

Determination of trim curves for a flapping-wing MAV

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ABSTRACT

This paper presents the results of a series of flight tests conducted in order to assess the steady-state flight characteristics and basic control behaviour of the DelFly, a flapping-wing micro aerial vehicle (FWMAV). Flights were conducted in an indoor motion tracking facility and included steady-level flight at a range of different velocities and turn manoeuvres. A number of different trim points were determined and approximate trim curves constructed to describe elevator effectiveness. Aileron effectiveness was then evaluated in terms of resulting turn radii and turn rates. The results provide insight into some of the basic flight properties of the DelFly and represent a starting point for further modelling work. The flight testing process also highlighted some of the major issues to be addressed in order to obtain meaningful experimental results.

1 INTRODUCTION

Flapping-wing micro air vehicles (FWMAVs) are very small and light, and possess a number of desirable flight properties, such as high manoeuvrability, power efficiency and the capability to fly at low speeds and hover.

However, the development, modelling and autonomous control of FWMAVs is hindered by the complex nature of flapping-wing flight. Flapping-wing flyers operate at low Reynolds numbers and produce largely unsteady aerodynamics which are not yet fully understood [1, 2]. Likewise, the flapping motion of the wings implies complex, time-varying flight kinematics and can lead to significant flexibility effects [3] and inertia effects [4] that are typically negligible in fixed-wing aircraft.

Several studies have been conducted in the field of modelling and simulation of FWMAVs, e.g. with the aim of providing models for control system development or of developing virtual simulation frameworks. A small number of flight test-based studies have been conducted recently to analyse and study various aspects of flapping-wing flight including flight performance [5], kinematics and dynamics [6, 7, 8, 9], and aerodynamics [10, 11]. However, studies based on free flight data remain relatively scarce.

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The small size of FWMAVs greatly limits the possibility of incorporating on-board equipment such as sensors, and the range of equipment that can be used without excessively affecting flight properties. In addition to this, facilities for systematic flight testing of MAVs are not yet widely available. Flight testing is however an indispensable element in the development of any type of flight vehicle and several properties cannot be assessed by alternative means.

Within this study a series of flight tests were conducted with the DelFly, in order to determine its trim points and analyse its basic control behaviour. Combined these two components describe a fundamental component of the steady-state behaviour of the DelFly and hence represent a basis for further dynamic modelling work. Additionally, since the DelFly used for these tests has the same actuators as the autonomously flying DelFly Explorer [12], the obtained results can be used to enhance the realism of existing DelFly Explorer simulations. These simulations are used to test the DelFly Explorer's stereo vision-based autonomous flight capabilities.

This paper is structured as follows. Section 2 briefly presents the DelFly and the flight testing facilities used. Section 3 presents the flight tests conducted to find trim points and assess elevator effectiveness, and the results obtained. Section 4 outlines the tests and results for the evaluation of turn behaviour and aileron effectiveness. Section 5 concludes with a summary of the main findings and an outlook on further work.

2 PLATFORM AND EXPERIMENTAL SETUP

The subject of these tests was the DelFly (cf. Figure 1), a FWMAV developed at the Delft University of Technology. The specimen used for these tests weighs approximately 22g and has wings arranged in an 'X' configuration, with a span of approximately 290mm. The vehicle can be piloted remotely by means of a transmitter, in addition to which it is possible to hard code specific control inputs. More extensive information on the DelFly can for instance be found in [13, 14, 15].

Tests were conducted in the TU Delft *Cyberzoo*, an indoor motion tracking facility measuring 10m×10m×7m and equipped with 24 cameras (cf. Figure 2). The tracking system provides information on the position and spatial orientation of the tracked object, which is equipped with a series of either retro-reflective or LED markers. A total of 6 LED markers

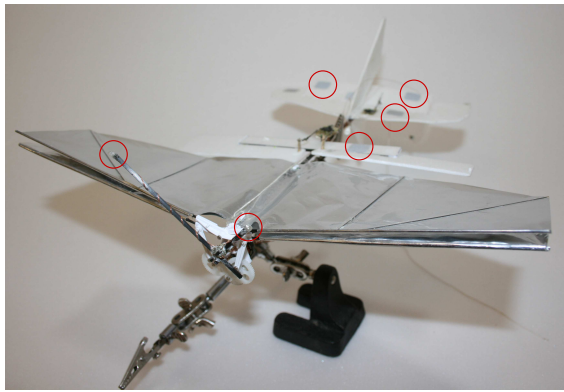


Figure 1: The DelFly with LED marker locations circled in red

were used in these tests and these were affixed at various locations on the structure of the DelFly, as shown in Figure 1.



