Finite-Span Effect on Vortex-Induced Vibration Simulations

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Abstract

The effects of using periodic boundary conditions when simulating vortex induced vibration (VIV) on a finite-span model are explored. When spanwise coherence is smaller than the simulated span, the peak VIV amplitude is under-predicted due to spreading of energy in frequencies around the Strouhal number.

Keywords: Vortex-Induced Vibration, Detached Eddy Simulations, spanwise coherence

1. Introduction

Vortex-induced vibrations (VIV) are commonly observed in bridge decks, cables, power conductors, risers in oil rigs, etc. The Kármán vortex shedding in the wake of the cylinder produces periodic forcing on the cylinder. In certain conditions the vortex-shedding frequency synchronizes ("lock-in") with the natural frequency of the system which results in high-amplitude oscillations (VIV) limited by the system damping. Experimental investigations of VIV are typically performed with finite-span cylinders with aspect ratios greater than 10 to minimize "end effects" (*cite*), where end-effect refers to the three-dimensional flow that results due to the finiteness of the model. End plates have been used in experiments (*cite*), which reduce but not completely eliminate the end effects as horse-shoe vortices develop at the intersection of the cable and the end plates.

This problem is avoided in simulations by using periodic boundaries in the span direction. While the periodic boundaries imply an infinitely-long cylinder, the finite size of the computational domain in the span direction imposes artificial periodicity in the flow. If spanwise variations are present in the flow and the length scale of these variations is larger than the simulated span, then span periodicity will likely yield incorrect results. For stochastic (turbulent) flows, this length scale can be measured using two-point correlations; in particular, spanwise coherence. Magnitude-squared coherence is defined as $\gamma^2(\Delta z, f) = \langle |S_{xy}(f)|^2 \rangle / (\langle S_{xx}(f) \rangle \langle S_{yy}(f) \rangle)$, where $S_{xy}(f)$ denotes cross-spectral density of the desired quantity (e.g., sectional lift) at points $\boldsymbol{x}$ and $\boldsymbol{y}$ separated by a distance Δz (along the span). $S_{xx}(f)$ and $S_{yy}(f)$ are auto-spectral densities at $\boldsymbol{x}$ and $\boldsymbol{y}$ respectively and angular brackets denote ensemble averaging.

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Figure 1 presents contours of $\gamma^2(\Delta z, \omega)$ of sectional lift for a static circular cylinder (aspect ratio, $L/D = 20$) simulation. Nondimensional frequency, $k = f\,D/V_\infty$ is used to plot coherence. Spanwise coherence is small everywhere except at the Kármán vortex-shedding frequency (f_v), given by the Strouhal number, $St = f_v D/V_\infty$ of around 0.2.

In this paper, we investigate the effect of span periodicity when simulating a circular cylinder experiencing VIV. While the effect of aspect ratio (span length to diameter ratio, L/D) have been investigated in VIV experiments (*cite*), such an investigation is lacking for simulations. (* provide a very brief summary of study on aspect-ratio-effects for flow over a cylinder *) We present detached eddy simualtion (DES) results of four models with $L/D = 1$, 2, 5, and 10. Displacement amplitude, lift spectra and spanwise coherence are analyzed to study the effect of span periodicity.

