closed-loop control.

Nomenclature

c = speed of sound
M = Mach number
U = flow speed in streamwise direction
U_∞ = freestream speed
SPL = sound pressure level
W = cavity width
D = cavity depth
L = cavity length
θ = momentum thickness $\int_0^\infty \frac{U}{U_\infty}\left(1-\frac{U}{U_\infty}\right)dy$

I. Introduction

A demonstration of closed-loop control of a single Rossiter[1] tone in a supersonic cavity flow is presented. In both subsonic and supersonic flows the Rossiter tone mechanism consists of four elements[2, 3]: (1) vortical disturbance amplification in the shear layer, (2) acoustic wave generation by impingement of the shear layer on the downstream corner of the cavity, (3) upstream wave propagation through the cavity, and (4) conversion of the pressure disturbances into vorticity waves in the shear layer (receptivity process). Some of the elemental processes, such as the saturation of disturbance amplitudes in the shear layer are known to be nonlinear.

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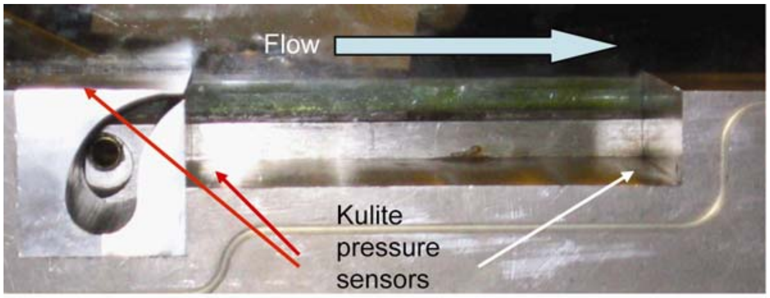


Figure 1. Photograph of cavity model with sidewall of the wind tunnel removed.

We showed in an earlier paper[4] that one can use open-loop forcing to study the dynamics of the overall sound producing mechanism. An actuator introduces controlled disturbances at fixed frequencies and amplitudes into the cavity, and the corresponding acoustic tone amplitude is measured. It is shown in this experiment that the response of the overall system is linear, even though elements of the resonance process are nonlinear. Linear behavior of a supersonic cavity flow is quite surprising, and contrasts with the typical nonlinear behavior seen in many subsonic cavity experiments[5]. By a linear response, we mean that cavity tone amplitudes are proportional to input amplitudes, and input disturbances at specific frequencies superposed on the background spectrum without mode interactions. Although the response of the acoustic tones inside the cavity are proportional to the disturbance input amplitudes, the gains are frequency dependent. Frequencies near the Rossiter modes are amplified, while frequencies between Rossiter tones are suppressed relative to the input amplitude.

Given that the system to be controlled is linear, and that the actuators used showed sufficient authority to generate tones larger than the background levels, one would expect closed-loop control to be effective in suppressing tones. In the following sections we describe the response of the cavity to closed-loop control.

II. Experimental Setup

The experiments were conducted in a supersonic wind tunnel with a freestream Mach number $M = 1.86$. A photograph of the cavity with the sidewall of the wind tunnel removed is shown in Fig. 1. The actuator nozzle block can be seen on the left side. Three Kulite pressure sensors were used. One was located upstream of the cavity in the floor of the wind tunnel, and two others were positioned in the floor of the cavity near the upstream and downstream corners as shown.

The approaching turbulent boundary layer thickness was estimated from schlieren images and from a total pressure probe rake. The velocity profile measured by the total pressure probe rake is shown in Fig. 2. Integration of the profile gave an estimate of the momentum thickness to be 0.78 mm, and the corresponding cavity length to momentum thickness ratio is 194.

A schlieren image of the flow over the cavity is shown in Fig. 3. In this case flow is from right to left. A leading-edge shock and the turbulent shear layer are visible over the top of the cavity. The radiating sound pattern can also be seen in this instantaneous snapshot.

