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Free flight force estimation of a 23.5 g flapping wing MAV using an on-board IMU

Matěj Karásek, Andries J. Koopmans, Sophie F. Armanini, Bart D.W. Remes and Guido C.H.E. de Croon¹

Abstract—Despite an intensive research on flapping flight and flapping wing MAVs in recent years, there are still no accurate models of flapping flight dynamics. This is partly due to lack of free flight data, in particular during manoeuvres. In this work, we present, for the first time, a comparison of free flight forces estimated using solely an on-board IMU with wind tunnel measurements. The IMU based estimation brings higher sampling rates and even lower variation among individual wingbeats, compared to what has been achieved with an external motion tracking system in the past. A good match was found in comparison to wind tunnel measurements; the slight differences observed are attributed to clamping effects. Further insight was gained from the on-board rpm sensor, which showed motor speed variation of $\pm 15\%$ due to load variation over a wingbeat cycle. The IMU based force estimation represents an attractive solution for future studies of flapping wing MAVs as, unlike wind tunnel measurements, it allows force estimation at high temporal resolutions also during manoeuvres.

I. INTRODUCTION

Micro Air Vehicles (MAVs) with flapping wings are an attractive alternative to common multi-rotor designs, as they have a potential of combining precise and highly manoeuvrable hovering flight with energy efficient forward flight. Reliable estimation of forces generated by flapping wings is important for understanding the underlying aerodynamic mechanisms, but also for development of flight dynamics models, which can subsequently be used for control design.

The traditional experimental approach is wind tunnel testing, where the MAV is fixed and the reaction forces are measured with a force balance, e.g. [1], [2], [3]. Nonetheless, these tests can only be conducted for constant speeds. In addition, the conditions differ from free flight since the body oscillations, which would occur in free flight due to flapping, are constrained. This restriction can be removed to a certain extent by a specially devised tether [4].

Recently, the development of external motion tracking systems allowed to estimate the in-flight forces from recorded temporal evolutions of body position and orientation [5], [6], [7]. In general, an agreement has been reported between the in flight estimates and wind tunnel measurements, although differences were found in the direction of the wing stroke [8]. These were attributed to structural vibrations of the MAV body, which can contaminate the force balance measurements depending on the clamping position. Besides, the external tracking allowed to capture also flight under non-steady conditions and was used for system identification, first employing time-invariant linear modelling approaches [5],

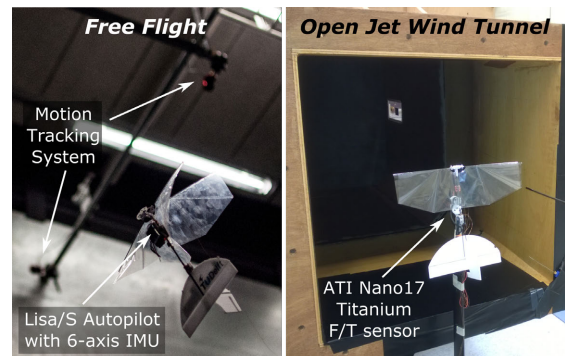


Fig. 1. Free flight forces are estimated from high temporal resolution on-board IMU data assuming rigid body dynamics (left). The results are compared to wind tunnel force measurements (right).

[9], later extending the model with a time variant part to also include the sub-flap dynamics [10].

Nevertheless, the sampling frequency of the tracking system was found to be a limiting factor, especially for studying the sub-flap effects [8]. The body position from the tracking system has to be differentiated twice to get the accelerations needed for force estimation via rigid body dynamics. This amplifies the errors in the tracking data and introduces a significant filtering effect. It was shown that 200 Hz position sampling results in a 32 Hz cut-off frequency in acceleration, only 2.5 times the flapping frequency of the studied MAV.

To overcome these limitations, we propose to use, similar to [11], an on-board IMU that captures the necessary accelerations directly and at high sampling rates. On an example of the DelFly II flapping wing MAV we demonstrate, for the first time, that the estimated forces are in good agreement with wind tunnel measurements (Figure 1). We first introduce the experimental setup consisting of on-board logging and external motion tracking systems (Section II). Then, we explain how the data is synchronized, processed and how the forces are estimated (Section III). Finally, we present the forces estimated for various body speeds and compare them to wind tunnel measurements (Section IV).

II. EXPERIMENTAL SETUP

A. DelFly II MAV with on-board autopilot

The DelFly II MAV used for the experiments is an insect-inspired flapping wing platform that was described and studied thoroughly in our previous work [12] and is displayed in Figure 2. For the tests presented here it was equipped with a Lisa/S autopilot board [13] consisting, besides other components, of a MCU (72MHz 32bit ARM Cortex-M3)

¹All authors with: Micro Air Vehicles Laboratory, Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands m.karasek@tudelft.nl

