Effect of Helmholtz Resonators on Boundary-Layer Turbulence

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Abstract

HELMHOLTZ resonators were investigated as a passive device for the purpose of modifying a turbulent boundary layer. Resonators, imbedded in a wall, also occur inadvertently when porous walls are used to reduce boundary-layer growth or as acoustic control devices in inlet ducts and combustors. In all cases it is of interest to know the effect of the resonators on the boundary layer.

Helmholtz resonators are formed by cavities that are vented by a small orifice (see Fig. 1). They respond to excitation from the shear layer at the orifice as well as from incident acoustic waves. Previous experimental work [1-4] has focused on the conditions for resonance in a single resonator. In the present study, a row of 10 resonators was positioned across the span of a wind-tunnel wall. Separate studies[5,6] were conducted to determine the response of the resonator row to the boundary layer and the interaction that occurred between adjacent resonators. The relevant results are that peak response was achieved at a freestream velocity of 26.5 m/s, and the frequency and amplitude of the cavity pressure oscillations were 570 Hz and 143 dB (equivalent to 80% of the freestream dynamic pressure). In addition, adjacent resonators showed a strong antiphase locking with an average coherence coefficient of 70% and a phase lag of 150 to 180 deg. The phase locking between resonators was localized, and coherence decreased rapidly with resonators that were further away.

Contents

Experiments were conducted in a wind tunnel with a test section of 0.71 m × 1.0 m and 2.7 m long (28 in. × 40 in. × 9 ft). Ten resonators were formed with orifices of diameter D = 1.03 cm (0.406 in.) and 0.305 cm (0.120 in.) thickness. They were spaced 3.05 cm (1.20 in) on centers occupying the central 27.5 cm (10.8 in) of the 1.0 m (40 in.) span. At the location of the resonators, with flow parameters chosen to produce a resonant condition, the boundary layer had a thickness of δ = 2.8 cm (1.1 in.), friction velocity u_τ = 1.0 m/s, and freestream speed of 26 m/s (58 mph). The corresponding Re_θ was 5500. Measurement locations were chosen at the streamwise (X) positions $X/D = -3, -0.5, 0.5, 3, 10, 20, 40$, and 80 together with six spanwise (Z) positions, three directly in line with the resonator orifices and three half-way between the orifices. Laser velocimeter measurements of the streamwise and vertical velocity were obtained and processed to yield values of the mean velocity, root-mean-square (rms) fluctuation, and Reynolds stress. To obtain details of the resonator-flow interaction, a cavity microphone and hot-film probe were employed to obtain correlations coefficients between the instantaneous velocity and cavity pressure. These data were used to calculate phase-averaged velocity maps.

Typical results are shown in Figs. 2 and 3 for velocity quantities. Figure 4 gives a typical map of the velocity perturbations that occur during each phase of the cavity pressure oscillation. Overall results are summarized as follows. At an upstream distance equal to three orifice diameters ($\sim 1\delta$), there are no noticeable effects. At the leading edge of the orifice, no change is observed in the mean streamwise velocity, but 10% increases in the rms velocities, and 80% increases in the Reynolds stress were measured for $y^+ (= yu^*/U) < 400$. The mean streamwise flow directly above the orifice had a decreased velocity in the log region that was associated with increases of 300%[3] in v', 30% in u', 550% in the Reynolds

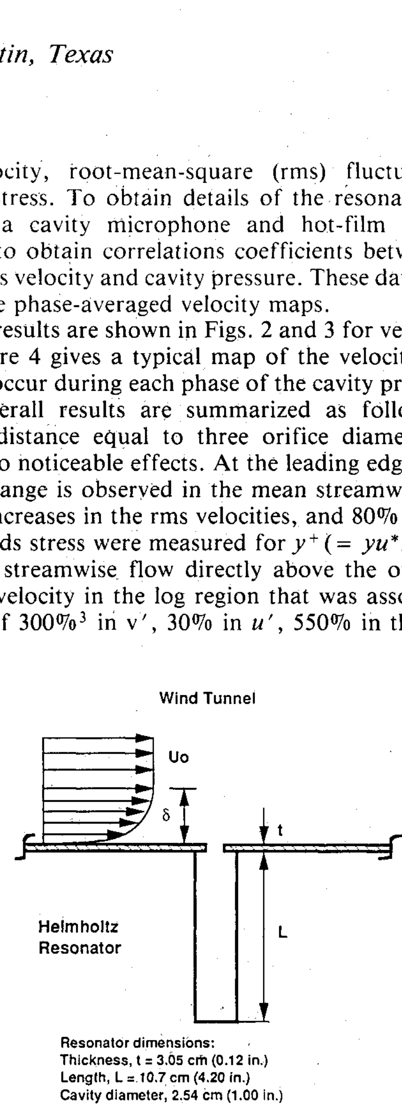

Fig. 1 Schematic of test setup; Helmholtz resonators behind the wall of a wind tunnel.

