Supersonic Cavity Response to Open-Loop Forcing

David R. Williams[1], Daniel Cornelius[1], and Clarence W. Rowley[2]

[1] Illinois Institute of Technology, Chicago IL 60616, USA,
david.williams@iit.edu,
WWW home page: http://fdrc.iit.edu/people/williams.php
[2] Princeton University, Princeton, NJ 08544, USA

Summary

The response of a supersonic cavity to open-loop forcing with a pulsed-blowing actuator is explored experimentally. It is shown that excitation at frequencies near the Rossiter modes are amplified, while frequencies between the first two Rossiter modes are attenuated. The results clearly demonstrate that the Rossiter modes in the supersonic cavity are weakly damped (not self-excited) modes. The supersonic modes are not saturated, and do not show the kind of nonlinear interactions with the forcing modes observed in subsonic flow. These differences between supersonic and subsonic flows are consistent with previously developed models of cavity oscillations, and the results suggest that linear techniques for the design of closed-loop controllers may be particulary effective for supersonic flows. For the flow regime studied, the oscillatory component of open-loop forcing does not play a significant role in the suppression mechanism in supersonic cavity flows.

1 Introduction

The interest in controlling resonant acoustic tones in cavities with modern active flow control techniques has both practical and fundamental motivations. The ability to suppress resonant acoustic tones in open aircraft cavities would reduce the possibility of structural fatigue and component damage related to the high acoustic loads[1, 2]. Resonant tones are correlated with high drag on the cavity [3]. Current practice uses passive devices, such as spoilers, to suppress the tones. This approach leads to an increase in drag, and does not always work at off-design conditions. Active flow control offers the possibility of tone suppression that can adapt to changing flight conditions.

On the fundamental side, the gross features of the acoustic resonance mechanism are reasonably well understood, but the details are not. Finding a suitable flow model and control architecture remains a challenge. The ”cavity problem” has become a canonical test case for both fluid dynamics and control theory. Major challenges for fluid dynamicists are to design effective actuators, determine appropriate scaling relations between the forcing and the flow field, and develop sufficiently accurate low-dimensional models of the cavity system. Control theorists search for robust and adaptive algorithms capable of suppressing tones under changing flight conditions.

The mechanism for acoustic resonance in cavities was identified by Rossiter[4]. There are four elements in the mechanism, 1) downstream propagation of vorticity waves in the cavity shear layer; 2) production of an acoustic wave by interaction of the shear layer with the downstream edge of the cavity; 3) upstream acoustic wave propagation; 4)receptivity at the leading edge, i.e., conversion of the pressure fluctuation to a vorticity wave. When the feedback of the acoustic wave to the leading edge of the cavity reinforces the vorticity wave amplitude in the shear layer, then the timing for resonance is correct. Rossiter derived an empirical formula for this process, which was slightly modified by Heller, et al. [5, 6] as shown below.

$$St = \frac{fL}{U} = \frac{m - \alpha}{\frac{M}{\sqrt{1+\frac{\gamma-1}{2}M^2}} + \frac{1}{\kappa}} \tag{1}$$

In this equation "m" is the integer mode number, α is a phase delay factor , and κ is the shear layer wave speed normalized by the freestream speed. Typical values for the adjustable constants are α= 0.25 and κ = 0.57, although substantial variations in both have been observed in experiments.

Many active flow control techniques have demonstrated the ability to suppress tones, particularly at subsonic speeds. The key strategy in all cases is to disrupt the Rossiter feedback mechanism. Passive, active open-loop, and closed-loop control approaches have shown varying degrees of success. Cattafesta, et al.[7] and Colonius[8] provide extensive reviews of active flow control techniques used, and discussions of the physical mechanisms involved in controlling cavity tones.

Active control with open-loop forcing of the shear layer attempts to suppress tones by forcing at a non-resonant frequency. Sarno and Franke[9], Shaw[10, 11], Samimy, et al.[12], and Cattafesta, et al.[13] have shown the ability to suppress cavity tones with the open loop approach. Cattafesta, et al.[13] compared suppression by closed-loop flow control to the open-loop case, and demonstrated that the closed-loop approach used an order of magnitude less power.

The mechanism by which open-loop forcing of the shear layer suppresses the resonant tones is not understood. Why, for example, when the shear layer is excited by a non-resonant frequency, would not the forcing frequency simply superpose on the baseline spectrum? Apparently some type of nonlinear interaction occurs between the base flow state and the forcing field, which interferes with the resonance mechanism. At least five different arguments for the open-loop suppression mechanism can be found in the literature, and have been itemized below. The sixth mechanism in the list refers to linear wave cancelation that can only occur with a closed-loop control system.