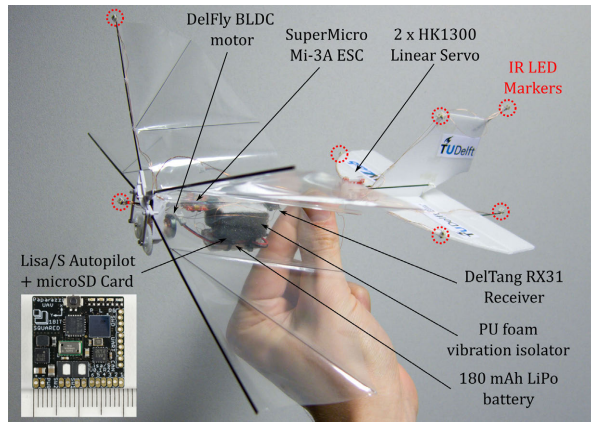


Fig. 2. DelFly MAV used in the free-flight experiments.

allowing to run the Paparazzi UAV autopilot system¹ and a 6 axis MEMS IMU (Invensense MPU6050). Its 3-axis accelerometer and gyroscope provide internally low pass filtered readings (cut-off at 256 Hz and 260 Hz, respectively) at high sampling rates (1 kHz and 8 kHz, respectively).

A microSD card has been added for logging the raw angular rates and accelerations, the motor and servo commands, and the motor speed provided by the speed controller (SuperMicro Mi-3A ESC module, flashed with a custom-modified BL Heli firmware to send a pulse with every switch of stator windings). The flapping frequency was computed from the motor speed via the reduction ratio of the gearbox (1:21.33). The data are logged with a 512 Hz sampling rate.

The autopilot was mounted, together with the battery (LiPo, 180 mAh), on a block of PU foam in order to isolate the high frequency vibrations and thus to prevent saturation of the IMU. For now, its size and stiffness were chosen empirically; the optimization of its damping characteristic will be a subject of further study. With all the additional components, the MAV had a total mass $m = 23.5$ g and its centre of gravity (CG) was located 68.5 mm behind the leading edges and 9.6 mm below the fuselage.

B. Motion tracking system

All the tests were conducted in the CyberZoo, a motion tracking arena of TU Delft equipped with 24 OptiTrack Flex13 cameras covering a tracking volume of 10 m x 10 m x 7 m and recording the body position and attitude at a frame rate of 120 Hz. For a reliable tracking performance, the DelFly was equipped with IR LEDs (OP280PS by OpTEK Technology) serving as markers for the tracking system; 4 LEDs were placed on the DelFly fuselage and tail to define the tracked body and 3 additional LEDs were placed at the wing-tip, rudder and elevator in order to know also the actual flapping angle and the true deflection of the control surfaces, see Figure 2.

C. Flight tests

Every set of tests started with a calibration procedure to determine the relative orientation of the IMU in the body

frame. Then, individual manually controlled flights were performed. The rudder was trimmed, so that the vehicle would fly an approximately straight line with zero stick command. Different speeds, and hence different angles of attack, were achieved by different trims of the elevator. Approximately level flight was attained by the operator through the throttle stick, which was only used for minor corrections, e.g. to compensate for the decreasing battery level.

The operator tried to fly straight segments through the centre of the tracking volume without touching the sticks. These segments were used for force estimation. An example of a flight trajectory during a single test is in Figure 3.

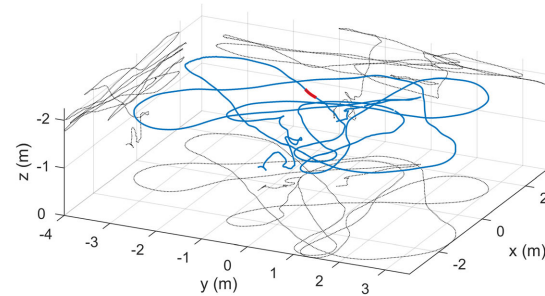


Fig. 3. An example of a tracked flight trajectory during a single test, including 2D projections into the 3 planes defined by the earth-fixed axes. The red part indicates the segment chosen for free flight estimation.

D. Wind tunnel tests

The estimated free flight forces were compared to wind tunnel measurements acquired with an equivalent vehicle for various wind speeds, flapping frequencies and body pitch angles. The experiments were carried out at the Aerodynamics Laboratory of TU Delft in a low speed open jet wind tunnel with a test section of 0.6 m x 0.6 m. The forces were captured at 10 kHz with a high precision 6-DOF force/torque sensor Nano17 Titanium from ATI-Industrial Applications, Inc. The vehicle was clamped and mounted directly to the force sensor, which was then mounted to a test rig that allowed changing the body pitch angle between 0 and 90°. The chosen clamping position (64.5 mm from the leading edge) should have minimized the effects of structural vibrations of the fuselage on the measurements [8]. A combination of a Hall effect switch mounted to the gearbox frame and a tiny NdFeB magnet placed on the driving gear of the flapping mechanism was used to have a reference of the mechanism position once every cycle.

III. DATA PROCESSING

The external motion tracking and on-board logging systems provide two datasets that need to be synchronized and processed. All the processing was done off-line using in-house written routines in MATLAB 2014b (MathWorks Inc.).

