METHODS FOR EFFICIENT FLIGHT TESTING AND MODELLING OF REMOTELY PILOTED AIRCRAFT WITHIN VISUAL LINE-OF-SIGHT

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Abstract

Remotely piloted scaled models not only serve as convenient low-risk flying test-beds but also can provide useful data and increase confidence in an eventual full-scale design. Nevertheless, performing advanced flight tests in a safe and cost-effective manner is often a challenge for organizations with limited resources. A typical scenario is testing within visual line-of-sight at very low altitude, a type of operation that offers major cost advantages at the expense of a reduced available airspace. This paper describes some of the authors' work towards efficient performance evaluation and system identification of fixed-wing, remotely piloted aircraft under these challenging conditions. Results show that certain techniques, manoeuvre automation, and platform-optimised multisine input signals can improve the flight test efficiency and the modelling process. It is also probable that some of the benefits observed here could be extrapolated to flight testing beyond visual line-of-sight or even to full-scale flight testing.

1 Introduction

Remotely piloted aircraft (RPA), in many forms, have always been used for studying, developing or demonstrating new designs, systems and technologies. For instance, a review of NASA's activities in this field up to 2009 is presented in [1]. Remotely piloted scaled models not only serve as convenient low-risk flying test beds [2, 3, 4, 5], but also can provide useful data and increase confidence in an eventual full-scale design [6, 7, 8, 9, 10]. This empirical method, often referred to as *subscale flight testing*, has been investigated at Linköping University during several years [11]. Nevertheless, performing advanced free-flight tests in a safe and efficient manner is often a challenge for organizations with limited resources.

In this context, an *efficient* flight test method can be defined as a cost-effective test method that generates high-quality data and that enables the evaluation and analysis of the results in a short time. While those main goals remain generally true, the characteristics of such a method may differ considerably depending on the test object, the operating conditions and the purpose of the tests. This investigation has been focused on finding techniques that could improve performance evaluation and system identification of fixed-wing RPA flying within visual line-of-sight (VLOS) at very low level (VLL); aiming at minimum complexity and low implementation cost.

1.1 VLOS: a Matter of Cost and Complexity

According to the existing regulatory frameworks for unmanned aircraft systems (UAS) in most countries, there is usually a considerable economic step between certified operations within visual line-of-sight (VLOS) and beyond visual line-of-sight (BVLOS) [12]. Although low-cost equipment for extended-VLOS (EVLOS) and BVLOS operations is readily available, a civil operator willing to obtain such permissions is usually forced to either certify the system according to nearly-full-scale standards or to operate inside costly segregated airspaces [13, 14, 15, 16]. This factors often motivate organizations with limited resources to operate in civil airspace following VLOS rules. Fig.1 exemplifies this situation by showing comparative cost estimates for flight testing a platform similar to those used for research at Linköping University. Two different scenarios are estimated taking into account the current Swedish civil air regulations [16] and commercial prices as of year 2018. Nearly all the flight test campaigns carried out by Linköping University are similar to the case named "Campaign 1".

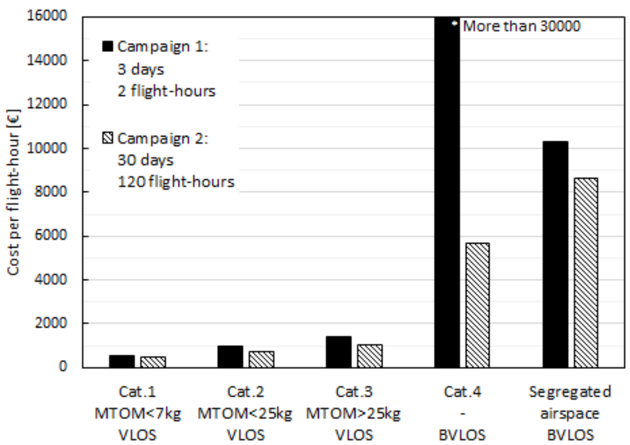

Fig. 1 Cost estimation for flight testing a typical research platform of Linköping University in Sweden, year 2018.