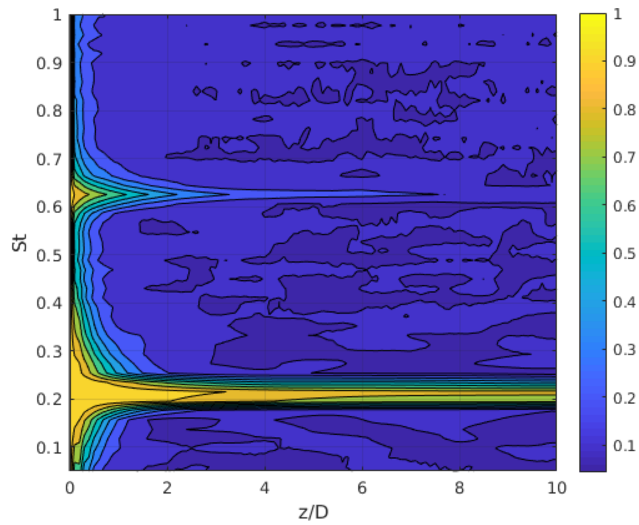


Figure 1: $\gamma^2(\Delta z, f)$ of lift for a static cylinder

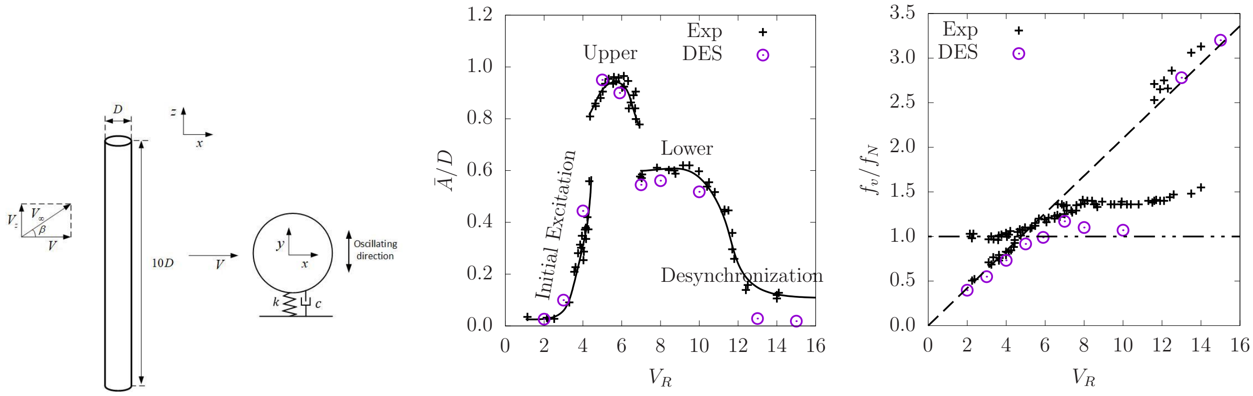
2. Computational Methodology and Verification

A coupled fluid-solid dynamics solver is used to simulate an elastically-mounted rigid circular cylinder experiencing VIV. The detached eddy simulation (DES) technique is used to model the flow and a forced single-degree of freedom mass-spring-damper system is solved to model the dynamics of the cylinder. The k-ω delayed detached eddy simulation (DDES) formulation by Yin *et al.* [1] is used here for the flow simulation. The details of the approach are described in Wu *et al.* [2].

Figure 2 (a) shows a schematic of the simulation setup and a comparison with measured data for a low mass-damping cylinder undergoing VIV. The following nondimensional numbers are matched between the experiments and the simulations: mass ratio, $m^* = 2.6$, mechanical damping ratio, $\zeta = 0.001$, and reduced velocity, $V_R = V_\infty/(f_N D)$, where f_N is the natural frequency of the mass-spring-damper system. As seen in Fig. 2 (b&c), the simulations accurately predict the displacement amplitude and the vortex shedding frequency of the cylinder over a wide range of V_R which includes the four branches identified in the experiment [3]: *initial excitation*, *upper*, *lower*, and *desynchronization*. Of particular interest is the "lock-in" phenomenon which occurs in the *upper* and *lower* branches.

3. Effect of Aspect Ratio

Simulations are performed for four values of aspect ratio, L/D $(= 1, 2, 5,$ and $10)$. For each configuration, seven values of reduced velocity V_R $(= 2, 3, 4, 5, 5.9, 7, 8)$ are evaluated; this range covers the *initial excitation*, *upper*, and *lower* branches observed during VIV of a low mass-damping cylinder.



(a) simulation setup (b) mean amplitude (c) frequency

Figure 2: Verification of the DES approach to predict VIV: (a) a schematic showing the simulation setup, (b) mean nondimensional displacement amplitude ($\bar{A}/D$), and (c) vortex shedding frequency (f_v) normalized by natural frequency of the system (f_N). Simulation results are compared against measurements from Ref. [3] for a range of reduced velocity (V_R).