A. Time synchronisation

The time synchronisation is realized by one of the body LED markers that goes on and off at the start and at the end of the on-board logging, respectively. However, since

¹<https://wiki.paparazziuav.org/>

the sampling rate of the tracking system (120 Hz) is much lower compared to the on-board logging (512 Hz), a random time shift of up to $1/120 \text{ s} = 8.33 \text{ ms}$ (equivalent to around 4 on-board samples) will still be present. This can represent up to 10 % of a flapping cycle; further mitigation of this remaining time shift will be proposed in Section III-D.

B. IMU data processing

The vehicle can operate at very low speeds, where the fuselage is nearly vertical. To avoid the singularity in the roll-pitch-yaw attitude representation, the body coordinate system was defined with respect to the hovering case (Figure 4).

The IMU was placed at $\mathbf{r}_{\text{IMU}} = [17, -1, 57.5] \text{ mm}$ (in body axes), but it was not fully aligned with the body-fixed frame. The relative orientation was found numerically from IMU and tracking data recorded during the calibration procedure, when the vehicle was positioned at different orientations.

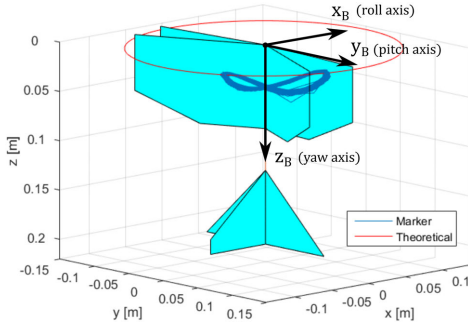


Fig. 4. Definition of body-fixed frame, theoretical stroke plane (red) and an example of upper-right wing tip trajectory recorded in-flight and transformed to body-fixed frame (blue).

Finally, the IMU data were transformed to body axes and low pass filtered using a 4th order Butterworth zero-phase filter (implemented as 'filtfilt' function of MATLAB). To facilitate the comparison with wind tunnel data, a 40 Hz cut-off, slightly above 3 times the flapping frequency, was used for both datasets to reduce the effects of structural vibrations present in the wind tunnel data, as recommended in [8].

C. State estimation

While only the IMU readings are needed for the force estimation, we also estimate the remaining states (attitude and body velocities) for comparison with the motion tracking system data. Body attitude was estimated by transforming the angular rates to Euler angle derivatives, and subsequently by integrating these. Because of accumulation of measurement errors during the integration process, the resulting drift needs to be compensated, either by accelerometer data or, when available, by the tracking system attitude angles.

In this work, we use a discrete complementary filter, which fuses two signals simply by assigning weights to each of them. A high weight $p \leq 1$ is given to the signal that is reliable at high frequencies but suffers from drift, e.g. a , and the signal that does not drift over time but has unreliable high frequency component, e.g. b , gets a low weight $(1 - p)$.

Output of such a filter, e.g. c , reads

$$c = pa + (1 - p)b. \quad (1)$$

In time steps, when the tracking system attitude is available, a lower value of $p = 0.9$ is used since the tracking system provides attitude with good accuracy even at higher frequencies. In the remaining time steps the roll and pitch angles are estimated from the accelerometer readings, assuming it only senses the gravity vector in the ground direction. A high value of $p = 0.999$ is used, because this assumption is rarely fulfilled.

Knowing the body attitude, defined by roll ϕ , pitch θ , and yaw ψ angles (Figure 4), the gravity vector can be subtracted from the accelerometer readings to obtain the pure body acceleration. Body velocity $[u, v, w]$ is computed by numerical integration of the body acceleration, while again using a complementary filter to remove drift whenever a matching velocity sample from the tracking system is available; the value of $p = 0.9$ is used. The tracking system velocity is computed by numerical differentiation using a central difference scheme.

Finally, angle of attack α and sideslip β are computed to facilitate the selection of flight segments where the flight can be considered steady. The definition is chosen so that the angle of attack, representing the angle between the longitudinal speed vector and the fuselage, is equal to 90° in hover (no wind is assumed)

$$\alpha = \text{atan2}(u, -w) \quad (2)$$

$$\beta = \text{atan2}(v, u), \quad (3)$$

The overall flight speed U is defined as the norm of the speed vector in longitudinal plane $[u, w]$.

D. Time shift compensation

As was mentioned in Section III-A, the time synchronisation achieved by a switchable LED marker will still leave us with a random time shift due to different sampling rates. This can be noticed in Figure 5, which compares the body roll estimated by the IMU to the tracking system data.

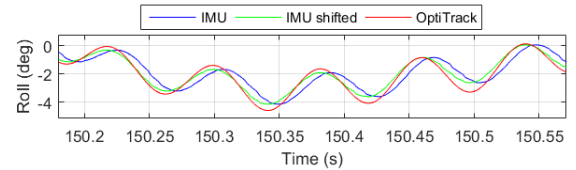


Fig. 5. IMU based roll angle before (red) and after (green) timeshift compensation by minimizing the sum of errors from the tracking data (blue). The signals were low pass filtered at 16 Hz to attenuate higher harmonics.

