Cavity Flow Control Experiments and Simulations

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Abstract. In this work we describe a summary of flow control research studies on active, passive and adaptive methodologies designed to attenuate large scale flow unsteadiness and the resulting pressure fluctuations in cavity flows. Spectral analysis of high frequency dynamic pressure measurements is used to determine the control effectiveness. Various control techniques, depending on their geometry and or distribution, can be advantageous in attenuating both the peaks and the broad spectral bands generated by flow unsteadiness. Increased effectiveness is associated with redistribution of the shear-layer vorticity. Combination of experimental and numerical results assists in understanding the underlying flow physics and interaction processes involved.

1. Introduction
Acoustic resonance, resulting from subsonic or supersonic flow over aircraft cavities, is a common occurrence in many engineering applications. The flows are known to create substantial pressure fluctuations within the cavity [1-4]. These fluctuations may cause damage to sensitive equipment inside the cavity or the cavity’s structure. Our aim is the development of an adaptive flow-resonance suppression system that can be effective at different flow speeds and can be readily adapted to account for changes in the flow.

Many cavity flow studies have been carried out to consider the effects of upstream mass injection. Vakili and Gauthier [5] applied steady mass injection through a porous plate upstream of the cavity and obtained almost complete suppression of the cavity oscillations. Unfortunately, implementation of this solution for modern aircraft is challenging. To obtain the desired effect, it would require installation of a compressed air system capable of ejecting the required mass flow through a porous plate into the free stream. For example, use of supersonic micro-jets for flow control has been elaborated by Zhuang [6]. Note that most affected aircraft have little room to spare, and for this application a cumbersome ducting system to use engine bypass would not be a viable option as an add-on. It would have had to be considered in the aircraft design from the beginning.

The current research is motivated by the desire to find a solution with comparable results to the upstream mass injection but with a much simpler implementation potential. The basic concept is to use cylindrical rods placed vertically in the flow upstream of the cavity. Essentially, the rods would take the place of the mass injection jets providing a simpler solution to the implementation of cavity flow control that result in significant attenuation. The authors believe that this is a novel concept, and the authors are not aware of any such use in a previous study.

The goal of the present research was to investigate the effects of a set of configurations of cylindrical rods, or “pins”, on the acoustic resonance, broadband noise level of a typical cavity and the
shear layer above it. Moreover, objectives of this work include to determine not only whether specific configuration would lead to significant results, but also to study the flow mechanisms that cause attenuation.

2. Modelling background
Aeroacoustic interactions generated due to high speed flow over cavities have been extensively studied both using physical and numerical models. In shallow cavities, such as those used for weapons bays, longitudinal resonance oscillations are frequently encountered. These oscillations have been associated with interactions of the shear layers with the cavity. As the shear layer interacts with the trailing edge of the cavity a self-exciting feedback mechanism is created. Perturbations travel upstream in the cavity causing an excitation of the shear layer at the leading edge. This interaction can lead to severe amplifications of oscillations and resonance frequencies [7-9]. Rossiter [8] developed a semi-empirical formula for the prediction of possible oscillation frequencies for open cavity flows based on the Strouhal number. Heller, Holmes and Covert [9] adapted Rossiter’s equation for application in the study of supersonic data.

Previous studies in active, adaptive and passive cavity flow control [5, 10-12] have shown successful results. The active flow control process [5] was able to greatly suppress the resonant tones but their implementation for certain systems applications could prove cumbersome or impractical.

3. Experimental approach
The experimental study is conducted in the High-Speed blow-down Wind Tunnel (HSWT) at the University of Tennessee Space Institute (UTSI) Gas Dynamics Laboratory. The wind tunnel test section consists of a 20 cm × 20 cm square duct that is 1.2 m long, with a test section Mach number of $M = 1.84$. Further details of the HSWT and the experimental setup are given in Ref. [13, 14].

4. Results and analysis
The experimental work utilized several different cavity configurations, including a baseline cavity test with no flow control, as a reference for comparison. Previous studies including determination of the baseline of the wind tunnel, where there was no cavity present, were performed; see the work by Fowler [11]. The broadband spectrum of the tunnel baseline is significantly lower and contains no resonant peaks.

Figure 1 illustrates acoustic spectra of the tunnel with a cavity installed and no pin plate for flow control. The first five modes are clearly visible; however, the fifth mode is small and disappears in all other configuration tests, so it is not further considered.

![Figure 1. Config. 1: Baseline cavity acoustic spectra compared to the modes from the modified Rossiter Equation.](image-url)
Distinct regions of fluid where density variations are present, such as boundary layers and shock waves, can be recorded using Schlieren flow imaging techniques. Video recordings of Schlieren images were taken in each experimental study, but here we illustrate only typical results.

