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Video measurements of instantaneous forces of flapping wing vehicles ☆

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ABSTRACT

Flapping wings for small aerial vehicles have revolutionary potential for maneuverability and endurance. Ornithopters fail to achieve the performance of their biological equivalents, despite extensive research on how animals fly. Flapping wings produce peak forces due to the stroke reversal of the wing. This research demonstrates in-flight measurements of an ornithopter through the use of image processing, specifically measuring instantaneous forces. Results show that the oscillation about the flight path is significant, being about 20% of the mean velocity and up to 10 g's. Results match forces with deformations of the wing to contrast the timing and wing shape of the upstroke and the downstroke. Holding the vehicle fixed (e.g. wind tunnel testing or simulations) structural resonance is affected along with peak forces, also affecting lift. Non-contact, in-flight measurements are proposed as the best method for matching the flight conditions of flapping wing vehicles.

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1. Introduction

Current research into the flight of flapping wing air vehicles with wingspans below 0.3 m, denoted miniature aerial vehicles (MAV), has identified the enormous complexity of flight at this scale compared to fixed wing aircraft [1–3]. New approaches to data acquisition and analysis are required to understand how to exploit aerodynamic and structural interaction and improve vehicle performance [4]. This paper measures the undisturbed flight of a flapping wing vehicle (ornithopter).

Many ornithopters exist which are able to maintain sustained flight. Simple designs use a twisted rubber band connected to linkages that flap the wings. Motors and remote controls allow longer and more controlled flight [5]. Despite the plethora of designs available, the underlying physics and the aerodynamic mechanisms that improve performance are not well understood. As a result, effective controllers for a flapping airframe, especially in gusty or confined environments, have not been developed. Better understanding could lead to design changes that expand or refine capacities, such as the ability to

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Nomenclature

A	amplitude of flap (m)
$\hat{A}$	acceleration based on locally weighted regression model (m/s^2)
a_0, a_1, a_2	polynomial coefficients of local model
B	locally weighted regression sample time ([–, s, s^2])
C_i	coordinates of vehicle in the i^{th} image (m)
$\hat{C}$	locally weighted regression of C (m)
$\hat{C}^{(j)}$	the filtered body center path for the j^{th} flap cycle (m)
$\hat{C}^{(j),*}$	the j^{th} normalized flap cycle path (m)
$\hat{C}^{ref}$	the reference filtered body center path (m)
$\hat{C}^*$	collection of all normalized flap cycle paths (m)
E	total error of marked points to transformed template points (m)
f	flapping frequency (Hz)
g	1 earth gravity, 9.806 m/s^2
h	span parameter for locally weighted regression (s)
I	total number of images
i	current iteration
k	index of reference feature dot
N	number of feature dots
$R(\theta)$	planar rotation matrix of angle θ
S_j	amplitude scaling parameters for the j^{th} flap cycle path
S_j^*	normalized amplitude scaling parameters for the j^{th} flap cycle path
St	Strouhal number
T	shifted and scaled time for locally weighted regression
t	time (s)
t_i	the i^{th} shifted and scaled time sample of T
U	flight speed (m/s)
$\overline{U}$	the set of indexes of dots that were matched in the current image
$\hat{V}$	velocity based on locally weighted regression model (m/s)
V_j	amplitude shifting parameters for the j^{th} flap cycle path (m)
V_j^*	normalized amplitude shifting parameters for the j^{th} flap cycle path (m)
W	locally weighted regression weighting matrix
w	weighting function for locally weighted regression
X_i	coordinates of feature dots in the i^{th} image (m)
$\overline{X}$	template of feature dots (m)
$\hat{X}$	marked dots on current image (m)
$\tilde{X}$	prediction of locations of feature points in current image (m)
$x_{i,n}, y_{i,n}$	coordinates of the n^{th} feature dot in the i^{th} image (m)
$\overline{x}_n, \overline{y}_n$	coordinates of the n^{th} feature dot in the template (m)
β_j	time shifting parameters for the j^{th} flap cycle path (s)
β_j^*	normalized time shifting parameters for the j^{th} flap cycle path (s)
Δ	change in vehicle position between the last two frames (m)
δ_x, δ_y	translation of template to matched points in current image (m)
θ	rotation of template to matched points in current image (rad)
ω_j	time scaling parameters for the j^{th} flap cycle path
ω_j^*	normalized time scaling parameters for the j^{th} flap cycle path
[1]	column vector of 1's
$\lceil \cdot \rfloor$	square matrix with $\cdot$ along the diagonal and 0's otherwise
$\lVert \cdot \rVert_2$	L$_2$ norm of the function

hover or perch [6]. In addition, without a functional understanding, designs will be ad hoc and suboptimal. Design optimization is important since payload capacity and power required typically limit practical applications.

Two main challenges arise when testing a small ornithopter. The small payload capacity limits sensor size, weight and placement. For this reason, non-contact methods are preferred. Videogrammetry methods are complicated by the large range of motion of the wings. Large motion causes dramatic changes in appearance and occlusions of features of interest. Second, flight is unsteady so the time history needs to be considered. Cycle average results can be used to design outer-loop controllers, assuming that the aerodynamics form a stable limit cycle, but cannot suggest how to design a better vehicle or determine strength requirements. The periodic effects of vortex shedding in force and wing shape need to be isolated in time in order to relate them to design parameters.

Fixed mounts are traditionally justified by assuming straight level flight [7]. As the wings flap up and down, the fuselage absorbs some of the peak force attenuating its effect by distributing it over a cycle [3,8]. Traditionally, test mounts have fixed the mounting point, so that the instantaneous force is measured. Magnetic levitation has been investigated, primarily for removing flow disturbances, but has been adapted to provide variable compliance and force measurement [9]. Not absorbing the peak forces may disrupt the natural structural response and the boundary layer for flapping wings. Just as stiffening a boundary condition increases vibration modes, the rigid mount alters the flapping mechanism resonance. The kinetic energy stored by the vehicle, if stored as strain energy of the wings, would cause substantial deflections altering the aerodynamic forces. The flexibility of flapping wings makes them sensitive to mounting stiffness.

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