1. Lifting the shear layer which changes the downstream reattachment point[14, 15] - modification of mean shear profile combined with lifting[16]
2. Change of shear layer stability characteristics by thickening the shear layer [8, 17]
3. Low-frequency excitation of the shear layer at off-resonance condition [9, 15, 13, 18–20]

4. High-frequency (hifex) excitation[17, 20]- accelerated energy cascade in inertial range ”starves” lower frequency modes[21] - mean flow alteration, which changes stability characteristics [22]
5. Oblique shock flow deflection and reduction of longitudinal flow speed [23]
6. Cancelation of feedback acoustic wave [13, 25]

The suppression mechanisms listed above are primarily intuitive, and do not offer much predictive capability. Progress toward developing a predictive model of the effect of shear layer thickening and the change in stability characteristics is discussed in detail by Colonius[8]. Sahoo, et al.[23] developed a physics based model to explain the mechanism by which micro-jets suppress cavity resonance in a supersonic flow. By considering the effect of an oblique shock formed at the leading edge of the cavity by the micro-jets, they were able to estimate the flow deflection angle and speed reduction effects. Their model correlated very well with the experimental data.

The objective of this experiment was to get a better understanding of the cavity response to open-loop forcing by systematically varying the forcing frequencies and amplitudes. The effect of dynamic pressure could be studied by changing the wind tunnel stagnation pressure. Our initial expectations were to find nonlinear interactions between the forcing field and the base state resonant modes, similar to the subsonic case, but this did not happen. The following sections describe the calibration of the pulsed-blowing actuator used for the forcing, and the pressure measurements of the cavity response when the forcing amplitude and frequency and dynamic pressure were varied.

2 Experimental Setup

The experiments were conducted in the supersonic wind tunnel at the Illinois Institute of Technology Fluid Dynamics Research Center. The facility is a blow down type wind tunnel with a variable throat area. The test section is 102 mm wide and 114 mm high. The Mach number was fixed at M=1.86 for this study and U_∞=629 $\pm$ 19m/s. Wind tunnel stagnation pressures (absolute) ranged from 0.31 MPa to 0.72 MPa. Operating the wind tunnel at different stagnation pressures made it possible to change the static and dynamic pressure in the test section, while keeping the Mach number fixed. The stagnation temperature in the wind tunnel was 290 K. The unit Reynolds number at M=1.86 was 49x10^6 per meter.

The cavity model was machined into the floor of the test section as shown in Fig.1. The sidewall of the wind tunnel was removed for this photograph to expose the details of the cavity and actuator nozzle block. The pulsed-blowing air from the siren valve enters through the side of the wind tunnel and enters the plenum of the nozzle block seen on the left side of the cavity.

The cavity is 152 mm long, 102 mm wide and 30.5 mm deep, giving it L/D = 5 and L/W = 1.5. Pressure fluctuations inside the cavity were recorded with two Kulite XCS-093 transducers located in the center span of the cavity floor at 8.25 mm and

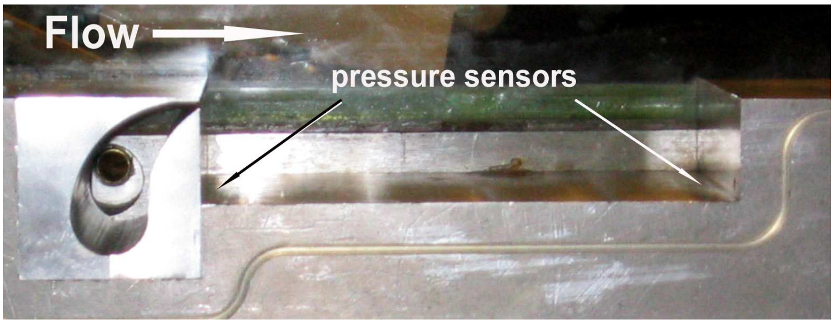

Figure 1 Photograph of cavity model in supersonic wind tunnel. The nozzle block is visible on the left (upstream) side of the cavity.

144 mm from the upstream cavity wall. The boundary layer thickness approaching the leading edge of the cavity was estimated from schlieren images and a boundary layer rake of total pressure probes to be δ = 8 mm.

The pulsed-blowing actuator consisted of a compressed air supply, siren valve and nozzle block. The siren valve manufactured by Honeywell was connected to the side of the nozzle plenum with a 75 mm long tube, giving a bandwidth of approximately 1.5 kHz. Two interchangeable nozzle blocks were constructed with different exit angles, one exiting parallel to the flow direction and the other at 45^o relative to the downstream direction. For both nozzles the exit spanned the width of the cavity and had a height of 3.2 mm.

Pulsed-blowing actuators require some flow through the system in order to produce oscillations, but with careful tuning of the plumbing system it is possible to generate oscillation amplitudes larger than the mean flow speed, producing instantaneously reversed flow. The actuator performance was documented using both a hot-wire anemometer to measure velocity at the slot exit, and a Kulite pressure transducer to measure the instantaneous pressure in the slot exit of the actuator nozzle. The face of the Kulite pressure sensor was oriented directly at the exit of the actuator to record the instantaneous total pressure. Time series traces of the velocity and pressure at 750 Hz forcing frequency with an actuator supply pressure of 124 kPa (absolute) are shown in Fig.2.

Velocity measurements of the mean velocity and root mean square (r.m.s.) velocity at the exit of the actuator are shown in Fig.3a. The forcing frequency was set at 750 Hz, while the supply pressure was varied from 101 kPa to 240 kPa. The velocity oscillation amplitude saturates as the supply pressure to the actuator is increased, while the mean velocity increases monotonically. This type of behavior is common for pulsed-blowing actuators. Attempts to increase oscillation amplitude by increasing the supply pressure often do more to increase the mean flow than the oscillatory component of velocity.