The pressure spectra measured with Kulite transducers (model XCS-093-5G) located upstream of the cavity lip and inside the cavity on the floor are shown in Fig. 4. The flow approaching the cavity shows a small peak at 4 kHz that may be associated with the throttling valve for the wind tunnel. Otherwise the spectrum of the incoming flow does not show any significant peaks. The Kulite transducer located inside the cavity near the upstream end of the cavity detected frequencies at the first six Rossiter modes. However, the peaks are not particularly strong with sound pressure levels less than

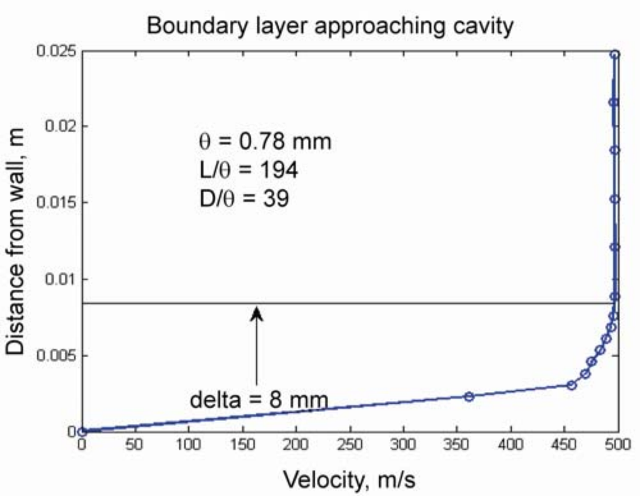


Figure 2. Boundary layer profile measured with stagnation pressure rake.

130 dB. In subsonic cavity experiments sound pressure levels are much higher, e.g., 160 dB are common. The low SPL levels are an indication that the supersonic cavity may not be exhibiting a non-linearly saturated limit cycle behavior commonly associated with Rossiter tones.

Two different types of actuators were used in these experiments. Many of the open-loop forcing experiments were done with a pulsed-blowing type of actuator driven by a Honeywell siren valve. The pulsed-blowing actuators have both mean and fluctuating components. The velocity and pressure amplitudes for both components were documented over a wide range of operating conditions in the paper by Williams, et al.[4] Because pulsed-blowing actuators cannot be phase coupled with a feedback signal, they are not suitable for dynamic closed-loop control systems. A voice-coil type actuator (zero-net-mass) was used for the feedback control experiments, in addition to some open-loop forcing experiments.

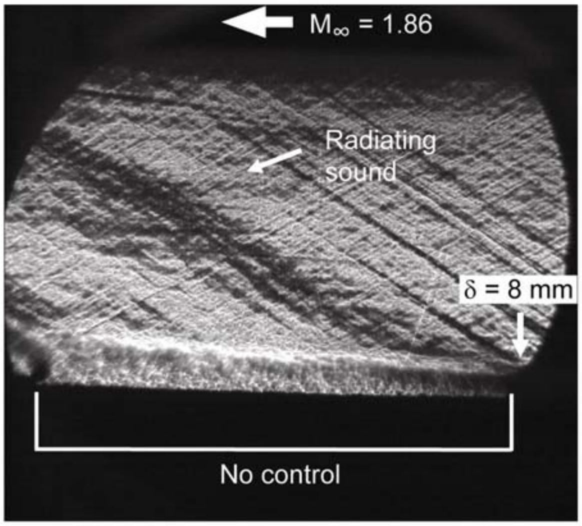


Figure 3. Instantaneous schlieren image of the shear layer over the cavity. Flow is from right to left. Estimate of shear layer thickness agrees well with boundary layer rake measurement shown in Fig. 2.

III. Results

Actuator amplitude scaling

It is important to understand and characterize the actuator input to the system. In particular one needs to understand how the actuator amplitude scales with changes in flow conditions in order to make the transition from the laboratory experiment to prototype flight conditions. The response of the actuator to changing wind tunnel dynamic pressure and changing static pressure can be easily studied in supersonic wind tunnels. The dynamic pressure is proportional to the tunnel static pressure, which in turn is proportional to the wind tunnel stagnation pressure. If we maintain a constant stagnation temperature, then the Mach number and the flow speed remain constant in supersonic flows, even when the stagnation pressure is varied. The response of the tone amplitudes with changing static pressure in the wind tunnel can be measured and compared to the effect of changing the actuator supply pressure.

In supersonic flow experiments the freestream static pressure can be varied by changing the settling chamber stagnation pressure as shown in Fig. 5(a). The actuator is operating at 800 Hz with a constant supply pressure of 101.6 kPa. The wind tunnel is operated at M =1.86, while the stagnation pressure are varied from 300 kPa to 600 kPa. After an initial increase in response amplitude, for the majority of the range it can be seen that the sound pressure level from the actuator decreases as the wind tunnel stagnation pressure increases. The reason for the initial increase in amplitude is not know, but the steady decrease in actuator authority is expected, because the pressure difference across the actuator is decreasing.

