Ornithopter's intra-flapping body pitch highly depends on wingbeat frequency

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1. Introduction

Many recent studies on flapping-wings UAV (Ruffier 2018) focused on the dynamic model in the vertical plane. Some authors modeled the flapping-wings UAV using airplane-like model (Sanchez-Laulhe et al. 2020) without considering the intra-flapping dynamics while others considered a sinusoidal motion (Norberg 1985).

During flight tests with Metafly developed by XTIM, we noticed that the flapping of wings creates a small body pitch oscillation of about ± 5° maximum amplitude called intra-flapping pitch.

In the first section, a complete description of the MetaFly and its specifications will be given. Subsequently, the experimental setup will be described as well as the method used to obtain the I/O data. Then, the dynamic model of the Metafly will be identified using experimental flight data and the identification results will be discussed in the last section.

2. Ornithopter description

The Metafly is very small and lightweight compared to existing ornithopters. Table 1 shows its main specifications.

Length	190 mm
Wingspan	290 mm
Wing chord	85 mm
Wing amplitude	55°
Flapping frequencies that keep the Metafly in the air	13-20 Hz
Mass / Mass with markers	10 / 13.2 grams
Flight duration	8 minutes

Table 1: Metafly specifications

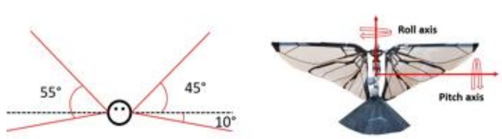

Figure 1: (Left) Wing total amplitude 55°; upstroke amplitude 45°; downstroke amplitude 10°. (Right) MetaFly pitch and roll axis.

The flapping wing mechanism designed by XTIM and patented by Van Ruymbeke (2013) gives a continuous alternative rotation movement of the wings. A miniature two-stages planetary gearset system connects the DC motor powered with a 3.7V liPo battery to the crank with a reduction up to 385. The reduction is set to 36 for the Metafly. Fig. 2 shows this flapping wing mechanism. The rotation of the crank causes the alternative rotation of the slideway around the wing L axis (this rotation is possible thanks to the slide linkage between the crank and the slideway). Gear L (fixed to the slideway) drag along gear R that will rotate around wing R axis at the same speed and symmetrically to the slideway. By connecting the left wing to the slideway and the right wing to Gear R, we obtain a continuous and synchronized alternative wingbeats.

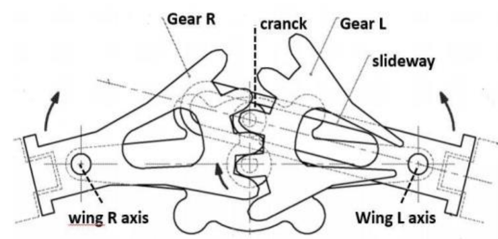

Figure 2: Metafly flapping wing mechanism (Van Ruymbeke 2013)

3. Experimental setup

To record and analyze the movements of the MetaFly, a VICON motion capture was used. The Vicon motion capture system was composed of a set of cameras emitting infrared light reflected by markers: the position and the orientation (quaternion) of the defined rigid body was given through VICON TRACKER software.

During the flight tests, two rigid bodies were recorded: (i) "wing" and (ii) "body" (Fig. 3). The flapping wings movement was obtained by calculating the quaternion between the "wing" orientation and the "body" orientation to isolate the wingbeat movement. The body pitch was directly obtained from the rigid body "body". Fig. 1 (right) shows the pitch and the roll axis.

Figure 3: Markers of rigid bodies "wing" (left) and "body" (right)

We observed during forward flight tests that the wingbeat created intra-flapping pitch. The VICON motion capture can lose track when the Metafly flies outside the detection volume (4x6x3 m^3) or report data with outliers due to e.g. markers occlusion. Consequently, only the parts where the Metafly was detected were selected and merged to identify the mathematical model (see Fig. 5, blue samples).

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4. Modeling of the intra-flapping pitch

Throughout the flight tests, we made two observations. First, the wingbeat movement causes an intra-flapping pitch at the same frequency. Second, the amplitude of the intra-flapping pitch increases until a certain value of the frequency (resonance) and starts decreasing. This is very similar to the behavior of dissipative systems subject to forced oscillations with low damping. Therefore, we chose a model with two poles to describe these dynamics. A zero is added to increase stability. The transfer function between the intra-flapping pitch, $\theta_{intra-flapping}$, and the wingbeat $\beta(s)$ is therefore reported in Equation 1.