The corresponding mean and r.m.s. pressure values at the actuator exit are shown in Fig.3b. The mean pressure steadily increases with supply pressure, while the

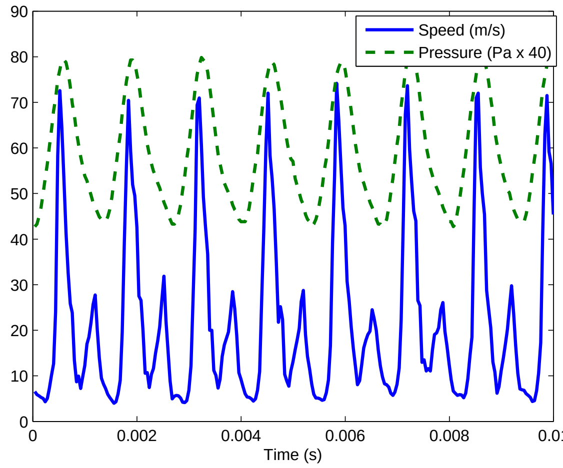

Figure 2 Velocity (solid line) and pressure (dashed line) time series at actuator exit plane. Actuator supply pressure = 124 kPa, frequency = 750 Hz

r.m.s. pressure grows at a much slower rate. The mean flow through the actuator is expressed as a blowing coefficient, B_c as defined in the following equation. Following Zhuang, et al. [24] the reference area is defined as the cavity length times cavity width.

$$B_c = \frac{\rho_{jet} A_{jet} U_{jet}}{\rho_\infty A_{ref} U_\infty} \tag{2}$$

The output from the pulsed-blowing actuator was strongly dependent of the forcing frequency. To document the frequency response of the actuator, the siren valve frequency was varied from 400 Hz to 2500 Hz, while maintaining a nominally constant input pressure of 138 kPa. Figure 4a shows a sharp cutoff in the r.m.s. velocity fluctuation amplitude near 1500 Hz. The r.m.s. pressure shown in Fig. 4b has a more gradual decay in amplitude with frequency.

3 Results

The fluctuating pressure was recorded with transducers in the floor of the cavity. The baseline response without forcing is presented in Sect.3.1. The response of the cavity to the open-loop forcing at different frequencies and amplitudes is described in Sect.3.2.

3.1 Baseline cavity behavior - no forcing

The supersonic cavity control experiments by Zhuang, et al.[24] measured a linear dependence of the overall sound pressure level with wind tunnel stagnation pressure.

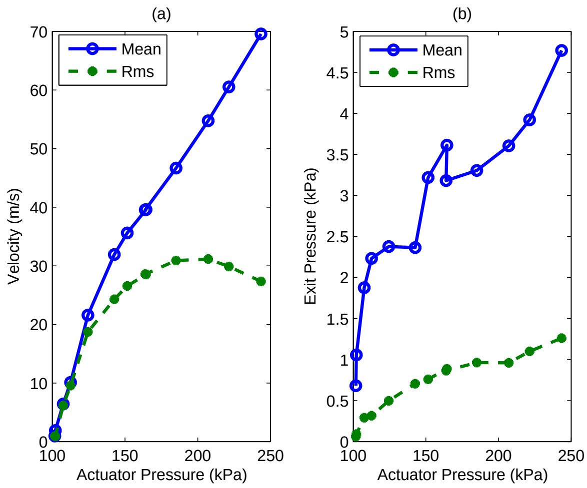

Figure 3 Supply pressure dependence of the mean and r.m.s. pressures measured at the actuator exit plane with 750 Hz forcing frequency.

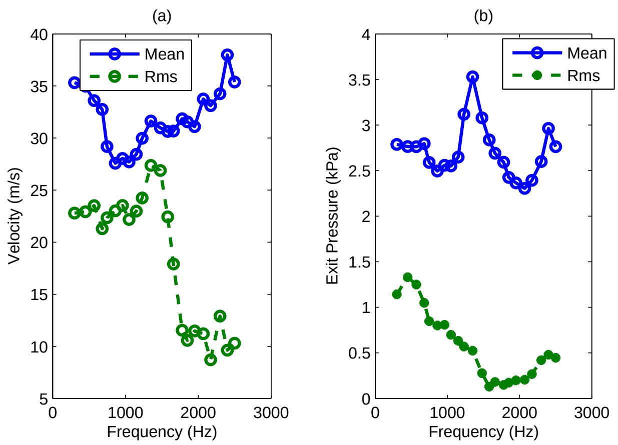

Figure 4 Frequency dependence of the mean and r.m.s. velocities measured at the actuator exit plane with a 138 kPa input pressure (B_c = .0010).

A similar linear dependence was found in this experiment as shown in Fig.5 for supersonic flow. At stagnation pressures below 300 kPa the flow was subsonic in the wind tunnel.