To estimate the observed time shift, a routine was programmed that shifts the IMU roll angle estimate (by up to half a wingbeat period in both directions) until a minimum of sum of squares of errors between the IMU and the tracking signal, resampled using spline interpolation, is found. The signals shifted by the estimated time are also displayed in Figure 5. Finally, the complementary filtering and all the subsequent steps are repeated with the shifted data.

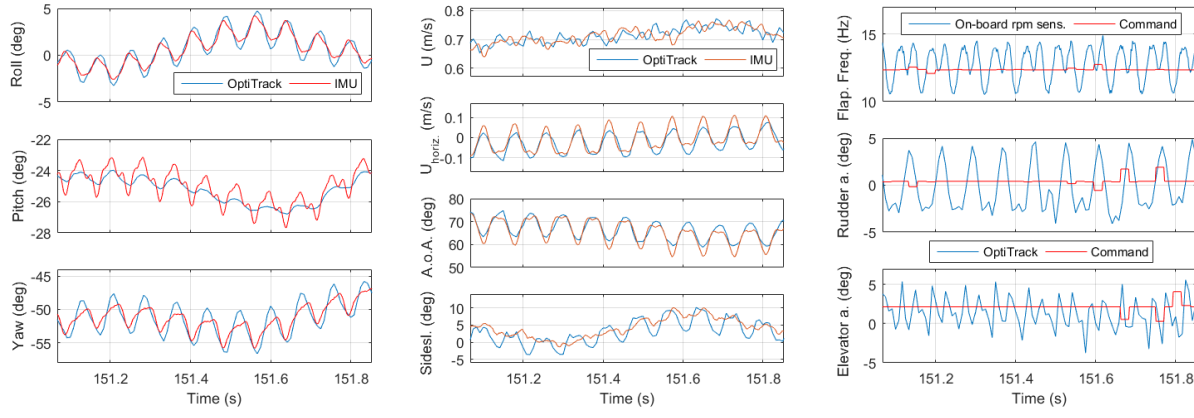


Fig. 6. Flight data over the segment selected for force estimation. Comparison of tracking data and IMU estimates (corrected for drift with tracking data).

E. Flapping angle and deflections of control surfaces

Additional markers are used to capture the flapping angle and rudder and elevator deflections. Knowing the hinge locations in the body frame and the distances between hinges and their corresponding markers, the respective angles were calculated by trigonometry. An example of the wing tip marker trajectory, recorded in flight and transformed to the body-fixed axes, is shown in Figure 4. A figure-of-eight trajectory (blue) can be clearly observed due to aerodynamic loads on the flapping wings causing the leading edges to bend out of the stroke plane (red circle).

F. Test segment selection

Each recorded dataset included the whole test flight, combining turns and straight segments. After every turn, the passively stable vehicle needed some time to return to its steady state. On top of that, random disturbances were present in the flight arena like small drafts, which could cause additional oscillations in body attitude. Thus, a careful selection of the segments where the vehicle was close to a steady and levelled flight was necessary.

We searched for segments where: 1) body speed, angle of attack, yaw angle and throttle command were approximately constant, 2) vertical speed, side-slip and rudder command were close to zero. The length of these segments was set to 10 wingbeats. An example of a time history of all the estimated variables over a selected segment, where the above conditions are met, is in Figure 6, comparing IMU data with tracking system corrections (red) to data based purely on the tracking system (blue).

Overall, the two data sets are in good agreement, although some differences can be noticed on sub-flap level. In particular, the amplitude of the inherent pitch angle oscillation seen by the tracking system is much smaller than the amplitude of the IMU based pitch angle. We have noticed that the foam block below the IMU, which serves to isolate the high frequency vibrations, has too low rotational stiffness in the pitch and yaw directions and indeed allows the IMU to oscillate especially around the pitch axis when in flight. The difference in yaw can originate also from the flexibility of the tail surfaces, on which the tracking markers are placed.

These differences then propagate also to other states. We plan to study different soft mount designs in future to mitigate this problem. Although the amplitude of relative rotation between the vehicle body (from the tracking system) and the IMU remains below $\pm 2^\circ$, the relative angular velocities and accelerations, used for transformation of accelerometer readings to CG in the following subsection, become significant and thus affect the estimated forces. We plan to perform a detailed analyses of these effects in our future work.

We can also observe that, although the commands remain nearly constant (the small changes are due to noise in the radio link), the flapping frequency and the deflections of control surfaces oscillate around the set point. The oscillation of control surfaces is likely due to a combination of structural flexibility and play in the hinges. The variation of the flapping frequency, calculated from the on-board logged motor rpm, is caused by a variable motor load due to flapping and has a surprisingly high amplitude: about ± 2 Hz or $\pm 15\%$ of the mean value. Nevertheless, the mean measured values follow the commands well.