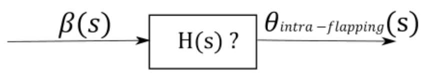

Figure 4: Transfer function model with input $\beta(s)$ and output $\theta_{intra-flapping}(s)$

$$H(s) = \frac{\theta_{intra-flapping}(s)}{\beta(s)} = \frac{K(\tau_2 s+1)}{(\tau_{p1}s+1)(\tau_{p2}s+1)} \qquad \text{(Eq. 1)}$$

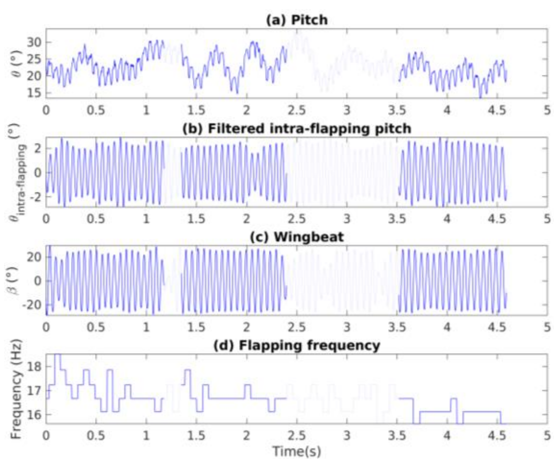

Figure 5: Effect of wingbeat movement on intra-flapping pitch. The three blue samples were merged to identify the dynamics using MATLAB. The excitations frequencies are limited by the flight envelope of the Metafly. The aerostructure creates a low frequency mode (~2 Hz, (a))

In order to extract the intra-flapping pitch from the Metafly pitch during its 3D flight, a Butterworth filter was applied between 11 Hz and 24 Hz. Note that the intra-flapping pitch is the AC component of the Metafly body pitch (Fig. 5).
MATLAB's System Identification Toolbox was used to identify the parameters of the transfer function H(s) from $\beta(s)$ and $\theta_{intra-flapping}(s)$ real data.

5. Results

The parameters values were found to be:

$K, \tau_z, \tau_{p_{1,2}}$	4.04, 8.38, -21.92 ± 101.15i
ζ, ω_n, f_n	0.21, 103.5 rad/s, 16.47 Hz

Table 2: Model parameters

The identified model fits the identification data to a 79.93% percentage. Fig. 6 shows that a fit of 87.82% is obtained by validating this model with another dataset. Hence, one can say that the model H(s) (eq. (1)) accurately represents the intra-flapping pitch dynamics of the Metafly. While analyzing the frequency response of the identified transfer function (Fig. 6, Bode diagram), one could observe a resonance effect at 16.51 Hz. One should note that the value of this frequency will depend on the biomimetic bird mass. This frequency was obtained with a mass of 1.2g on the wings, compared to the original wing mass of 0.42g.

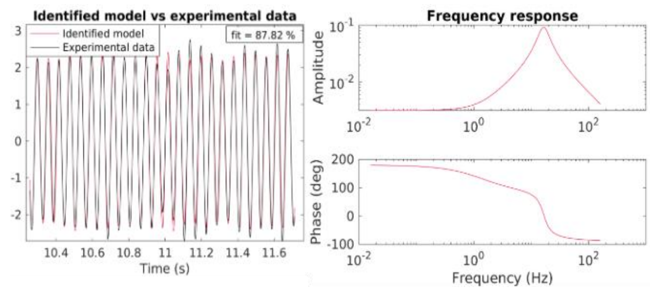

Figure 6: Validation with separated data (left). Bode diagram of H(s) (right)

6. Conclusions

First, a VICON motion capture was used to track the wingbeat movement around the roll axis as well as the body pitch. During these tests, a resonance effect in the intra-flapping pitch was observed at 16.51 Hz. The model fitted the estimation data to 79.93% and the validation data to 87.82%. It could be interesting for future work to investigate (i) the effect of the mass of wing markers on the "resonant" frequency of intra-flapping pitch dynamics, (ii) the use of markerless technologies and (iii) the effect of aerodynamic forces on the wingbeat during aggressive maneuvers.

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