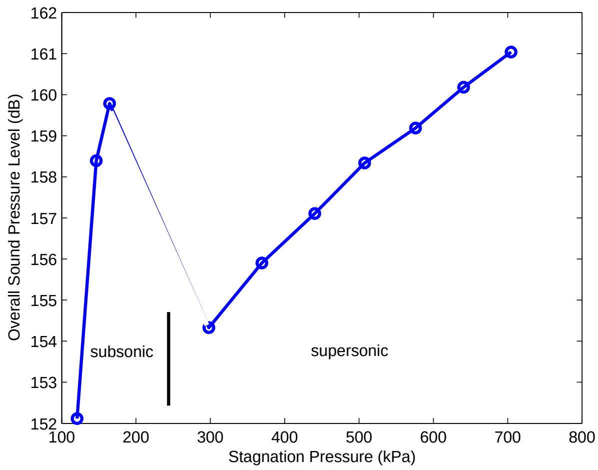

Figure 5 Overall sound pressure level increases linearly with stagnation pressure in the supersonic flow regime.

Pressure spectra measured by the upstream pressure sensor are shown in Fig.6 for different wind tunnel stagnation pressures. Without forcing six identifiable Rossiter modes can be found in the spectra. The best fit of the Rossiter equation (1) to the data was obtained using α=0.2 and κ=0.4. The predicted mode frequencies are indicated by the vertical lines in Fig.6. A close look at the figures shows that increasing the wind tunnel stagnation pressure does not affect the resonant frequencies, but does increase the amplitude of the spectral peaks.

3.2 Cavity response to periodic forcing

The performance of pulsed-blowing actuators is dependent on the pressure difference between the supply pressure and the pressure at the actuator nozzle exit. Increasing the wind tunnel stagnation pressure increases the static pressure in the test section, which may reduce the effectiveness of the pulsed-blowing actuator. A plot of 800 Hz peak amplitude against the wind tunnel stagnation pressure at fixed forcing amplitude is shown in Fig.7a. Above a stagnation pressure of 450 kPa the cavity response decreases with the dynamic pressure. Similarly, the dependence of the 800 Hz peak amplitude on the actuator supply pressure is shown in Fig.7b. Initially the peak growth is proportional to actuator supply pressure, then the cavity response

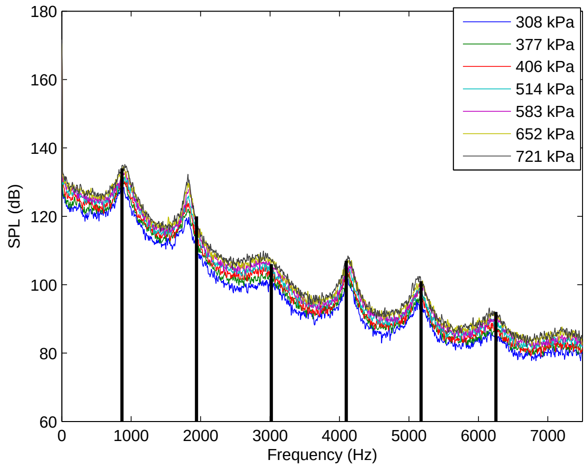

Figure 6 Pressure spectra with no forcing are superposed. Each spectrum increases in amplitude as the wind tunnel stagnation pressure (values shown in the legend) is increased.

begins to saturate at actuator pressures above 140 kPa. This behavior is consistent with the saturation of the fluctuating velocity levels seen in Fig.3. It can be shown that the actuator response scales with the pressure difference across the actuator.

The pulsed-blowing actuator was set to a frequency of 1000Hz and a supply pressure of 170kPa. The wind tunnel stagnation pressure was fixed at 584 kPa, giving a static pressure in the test section close to the calibration conditions. The pressure spectrum measured before the wind tunnel was started is shown in Fig.8 as the dashed line. The spectrum obtained with the wind tunnel running at M=1.86 is superposed in the figure as a solid line. The input from the actuator was amplified 25 dB above the no-flow condition by the cavity.

There was some concern that the sharp peak in the spectrum at the forcing frequency was not a fluid dynamic response of the cavity, but possibly an acoustic signature of the actuator, such as, a simple superposition of the forcing field. To check this, the forcing frequency and amplitude were varied, and the response of the cavity measured to get a better understanding of the nature of the forcing peak.

The actuator frequency was changed to 800 Hz, slightly below the first Rossiter mode at 880 Hz. The amplitude of the pulsed-blowing actuator was changed by adjusting the supply pressure. The pressure spectra are superposed in Fig.9a along with the baseline (no-forcing) case. Each spectrum corresponds to a different supply pressure to the actuator. The growth of the unsteady forcing peak with increasing supply pressure can be seen. We also found that nonlinear mode interactions (combination modes) do not appear, which is significantly different behavior than the subsonic flow case.