G. Force estimation

In this work, we only focus on straight steady flight and assume a full symmetry of the MAV; the force in lateral direction is considered to be zero. Assuming further that the MAV is a rigid body, the in-flight forces can be estimated from the accelerations at CG. The filtered accelerometer readings $\mathbf{a}_{\text{IMU}}$, which already include the gravitational acceleration, can be transformed to CG using the filtered gyro readings as

$$\mathbf{a}_{\text{CG}} = \mathbf{a}_{\text{IMU}} + (\Omega^2 + \dot{\Omega})(\mathbf{r}_{\text{CG}} - \mathbf{r}_{\text{IMU}}), \quad (4)$$

where Ω represents the angular velocities tensor measured by the gyro, $\dot{\Omega}$ is its derivation, computed numerically using central difference scheme, and $\mathbf{r}_{\text{IMU}}$ and $\mathbf{r}_{\text{CG}}$ are the position vectors of IMU and CG in body-fixed frame, respectively.

Knowing the CG acceleration, the forces can be expressed by reformulating the rigid body equations of motion as

$$\begin{aligned} X &= m a_{\text{CG}x} \\ Z &= m a_{\text{CG}z}. \end{aligned} \quad (5)$$

The resulting forces include not only the efforts resulting from the flapping wing aerodynamics, but also the inertial effects of the flapping wings. While this may make it harder to compare these results to numerical aerodynamic simulations, it allows direct comparisons with wind tunnel measurements, where the force balance also captures both of these effects.

IV. RESULTS

A. Flight envelope

In total, we conducted flights at 5 different elevator settings, covering nearly the entire flight envelope of the vehicle for a fixed CG. The observed combinations of angle of attack and speed during the various flights are depicted in Figure 7. Figure 8 shows the relationship between the mean speed, flapping frequency and elevator deflection. In accordance with our previous observations, all these relationships are approximately linear.

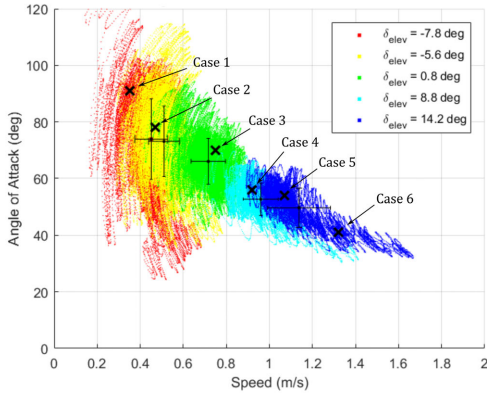


Fig. 7. Observed combinations of speed and angle of attack for various elevator deflections (colour coded). The black dots and the error-bars represent the mean values and standard deviations for each elevator setting. Black crosses show the conditions for which the in-flight forces will be estimated in Section IV-B.

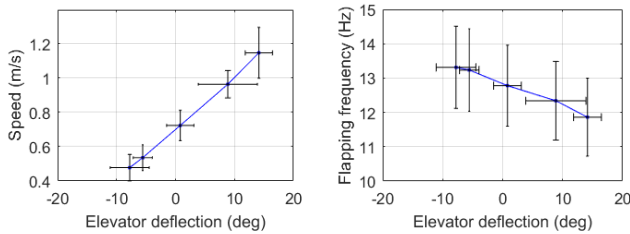


Fig. 8. Variation of body speed (left) and flapping frequency (right) with elevator deflection. Both relationships are approximately linear. The error-bars represent the standard deviation from the mean values.

B. Free flight forces

The forces acting on the vehicle were estimated using equations (5). The segments of steady flight were split into individual wingbeats using the wing tip angle from the tracking system, resampled with spline interpolation to match the IMU samples.

The wind tunnel forces used for comparison were split and processed in the same way. Because the in-flight data use wing tip position as a reference while flapping mechanism position was used in the wind tunnel, a phase shift between the two measurements may be present due to the deformation of the leading edge, depending on the aerodynamic loads at different testing conditions. To mitigate this, the free flight data were shifted with respect to the wind tunnel data until a minimal sum of squares of errors between the two sets was reached. The Z force component was used for the temporal alignment as it is less sensitive to potential contamination by structural vibrations of the clamped fuselage.

The forces were estimated for various flight conditions, displayed as Cases 1 to 6 in Figure 8 and summarized in Table I. Figure 9 displays the force evolution over two wingbeats for the straight flight cases (Cases 2 to 5). The beginning of each wingbeat is defined as the moment when the two wings clap. The lines plotted in lighter shades show individual wingbeats (10 in total), the darker shades show the average time history. The wing angle of the upper wing is also displayed for reference.

We can observe that the variation among individual wingbeats in the free flight data (blue) is quite small and improved compared to what was achieved with a tracking system only in the past (Figures 14b and 18 in [8]). Since we did not have wind tunnel measurements for the exact conditions that were experienced in flight (the wind tunnel tests were done prior to the free flight tests), the closest available measurement conditions were chosen, see Table I. Nevertheless, the match between the in-flight and wind tunnel thrust forces, defined as $-Z$, is very good.

Bigger differences can be seen in the normal, X, force component, which may partly come from the structural vibrations of the clamped body seen by the force sensor in the wind tunnel. We can see a reasonable match even in the cycle averaged values, see Table II, although the measurement conditions were not always the same.