Figure 2: The DelFly in the Cyberzoo; the motion tracking cameras are fixed to the struts shown in the image

3 TRIM CURVE DETERMINATION

The aim of this set of tests was to determine trim conditions across a portion of the DelFly's flight envelope, and to relate the input required to establish and maintain these to the resulting flight conditions. By relating control inputs to the resulting steady flight conditions, trim curves describe the steady-state behaviour of a flight vehicle across the flight envelope and are thus essential for both modelling and practical purposes.

3.1 Flight testing for trim point search

Trim conditions were defined in terms of forward flight velocity V and pitch attitude Θ . As the DelFly is intended for indoor flight and only operates within a limited altitude range, altitude can be omitted as a trim variable. The control inputs considered were the flapping frequency f_f , which is a form of thrust control, and the elevator deflection

δ_e . In practice it was found that longitudinal steady flight conditions are most effectively changed by means of elevator deflections, with the flapping frequency being used only for slight trim adjustments, and therefore flapping frequency was not used for the final trim curves at this stage.

The flight test procedure consisted in fixing the elevator at progressively changing deflection angles, covering the maximum possible range still allowing for steady flight and permitted by the testing facilities. The elevator deflection was hard-coded before each flight. The throttle, controlling the flapping frequency, was then adjusted manually by means of a transmitter to maintain a constant altitude and velocity, which also resulted in a constant pitch attitude. Whilst the aim was to explore a wide range of flight conditions, the size of the arena posed a limit to the possible range of flight velocities to investigate. At high velocities the DelFly would have covered the entire length of the arena in few seconds, leading to insufficient data, as well as entailing a high probability of crashing.

Measurements included the spatial position and attitude of the vehicle, provided by the tracking system, as well as the elevator control inputs. Given that the current test setup did not allow for actual elevator deflections to be measured, the control inputs applied by the pilot through the transmitter were measured instead.

Following the tests, pitch attitude was calculated from the measured quaternions, and velocities were obtained by numerically differentiating the measured position time series. Although ideally the tests should have been conducted at a constant altitude, evidently this is not wholly possible in real-life testing, hence to exclude the effect of any vertical velocity component, the in-plane velocity was used for analysis instead of the total velocity. Basic post-processing operations were applied to remove outliers and tracking interruptions from the data.

A total of eight flights was conducted, using the same vehicle and configuration and the same procedures. Given that the elevator deflection was hard-coded, each change in input required reprogramming and thus involved a separate flight.

3.2 Trim point search results

Table 1 summarises the results of the described tests in terms of the average values and standard deviations (reported in brackets) computed for the in-plane velocity, pitch attitude and elevator command from each of the flights. In order to obtain more accurate results, only the straight and level segments of the flights were used in the evaluation. An example of velocity measurements obtained in samples out of different flights is depicted in Figure 3.