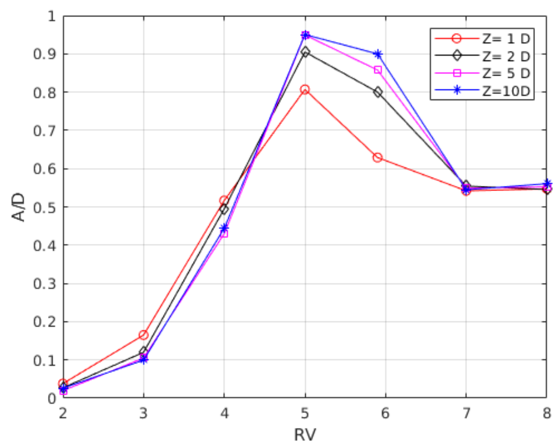
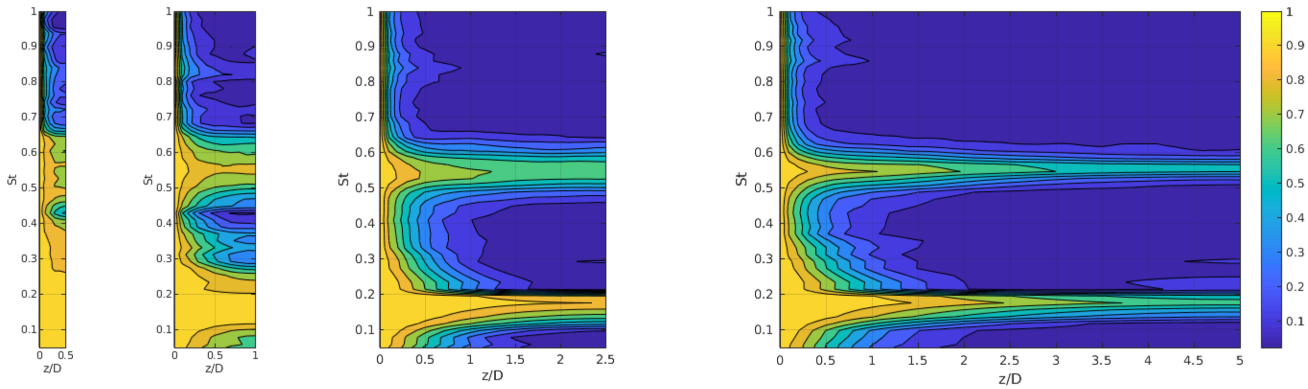


Figure 3: Comparison of predicted non-dimensional mean amplitude $\bar{A}/D$ using cylinder models of different span lengths.

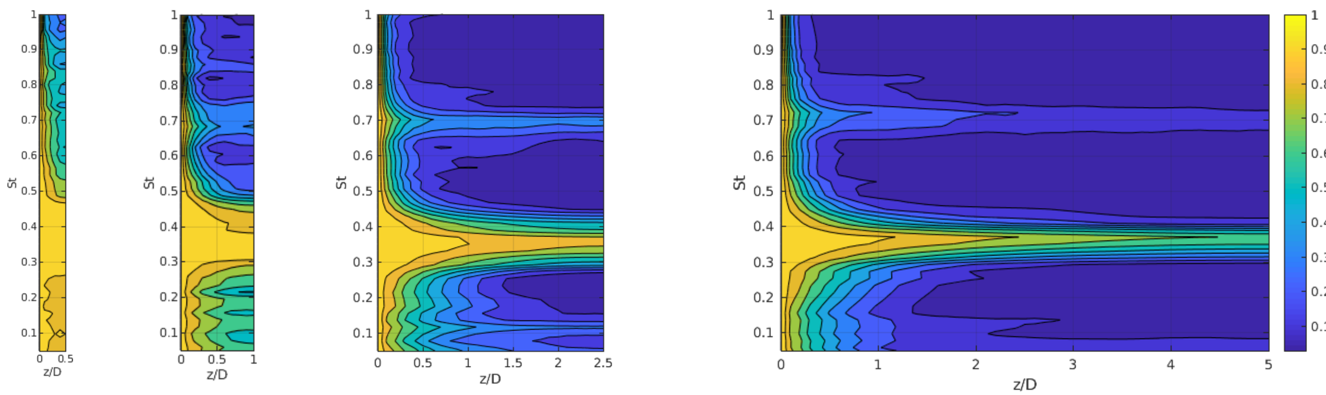
Figure 4 and 5 present force coefficients coherence for different spans cylinders ($Z = 1D, 2D, 5D$, and $10D$). For longer cylinders ($Z = 5D$ and $10D$) are only correlated to the peak vortex shedding frequency and its harmonics. However, the shorter cylinders ($Z = 1D$ and $2D$) have more wider coherence for more frequencies??