C. Body speed effect

The effect of the body speed on in-flight forces can be observed in Figure 10, where the estimated forces were aligned using the wind tunnel data as we described in the previous section.

We can see a clear trend in both force components. Because the body will incline forward with increasing speed, reducing the angle of attack, the thrust component needs to increase, while the normal force needs to decrease. This can be clearly observed both in the line graphs as well as in the cycle averaged values shown in Table II. The thrust force evolution keeps a similar shape, with two peaks and two troughs within a wingbeat. The first trough (around non-dimensional time $\hat{t} = 0$) and the first peak (around $\hat{t} = 0.25$) are shallower and larger, respectively, due to the clap and peel mechanism, which occurs when the lower and upper wings meet [12, Chapter 6].

The pattern of the normal force remains also repetitive, although more complex. The peaks and troughs of the normal

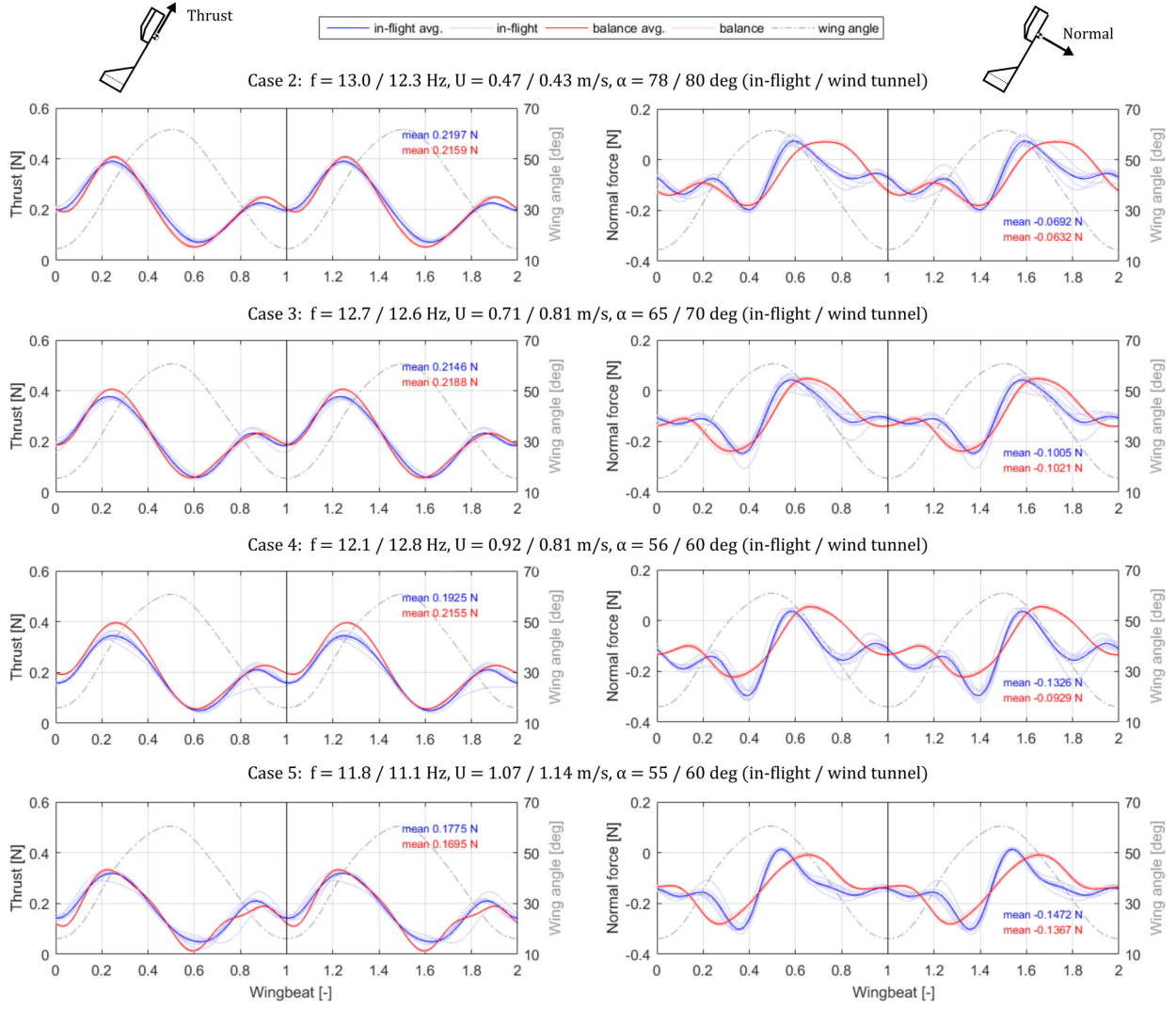


Fig. 9. Forces estimated in-flight compared to wind tunnel measurements for different flight conditions. Left and right columns show the thrust and normal forces, respectively. Flight and wind tunnel conditions for each of the cases are shown in the title of each row, and are also summarized in Table I.

TABLE I
COMPARISON OF CONDITIONS IN-FLIGHT (LEFT PART) AND IN THE WIND TUNNEL (RIGHT PART).