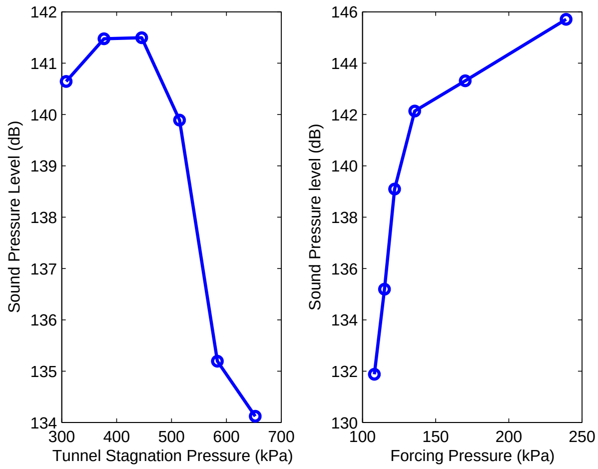

Figure 7 Decay and growth of the 800 Hz spectral peak amplitude with: a) changing wind tunnel stagnation pressure (actuator supply pressure = 101.6 kPa); b) changing actuator supply pressure (wind tunnel stagnation pressure = 584 kPa). Actuator frequency = 800 Hz

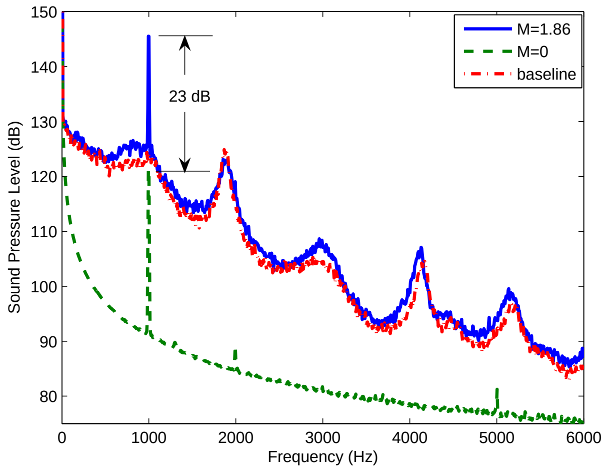

Figure 8 Comparison of pressure spectra at 1000 Hz forcing frequency (dashed line is for no flow in wind tunnel and solid line is for supersonic flow) shows amplification by the flow. Wind tunnel stagnation pressure = 584 kPa and actuator supply pressure = 170 kPa (B_c=.0013).

The 800 Hz peak amplitude with supersonic flow is plotted against the forcing amplitude in the quiescent wind tunnel in Fig.9b. The dashed line has a slope of 1.0, which implies a linear relationship between the forcing and response amplitudes. The data appear to be close to displaying a linear relationship.

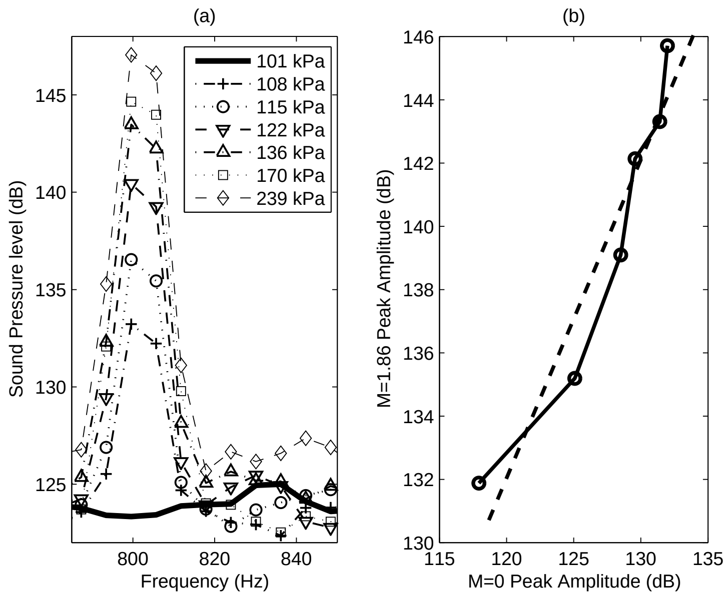

Figure 9 Growth of the 800 Hz peak with increasing forcing amplitude- a) spectral peak increases with changing actuator supply pressure; b) peak response amplitude plotted against the pressure measured in the quiescent cavity.

Next the forcing frequency was changed to 1300 Hz, which was between the first and second Rossiter mode. Figure10 compares the baseline spectrum (quiescent wind tunnel) with the forced case. At this frequency the cavity response is lower than the acoustic forcing level without flow in the tunnel, indicating that the cavity system is attenuating the disturbance.

