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## Method of reconstructing the wing-beat movement from the body pitch data of an ornithopter

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### 1. Introduction

The flight dynamic of ornithopter has been widely studied: authors used often airplane like models (Sanchez-Laulhe et al. 2020) but some others considered the sinusoidal flapping wings movement in their model (Norberg 1985). In an ornithopter such as the Metafly developed by XTIM (Van Ruymbeke 2013), the flapping of the wings creates an intra-flapping pitch: the identification of a transfer function model between the wingbeat and the intra-flapping pitch has been recently investigated using the wing orientation captured by a motion capture system (Ndoye et al. 2021).

This present study suggests a method to reconstruct the flapping movement (i) only from the body pitch orientation recorded from a motion capture system or a gyroscope and (ii) without using the wing orientation captured by a motion capture system.

First a description of the MetaFly and the data acquisition procedure is given. Then, an explanation about how to reconstitute the flapping wings signal from the intra-flapping pitch and the mechanical specifications is given. Finally, a comparison is done between the model identified with the ground-truth wing-beat angle and the reconstructed wing-beat signal.

### 2. Methods

#### 2.1. MetaFly's description and experimental setup

The Metafly (mass: 10 grams, body length: 190mm, wingspan: 290mm) had a total wing-stroke amplitude of  $2 \cdot \beta_{max} = 55^\circ$  (see Figure 1b). These mechanical characteristics applied by the miniature motor have been here assumed to be constant in flight.

Three reflective markers were placed in the MetaFly to create an object 'body' (Figure 1c) whose ground-truth position and Orientation were taken by the Vicon motion capture system (MoCap). The body pitch was therefore captured (see Figure 2).

The intra-flapping pitch is considered as the AC component of the body pitch. A Butterworth filter

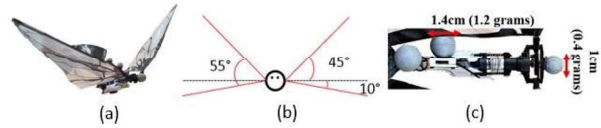


Figure 1. (a) Metafly. (b) Total wingstroke amplitude  $55^\circ$ ; upstroke  $45^\circ$ ; down-stroke  $10^\circ$ . (c) 'body' markers.

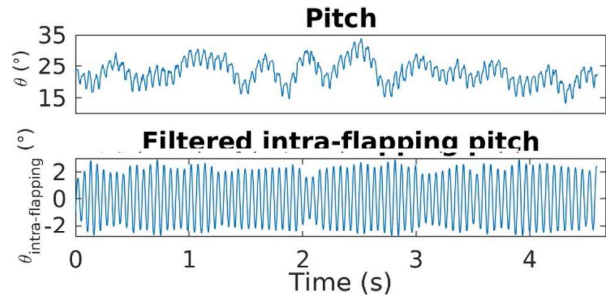


Figure 2. Body pitch recorded from motion capture system; Intra-flapping pitch from filtered value of the body pitch.

was applied between 11 Hz and 24 Hz to extract this intra-flapping pitch (Figure 2).

#### 2.2. Reconstructing the wing-beat sinusoidal movement

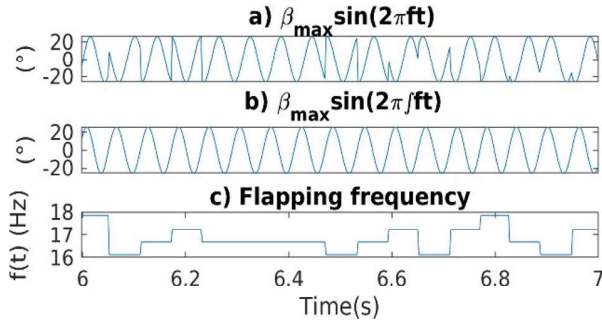
By construction, the wing beat is a sinusoidal movement whose frequency varies according to the rotation speed of the miniature motor (Van Ruymbeke 2013) (which is unknown in the present case). Knowing that the intra-flapping pitch is produced by the wing-beat, the intra-flapping pitch frequency is identical to the flapping wing frequency. The idea is to compute the frequency for each wing-beat, i.e. at each rising front of the intra-flapping pitch oscillations. Hence, it is possible to reconstruct the wing-beat movement  $\beta(t)$  as simple sinus as follows:  $\beta_{max} \sin(2\pi f(t)t)$ .

We deduced the flapping frequency in a discrete manner. Therefore, two points needed to be corrected to better reconstruct the wing beat movement from only the body pitch: (i) the phase switch peaks due to the frequency discrete change (Figure 3a), and (ii) the phase shift between  $\beta_{max} \sin(2\pi \int f t)$  (Figure 3b) and  $\theta_{intra-flapping}$ . To correct the phase switch, the following signal processing equations were used:

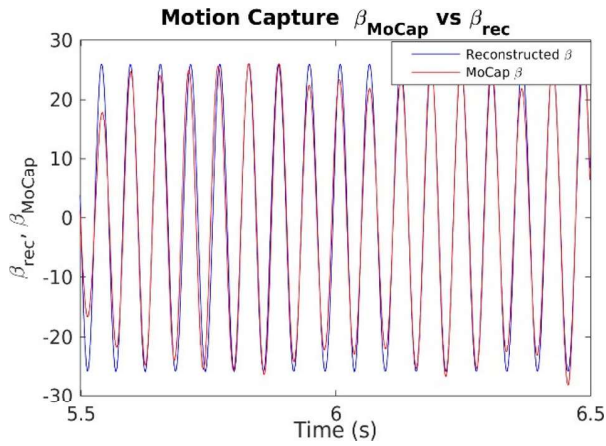
$$\omega(t) = \frac{d\phi(t)}{dt} \Rightarrow f(t) = \frac{1}{2\pi} \omega(t) = \frac{1}{2\pi} \frac{d\phi(t)}{dt} \quad (1)$$

where  $\omega(t)$  is the instantaneous angular frequency,  $\phi(t)$  is the instantaneous phase and  $f(t)$  the instantaneous frequency. We can deduce:

$$\phi(t) = 2\pi \int f(t) dt \Rightarrow \sin(\phi(t)) = \sin\left(2\pi \int f(t) dt\right) \quad (2)$$



**Figure 3.** Correction of the phase switching peaks: a) raw and b) reconstructed sinus function from the frequency deduced in a discrete way in c).



**Figure 4.** Flapping angle signals comparison.

**Table 1.** Parameters of 1 zero and 2 poles model of intra-flapping pitch dynamics (Ndoye et al. 2021).

	Model identified with $\beta_{meas}$	Model identified with $\beta_{rec}$
$K$	5.60	2.71
$\tau_z$	24.74	36.95
$\tau_{p1,2}$	$-29.48 \pm 90.99i$	$-15.22 \pm 99.73i$
$\zeta$	0.31	0.15
$w_n, f_n$	95.66 rad/s, 15.22 Hz	100.89 rad/s, 16.06 Hz

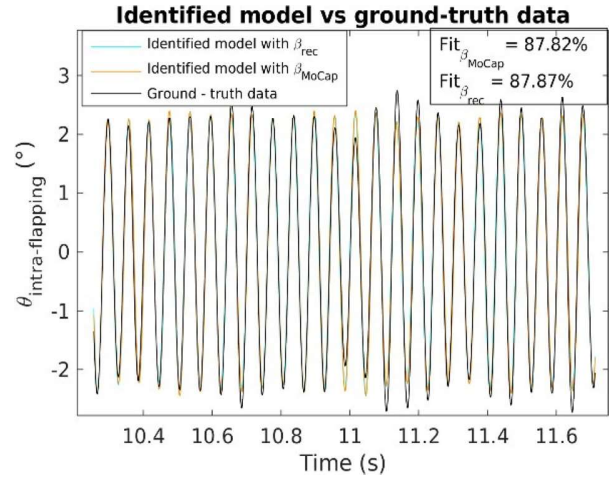
Finally, to correct the phase shift between the intra-flapping pitch signal and the flapping wing signal, a peak detection method was used:

Find peaks of  $\theta_{intra-flapping}$  and their time location  
 Find peaks of  $\beta_{max} \sin(2\pi \int f t)$  and their location  
 $\delta t \leftarrow peaks_{\theta_{intra-flapping}} - peaks_{\beta_{max} \sin(2\pi \int f t)}$   
 $\beta_{rec} \leftarrow \sin((2\pi \int f(t) dt) + \delta t)$

### 3. Results and discussion

Figure 4 shows the wing beat movements: the reconstructed wing beat movement follows accurately the ground-truth wing beat movement.

As an example, we now used this reconstructed wing-beat movement  $\beta_{rec}$  to identify the model of the



**Figure 5.** Comparison between ground truth and intra-flapping pitch models. One model is identified using the reconstructed wingbeat movement  $\beta_{rec}$  and the second one is identified using the ground-truth wingbeat  $\beta_{MoCap}$  as measured by MoCap.

intra-flapping pitch dynamics and compared it with recent results done with  $\beta_{MoCap}$  (Ndoye et al. 2021). The identification was done using MATLAB's *System Identification Toolbox*. Table 1 shows a comparison between the parameters identified with the ground-truth wing-beat movement and the reconstructed wing-beat movement. Note that both give a similar natural frequency. Figure 5 demonstrates the similarities between the identified models. Identifying with  $\beta_{MoCap}$  gave a fit of 79.93%, whereas the model identified with  $\beta_{rec}$  fitted the experimental data to a 85.95%. While validating with another data set,  $\beta_{MoCap}$  gave a fit of 87.82% and the model identified with  $\beta_{rec}$  fitted the experimental data to 87.87%.

### 4. Conclusions

This article showed how to reconstruct the flapping wing movement from only the body pitch measurement of an ornithopter. The ground-truth and the reconstructed flapping movement are very similar (Figure 4). Therefore, the reconstructed wingbeat can be used for modeling. It will allow us to avoid putting additional markers or sensors on the wings adding mass and creating unwanted aerodynamic effects. However, this study assumed that the wing is rigid with constant wingstroke amplitude and does not consider the effect of aerodynamic forces on the wing in flight.

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## Disclosure statement

No potential conflict of interest was reported by the authors.

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