#	Elev. defl. (°)	Speed (m/s)	Pitch (°)	Ang. of attack (°)	Sideslip (°)	Flap. freq. (Hz)	Speed (m/s)	Ang. of attack (°)	Flap. freq. (Hz)
1*	-8.5 ± 0.36	0.35 ± 0.012	12.9 ± 0.68	91.4 ± 4.07	7.7 ± 4.07	13.0 ± 0.07	0.43	80	12.3
2	-5.3 ± 0.43	0.47 ± 0.021	15.9 ± 0.49	77.8 ± 2.71	-9.9 ± 2.71	13.0 ± 0.05	0.81	70	12.6
3	1.3 ± 0.42	0.72 ± 0.022	25.0 ± 0.93	64.6 ± 2.54	-4.0 ± 2.54	12.8 ± 0.07	0.81	60	12.8
4	9.3 ± 0.56	0.93 ± 0.011	34.2 ± 0.50	56.3 ± 0.73	-0.3 ± 0.73	12.2 ± 0.04	1.14	60	11.1
5	15.0 ± 0.19	1.07 ± 0.009	40.0 ± 0.21	54.6 ± 0.83	-7.0 ± 0.83	11.8 ± 0.05	1.16	45	11.1
6*	14.1 ± 0.23	1.31 ± 0.021	43.1 ± 0.76	41.2 ± 0.51	7.4 ± 0.51	12.1 ± 0.04			

Free flight values are displayed as mean $\pm$ standard deviation of the averages of individual cycles. *A steady turn was observed in these cases.

TABLE II
COMPARISON OF CYCLE AVERAGED FORCES FROM THE FREE-FLIGHT EXPERIMENT (LEFT) AND FROM THE WIND TUNNEL (RIGHT).

#	X force (mN)	-Z force (mN)	Vert. force (mN)	Horiz. force (mN)	X force (mN)	-Z force (mN)	Vert. force (mN)	Horiz. force (mN)
1*	-54 ± 5.0	223 ± 5.0	230 ± 5.2	-2.6 ± 5.2	-63 ± 0.7	216 ± 1.5	224 ± 1.5	-25 ± 0.7
2	-69 ± 9.9	220 ± 3.3	230 ± 4.7	-5.3 ± 9.4	-102 ± 1.8	219 ± 1.0	241 ± 0.9	-21 ± 1.8
3	-101 ± 7.4	215 ± 3.8	237 ± 3.7	0.6 ± 7.7	-93 ± 1.5	215 ± 0.5	233 ± 0.9	27 ± 1.3
4	-133 ± 5.3	193 ± 5.3	233 ± 5.7	-0.5 ± 4.6	-137 ± 1.1	169 ± 0.7	215 ± 1.0	-34 ± 0.9
5	-147 ± 3.8	177 ± 4.4	229 ± 4.7	1.3 ± 3.4	-155 ± 1.1	157 ± 0.4	221 ± 0.9	0.9 ± 0.7
6*	-164 ± 4.6	169 ± 4.3	218 ± 4.2	-19 ± 4.8				

All values are displayed as mean $\pm$ standard deviation of the averages of individual cycles. *A steady turn was observed in these cases.

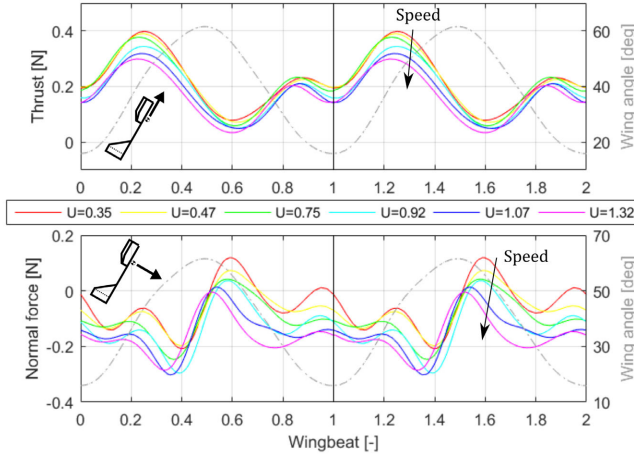


Fig. 10. Forces estimated in-flight for different body speeds (legend values are in m/s).

force seem to occur earlier in the wingbeat as the body speed increases. Finally, Table II also displays cycle averaged forces transformed into vertical and horizontal directions. We can see that, as expected for a levelled steady flight, the predicted values in vertical direction are very close to the body weight and the horizontal component remains very close to zero in all the cases.

V. CONCLUSIONS

We have presented free-flight forces acting on a flapping wing MAV that were estimated using solely the data from an on-board IMU. Compared to previous free flight experiments with motion tracking, the presented approach provides data with more details due to higher sampling rates and lower variation among individual wingbeats. Additionally, an on-board rpm sensor revealed large motor speed variation of $\pm 15\%$ due to load variation over the wingbeat.