1.2 Efficiency, a Key Factor

Performing flight tests with remotely piloted aircraft systems (RPAS) in general, and under VLOS rules in particular, requires different approaches than those traditionally followed in manned aircraft. This becomes clear from a comparison between flight-testing methods for conventional [17, 18] and unmanned vehicles [19, 20, 21]. A short testing time, need for constant manoeuvring, and imprecision of remotely executed excitation manoeuvres are some of the factors that complicate the process. These challenges become even more evident when the test objects are heavy and complex dynamically scaled models typically used in research projects such as [3] and [22]. This last reference describes an earlier flight testing campaign carried out by Linköping University using the platform shown in Fig.3. This jet-powered aircraft is currently one of the most advanced research platforms at Linköping University and it has served as a testbed for validating most of the techniques presented in this paper.

Fig. 2 introduces various subscale demonstrators built by Linköping University in order to illustrate the extremely reduced time available for manoeuvring inside a given test window when the flight is done within VLOS. Experience has shown that test windows larger than 500 meters are difficult to achieve due to the need for appropriate safety margins, aircraft manoeuvrability and visibility constraints. This figure shows an optimistic estimation of time based on straight-and-level flight along the entire test window. In reality, dynamic flying and weather conditions may significantly alter the available time to execute each test manoeuvre.

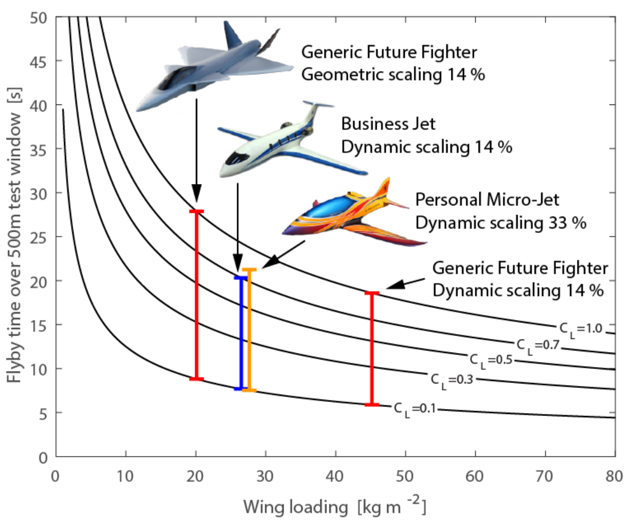

Fig. 2 Estimation of time available inside a 500-meter test window for different subscale demonstrators, assuming straight-and-level flight.

2 Methodology

Flight testing methods have been extensively discussed in the literature. Publications [17] and [18] are two typical references that focus entirely on manned aircraft. In addition, other publications dealing with flight testing RPA have begun to appear [19, 20, 21]. Nevertheless, although flying RPA under VLOS rules is a common practice it is still rare to find published discussions about this particular scenario.

The techniques proposed here do not originate from a particular methodology. Some of them have been adapted from traditional industrial practices and full-scale techniques, whereas others are based on the authors' experience operating UAS and inspired by radio-controlled model flying techniques. An extensive discussion on testing methodologies is not intended, and this paper only covers particular techniques that are considered most relevant and that differ from other scenarios or applications.

Fig. 3 The GFF demonstrator: a 2-meter, jet-powered platform used for research at Linköping University [22].

The subscale demonstrator of the *Generic Future Fighter* (GFF) concept [23], shown in Fig.3, is used here as a representative example of a challenging platform for remote flight testing within VLOS. Although it originated from a conceptual-design exercise between Saab and Linköping University, this generic design has no couplings to any current or future Saab products.

2.1 Infrastructure

One advantage of flight testing RPA within VLOS is that it often does not demand a large infrastructure. The resources needed to support, operate and maintain these systems are in some cases only slightly more than those required by radio-controlled models for hobbyist activities.

If operating in civil airspace, the minimum crew and the competences required to perform UAS operations may be directly specified by the authorities. For platforms with a take-off mass (TOM) lower than $25kg$, as most of the research platforms flown by Linköping University, the current Swedish regulation [16] specifies requirements only for the pilot-in-command, who must behold an approved certificate of competence. However, for platforms with a TOM higher than $25kg$, up to four different roles are specified. Besides these requirements, the authors have identified at least three different roles that, based on experience, can be considered the minimum crew needed to conduct efficient flight tests in VLOS:

- test conductor, responsible for controlling the test execution and data acquisition;
- pilot, flying the aircraft remotely from the ground control;
- test monitor, supervising the safety area and evaluating the obtained results between flights.

