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Controlling Vortex characteristics in lifting bodies using Diatomic Phononic Crystals

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Abstract: Phononic Materials (PMs) with precisely engineered dynamics have emerged as promising candidates to achieve passive flow control in various flow configurations. Inspired by this goal, we study the effect of truncation resonance frequency, static and dynamic deformation of a PM on the emergent vortex-shedding dynamics, e.g., frequency, intensity (circulation), in air-flow past an inclined plate.

The characteristics and presence of various fluid flow structures, e.g., vortex structures and transition instabilities in fluid flow over an airfoil, significantly impact the aerial vehicle performance. Consequently, modeling and control of the spatio-temporal characteristics of these flow structures has been an active area of research in fluid dynamics, prompting the development of various active and passive flow control strategies over the past few decades. Active strategies offer a relatively superior level of precision and control in dictating the flow dynamics; however, they often involve complex and heavy electronics requiring a significant external energy supply, hindering their practical operability. Alternatively, passive flow control strategies directly extract energy from the fluid to alter the flow characteristics. Specifically, strategies leveraging the fluid-structure interaction (FSI) of compliant structures with a given fluid flow have significant potential for flow control. However, most existing studies primarily leverage homogeneous, highly deformable surfaces (e.g., silicone membranes), offering material compliance as the only 'tuning' parameter to adapt the FSI dynamics that affect multiple flow characteristics (e.g., frequency, wavelength, spectral energy content, and phase), limiting their capability. In this context, phononic materials (PMs) with engineered internal architectures and behavior offer an enhanced tuning capability, opening avenues for novel passive flow control strategies leveraging fluid-PM interactions.

Following the pioneering work by Hussein *et al.*[1], subsequent research studies have successfully demonstrated the PM capability in mitigating transition instabilities[2,3], controlling vortex characteristics[4] in various flow configurations. Aligning the frequency of a truncation resonance (TR) in the phononic band-gap of the PM with an inherent flow frequency to be altered is a common theme across these early fluid-PM interaction studies. These studies highlight the multi-dimensional parameter space offered by PMs compared to homogeneous compliant surfaces, significantly improving the customizability of the FSI dynamics, and present a valuable first step towards understanding the rich interaction dynamics between PMs and various flow structures. However, a framework to identify and study the causality of the relevant PM behavioral characteristics on the emergent FSI dynamics remains elusive.

Progressing towards this goal, Fig. 1a illustrates the canonical FSI configuration we choose to study - flow past an infinitely thin inclined plate with a compliant section featuring a PM, i.e., diatomic phononic crystal with prescribed TR characteristics as a subsurface. As a preliminary step, we perform fluid simulations at Re=400 for a fully rigid inclined plate at angles of attack, $\alpha=12^o$ and $\alpha=15^o$, and identify the characteristics of the target flow structures, i.e., flow vortices. Fig. 1b plots the vorticity contours for the two angles of attack, $\alpha=12^o$ and $\alpha=15^o$, indicating the presence of a critical angle of attack, above which there is a default existence of vortex-shedding behavior as the fluid flows past the inclined plate. Therefore, we choose these two baseline configurations, with and without vortex shedding, and the vortex shedding frequency, f_{VS}=0.583, in the $\alpha=15^o$ case as a reference frequency, to systematically investigate the effect of various PM configurations on the flow vortex characteristics. The study identifies the TR frequency ratio, f_{TR}/f_{VS}, the mean static deformation, δ, and the absolute displacement amplitude envelope, λ, at resonance of the compliant section, as critical PM behavioral parameters influencing the vortex characteristics in the steady state.

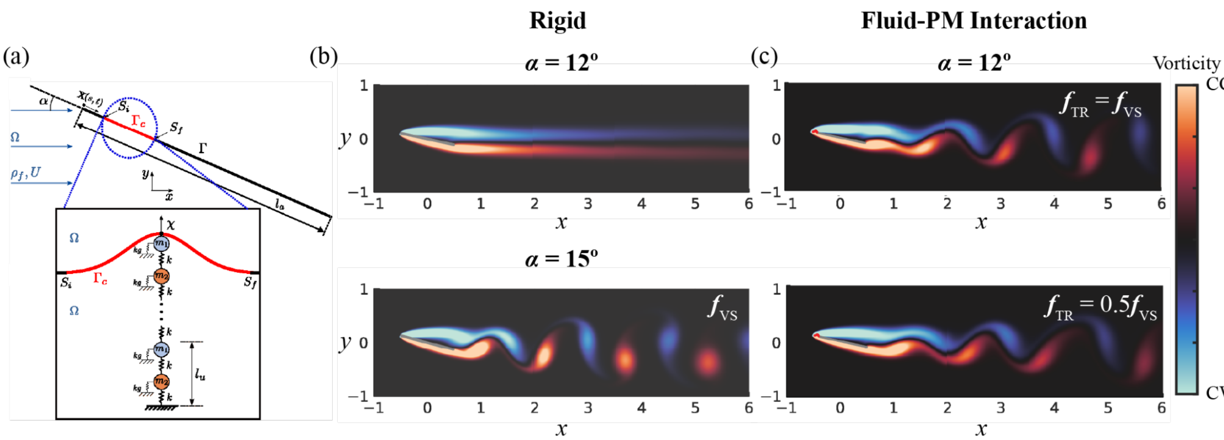

Figure 1 FSI of a diatomic phononic crystal with flow over an inclined plate. **(a)** Schematic of the inclined plate and zoom-in view of the compliant section, featuring the diatomic phononic crystal as a subsurface. **(b)** Steady-state vorticity contours of flow over rigid inclined plates at angles of attack, α=12°, and α=15°. **(c)** FSI simulation results for α=12°, where the PM is engineered with a $f_{TR} = 0.5f_{VS}$ and $f_{TR} = f_{VS}$. (CW-Clockwise, CCW-Counterclockwise)

In this talk, we present simulation results for the α=12° case, where we fix an appropriate mean displacement, δ, and probe the effect of changing f_{TR}/f_{VS} and λ. Given a sufficient λ, we observe that the FSI leads to the generation of flow vortices of a prescribed frequency that closely corresponds to the designed f_{TR}, significantly altering the flow characteristics compared to the baseline rigid plate case. Fig. 1c plots the vorticity contours for two representative FSI cases where the f_{TR}/f_{VS}=0.5,1, respectively, illustrating the impact of the PM dynamics on the spatio-temporal characteristics of the generated vortices. The effect of having stronger FSI dynamics, i.e., increasing λ, on the vortex characteristics, specifically the frequency and flow circulation, will also be discussed. Finally, we summarize the general observations that can inform PM design for effective FSI in various settings and present an outlook for the FSI simulations in the α=15° case, where the PM will now interact with pre-existing vortex flow structures.

References

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