Acoustic Metamaterials in Flow

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Due to negative acoustic and structural externalities, it is often advantageous to reduce or attenuate turbulent boundary layer (TBL) surface pressure fluctuations. However, this study aims to harness the energy from TBLs to excite acoustic metamaterials as illustrated in Figure 1. A cross-sectional view of an example metamaterial is shown in Figure 1, with a smooth side exposed to grazing flow and the opposite side lined with an array of closed-end cavities. The thickness of the metamaterial is L, the cavity radius is a, and the cavity spacing is λ_g. A turbulent boundary layer is formed on the upper flow surface producing a stochastic unsteady surface pressure field. These pressure fluctuations are filtered and transmitted through the surface via the modal response of a tensioned, flexible membrane or micro-perforated cap covering a resonator tube which can be tuned to a desired frequency. The membrane and resonator transfer energy from the boundary layer to the underside of the surface without significant disturbance to the flow above. The periodic array of cavities on the underside of the surface supports the generation of Acoustic Surface Waves (ASW), waves that propagate along the surface but decay exponentially in the surface normal direction. The ASW exist along the boundary of the acoustic impedance mismatch between the fluid and the acoustic grating cavity structure, $z_{air} \neq z_{ag}$. This increases the wave momentum along the surface and thus does not allow the propagation of waves away from the surface to the far field. This effectively traps and guides the ASWs along the surface [1]. Further, end effects between resonant cavities are coupled such that the impedance condition reduces the velocity of the ASW traveling along the surface [1-3].

A facility was constructed at Virginia Tech to measure ASWs trapped along different metamaterial configurations. Initial tests were performed in a quiescent environment to corroborate results from Ward [1]. The quiescent metamaterial contained a 2D array of open-ended cavities oriented in a grid with $a = 3.18$ mm, $L = 9.53$ mm, and $\lambda_g = 8$ mm. The surface was excited with a Gaussian modulated waveform packet produced from a point source speaker. The resulting acoustic surface waves were measured using a Bruel and Kjaer 4182 probe microphone. The microphone was placed 0.5 mm away from the surface and was traversed in a 1D line scan at increments of 0.7 mm. Spatial and time domain Fourier transforms were conducted to construct the dispersion diagram shown in Figure 2, where the abscissa is the horizontal wavenumber, k_x, and the ordinate is the frequency, f, in Hz. The phase velocity is defined as $v_p = 2\pi f / k_x$, and the group velocity is the gradient, $v_g = \partial(2\pi f)/\partial k_x$. The contour levels represent the magnitude of the acoustic surface wave pressure in decibels. The sound line is represented by the solid white line, along which, the group and phase speeds are both equal to the speed of sound in air. The peak in the wavenumber-frequency spectrum of the ASW follows the sound line up to a frequency of approximately 10 kHz. As the frequency approaches the idealized resonant frequency of the cavities for this surface, $f_{res} = 14$kHz, the peak curves away from the sound line indicating the presence of dispersive ASW. The second peak at higher frequencies crossing the sound line is produced by another ASW travelling diagonally across the grid pattern of cavities. The result appearing at $k_x < -400$m^{-1} is an image produced by the Fourier transform.

Further results to be presented will detail the design of a surface intended to operate in grazing flow and to be excited by TBL surface pressure fluctuations, as depicted in Figure 1. The performance of this surface to both capture and guide the energy harvested from the TBL will be evaluated.

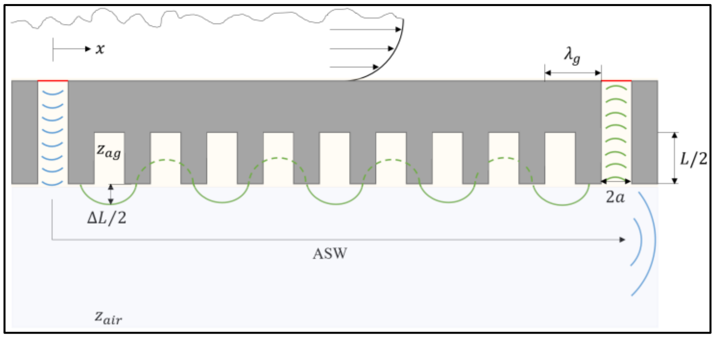

Figure 1. Side-view diagram of a 1D cavity array excited by a TBL. The ASW (—) originate from the TBL-energized membrane (—) on the furthest upstream cavity. The standing ASW (—) form when the ASW frequency matches the resonant frequencies of each cavity. The solid line represents positive pressure differential while the dashed line represents negative pressure differential. At the most downstream cavity, the trapped ASW energy is re-introduced to the flow via another membrane.

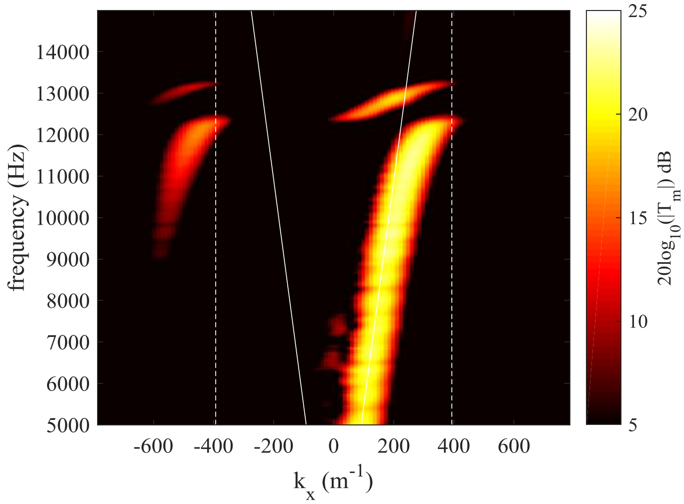

Figure 2. Dispersion diagram from a 1D line scan over the metamaterial. The sound lines, $k_x = \frac{2\pi f}{c}$, (solid line) and the Brillouin zone boundaries, $k_x = \frac{k_g}{2} = \frac{\pi}{\lambda_g}$, (dashed lines) are displayed on the plot

References

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[3] Wang, X., "Theory of Resonant Sound Transmission through Small Apertures on Periodically Perforated Slabs," *Journal of Applied Physics,* Vol. 108, 064903, 2010.