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Nonlinear dynamics of a system of coupled piezoelastic airfoil oscillators

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SUMMARY:
Large horizontal axis wind turbines are typically systems of choice for harnessing wind energy. However, there are terrains and environments where it is impractical to set up these systems. Under such conditions, a system of aerodynamic oscillators can be used to harvest wind energy on a smaller scale, in particular, for relatively low wind speeds. The oscillator can be chosen to an airfoil mounted on structural support with instrumented piezoelectric layers. When placed in a freestream, the flutter instabilities are generated in the airfoil and the strain energy generated in the structural support can be converted to electrical power. In this work, to computationally model the response for a system of oscillators, the fluid is modelled by using the unsteady vortex lattice method. Parameters such as the freestream speed, the number of oscillators, and the spacing between oscillators are varied and the resulting influence on the system dynamics is studied. The results are used to discuss how nonlinear dynamics can be leveraged to design the system of aerodynamically coupled oscillators and maximize the power generated.

Keywords: unsteady vortex lattice method, aerodynamic coupling, aeroelastic flutter

1. INTRODUCTION

The interactions between oscillating bodies placed in a freestream of fluid, whether air or water, has been of interest to researchers and engineers. Applications such as offshore structures, submarine periscopes, electrical transmission lines among others have sparked an interest in studying interactions involving cylindrical bluff bodies. The earliest known application for airfoil shaped bodies was the biplane, which is a rather inefficient solution for generating steady aerodynamic lift. Currently, there is an interest in designing novel systems for harvesting clean energy. To this end, here, a system of airfoil oscillators, which is instrumented piezoelectric layers and undergoing flutter induced limit cycle oscillations, is conceived. Through experimental studies, researchers have demonstrated the feasability of single oscillator systems (Bryant and Garcia, 2011; Erturk et al., 2010). However, in both studies it was seen that the overall power output generated by the airfoils was low. In order to improve the output, a system of multiple airfoil oscillators can be considered. For such a system aerodynamic interactions take place through transmission of energy through the airflow surrounding the airfoil. Depending on the different parameters, such as number of oscillators, system configuration spacing between oscillators, and the free stream speed, the system nonlinear behavior can be leveraged to obtain high power outputs.

2. COMPUTATIONAL MODEL

Currently, no generalized analytical models exist for studying the aerodynamic interactions between multiple airfoil oscillators. Hence, computational models are needed to model these aerodynamic interactions. Unsteady vortex lattice methods (UVLM) can be used to obtain potential flow solutions for incompressible, inviscid and irrotational flow. The UVLM scheme is widely used for aeroelastic studies. This scheme can be used to obtain a medium fidelity, free wake solution for studying thin airfoils and the associated computational cost is significantly less compared to those of other CFD schemes. Bound vortices are used to model thin airfoils and free vortices are used to model the wake, which is convected with the freestream. To study airfoil oscillators, a co-simulator scheme is used (Roccia, Preidikman, et al., 2017). The scheme consists of a structural simulator to model the airfoil structural support and a fluid simulator to model the fluid flow. At each time step, information is exchanged between the two simulators and the governing equations are iteratively solved until convergence is achieved. As a baseline study, the experimental airfoil oscillator from prior work (Erturk et al., 2010) is modeled by using the co-simulation scheme, and the different system parameters available for the structural spring, the torsional spring, and the piezoelectric circuit are used. Moving forward, by using the co-simulation scheme, one can study various configurations with multiple aerodynamic oscillators.