It is difficult to make general statements about the location of appropriate test facilities: requirements such as runway, airspace, remoteness, and supporting equipment are usually based on the test article, the specific research plan, and the pertinent internal or external regulations. Other programmatic factors such as transportation cost and expenses may also play an important role [3]. The main advantage of flight within VLOS is that tests are not restricted to general-aviation airfields, but can also be carried out in model-flying fields, a convenient possibility that considerably increases the number of candidates and significantly lowers the operating cost.

2.2 Concept of Operations

The research requirements are transformed into a flight test plan by breaking down the desired scenarios into short manoeuvres or *test points*. As in manned-aircraft, both flight time and risk can be minimised by carefully choosing the sequence of test points [18]. In this scenario, it is recommended to also pay attention to local atmospheric conditions, available airspace for manoeuvring, and fuel-weight fluctuations; where the latter could notably affect light-weight platforms. It has been observed that, given the short duration of the flights and the exposure to arbitrary external perturbations, it may be convenient to leave room in the test plan for eventual repetitions of test points or even entire sequences. Several flights per session are normally possible and keeping a certain degree of flexibility - although avoiding improvisation - can be beneficial.

The proposed concept of operations is outlined in Fig. 4. The three roles presented earlier should be in constant communication and their tasks should not be exchanged during the entire flight, which typically takes 10 to 15 minutes. The pilot-in-command should not lose direct visual contact with the aircraft at any time between engine start and shut-down, and therefore relies on spoken communication and audio signals to gain complete awareness of the aircraft status and the surroundings. Standardised flight-test cards streamline the communication between the pilot and the test conductor. During the flight, the test conductor reads out the respective test point to the pilot including the desired airspeed, attitude and aircraft configuration at the beginning of the manoeuvre. In addition, the test conductor can write down on the test card any relevant observation that needs to be documented. Furthermore, the pilot workload may be reduced further if the excitation manoeuvres are pre-programmed, a technique that eliminates the need for memorising the execution of each test manoeuvre. Besides a limited real-time monitoring of the sensor signals, the authors customarily download and verify the acquired data as soon as the aircraft has landed.

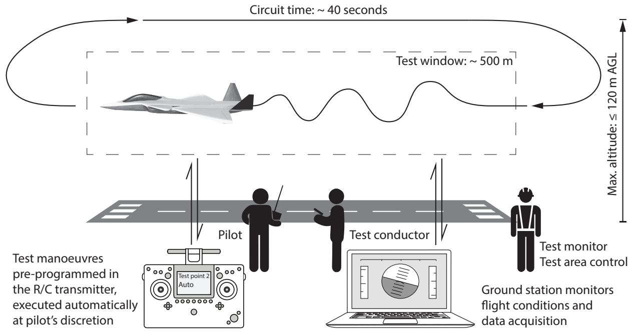

Fig. 4 Diagram of the proposed concept of operations for safe and efficient flight testing within VLOS.

In case of an emergency or loss of control, there must be a well-established and well-trained flight termination procedure to immediately bring down the aircraft within the designated safety area and with the minimum energy possible. The aircraft should have the necessary onboard system to carry out this procedure autonomously even if the control link is lost. In fact, this is sometimes a condition specified in civil UAS regulations, as in [16].

While the maximum allowed distance between the aircraft and the pilot is ultimately determined by the definition of VLOS stated in the regulations, the most common presumption is 500 meters. The maximum allowed flight altitude commonly lies between 120 and 150 meters above ground level (AGL), although this is subject to local airspace rules or temporary clearances from the air traffic control services. The result is a cylindrical airspace of very limited dimensions, heavily affected by ground turbulence and surface obstacles. It can be divided into three areas, which should be marked with clear visual references:

- a safety area, where only crew members are allowed;
- a nominal manoeuvring area;
- and a designated test window.

Fig.5 shows an example of this distribution. The orientation and placement of the areas will depend on ground obstacles, visibility, sun position, and wind direction.