On the other hand, when the supply pressure to the actuator increases, the sound pressure level also increases as shown in Fig. 5(b). If the

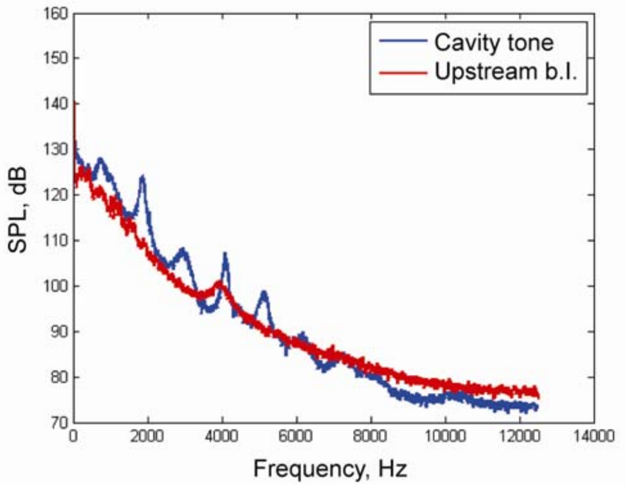
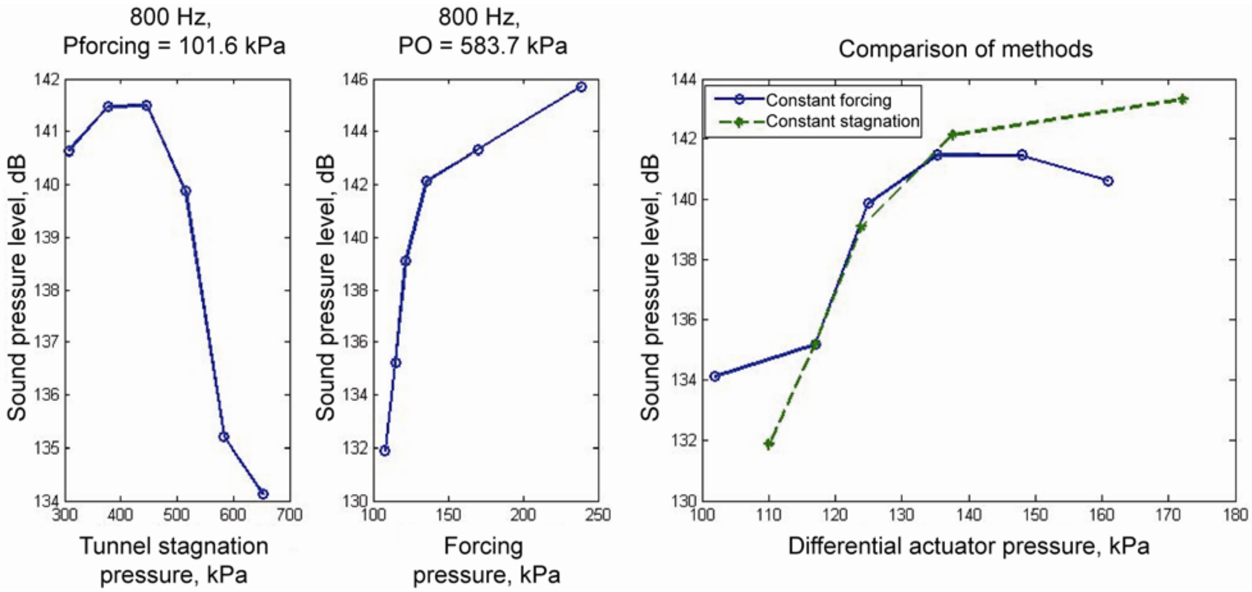


Figure 4. Comparison of pressure spectra measured in the approaching boundary layer (red line) and inside the cavity at the upstream floor location.



a) b) c)

Figure 5. Sound pressure levels in the supersonic cavity are shown with independent changes in wind tunnel stagnation pressure (a) and supply pressure to the actuators (b) (Figs. 7(a) and 7(b) in Ref. 4). The plots approximately collapse in (c) when plotted against the differential pressure across the actuator.

differential pressure across the actuator is computed, then the data from Figs. 5(a) and 5(b) collapse onto a single curve as shown in Fig. 5(c). Therefore, the scaling of the tone amplitude is proportional to the pressure difference across the actuator, which is proportional to the wind tunnel stagnation pressure.

