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# Investigation of vortex development on accelerating spanwise-flexible wings

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ABSTRACT

The effect of spanwise flexibility on the development of leading-edge vortices for impulsively started flat plates at low Reynolds numbers has been investigated. A theoretical model is proposed, based on the Euler–Bernoulli beam theory, coupled with a vortex growth model based on vorticity flux through a leading-edge shear layer. The model was validated for rigid and flexible flat plates undergoing a towing motion at an angle-of-attack of 45°. It is shown that a phase-delay in lift and drag generation occurs between rigid and flexible cases. The model indicates decreasing vorticity along the span as the wing is accelerated and begins to bend. Particle image velocimetry measurements conducted at three different spanwise planes showed a delay in vortex growth along the span, despite a uniform spanwise circulation. This uniform spanwise distribution of circulation is in contrast to the quasi-two-dimensional model, which predicted a reduced circulation near the profile tip where plate motion was delayed. It is therefore concluded that circulation must be dynamically redistributed through vorticity convection during the impulsive motion.



## 1. Introduction

The current development of Micro-aerial vehicles (MAVs) and autonomous underwater vehicles (AUVs) is often inspired by the highly optimized, unsteady propulsion found in nature. Propulsion systems are typically modeled on the motion of flapping insect wings or undulating fish tails, respectively. In the case of swimming animals, evolution has converged on flexible lunate-shaped tail-fins and flukes for four separate aquatic species of independent ancestry, see Hartloper and Rival (2013). A recent investigation by Lucas et al. (2014) identified equivalent flexibility characteristics in animal wings and fins across a large variation in animal size, environment and biological origin. Furthermore, it was shown by Cleaver et al. (2013) that optimally flexible wings oscillating near their natural frequency results in large lift enhancement relative to rigid cases in the presence of a free-tip. In a computational study by Young et al. (2009), the power economy of insect wings was improved by allowing deformations in both camber and twist. The question arises if this wing planform and flexibility can be applied to MAV or AUV design in order to achieve the same impressive flight and swimming performance achieved by natural swimmers and flyers. For instance, Flammang et al. (2011) suggested that a robotic swimmer would have to mimic the active-stiffness of aquatic animals to achieve the same swimming performance. The present study examines a rapid

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**Nomenclature**

| | |
|---|---|
| $\alpha$ | angle of attack |
| $\varphi$ | deflection angle |
| $\Gamma$ | circulation |
| $\mu$ | mass distribution |
| $\rho_f$ | fluid density |
| $\rho_s$ | solid density |
| $\xi_n$ | generalized coordinate |
| $\omega_i$ | vorticity |
| $\omega_n$ | eigenfrequency |
| $A$ | structural area |
| $b$ | span |
| $c$ | chord |
| $C_N$ | coefficient of normal force |
| $d$ | shear-layer thickness |
| $D$ | drag |
| $EI$ | bending stiffness |
| $\tilde{f}_n$ | generalized force |
| $L$ | lift |
| $\tilde{m}_n$ | generalized mass |
| $m'$ | mass per unit span |
| $m_{\mathrm{am}}$ | added mass |
| $N(x_t, t)$ | load distribution |
| $t^*$ | dimensionless time |
| $\Delta t^*$ | ramp time |
| $u_\Gamma$ | vortex convection velocity |
| $u_b$ | bending velocity |
| $u_\infty$ | local free-stream velocity |
| $u_{\mathrm{eff}}$ | effective velocity |
| $u(0, t)$ | inner shear-layer velocity |
| $u(d, t)$ | outer shear-layer velocity |
| $x_\Gamma$ | vortex displacement |
| $x_n$ | chord-normal coordinate |
| $x_t$ | spanwise coordinate |
| $x_s$ | chordwise coordinate |
| $w(x_t, t)$ | wing deflection |
| $W_n$ | eigenmode |

acceleration from rest, similar to the escape response of a prey animal. This escape behavior often exploits profile flexibility to accelerate large volumes of fluid from rest, as shown by Gazzola et al. (2012). Herein, an impulsively started flat plate will be considered as an analog to an animal wing or fin motion from rest.

At the Reynolds numbers experienced by natural swimmers and flyers, unsteady effects dominate the generation of high lift forces required for rapid accelerations. During a rapid wing or fin motion the flow detaches from the body in a coherent leading-edge vortex (LEV) and the resulting force generation is primarily due to the low pressure of the local suction. Studies have shown that the development of LEVs is common throughout the range of Reynolds numbers $\mathrm{Re} \le \mathcal{O}(10^4)$, as shown by Garmann et al. (2013), which corresponds to typical flow regimes experienced by MAVs, as discussed by Torres and Mueller (2004). According to a recent study by Pitt Ford and Babinsky (2013), the LEV is the dominant contributor to circulation near accelerating profiles at low Reynolds numbers. Therefore the stability of such LEVs is crucial for high-lift production at low Reynolds numbers. Although the mechanism of LEV stability is not understood, Kim and Gharib (2011) identified delayed LEV detachment for spanwise flexible profiles in the presence of a free tip. In order to gain an understanding of LEV development with respect to flexible wings, a hypothesis regarding how a phase-delay in effective flow velocity could affect the LEV growth along the span is derived.

An LEV can be idealized as a concentrated vortex line along the leading-edge on the suction surface of the wing; see Beem et al. (2012). Recently, Rival et al. (2014) found that the stable attachment of the LEV is determined by its size in relation to the wing's chord length. As the LEV grows, the rear stagnation point moves along the chord until it reaches the trailing edge, at which point the LEV separates and detaches from the wing. Thus, stable attachment of the LEV is limited by its size and growth rate, which is thought to be influenced by vorticity transport within the LEV:

$$\underbrace{\frac{\partial \omega_i}{\partial t}}_{\text{change in vorticity}} + \underbrace{u_j \frac{\partial \omega_i}{\partial x_j}}_{\text{convection}} = \underbrace{\omega_i \frac{\partial u_i}{\partial x_j}}_{\text{tilting and stretching}} + \underbrace{\nu \frac{\partial^2 \omega_i}{\partial x_j \partial x_j}}_{\text{diffusion}}, \tag{1}$$

where $\omega$ is vorticity, $u$ is velocity and $\nu$ is the kinematic viscosity. The terms from left to right are the rate of change in vorticity due to unsteadiness, convection of vorticity, vortex stretching and diffusion, respectively. The Reynolds numbers considered in this study are assumed to be sufficiently large so that the time scales of diffusion are much slower than the time scales associated with LEV growth and convection. This conclusion is also supported by Cheng et al. (2013) where the diffusion terms for similar Reynolds numbers were deemed negligible. This leaves two terms, which contribute to vortex growth: the convection term and the tilting/stretching term. As the LEV is continuously fed with vorticity-containing mass through the shear layer, it is crucial that vorticity is convected or that vortex stretching occurs in order to maintain vortex size and delay LEV detachment. Vorticity convection can only take place if both a spanwise variation in vorticity and a non-zero spanwise flow are provided. For the presence of vortex stretching it is necessary that the spanwise velocity varies over the span.

The gradients necessary for vorticity transport can be produced by either spanwise profile flexibility or a spanwise phase-delay in effective velocity. Therefore, the purpose of the present study is to determine the role of spanwise profile flexibility and spanwise phase-delay on LEV growth. Specifically, this study intends to determine how a spanwise variation in vortex growth affects lift and drag production under impulsively started accelerations.