The forcing frequency was varied from 500 Hz to 2400 Hz in 100 Hz increments, while maintaining a constant input pressure to the actuator of 170 kPa. The measured spectra are superposed in Fig.11a. The response contains both the frequency response of the actuator and that of the cavity system. At the lower forcing frequencies near the first Rossiter mode, the actuator frequency response is reasonably constant (see Fig.4), and the response of the cavity follows the peak seen in the unforced spectrum. As the frequency is increased toward the second Rossiter mode, the amplitudes of the cavity response decrease for two reasons. First the actuator frequency response decreases (Fig.4), and second, as shown in the previous figure,

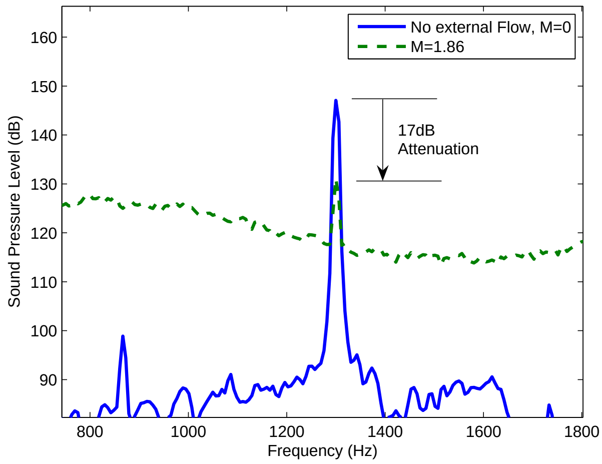

Figure 10 1300 Hz forcing amplitude shows attenuation between Rossiter modes. Actuator supply pressure = 170 kPa (B_c = .0013).

the cavity system is attenuating disturbances between the Rossiter modes relative to the input disturbance amplitude.

To isolate the cavity system dynamics from these measurements it is necessary to account for the actuator frequency response. To do this, we measured the peak amplitude at each forcing frequency in the quiescent wind tunnel, M=0. The “gain” was defined as the difference between the dB level of the peak amplitude with the tunnel running and the quiescent tunnel measurement. The gain is shown in Fig.11b. Positive gain is seen around the first two Rossiter mode frequencies, and negative values corresponding to attenuation are located between the Rossiter modes. The corresponding phase between the actuator oscillations and the oscillating pressure field is plotted in Fig.11c.

4 Discussion

The results of the previous section strongly suggest that for the flow regime studied, the cavity flow behaves as a linear amplifier, amplifying the actuator signal at its resonant frequencies, and attenuating it at other frequencies. This linear relationship is supported both by the linear scaling with amplitude in Fig. 9, as well as the response to the forcing at different frequencies in Fig.11, in which the pressure spectrum is altered only at the frequency of forcing. Previous experiments [12] have shown that for some subsonic flows, a much more complicated nonlinear interaction of frequencies occurs. No such coupling was observed in the present experiment.

The differences between the supersonic results here and previous subsonic results may be explained by models such as those described in [26]. These models

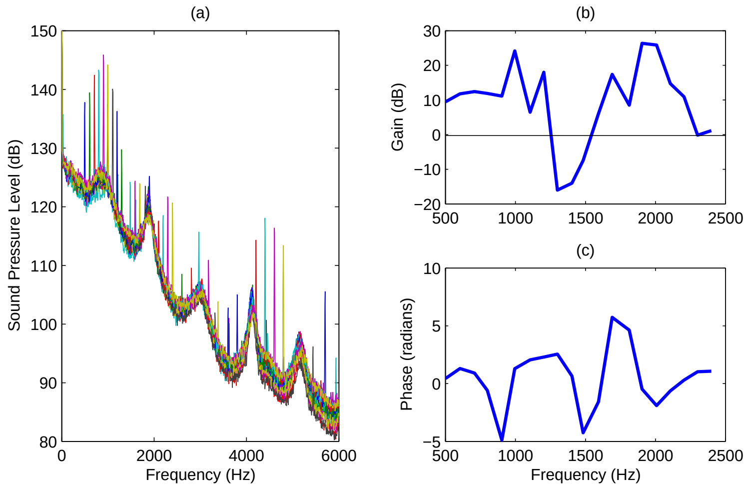

Figure 11 Effect of different forcing frequencies on spectrum with constant actuator supply pressure - a) spectrum; b) gain; c)phase

consider the cavity flow as a dynamical system with a fixed point (i.e., a steady solution of the Navier-Stokes equation, which is close to the mean flow), which may be either stable or unstable, depending on the total loop gain present in the Rossiter mechanism. For many flow regimes, the flow acts like a stable, but lightly-damped oscillator, amplifying disturbances at resonant frequencies. If the loop gain increases (for instance, in a flow with a thinner boundary layer), then the fixed point can become unstable, a stable limit cycle is formed, and nonlinearities determine the amplitude of the oscillations. Experiments by Rowley, et al.[26, 27] with subsonic cavity flows determined that some of the Rossiter modes were not self-excited (depending on Mach number), but instead were weakly damped. Kerschen, et al.[28] and Alvarez, et al.[29] developed an analytic model for the cavity resonance mechanism, which was capable of predicting growth rates of the unstable modes, and also found many modes to be weakly damped. In the case of weakly damped modes, the cavity will amplify (or attenuate) external disturbances to a level dependent on the initial amplitude of the disturbance, growth rate through the shear layer, and receptivity.

The results of the previous section are consistent with the existence of a stable fixed point, and a linear mechanism for amplification. Supersonic flows may be more likely than subsonic flows to operate in this linear regime, because compressibility reduces the amplification of instabilities in the free shear layer (i.e., the amplification of Kelvin-Helmholtz modes decreases as Mach number increases), and so one would expect the total loop gain to decrease as Mach number increases. Of course, other factors such as boundary layer thickness also influence the total shear layer amplification, so Mach number is clearly not the only parameter relevant for determining the stability of the flow. A careful study of the flow regimes and scaling laws determining the regions of stability of the cavity flow would be valuable for understanding the dynamics of these flows.