The results in Fig. 6 compare the 800 Hz sound pressure level in the cavity with the wind tunnel operating at $M = 1.86$ to the same actuation conditions when the wind tunnel is not running. The abscissa corresponds to the amplitude of the input from the actuator, and the ordinate measures the response in the cavity. At this frequency, the cavity system amplifies the input disturbance. For example, an 800 Hz tone input at 120 dB (tunnel off) produces a 133 dB tone with the tunnel on. The cavity system amplifies the tone with a gain of 13 dB. As the input amplitude from the actuator is increased, the tone amplitude increases linearly. For reference purposes, a 1:1 slope is shown by the dashed line in Fig. 6 indicating the linear behavior.

The response of the spectrum to an 800 Hz disturbance with increasing actuator supply pressure is shown in Fig. 7(a). The response of the cavity to 800 Hz open-loop forcing over a wider range of frequencies can be seen in Fig. 7(b). The lower dashed line shows the input spectrum measured with the wind tunnel off. The pulsed-blowing actuator operating at an 800 Hz frequency is also producing a strong 1600 Hz harmonic. The response of the cavity is shown by the upper solid line. Amplification of the input tone at 800 Hz can be seen in Fig. 7(b) along with attenuation of the 1600 Hz tone. The system does not amplify all frequencies with the same gain. By sweeping the actuator frequency over a wide range, the regions of amplification and attenuation in the cavity signal were documented. The frequency and phase response of the cavity system was documented in this system identification experiment.

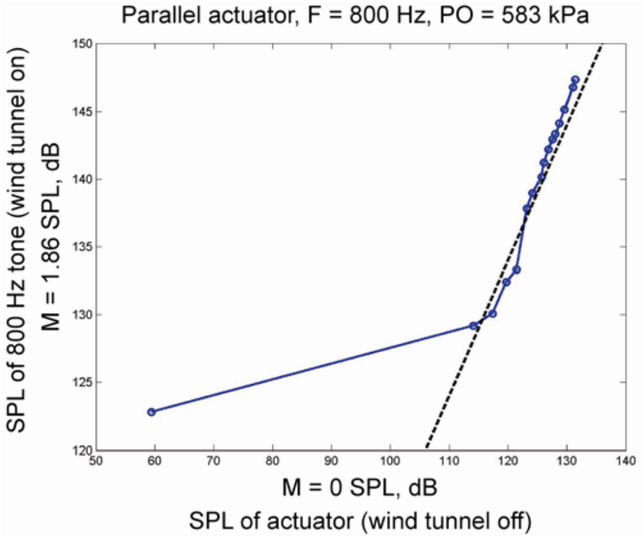
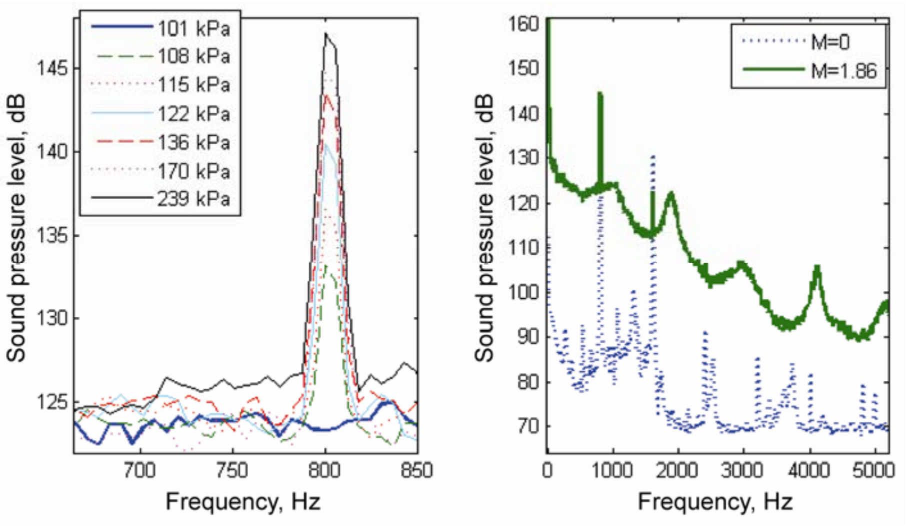


Figure 6. Open loop forcing at 800 Hz with changing actuator amplitude.