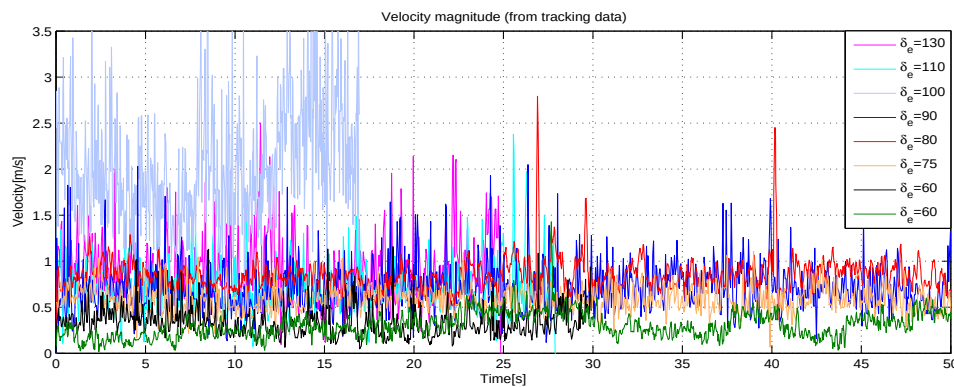


Figure 3: Velocity measurements obtained in extracts from different flight tests

The elevator commands are expressed as integer values between 0 and 250, where 0 indicates a full downward deflection. In view of the fact that elevator commands were hard-coded prior to each flight, these were assumed to be constant. In fact even a perfectly constant command does not result in an entirely constant deflection, due to vibrations and other disturbances occurring in flight, but the effects of this were assumed to be limited. Moreover, it should be emphasised that the same command value may have led to slightly different deflections during different flights, owing to external influences and changes in the hardware, e.g. as a consequence of repair work. For the same reasons, equal deflections may also have had slightly different effects during separate test runs.

Table 1: Average measurements obtained from steady level flight tests for trim point determination

Flight#	$\bar{\delta}_e [^\circ]$	$ \bar{V}_{plane} [m/s]$	$\bar{\Theta} [deg]$
1	60	0.41 (0.15)	85.12 (3.72)
2	60	0.33 (0.16)	83.86 (7.53)
3	75	0.58 (0.14)	70.54 (3.25)
4	80	0.83 (0.20)	65.95 (2.63)
5	90	0.91 (0.28)	68.47 (6.46)
6	100	2.01 (0.54)	59.57 (2.61)
7	110	0.82 (0.27)	71.45 (3.78)
8	130	1.13 (0.40)	61.09 (6.57)

It can be observed that elevator deflection is directly proportional to in-plane velocity and inversely proportional to pitch attitude. Both trends can be described relatively well by linear fit lines, as shown in Figures 4 and 5. These lines represent approximate trim curves for the DelFly, quantifying the effect of elevator input manoeuvres on its steady-state flight behaviour.

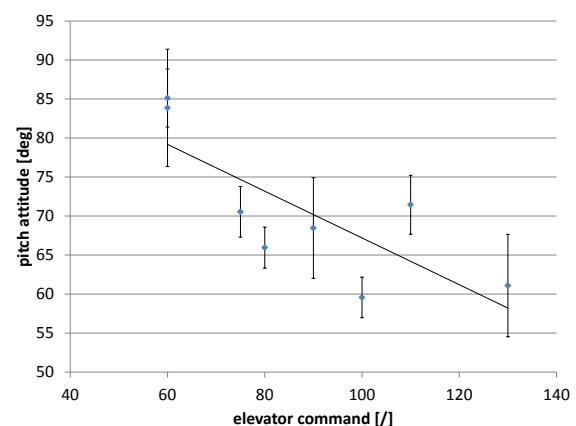


Figure 4: Trim curve: pitch attitude versus elevator command

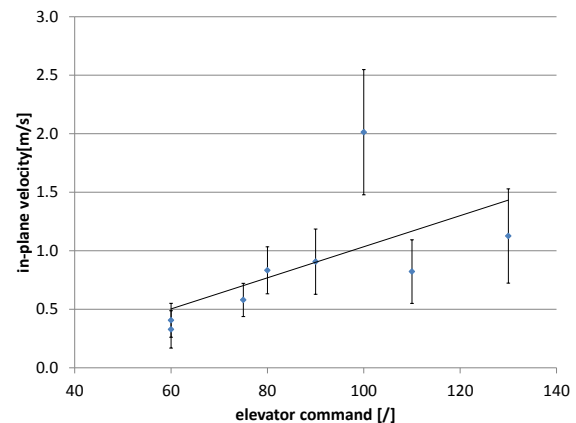


Figure 5: Trim curve: in-plane velocity versus elevator command

As can be remarked in the plots and in Table 1 (flight #6), one of the velocity measurements appears to be anomalous in the light of the remaining data. Although further testing

would be required to ascertain anything, it is assumed that the outlier was caused either by some form of external disturbance or by an unintended change in the physical state of the DelFly occurring between tests.

Besides yielding a simple input-output model for the elevator, these tests yield an overview of typical trim conditions for the DelFly, in terms of velocity and pitch attitude. Figure 6 shows that in steady level flight, velocity is inversely proportional to pitch attitude. Again, this is as expected from theory, however the quantitative results constitute some insight into DelFly's flight behaviour and provide a good starting point for further flight tests and modelling work.