![Schlieren photographs of two pin heights filling the entire plate](image)

**Figure 2.** Schlieren photographs of two pin heights filling the entire plate. (a) 3.2 mm (⅛") pins for configuration 3; (b) 12.7 mm (½") pins for configuration 13. The increased shear layer thickness over the cavity is indicated by the arrows at the bottom right of the images.

For the slightly rotated images, the tunnel floor is horizontal and is marked by a solid (red) line over the solid black floor. The incline is due to video camera’s set up angle. In the baseline configuration with a solid plate (no holes) upstream of the cavity two important observations can be noted: First, as expected, there will be an oblique shock that forms at the leading edge. Second, a region of low speed flow (the boundary layer) is anticipated along the tunnel floor. When we replaced the solid plate with the empty pin plate (96 holes) the Schlieren image shows weak shocks forming for each row of holes, the strongest being at the front of the plate. Figure 2 shows the Schlieren images for two full plate configurations with different pin heights. A large number of pin configurations were studied. Details can be found in [13 &14]. Two selected pin distributions, with the best attenuation, were further studied.

Particle Image Velocimetry (PIV) data were obtained using 120 image pairs. Figure 3 shows typical results.

![Typical PIV field of view with non-dimensional axes, pin config. 15.](image)
The field of view for this image is roughly 5 cm (2 in.) of the leading edge, around 20% length of the cavity, as well as a similar distance of the upstream surface where the vertical pin configurations are located. Due to optical limitations of the PIV system, only 2.5 cm (1 in.) of the surface immediately preceding the leading edge is available. In Figure 4 the plots are on non-dimensionalized axes where zero is the leading edge.

![Figure 4. Averaged non-dimensional PIV vorticity magnitude contour plots; a) Baseline cavity, b) Configuration 12, d) Configuration 13, e) Configuration 15, f) Configuration 16.](image)

Velocity and vorticity field plots revealed that the presence of vertical pins impacted the flow velocity distribution and hence the vorticity in the shear layer. Pins resulted in thickening of the shear layer over the cavity which changed kinetic energy exchange in flow’s interactions with the cavity, resulting in varying amounts of suppression as measured by Sound Pressure Level (SPL). The largest suppression of the overall broadband spectra was determined to be connected to pin configurations which have staggered and widely spaced pins. Vorticity plots showed that these configurations seem resulted in more effective diffusion of the vorticity in the shear layer which results in improved peaks and broadband suppression. The various flow fields and attenuation effects resulting from the pin distributions are good indications for the effectiveness of this technique as a cavity flow control tool. Schlieren images, PIV velocity and vorticity data, including error analysis are for example discussed by Thiemann [13] and Meganathan [15].
Two selected pin distributions, with the best attenuation, were further studied. The effects of uncertainty in the experimental data and CFD predictions are considered collaboratively to help resolve potential ambiguities. Figure 5 displays an image obtained with CFD. Compared with the baseline, the pins have altered the flow distribution over the cavity, including vorticity and reduction of coherence in the shear layer vorticity. This resulted in thickening of the shear which then minimized coherent interactions with the cavity. Comparison between the 3-D numerical modelling and the experimental results help in understating of the uncertainties involved.

![Figure 5. Typical CFD models, showing pressure and Mach number of the flow cavity field.](image)

The effects of uncertainty in the experimental results and CFD predictions are considered collaboratively to help resolve potential ambiguities. The pins altered the flow characteristics over the cavity, including redistribution and dispersion of coherent vorticity in the shear layer. This resulted in thickening of the shear which reduced coherent interactions with the cavity.

5. Conclusions
The summary report reflects our ongoing efforts to develop cavity flow control techniques using experimental and complimentary CFD modeling studies. Selected pin configurations were tested and numerically modeled to help determine and understand the flow events within a cavity with $L/D = 4.89$ at $M = 1.84$ and $Re = 9.89 \times 10^6$ /ft. Cavity acoustics and sound pressure levels, and flow fields were measured and modeled. Pressure frequency spectra, were affected by the pins’ arrangements, in various distributions, upstream of the cavity. CFD results helped in analysis of flow results and determining the pins’ interruption of the shear layer development as the mechanisms of effectiveness in cavity flow control. Further experiments with new pin spacing configurations are recommended, including Particle Imaging Velocimetry (PIV) measurements in the trailing edge of the cavity to record data in the cavity region near its rear bulkhead.
Acknowledgments
The authors thank Joel Davenport, Chris Armstrong, Andrew Davis and Jack LeGeune for their help in fabrication, installation and operation of the wind tunnel experiments. The authors would also like to thank Christian Parigger for his valuable editorial support.

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