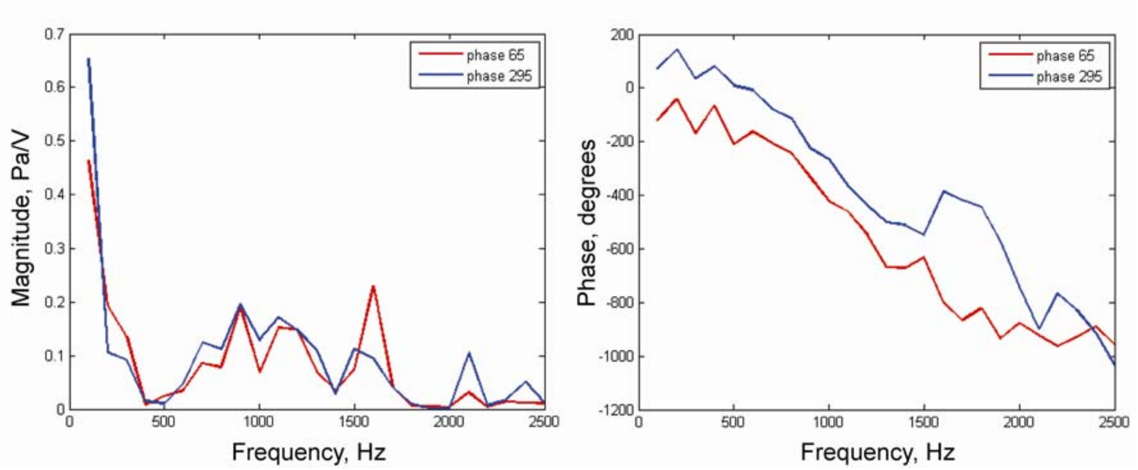
a) b)

Figure 7. Peak amplitudes in the sound spectrum at 800 Hz forcing: (a) with tunnel on (Fig. 9 in Ref. 4); (b) both tunnel on (solid line) and off (dashed line).

An important observation is that open-loop forcing of this linear system does nothing to suppress the Rossiter tones.[§] We find the energy from the actuator being amplified or attenuated depending on frequency, but mode interactions do not occur. There is no possibility of phase coupling between modes in an open-loop control of a linear system. To achieve phase coupling between the linear Rossiter modes and the actuator it is necessary to use a feedback controller. The results of closed-loop control experiments are described in the next section.

Closed-loop control results

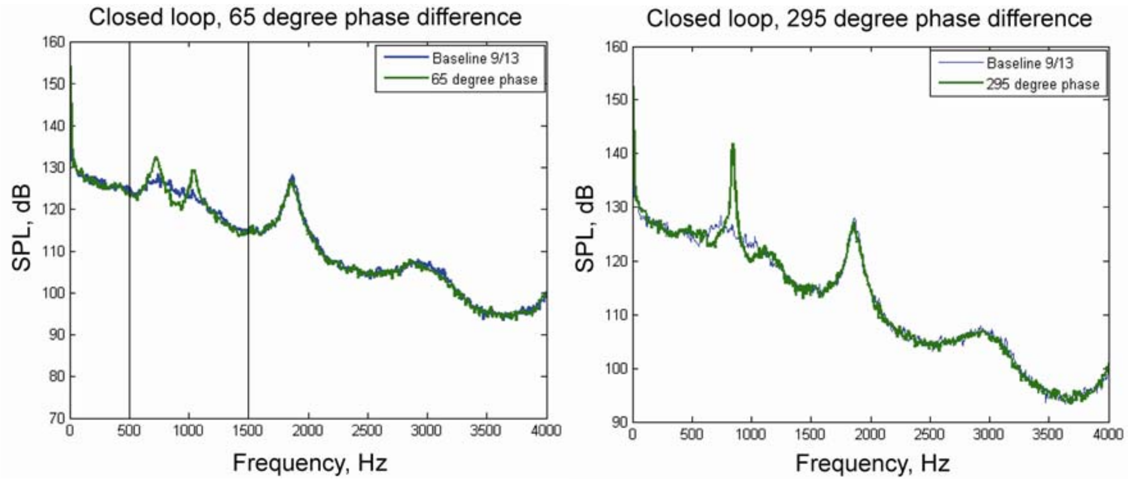
The closed-loop control hardware consisted of a manually controlled phase and gain of the feedback signal, which was taken from the pressure transducer located in the upstream floor of the cavity. The transfer functions in Bode plot form are shown in Fig. 8 corresponding to two different phase settings, nominally 65° and 295°. The



a) b)