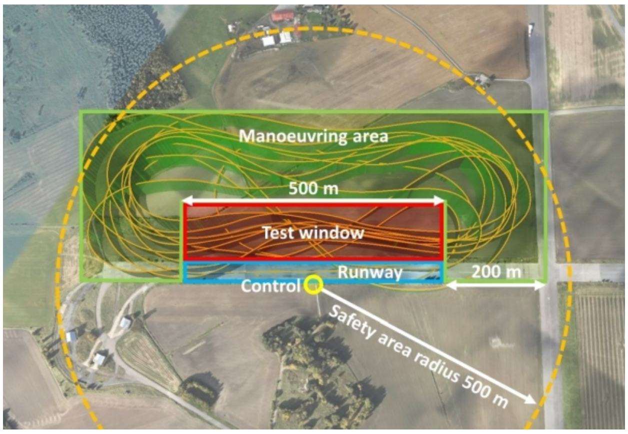

Fig. 5 Trajectory during a flight test of the GFF platform, following the proposed concept of operations.

2.3 Automation of Manoeuvres

The authors have developed a novel method for commanding precisely pre-programmed excitation manoeuvres without the need of a closed-loop flight controller or an on-line ground station. On one hand, this benefits the smallest low-cost platforms by further simplifying their development. On the other hand, it may allow more complex platforms to perform automated flight test manoeuvres even before their flight control system is mature enough to fly autonomously, or in the case that this is not allowed by the applicable regulations. In any case, this method reduces effectively the workload of the pilot, who can focus on the challenging task of flying the aircraft through the narrow manoeuvring area at the required speed, altitude and attitude; see figures 4 and 5.

This method is based on a custom-made application written in *Lua* language [24] that runs on the radio-control transmitter in parallel to its standard software. The capability of interpreting Lua scripts has been introduced recently by some radio-control system manufacturers and it has been used mainly by hobbyists to visualize telemetry data in sophisticated ways or to customise the user interface. The authors explored the possibility of using this capability to actuate flight controls following complex pre-defined signals. The result is a Lua application that makes it possible to assemble an entire sequence of test points in a convenient way. The application is designed to use an external library of input signals that can be updated or extended at any moment. Both analytically-described functions and discrete point-defined signals can be loaded. Once a test sequence has been configured, the script can also be used as electronic documentation for each flight test.

During the flight, the pilot selects the corresponding test point and triggers the manoeuvre by flipping and holding a switch. The corresponding signals will be then executed on the intended control surfaces according to the specified timing and recurrence. An information window, displayed on the transmitter's screen, shows the test point status and any incidences, see Fig. 6. In addition, audible signals and commands are played out through the transmitter's speakers so the pilot does not need to lose visual contact with the aircraft. Several safety mechanisms have been introduced during the development of the application in order to avoid any malfunction to affect the platform's controllability. Ultimately, the pilot can abort at any time and regain manual control by releasing the trigger switch. Due to the current hardware limitations, the signals can be transmitted up to a maximum frequency of 50 Hz. This rate is close to the typical refresh rate of radio-control systems, and so far it has been sufficient for the tested applications.

Fig. 6 Information window of the application during the execution of a test point, integrated on a transmitter Jeti Model DC-24.

The Lua application is under continuous development at Linköping University. The latest release includes the use of *virtual flags* to mark the exposure periods on the logged data in order to allow automatic selection and post-processing of the desired flight segments. It is planned to release a generic version of this application as open-source software in the near future.

2.4 Optimised Manoeuvres for Performance Evaluation

During performance flight testing, manned aircraft are usually flown very accurately in still air and the large airspace available allows conducting stable test points [17, 18, 25]. As discussed earlier, this is not the case when flight testing RPA within VLOS. The time to execute each test point is extremely limited (see Fig. 2) and level, trimmed flight is hardly achievable. The acquisition of performance data such as lift-to-drag polars of the aircraft using traditional approaches becomes problematic. Short manoeuvres with a rich information content are preferred over extensive exploration of the flight envelope. The advantages, in terms of efficiency, of dynamic test techniques with respect to steady-state test techniques have been noted previously in literature [25]. This kind of manoeuvres seem very well suited for performance testing of RPA under the constraints of VLOS-flight. Table 1 summarises some of the flight manoeuvres considered efficient for acquiring performance data.

Table 1 Various dynamic flight manoeuvres considered useful for performance evaluation within VLOS. Some have been inspired by manned-aircraft techniques described in [25].