A good agreement was observed when comparing the results to wind tunnel measurements taken under similar conditions, especially for the thrust force. This confirms that wind tunnel measurements can be used to study flapping wings aerodynamics, but attention needs to be paid when interpreting the results in the direction normal to the fuselage, as these may be affected by the structural vibrations of the clamped MAV body.

When processing the results, several issues arose that will deserve our attention in future tests. In particular, the low rotational stiffness of the autopilot board foam mount, isolating the high frequency vibrations, allowed relative rotation of the IMU with respect to the body. We plan to optimize the mount design and perform a detailed analyses of the effects of the relative rotation in future.

Further, a stiffer fuselage should be used to minimize the structural vibrations effect in the wind tunnel measurements and these tests should be carried out after the free flight tests so that the exact conditions can be replicated. Finally, a Hall effect switch used in the wind tunnel should be added also

on-board, so that the flapping mechanism position can be logged and a more consistent time synchronisation with the wind tunnel data can be achieved.

The presented approach brings high quality free flight data that can be useful for flight dynamic modelling or even aerodynamic studies. In future, the experiments and data processing can be extended to manoeuvring flight, so that system identification over the entire flight envelope of the DelFly MAV can be carried out.

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REFERENCES

- [1] T. V. Truong, D. Byun, M. J. Kim, K. J. Yoon, and H. C. Park, "Aerodynamic forces and flow structures of the leading edge vortex on a flapping wing considering ground effect," *Bioinspiration & biomimetics*, vol. 8, no. 3, 2013.
- [2] Q. V. Nguyen, W. L. Chan, and M. Debiase, "Performance test of a hovering flapping wing micro air vehicle with double wing clap-and-fling mechanism," in *International Micro Air Vehicle Conference and Competitions (IMAV)*, Aachen, Germany, September 15-18, 2015.
- [3] C. Rose and R. S. Fearing, "Comparison of ornithopter wind tunnel force measurements with free flight," in *2014 IEEE International Conference on Robotics and Automation (ICRA)*, 2014, pp. 1816–1821.
- [4] J.-S. Lee and J.-H. Han, "Experimental study on the flight dynamics of a bioinspired ornithopter: free flight testing and wind tunnel testing," *Smart Materials and Structures*, vol. 21, no. 9, 2012.
- [5] J. Grauer, E. Ulrich, J. E. Hubbard, D. Pines, and J. S. Humbert, "Testing and System Identification of an Ornithopter in Longitudinal Flight," *Journal of Aircraft*, vol. 48, no. 2, pp. 660–667, 2011.
- [6] J. V. Caetano, M. Percin, C. C. de Visser, B. W. van Oudheusden, G. C. H. E. de Croon, C. de Wagter, B. D. W. Remes, and M. Mulder, "Tethered vs. free flight force determination of the DelFly II Flapping Wing Micro Air Vehicle," in *2014 International Conference on Unmanned Aircraft Systems (ICUAS)*, 2014, pp. 942–948.
- [7] A. Jennings, M. Mayhew, and J. Black, "Video measurements of instantaneous forces of flapping wing vehicles," *Mechanical Systems and Signal Processing*, vol. 64–65, pp. 325–336, 2015.
- [8] J. V. Caetano, M. Percin, B. W. van Oudheusden, B. W. D. Remes, C. de Wagter, G. C. H. E. de Croon, and C. C. de Visser, "Error analysis and assessment of unsteady forces acting on a flapping wing micro air vehicle: free flight versus wind-tunnel experimental methods," *Bioinspiration & biomimetics*, vol. 10, no. 5, 2015.
- [9] J. V. Caetano, C. C. de Visser, G. C. H. E. de Croon, B. D. W. Remes, C. de Wagter, J. Verboom, and M. Mulder, "Linear Aerodynamic Model Identification of a Flapping Wing MAV Based on Flight Test Data," *International Journal of Micro Air Vehicles*, vol. 5, no. 4, pp. 273–286, 2013.
- [10] S. F. Armanini, C. C. de Visser, G. C. H. E. de Croon, and M. Mulder, "Time-Varying Model Identification of Flapping-Wing Vehicle Dynamics Using Flight Data," *Journal of Guidance, Control, and Dynamics*, vol. 39, no. 3, pp. 526–541, 2016.
- [11] J. A. Grauer and J. E. Hubbard, "Inertial measurements from flight data of a flapping-wing ornithopter," *Journal of Guidance, Control, and Dynamics*, vol. 32, no. 1, pp. 326–331, 2009.
- [12] G. C. H. E. de Croon, M. Percin, B. D. W. Remes, R. Ruijsink, and C. de Wagter, *The DelFly - Design, Aerodynamics, and Artificial Intelligence of a Flapping Wing Robot*. Springer Netherlands, 2016.
- [13] B. D. W. Remes, P. Esden-Tempski, F. Van Tienen, E. Smeur, C. de Wagter, and G. C. H. E. de Croon, "Lisa-S 2.8g autopilot for GPS-based flight of MAVs," in *International Micro Air Vehicle Conference and Competition (IMAV)*, Delft, The Netherlands, August 12-15, 2014, pp. 280–285.