Figure 6 shows ... different peak value, wider, lower psd smaller L/D.



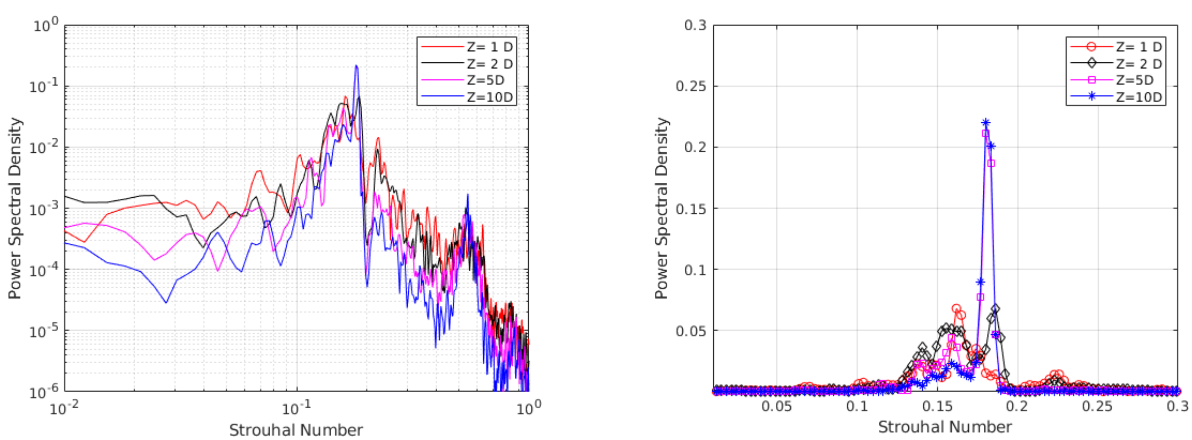
(a) $1D$ (b) $2D$ (c) $5D$ (d) $10D$

Figure 4: Lift coherence for various aspect ratio at $V_{R,n} = 5$



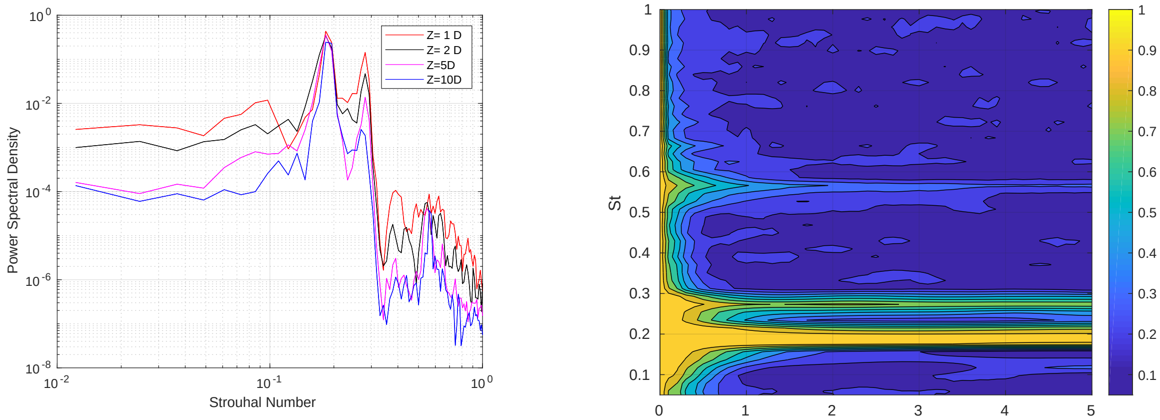
(a) $1D$ (b) $2D$ (c) $5D$ (d) $10D$

Figure 5: Drag coherence for various aspect ratio at $V_{R,n} = 5$

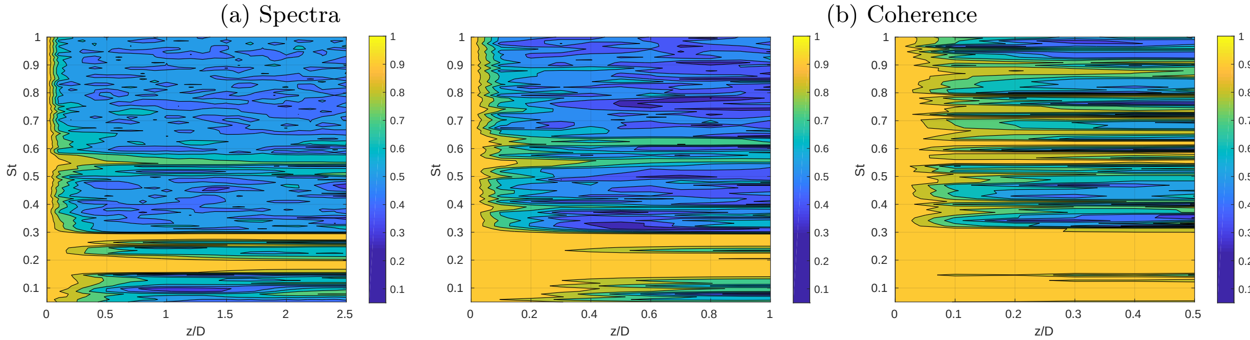


(a) Power spectral densities of C_l (b) Zoom-in

Figure 6: Comparison of predicted power spectral densities (PSDs) of C_l for various frequencies at $V_{R,n} = 5$.