Manoeuvre	Conditions	Results
Slow-down: deceleration to high AOA by pulling up	Constant thrust, any configuration, load factor close to 1g	Several trim and polar points up to maximum AOA
Vertical "roller-coaster": gentle push-over followed by pull-up	Constant thrust, any configuration, load factor from 0g to 2-3g	Several polar points around trim point, lift variations
"Bleed-off" closing banked turn in horizontal plane	Constant thrust, constant altitude, load factor increasing from 1g to maximum	Several polar points up to maximum load, load factor vs AOA
"Wind-up" closing spiral turn*	Constant thrust, constant speed, load factor increasing from 1g to maximum	Several polar points up to maximum load, load factor vs AOA

* This manoeuvre could be unfeasible at very low level over the terrain since it involves trading altitude for speed.

Another obstacle that usually arises during flight testing of RPA within VLOS is that the flight conditions of the aircraft are not always easy to assess accurately from an external point of view. In order to increase pilot awareness without the need for visually monitoring instruments, the authors have implemented a system of audible signals that inform about critical parameters such as airspeed. For example, the airspeed readings received from the platform via telemetry are transformed in the transmitter into beeping sounds of variable pitch, in a similar way to the electronic variometers typically found in gliders. Once this audible feedback is adjusted to the target value, this technique allows the pilot to maintain the desired the airspeed without the need for a closed-loop control system.

2.5 Optimised Manoeuvres for Flight-Mechanical Characteristics

Due to the short flyby time available for each test run, efficient manoeuvres that give informative excitation are needed. For this type of testing, the problem is to find input signals that effectively trigger the flight mechanical motion. For small-disturbance testing, the motion can be described by a linear system

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) + w(t) \\ y(t) &= Cx(t) + v(t). \end{aligned} \tag{1}$$

The pitching motion of the GFF is used as an example: the states $x(t) = \begin{bmatrix}\alpha(t) & q(t)\end{bmatrix}^T$ are the angle-of-attack and the pitch rate, and the inputs $u(t) = \begin{bmatrix}\delta_e(t) & \delta_c(t)\end{bmatrix}^T$ are the elevator and canard deflections. The definitions of these are shown in Figure 7.

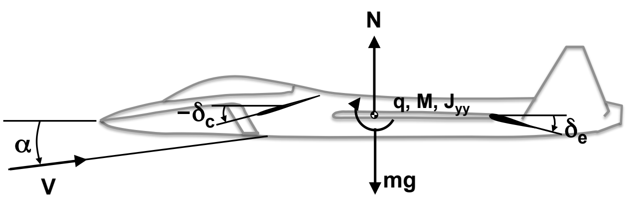

Fig. 7 Definitions of the variables used for the GFF.

In (1), $w(t)$ and $v(t)$ are the process and measurement noise respectively. It should be noted that the process noise is represented by turbulence and can therefore not be assumed to be white.

One type of input that could be used is the multisine signal described in [26]. A multisine signal has the form

$$u(t) = \sum_{r=1}^{N_u} A_r \cos(\omega_0 rt + \varphi_r) \tag{2}$$

where ω_0 is the base frequency. A_r and φ_r are the amplitudes and phases of signal frequency $\omega_0 r$. To get a multisine signal with an even amplitude, a crest factor optimization can be used. In Figure 8 a crest-factor optimized multisine signal with five frequencies, generated with the toolbox described in [27], are compared to a commonly used double pulse.

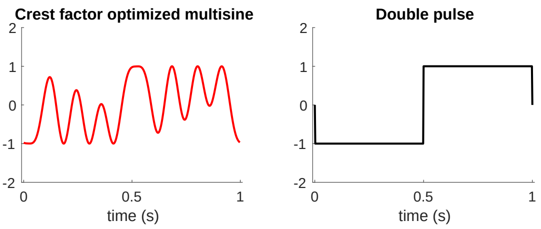

Fig. 8 Example of a multisine in red and double pulse in black.

The benefit of using a multisine approach is that two signals are uncorrelated if they are separated in frequencies. This fact can be used to shorten the excitation time during a test run. The effect can be seen in Figure 9 where two simulated test input signals are shown. The multisines are executed simultaneously for the elevator and canard with low correlation as can be seen in Table 2. The double pulse input needs to be separated in order to have relatively low correlations, which can be seen in Table 3. If the double pulse inputs are executed simultaneously the correlations will be higher, which could lead to worse identification conditions.

