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# A parametric investigation of the propulsion of 2D chordwise-flexible flapping wings at low Reynolds number using numerical simulations

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## ABSTRACT

This paper presents a numerical investigation of the effects of chordwise flexibility on flapping wings at low Reynolds number. The numerical simulations are performed with a partitioned fluid–structure interaction algorithm using artificial compressibility stabilization. The choice of the structural dimensionless parameters is based on scaling arguments and is compared against parameters used by other authors. The different regimes, namely inertia-driven and pressure-driven wing deformations, are presented along with their effects on the topology of the flow and on the performance of a heaving and pitching flapping wing in propulsion regime. It is found that pressure-driven deformations can significantly increase the thrust efficiency if a suitable amount of flexibility is used. Significant thrust increases are also observed in zero pitching amplitude cases. The effects of the second and third deformation modes on the performances of pressure-driven deformation cases are discussed. On the other hand, inertia-driven deformations generally deteriorate aerodynamic performances of flapping wings unless the behavior of the wing deformation is modified by the presence of sustainable superharmonics in a way that produces slight improvements. It is also shown that wing flexibility can act as an efficient passive pitching mechanism that allows fair thrust and better efficiency to be achieved when compared to a rigid pitching–heaving wing.

## 1. Introduction

The capacity of insects and birds to fly as well as the way different marine animals swim is fascinating. Indeed, each of these species has a specific locomotion mode that involves aerodynamic or hydrodynamic mechanisms. Although man has developed strong technologies that allow him to fly and swim, most of these technologies are based on stationary flow dynamics (submarines, fixed-wing and rotary-wing aircraft). On the contrary, only a few flying and swimming species use steady flow mechanisms. Most of them use flapping wings or fins with different kinematics. Indeed, it is now well known that devices based on steady aerodynamics such as fixed wings and rotors are not efficient at low Reynolds number. Moreover, the classical theory of aerodynamics predicts insufficient lift to support the weight of insects (Ansari and

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## Nomenclature

| | |
|---|---|
| $A$ | beam cross-section area |
| $a$ | linear system matrix coefficient |
| $\mathbf{b}$ | linear system right-hand side |
| $b$ | wing span |
| $C$ | external moment on a beam |
| $\mathbf{c}$ | relative convective velocity |
| $c$ | chord length |
| $C_P$ | power coefficient |
| $C_p$ | pressure coefficient |
| $C_T$ | thrust coefficient |
| $\mathbf{d}$ | displacement vector field |
| $E$ | Young modulus |
| $E^*$ | normalized rigidity |
| $e$ | wing thickness |
| $e^*$ | normalized wing thickness |
| $\tilde{e}$ | Green–Lagrange strain |
| $\mathbf{F}$ | force vector |
| $f$ | frequency |
| $f^*$ | reduced frequency |
| $\mathbf{H}$ | momentum equation discrete operator |
| $h$ | heaving displacement |
| $h^*$ | normalized heaving amplitude |
| $h_0$ | heaving amplitude |
| $I$ | beam cross-section area moment of inertia |
| $I'$ | beam cross-section area moment of inertia per unit span |
| $M$ | internal bending moment in a beam, moment |
| $N$ | internal normal force in a beam |
| $\hat{\mathbf{n}}$ | unit surface normal vector |
| $P$ | power |
| $p$ | pressure field |
| $R$ | residual functional |
| $Re$ | Reynolds number |
| $S$ | surface, external shear force on a beam |
| $T$ | traction force, thrust force |
| $t$ | time |
| $U_\infty$ | freestream velocity |
| $V$ | volume |
| $\mathbf{v}$ | velocity vector field |
| $\hat{\mathbf{v}}$ | control surface velocity |
| $w$ | lineic load on a beam |
| $\mathbf{x}$ | coordinate vector |
| $x_\mathrm{P}$ | pitching axis position (pivot point) |
| $x_\mathrm{P}^*$ | normalized pitching axis position |
| $\alpha$ | angle of attack |
| $\alpha_\mathrm{Eff}$ | effective angle of attack |
| $\alpha_{T/4}$ | angle of attack at the quarter period |
| $\tilde{\chi}$ | curvature of the deformed beam |
| $\boldsymbol{\delta}$ | displacement vector in rotated frame |
| $\delta_P^*$, $\delta_I^*$ | normalized flexibility |
| $\eta$ | efficiency |
| $\mu$ | dynamic viscosity |
| $\nu$ | kinematic viscosity |
| $\omega$ | vorticity field ($z$-component) |
| $\psi$ | finite-element shape function |
| $\tilde{\psi}$ | artificial compressibility coefficient |
| $\rho$ | density |
| $\rho^*$ | density ratio |
| $\Sigma$ | pressure-to-inertia ratio |
| $\boldsymbol{\sigma}$ | Cauchy stress tensor field |
| $\tau$ | shear load |
| $\theta$ | pitching angle |
| $\theta_0$ | pitching amplitude |
| $\theta_\mathrm{Eff}$ | effective pitching angle |

Knowles, 2006; Dickinson et al., 1999; Ellington et al., 1996). Therefore, it is clear that the unsteady mechanisms account for the actual performance of flapping wings. Ansari and Knowles (2006) and Sane (2003) present a review of these unsteady flow mechanisms which are the clap-and-fling mechanism (Weis-Fogh, 1973), the leading edge vortex and delayed stall (Walker, 1931; Maxworthy, 1979; Ellington et al., 1996), the Wagner effect, the wing–wake interactions, the apparent mass effect, and the Kramer effect.

The study of flapping wings was, consequently, deeply investigated in the last few years. Both numerical and experimental studies were carried out to assess this complex problem (Anderson et al., 1998; Isogai et al., 1999; Pedro et al., 2003; Young and Lai, 2007). Recent reviews by Shyy et al. (2008, 2010), Ansari and Knowles (2006), and Platzer et al. (2008) also provide a good overview of the works that have been done in the field. One of the aspects of flapping wings that received a lot of attention recently is the wing flexibility. While many papers have been published on the subject, the effects of wing flexibility remain to be completely understood. As such, this paper aims at providing additional insights of this phenomenon.

One of the early study of the effect of flexibility on the propulsion of an oscillating airfoil is presented by Katz and Weihs (1978). They study pitching and heaving flexible massless airfoils that deform passively in 2D. Therefore, all scenarios considered involve strong fluid–solid interactions since only the pressure forces are deforming the airfoil, which is the case in most marine applications. They found that flexibility reduces the overall lift on the airfoil. However, because of the deformation, the lift orientation is nearer the direction of advance and, consequently, higher efficiency is to be expected. In general, they observe that chordwise flexibility reduces the thrust but increases the efficiency. When the flexibility remains moderate, the loss of thrust is tolerable but in the case of very flexible airfoils, the thrust is reduced below practical levels even if the efficiency still increases.

Eldredge et al. (2010) and Toomey and Eldredge (2006) studied the effects of chordwise flexibility on a flapping wing undergoing hovering kinematics using 2D numerical simulations. Their numerical method is based on a Lagrangian vortex method strongly coupled with a solid-body motion solver that mimics flexible wing by using rigid parts linked elastically. Similar to Katz and Weihs (1978), they observe the general trend that wing flexibility both reduces the aerodynamic forces