When a system is in a self-excited limit cycle, then the final amplitude is determined by nonlinear saturation. No evidence of nonlinear behavior was observed in the spectra obtained in this experiment. Sum and difference combination modes between the forcing and the Rossiter modes did not appear, and the existing peaks in the spectra did not appear to be affected by the forcing. The linear behavior of the shear layer suggests that linear control approaches, such as those developed by Becker, et al.[30] may be useful for supersonic cavity control.

Finally, a nonlinear response mechanism is necessary for the cavity to be modified by the oscillatory forcing at frequencies different from the forcing frequency. In a linear system, excitation at a single frequency cannot suppress more than one Rossiter tone simultaneously. However, many other investigators have been able to suppress the tones with actuators that add mass or momentum to the system. To examine the effects of steady flow injection, the siren valve was removed from the actuator and steady blowing was applied to the nozzle block with a 45^o exit angle. The results are shown in Fig.12. With a 409 kPa forcing pressure and a blowing coefficient B_c = 0.036, the Rossiter tone peaks are significantly reduced in amplitude. This blowing coefficient is two orders of magnitude larger than the values used in identifying the response of the cavity to open-loop forcing described earlier in the paper. This result strongly suggests that the tone suppression is accomplished purely by the steady flow mass addition, and the oscillatory component does not play a significant role in the suppression.

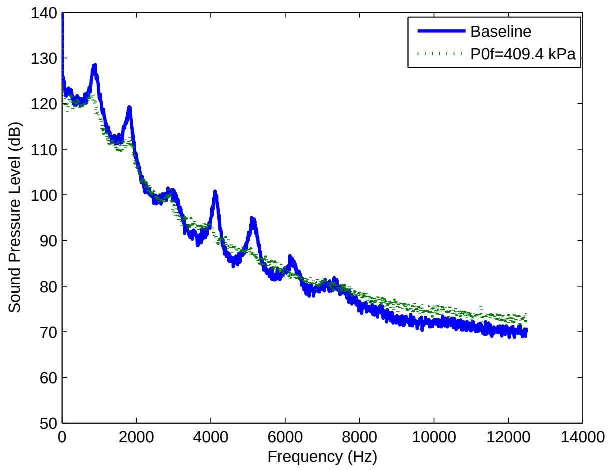

Figure 12 Steady flow addition with no oscillatory component suppresses the tones, B_c = .036.

5 Conclusion

Open-loop forcing experiments with an $L/D = 5$ cavity have been conducted at M=1.86. A pulsed-blowing type actuator was used to provide controlled inputs of mean and oscillating flow at the upstream edge of the cavity. The objective was to systematically vary the forcing frequency and amplitude, and the dynamic pressure in the wind tunnel to obtain a better understanding of the cavity system response to open-loop forcing. The behavior of the supersonic cavity was significantly different than has been observed in subsonic flow experiments. Nonlinear interactions between the forcing and the naturally occurring Rossiter modes was not observed in this experiment. However, strong amplification of the input disturbances occurred when the forcing frequency was close to a Rossiter mode, and attenuation occurred when the forcing frequency was between Rossiter modes. In regions of amplification, the increase in the cavity response amplitude was proportional to the input disturbance amplitude, which suggests the overall system behaves linearly. The Rossiter modes were clearly not in a nonlinearly saturated state, because their amplitude could be increased by 20dB with small amplitude inputs of the external forcing.

Acknowledgements

The many helpful suggestions from Tim Colonius and Lou Cattafesta are gratefully acknowledged. The work by C. W. Rowley and D. R. Williams was supported by AFOSR under grants F49620-03-1-0081 and F49620-03-1-0074 with program managers Sharon Heise and John Schmisseur.

References

[1] J.E Grove, M. A. Pinney, and M.J. Stanek: "A Cooperative Response To Future Weapons Integration Needs". Applied Vehicle Technology Panel, Symposium on Aircraft Weapon System Compatibility and Integration, NATO- R&T Organization, Sept. 1998, pp 24-1 - 24-12.

[2] J. Grove, L. Shaw, J. Leugers and G. Akroyd: "USAF/RAAF F-111 Flight Test with Active Separation Control". AIAA 2003-0009, Jan. 2003.

[3] O.W. McGregor and R. A. White: "Drag of Rectangular Cavities in Supersonic and Transonic Flow Including the Effects of Cavity Resonance". AIAA Journal, **8**, 1970, pp. 1959-1964.

[4] J. E. Rossiter: "Wind-Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds". Aeronautical Research Council Reports and Memoranda No. 3438, London, Oct. 1964.

[5] H.H.Heller, D.G. Holmes, and E.E. Covert: "Flow Induced Pressure Oscillations in Shallow Cavities". J. of Sound and Vibration, **18**, No. (4), 1971, pp.545-553.

[6] H.H. Heller and D. Bliss: "The Physical Mechanism of Flow-Induced Pressure Fluctuations in Cavities and Concepts for their Suppression". AIAA Paper 75-491, March 1975.