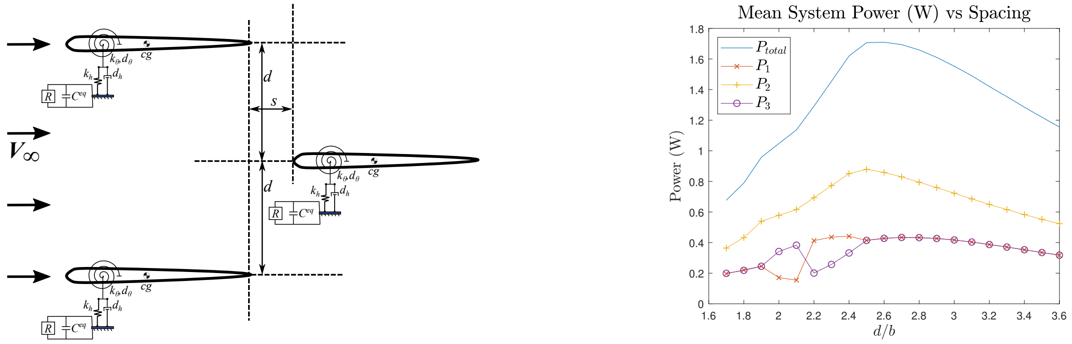
3. RESULTS & DISCUSSION

Researchers have previously studied the effect of freestream speed and and system configuration for a system of two airfoils undergoing flutter oscillations (Roccia, Verstraete, et al., 2020). It was shown that having two oscillators decreased the critical flutter speed of the system. For a self excited system, this would extend the operational regime of the system. In the same paper, the authors studied the effect of spacing between airfoils. As the vertical spacing between the airfoils was gradually increased, the individual airfoil response converged to the mean response observed for an individual oscillator. However, for closer spacing between airfoils, a significant departure from the single oscillator response was observed. This points towards aerodynamic interactions taking place between the oscillators, which alter the overall response of the system. In this section, results obtained for different system parameters are presented and physical insights are gleaned and discussed.

3.1. Effect of number of oscillators

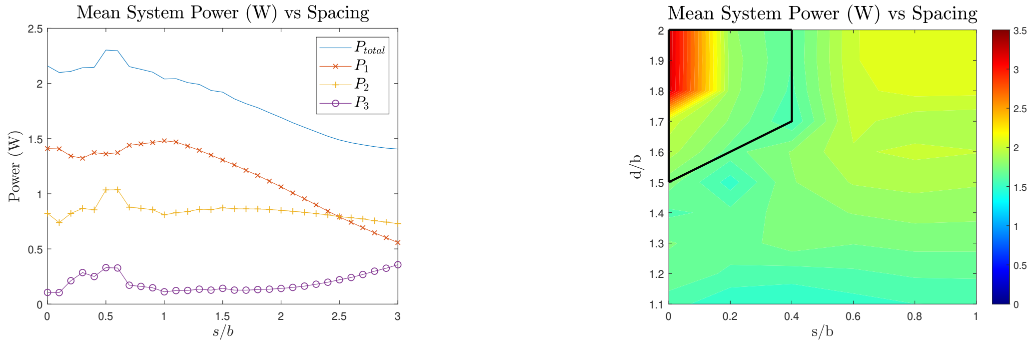
To illustrate the effect the number of airfoil oscillators has on the system response, first, the critical flutter speeds for one to four oscillator systems were found to be 9.45, 7.78, 7.29 and 7.10 m/sec, respectively. The airfoils are stacked vertically and the vertical distance d between the airfoils is set to the semi-chord length b of the airfoils. While the critical flutter speeds were found to decrease with additional airfoils, for a chosen spacing, the improvement in operational range becomes marginal as the number of oscillators is increased form two to three or three to four. It is also seen that with increasing number of airfoils, due to increased aerodynamic interactions, collisions between airfoils can occur at low speeds and these collisions are not ideal from a structural integrity perspective. Beyond the critical flutter speed, it is also of interest to know what an optimal system of airfoil oscillators would be. To that end, systems having two to seven oscillators are simulated. In each case, the airfoils were separated by 0.3 m which is about 2.4 times the semi-chord length b of each airfoil and a freestream speed of 10 m/sec was considered. After the transients have decayed, the mean system power output (averaged over the airfoils) is recorded and and was found to be 0.39, 0.55, 0.45, 0.40, 0.47, & 0.47 W for the system of two oscillators to seven oscillators, respectively. The output is found to have a peak value for the three oscillator case. Hence, while increased number of airfoils would mean an increase in the overall aerodynamic interactions taking place in the system, the nature of the interactions may even attenuate the overall power output.