(a) Spectra (b) Coherence



(c) Coherence, $L/D = 5$ (d) Coherence, $L/D = 2$ (e) Coherence, $L/D = 1$

Figure 7: $V_{R,n} = 3$

4. Conclusion

References

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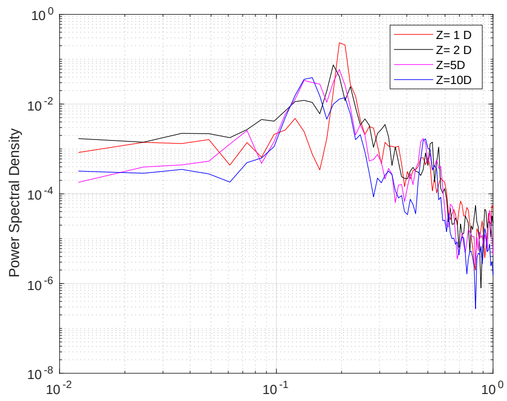
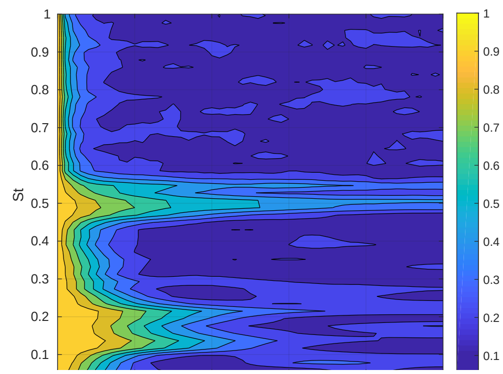
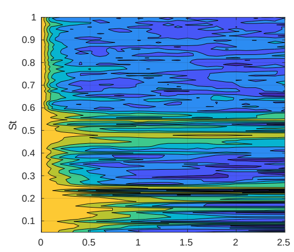


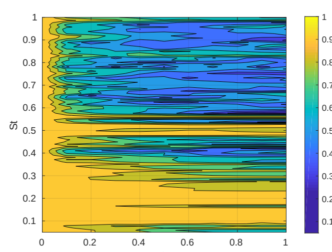
(a) Spectra



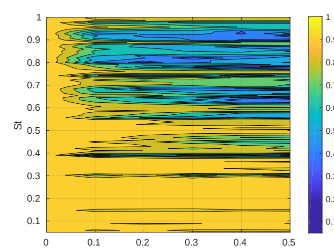
(b) Coherence, $L/D = 10$



(c) Coherence, $L/D = 5$



(d) Coherence, $L/D = 2$



(e) Coherence, $L/D = 1$

Figure 8: $V_{R,n} = 5.9$