[7] L. Cattafesta, D.R. Williams, C. Rowley, and F. Alvi: "Review of Active Control of Flow-Induced Cavity Resonance". AIAA 2003-3567, June 2003.

[8] T. Colonius: ”An overview of simulation, modeling, and active control of flow acoustic resonance in open cavities”. AIAA 2001-0076, Jan. 2001.

[9] R.L. Sarno and M.E. Franke: ”Suppression of Flow-Induced Pressure Oscillations in Cavities”. J. of Aircraft, **31**, No. 1, 1994, pp. 90-96.

[10] L. Shaw: ”Active Control for Cavity Acoustics”. AIAA 98-2347, June 1998.

[11] L. Shaw, and S. Northcraft: ”Closed Loop Active Control for Cavity Acoustics”. AIAA Paper 99-1902, June 1999.

[12] M. Samimy, M. Debiasi, O. Efe, H. Ozbay, J. Myatt, and C. Camphouse: ”Exploring Strategies for Closed-Loop Cavity Flow Control”. AIAA 2004-0576, Jan. 2004.

[13] L.N. Cattafesta, S. Garg, M. Choudhari and F. Li: ”Active Control of Flow-Induced Cavity Resonance”. AIAA 97-1804, June 1997.

[14] L.S. Ukeiley, M.K. Ponton, J.S. Seiner and B. Jansen: ”Suppression of Pressure Loads in Cavity Flows”. AIAA 2002-0661, Jan. 2002.

[15] P.C. Bueno, .H. nalmis, N.T. Clemens and D.S. Dolling: ”The Effects of Upstream Mass Injection on a Mach 2 Cavity Flow”. AIAA 2002-0663, Jan 2002.

[16] L.S. Ukeiley, M.K. Ponton, J.M. Seiner and B. Jansen: ”Suppression of Pressure Loads in Cavity Flows”. AIAA J., **42**, No. 1, Jan 2004, pp. 70-79.

[17] L.S. Ukeiley, M.K. Ponton, J.M. Seiner, and B. Jansen: ”Suppression of Pressure Loads in Resonating Cavities Through Blowing”. AIAA 2003-0181, Jan. 2003.

[18] D. Fabris and D.R. Williams: ”Experimental Measurements of Cavity and Shear Layer Response to Unsteady Bleed Forcing”. AIAA 99-0606, Jan. 1999.

[19] G. Raman, S. Raghu and T.J. Bencic: ”Cavity Resonance Suppression using Miniature Fluidic Oscillators”. AIAA 99-1900, May 1999.

[20] R.F. Schmit, D.R. Schwartz, V. Kibens, G. Raman, J.A. Ross: ”High and Low Frequency Actuation Comparison for a Weapons Bay Cavity”. AIAA 2005-0795, Jan. 2005.

[21] M. Stanek, G. Raman, V. Kibens, J. Ross, J. Odedra and J. Peto: ”Control of Cavity Resonance through Very High Frequency Forcing”. AIAA 2000-1905, June 2000.

[22] M.J.Stanek, G. Raman, J.A. Ross, J. Odedra, J. Peto, F. Alvi, and V. Kibens: ”High Frequency Acoustic Suppression - The Mystery of the Rod-in-Crossflow Revealed”. AIAA 2003-0007, Jan. 2003.

[23] D. Sahoo, A. Annaswamy, N. Zhuang, and F. Alvi: ”Control of Cavity Tones in Supersonic Flow”. AIAA 2005-0793, Jan. 2005.

[24] N. Zhuang, F.S. Alvi, M.B. Alkislar, C. Shih, D. Sahoo and A.M. Annaswamy: ”Aeroacoustic Properties of Supersonic Cavity Flows and Their Control”. AIAA 2003-3101, 9th AIAA/CEAS Aeroacoustic Conf., Hilton Head South Carolina, May 2003.

[25] L.N.III Cattafesta, D. Shukla, S. Garg and J.A. Ross: ”Development of an Adaptive Weapons-Bay Suppression System”. AIAA 99-1901, May 1999.

[26] C.W. Rowley, D.R. Williams, T. Colonius, R.M. Murray and D.G. MacMynowsky: ”Linear models for control of cavity flow oscillations”. J. Fluid Mech., **547**, Jan 2006, pp.317-330.

[27] C.W. Rowley and D.R. Williams: ”Dynamics and Control of High-Reynolds Number Flow over Open Cavities”. Annual Review of Fluid Mechanics, **38**, 2006, pp. 251-276.

[28] E.J.Kerschen and A. Tumin: ”A Theoretical Model of Cavity Acoustic Resonance Based on Edge Scattering Processes”. AIAA 2003-0175, Jan. 2003.

[29] J.O.Alvarez, E.J.Kerschen and A. Tumin: ”A Theoretical Model for Cavity Acoustic Resonance in Subsonic Flow”. AIAA 2004-2845, June 2004.

[30] R. Becker, M. Garwon and R. King: ”Development of model-based sensors and their use for closed-loop control of separated shear flows”. ECC, 2003.