3.2. Effect of spacing



(a) Oscillator system layout

(b) Parallel configuration



(c) Tandem configuration

(d) Staggered configuration

Figure 1. Effect of configuration on system power output.

The spatial arrangement of oscillators with respect to each other can have an effect on the overall system response. To illustrate this dynamics, for a system of three airfoil oscillators, a parametric study was conducted for a freestream speed of 10 m/sec. A general layout of the system is shown in Fig. 1a. Parallel and tandem configurations refer to configurations wherein the airfoils are arranged vertically and horizontally, respectively. For the chosen configuration, one of the spacing parameters d and s is changed and the other parameter is set to zero. The staggered configuration, which is the most general configuration, is shown in Fig. 1a. In this case, both spacing parameters are varied. The results obtained from the parametric studies are shown in Figs. 1b, 1c, and 1d respectively. A peak output was obtained for the parallel configuration at the spacing of $d/b = 2.6$, fo the tandem configuration at the spacing of $s/b = 0.5$, and for the staggered configuration at the spacings of $d/b = 2.0$ & $s/b = 0.0$. The following discussion is based on these specific cases. With the parallel arrangement. it has been noticed that a periodic system output is obtained and the phase differences between the pitching motions of the oscillators influence the system output (Wu et al., 2015). In that study,for a mechanically driven system of pitching airfoils, it was concluded that a 180° phase difference between the pitching motions of the inner airfoil with respect to the peripheral airfoils resulted in the optimal power output. Here, for airfoils experiencing self-excited flutter oscillations, a similar behavior was observed and in fact the phase difference can be tuned by adjusting the spacing between oscillators. In case of the tandem system. it is seen that a major proportion of the power output is produced by the foremost oscillator, which experiences a uniform freestream. This is because the second oscillator is in the wake of the first oscillator and the freestream is entirely broken by the time it reaches the last airfoil which is seen to have a minimal power output. For the chosen spacing, the second airfoil is found to arrest the flow behind the first airfoil and this increases the pressure and overall aerodynamic loads around this airfoil. This represents an inefficient system, since even though all airfoil oscillators have the same specifications certain oscillators produce a consistently low output. This effect is less pronounced for the parallel case. An arrangement to obtain the best of both configurations is the staggered configuration. The peak mean system output in the staggered case is found to be 3.27 W versus 2.30 W and 1.71 W respectively for the tandem and parallel cases. The airfoils with the least power outputs have values of 0.88 W, 0.33 W, and 0.43 W, respectively. In Fig. 1d the boxed zone is used to enclose the configurations for which a single frequency dominated periodic response is obtained. For the other configurations, the response for all three airfoils showed a significant presence of multiple frequencies in the response. On the contrary, with the responses outside the boxed zone a certain symmetry was observed. The peripheral oscillators in these cases show an approximately equal plunge response amplitude. However, in the boxed zone, one of the peripheral oscillators has a significantly higher power output than the other. For the staggered case, the outputs were 1.76 and 0.88 W for the peripheral oscillators. This was a result of the stagnation zones that were formed for an extended period near the peripheral airfoil and this leads to enhanced aerodynamic loads and an enhanced voltage output.

4. CONCLUSION

For a system of aerodynamically coupled oscillators, nonlinear aerodynamic interactions and power generated were examined through computational studies. The response characteristics for three different oscillator configurations were studied and the merits and drawbacks associated with them were discussed. Staggered configurations of airfoil oscillators have not been previously studied for power generated and they merit further investigations. It is also expected that experimental studies can help advance the understanding of physics of aerodynamic interactions in these systems and also help design energy harvester systems for low wind speeds.

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