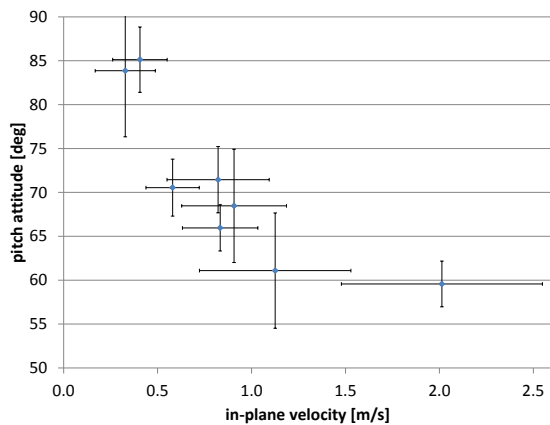


Figure 6: Experimentally found trim conditions: pitch attitude versus total velocity

4 STEADY TURNS TESTS

These tests were designed to analyse the aileron effectiveness and turn behaviour of the DelFly in terms of aileron commands and resulting turn radii and turn rates.

4.1 Flight testing and data analysis

Starting from a trimmed flight condition, progressively varying aileron inputs were applied and the ensuing turns analysed in terms of turn rate and turn radius. Aileron commands were applied manually by means of the transmitter and included inputs in both directions, in an attempt to detect any asymmetric effects.

The effectiveness of the ailerons evidently varies with the flight conditions at the time of input, thus for a complete evaluation a range of different initial flight conditions spanning the flight envelope should be used. However, in a first instance an example starting condition was chosen in order to obtain some initial insight and to evaluate the effectiveness of this type of test. Specifically, results refer to an approximate initial steady flight velocity of 0.3 m/s and pitch attitude of

80° , which is the typical flight attitude of the DelFly.

Since only a single starting condition was considered, several measurements could be conducted in the course of the same flight, by alternating between turns and straight and level flight segments. In actual fact this was not always possible due to various problems in the experimental setup, some of which will be mentioned subsequently.

Measurements included the positions and attitudes of the vehicle, and the aileron commands. Once again, only the commanded values could be measured, rather than the actual control surface deflections.

Turn rates were calculated through numerical differentiation of the yaw attitude as determined from the quaternion measurements. Turn radii were obtained by means of least squares fitting of circles through the measured flight trajectories, according to the algorithm described in [16]. For this, the turns were assumed to take place on a constant altitude plane, on which a circle could be fitted. Although some small variations in altitude did occur during the turns, in most cases these were negligible and effective fits were obtained, e.g. as shown in Figure 7. Manoeuvres involving large variations in altitude or velocity were excluded from the final evaluation.

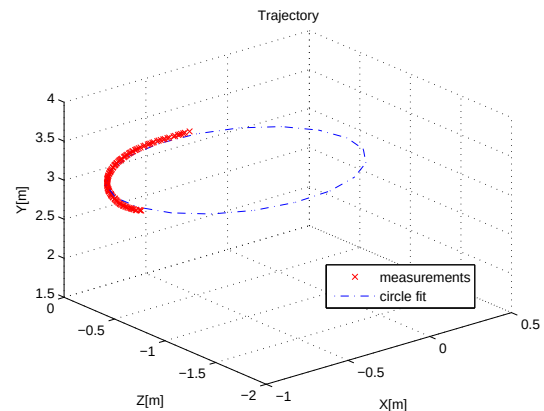


Figure 7: Example of least squares fitting of a circle to a trajectory segment during a turn

A number of problems was encountered in the process of conducting this set of tests. On the one hand, we experienced some problems with the motion tracking system, resulting in a fairly inconsistent tracking performance for these tests. The small size of the LEDs onboard the DelFly implies that the system should be set rather sensitively. Consequently, in some light conditions it is easy to obtain a higher number of either false positives or false negatives, depending on

the threshold and update frequency settings in the motion tracking system.

On the other hand, there were a number of issues with the platform itself. The DelFly has an extremely light structure, which is fragile and easily damaged. Furthermore, even slight changes to the structure, e.g. as a consequence of minor flight incidents, can affect the flight behaviour noticeably, so that the behaviour varies relatively easily and frequently to some extent. This complicates the conducting of flight tests and the evaluation of the obtained data.

