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Discrete and periodic vortex loading on a flexible plate; application to energy harvesting and voiced speech production

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ABSTRACT

Flow-induced vibrations of flexible surfaces driven by coherent vortical structures are ubiquitous in engineering and biological flows; from the extraction of fluidic energy via oscillating electro-active polymers to vocal fold dynamics during voiced speech production. These scenarios may involve either discrete or periodic loading conditions due to the advection of vortices past the structure. This work considers, as a function of the vortex production frequency, the fluid-structure interaction that occurs as vortices are propagated tangentially over flexible plates with variable structural properties. Velocity fields are acquired with particle image velocimetry and used to compute the vorticity and pressure fields, while the plate energy is estimated from its kinematics. Primary and secondary peaks in plate deflection amplitude and the plate energy as a function of vortex production frequency are observed at integer fractions of the fundamental plate frequency. At resonance conditions, plate energy relative to discrete vortex loading is increased by approximately three orders of magnitude, while the sub-harmonics increase the plate energy by about two orders of magnitude. Additional physical influences on the energy exchange process, including vortex-to-plate spacing and Strouhal number, are also investigated, detailing the importance of spatial and temporal interactions. The magnitude of the initial plate deflection as the vortex ring approaches the plate, due to persistent vibrations from previous interactions, is shown to retard the time at which the maximum load is applied as the increased relative vortex-to-plate spacing weakens cross-sign vorticity interactions. Finally, plate properties are scaled to model the structural properties of the vocal folds and the effect of intra-glottal vortices on vocal fold dynamics is quantified, where a negligible influence is observed.

1. Introduction

Flow-induced vibrations due to vortical structures have been a topic of interest for decades [1–3]. Vortex production within a flow field may arise for a variety of reasons, including flow separation [1], turbulent boundary layer formation [4], or in the wakes of bluff bodies [5]. If a flexible plate is immersed in a fluid flow, unsteady disturbances in the pressure field will incite vibrations in the structure. Variations in the fluid physics and plate properties can produce a wide range of structural responses [6], where vibrations induced by vortices may be employed to extract energy from the ambient environment by using electro-active polymers, which convert strain energy into electrical energy [7–10]. The extracted energy can be used to power both small and medium-scale devices such as consumer electronics [11], structural health monitors [7] and aquatic tracking systems

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[12]. In energy harvesting applications, flexible plates are often placed in the wake of a bluff body, where a von Kármán vortex street is formed, giving rise to vortices that periodically advect over both sides of the plate, inciting oscillations that can be converted to electrical energy [9,13–17].

Plate dynamics under periodic fluid loading have been investigated for a variety of scenarios in an attempt to increase plate oscillation amplitudes and the subsequent energy extraction. When placed in the wake of a bluff body, the maximum voltage output from piezoelectric plates has been shown to occur when the periodic vortex shedding frequency is matched with the natural frequency of the plate [18]. Higher plate oscillation modes have also been found to lock-on to the shedding frequency of the von Kármán vortex street that forms in the wake, where the amplitude of these modes is correlated with the width of the undisturbed vortex street [19]. Using PIV, it has also been shown that deformation of the membrane is synchronized with the position of the vortices passing over it. In all of these studies, plate oscillations were maximized by matching the vortex production frequency with the fundamental frequency of the plate. This condition is often used as a design criterion for energy harvesting applications; however, the conditions where the frequencies were not matched (off-design conditions) have not been considered.

While most coherent vortical structures, like those found in a von Kármán vortex street, provide cyclic loading, in the more general case, vortices may be generated randomly or at varying frequencies. To this end, some studies have considered the interaction of discrete vortices with deformable surfaces. Peterson and Porfiri [20] reported that approximately 1% of a vortex ring's energy will be transferred into plate strain energy when it normally impacts the tip of a plate. Numerical investigations of similar configurations utilizing a vortex dipole, as opposed to a vortex ring, have explored the influence of Reynolds number, finding a maximum of approximately 5% energy transfer from the vortex dipole to the plate is achievable [21], with recent experimental investigations validating the numerical findings [22].

Goushcha et al. [23] performed an experimental study of vortex rings advecting tangentially over a plate, for both discrete and periodic vortex production. This configuration is analogous to off-design energy harvesting conditions where a shift in flow trajectory may move a flexible structure outside of the wake of a leading bluff body. When two consecutive vortices with a period of vortex production equal to the fundamental period of plate oscillation advected over the plate the maximum deflection amplitude was increased. However, the steady-state plate response to continuous periodic vortex loading, and for varying vortex production frequencies, was not reported.

More recently, a fluid-structure interaction model of the same configuration as Goushcha et al. [23] was developed [24] by coupling a potential flow model with Kirchhoff-Love plate theory [25]. Differences between the numerical and experimental approaches were observed due to insufficient experimental data to fully-validate the numerical model and the inherent assumption of inviscid flow in the potential flow model. There is, therefore, still a lack of understanding regarding the steady-state response of cantilevered plates when subjected to periodic, unilateral loading that is not synchronized with the plate fundamental frequency, and a determination of how this impacts the fluid-plate energy exchange.

Periodic pressure loadings due to vortex advection over a flexible surface are also of interest in the study of voiced speech production [26–29]. Vortices are produced as the glottis (the opening between the vocal folds) forms into a divergent channel during the closing phases of the phonatory cycle, producing an adverse pressure gradient that leads to flow separation and vortex formation within the glottis [29]. Difficulties in definitively determining the impact of intra-glottal vortices on the vocal fold dynamics arise, however, due to the challenge in decoupling the vortex pressure loading from the total aerodynamic loading. Nevertheless, it has been hypothesized that these separation vortices have a significant impact on the vocal fold dynamics, with the reduced core pressure assisting in the rapid closure of the vocal folds, thereby enhancing the resultant acoustical energy content [28,30,31]. To the contrary, lumped-element investigations have shown that when an ad-hoc pressure distribution representative of vortical loadings is applied to the vocal fold surface the influence on the resultant vocal fold dynamics is negligible [32]. Similarly, investigations of vortex-VF interactions using a potential flow model concluded that that the pressure signature arising from the vortex cores had a minimal influence on the vocal fold dynamics [33]. Unfortunately, the ad-hoc estimation of the vortex pressure loading [32], and the non-physiological insertion of the vortices into the flow field [33], does not allow for a definitive interpretation of how intra-glottal vortices influence vocal fold dynamics during normal voiced speech production. Consequently, the importance of vortical structures as an energy transfer mechanism for driving normal voiced speech production remains unresolved.

The current study builds upon previous work [34], where the fluid-structure interaction of a discrete vortex ring advecting tangentially over a cantilevered plate was investigated as a function of vortex separation distance from the plate. This study seeks to elucidate the impact of fluid loading periodicity on the dynamics of a flexible, cantilevered plate, with an emphasis on the time scales that govern the interaction when the vortex production frequency is not synchronized with the fundamental frequency of the plate. As such, the objectives of this study are to: (1) determine how discrete versus periodic vortex loading impacts the fluid-structure interactions for the scenario of vortex rings advecting tangentially over a cantilevered plate, which will be investigated for various plate configurations, specified by a non-dimensional mass parameter; (2) utilize the findings to gain insight into the fields of energy harvesting and voiced speech production. This formulation is particularly advantageous for investigating the influence of vortex advection over the vocal fold surface on phonatory dynamics, as it allows the vortex loading to be decoupled from the aerodynamic loading of the bulk fluid flow; a capability that has not been achievable to date.

The manuscript is outlined as follows: the problem formulation is introduced in §2, the experimental methods are presented in §3, results are discussed in §4, and §5 is left for the conclusions.

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