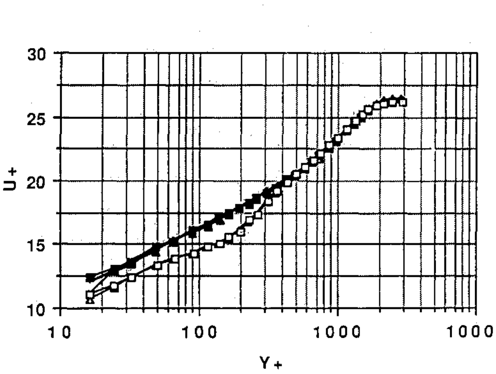

Fig. 2 Mean velocity profiles downstream of the resonators at x/D = 3; open symbols are with resonators; solid symbols are for a smooth wall.

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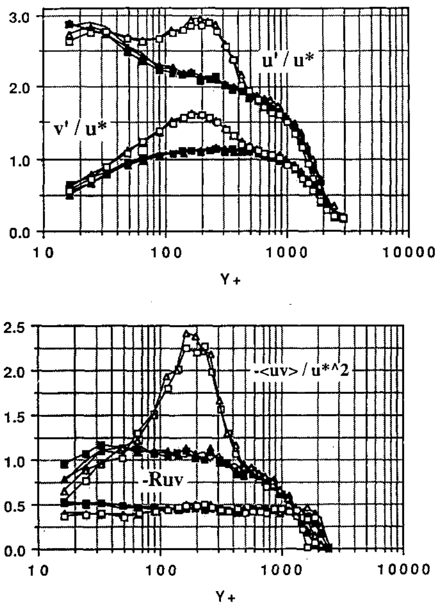

a)

b)

Fig. 3 Turbulence quantities at $x/D = 3$ turbulence rms intensities a) Reynolds stress and correlation coefficient, b) open symbols are with resonators; solid symbols are for a smooth wall.

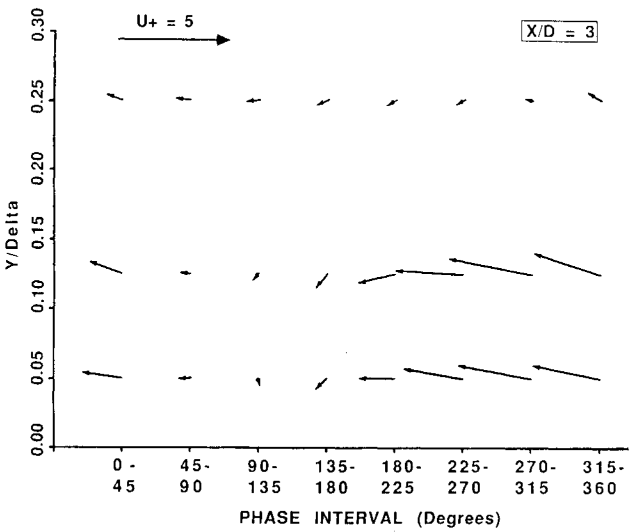

Fig. 4 Vector plot of resonator induced velocity fluctuations through the boundary layer corresponding to each phase of the cavity pressure oscillation.

stress, and ± 10% changes in R_{uv}. In addition, a significant change in the mean vertical velocity profile was measured in this region with a value of $V/U_0 = +2\%$ at $y_+ = 100$. This perturbation is maintained downstream for at least three diameters (~ 1δ); it is here that the changes in velocity fluctuations, Reynolds stress, and vertical velocities have decreased, and a return to standard values is observed for $y_+ < 30$. The flow at points halfway between orifices was unaffected by the resonators up to this point.

The fluid oscillations in the perturbed region of the flow were strongly correlated, correlation coefficient of 0.4, with the cavity pressure oscillations. Calculations of the integral length scale of the streamwise velocity indicate a reduction from typical values. This is most marked at the orifice trailing edge where a 60% reduction was observed at $y/\delta = 0.05$. Averaging the velocity fluctuations for a given phase in the cavity pressure cycle also showed a strong correlation between fluid oscillations and pressure oscillations. The largest disturbance to the flow occurs on outflow, which produced a velocity deficit. Significant variations in the uv product were found throughout the cycle with values ranging from three times the average to values that were positive. At $X/D = 3$ only, the remnants of outflow caused significant changes from the mean flow. This always produces a negative value for the uv product. The variations of the Reynolds stress from the average were only 50% at this point.

By 10 diam downstream (~ 3δ), the perturbations were less noticeable having spread across the boundary layer laterally and vertically. However, the largest changes were still observed in the log region. At this point all spanwise positions have been affected, and the changes were still characterized by a velocity defect and increased turbulent fluctuations and Reynolds stress of about 5%. No significant differences in the vertical or the uv correlation coefficient were found at this location. Directly downstream from the orifice, correlations of about 10% with the cavity pressure oscillations were still observed from $y/\delta = 1/8$ to $1/4$. Phase-averaged data at this location showed that the amplitude of correlated motions decreased by 80% from those at $X/D = 3$. No significant pressure-velocity correlations were found at positions between resonators. This may be due to distortion from turbulent mixing or due to destructive interference from the resonators to either side that are oscillation out of phase.

At 20 diam downstream (~ 7δ), a small velocity defect is still found at some locations along with a 3% increase in turbulent fluctuations; although the Reynolds stress is no longer noticeably different from the natural flow. No significant pressure-velocity correlations are found anywhere. Both turbulence and mean profiles measured at 40 and 80 diam downstream have returned to their normal values.

Acknowledgment

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