In the course of the turn tests the DelFly was for instance found to have a tendency to turn in one direction in the absence of input. This in some cases caused difficulty in establishing to what extent a turn was the result of an aileron deflection, and to what extent it resulted from a previously existing tendency.

These issues must be borne in mind when considering the outcome of these tests, and make the conducting of further tests indispensable to verify the current findings.

4.2 Results

Figure 8 summarises the results of these tests, and shows aileron input magnitude versus turn radius and turn rate respectively. Aileron inputs magnitudes are given as integer values between 0 and 125, where 0 is a neutral position.

As expected, the plots suggest that turn rate is directly proportional and turn radius inversely proportional to aileron input, and both relationships appear to be somewhat linear. However there is also a considerable degree of scatter in the data. This can partly be attributed to the relatively low quality of the measurements made in these tests, which required significant post-processing operations and even then resulted in only a limited number of usable segments.

Due to the issues in the flight testing process, some of which were addressed previously, a meaningful assessment of differences between the responses to opposite sign aileron inputs was not possible. Despite these limitations, however, relatively clear trends can be recognised in the results, suggesting that further testing might provide clearer and more extensive insight and that on a high level the chosen approach is reasonably effective. The linear fits through the obtained plots allow for specific aileron inputs to be mapped to specific turn rates and turn radii, enabling an approximate prediction of the steady turn behaviour of the DelFly.

More significant results would require a larger amount of data. Furthermore, a complete description of the DelFly's turn behaviour would also require conducting the same test starting from a range of different initial trim conditions.

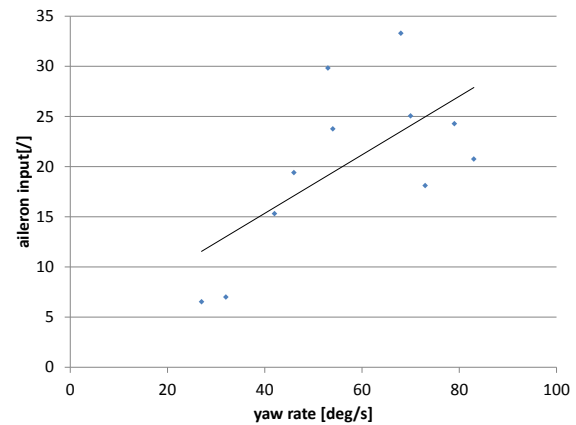


Figure 8: Aileron input versus turn rate for flight segments containing different turn manoeuvres

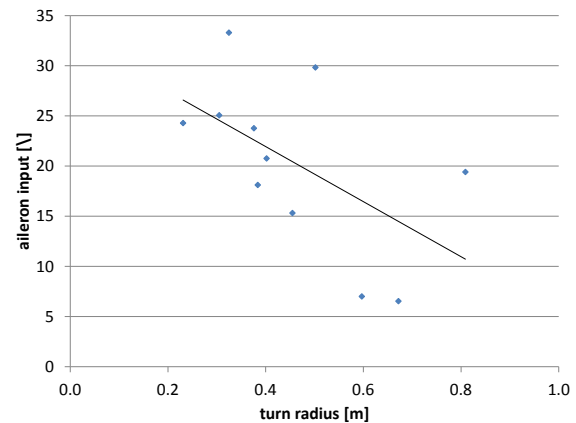


Figure 9: Aileron input versus turn radius for flight segments containing different turn manoeuvres

5 CONCLUSION

A series of simple flight tests was conducted in the TU Delft motion tracking facility *Cyberzoo*, with the objective of investigating a number of basic flight properties of the DelFly. The collected data was used to map control inputs to resulting steady flight conditions, and thereby to provide an initial overview of control effectiveness and input-output behaviour. Furthermore, a number of trim conditions were identified for the DelFly, covering a portion of its flight envelope. The results constitute a basis for more extensive modelling and can be used to lend more realism to the simulated DelFly Explorer model. Additional flight tests will be conducted to validate the current findings and add to them, e.g. by covering a wider range of flight conditions including climb and acceleration manoeuvres. More complex and comprehensive flight dynamic modelling of the DelFly is also planned.

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