Figure 8. Two controller transfer functions measured with no flow in the wind tunnel are shown in magnitude (a) and phase (b) for nominal phase settings of 65° and 295°. A time delay of approximately 16ms exists between the voltage signal input to the power amplifier and the response of the Kulite transducer is responsible for the linear phase variation with frequency.

[§] I. Wygnanski pointed out that we are discussing a two-dimensional system, and three-dimensional linear actuation may act to suppress the resonance, but that is yet to be explored.



a) **b)**

Figure 9. Sound pressure level spectra with and without closed loop control. The phase shift circuit was set at 65° (a) and 295° (b).

phase was obtained from the cross-spectrum of the output signal from the upstream Kulite pressure transducer and the voltage input to the power amplifier. Measurements at input frequencies ranging from 100 Hz to 2,500 Hz were obtained with no flow in the wind tunnel. The phase variation with frequency corresponds to a constant time delay of approximately 16 ms between the input and output signal.

The effect of closing the loop on the acoustic spectrum in the cavity is shown in Figs. 9(a) and 9(b). The passband of the filter is indicated by the two vertical lines. The blue line shows the baseline spectrum without control. The green line spectrum is with feedback control activated. With a 65° phase shift there is a small region of suppression around 800 Hz, with sideband regions of amplification at 750 Hz and 1,100 Hz. We believe these regions are produced by the finite bandwidth of the actuator, and correspond to lobes in the sensitivity function.

When the phase shift circuit in the controller is changed to 295°, a fundamental change in the spectrum occurs. A strong peak appears at 800 Hz, indicating that the controller is reinforcing the tone at that frequency. Clearly the feedback controller is affecting the dynamics of the cavity. To our knowledge this is the first demonstration of feedback control in a supersonic cavity.

IV. Conclusions

Open and closed loop flow control experiments were conducted on a supersonic cavity at $M = 1.86$. The results provide some insight into how the cavity system responds to two-dimensional disturbance inputs. For instance, the tones emanating from this particular supersonic cavity changed linearly to disturbances introduced by open-loop forcing, even though certain fluid dynamic elements of the tone resonance mechanism must be nonlinear. By linear behavior we mean that the tones emanating from the cavity are proportional to the input disturbance amplitude (modified by a gain), and the forcing frequency is superposed on the spectrum without interactions with other modes.

The amplitude of the cavity tones were shown to scale with the ΔP across the actuator. If the pressure to the actuator is constant and the static pressure in the flow increases, then the tone amplitude decreases. If the pressure in the wind tunnel is constant and the supply pressure to the actuator increases, then the tone amplitude increases. A comparison of the SPL dependence on the pressure difference collapses the data reasonably well.

In subsonic cavity control experiments, it is known that open-loop forcing of a shear layer will suppress Rossiter tones[6]. The "hifex" technique[6–8] is an example of this effect. However, no such effects of suppression were observed in the linear cavity case. Consequently, open-loop control will not suppress the Rossiter tones in this cavity, unless amplitudes sufficiently large to induce nonlinear effects are used.

When a closed-loop feedback controller is used, it becomes possible to phase-lock the input disturbances with the tones in the cavity. Tone suppression with closed loop control (and the wave cancellation mechanism) appears to be feasible, provided the actuator has sufficient bandwidth and an appropriate controller is designed. Tone enhancement also appears to be possible, when the phase between the actuator and the acoustic tone is adjusted to reinforce the signal.

One final caveat regarding the linear behavior should be made, i.e., one cannot assume that all supersonic cavities behave linearly. We do not know the specific reason for the linear behavior observed in this cavity. The loop-gain in the Rossiter process responsible for the acoustic tones must be less than one, leading to weakly damped oscillations instead of the nonlinearly saturated limit cycle behavior. Weaker amplification of coherent disturbances in the supersonic shear layer is a possibility, and Anatoli Tumin suggests that the mean-coherent signal interaction is weaker in supersonic flow than in subsonic flow.

Acknowledgments

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