Although the current system capabilities include real-time monitoring of some onboard sensors, it would be desirable to also monitor the

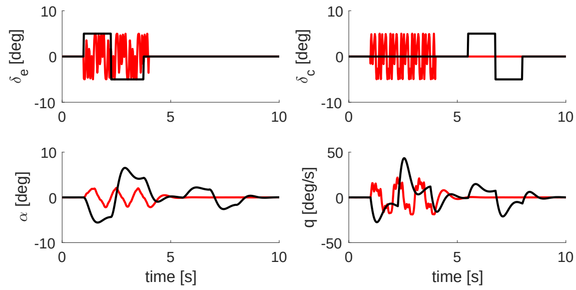

Fig. 9 Input signals: multisine in red and double pulse in black.

Table 2 Absolute value of correlation between regressors for the multisine input shown in Fig. 9.

	δ_e	δ_c	α	q
δ_e	1.00	0.00	0.08	0.30
δ_c		1.00	0.02	0.01
α			1.00	0.32
q				1.00

Table 3 Absolute value of correlation between regressors for the double pulse input shown in Fig. 9.

	δ_e	δ_c	α	q
δ_e	1.00	0.00	0.76	0.68
δ_c		1.00	0.26	0.41
α			1.00	0.57
q				1.00

flight mechanical characteristics on-line during the test runs. This could be used to see if anything unexpected occurs during the flight and also to ensure that enough excitation is in the data to be able to make an accurate post-flight analysis. Both of these reasons can contribute to making the testing more efficient. In [28] one such method, using a frequency domain approach in combination with a complex least squares method, is given. However, when flying at low altitude, as is the case for a subscale aircraft within VLOS, ground turbulence will be an issue to consider. This might lead to biased estimates for a least squares method since the problem is of an Errors-In-Variable character. An Instrumental Variable (IV) approach is a common way of dealing with this type of problem. An algorithm using this approach is given in [29]. This can improve the algorithm performance. Suitable instruments, which are uncorrelated with the noise but correlated with the regressors, have to be chosen. An idea is to use data from simulations of a known model data as instruments. In this example, data from an earlier flight test have been used for identification. The resulting model is given as

$$\dot{x}(t) = \begin{bmatrix} -1.88 & 0.65 \\ -36.39 & -2.77 \end{bmatrix} x(t) + \begin{bmatrix} -0.33 & -0.37 \\ -39.04 & 17.49 \end{bmatrix} u(t)$$
$$y(t) = \begin{bmatrix} 1.00 & 0.00 \\ 0.00 & 1.00 \end{bmatrix} x(t) \tag{3}$$

The instruments are generated by simulating the flight at each test run using (3) with the same input signals as in the real flight. This will give a noise-free data set that should be good enough to use in the estimation process.

3 Results

Recent flight tests in which the presented methodology has been applied show an improvement in efficiency regarding the amount of information identified against the flight time used. The semi-automated flight test sequence and the manoeuvres with high information content are completed by specialised post-flight analysis scripts developed in *MATLAB*, enabling quick verification and first evaluation of the obtained data right after landing.

3.1 Acquisition of Performance Data

Figs. 10 and 11 show an example of performance data, lift coefficient of the GFF demonstrator in this case, reduced from a single 10-minute flight that included vertical dynamic manoeuvres. At the time of writing, a novel thrust measurement system is being installed on this platform. This system is expected to improve the accuracy of the polar estimations, now based on corrected static thrust measurements. More details and results from this technique will be presented soon after the next flight test campaign.

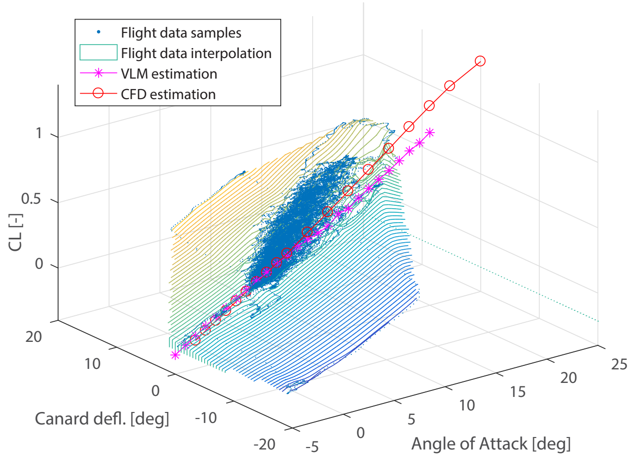

Fig. 10 Cloud of lift data samples obtained during a single flight with dynamic manoeuvring.

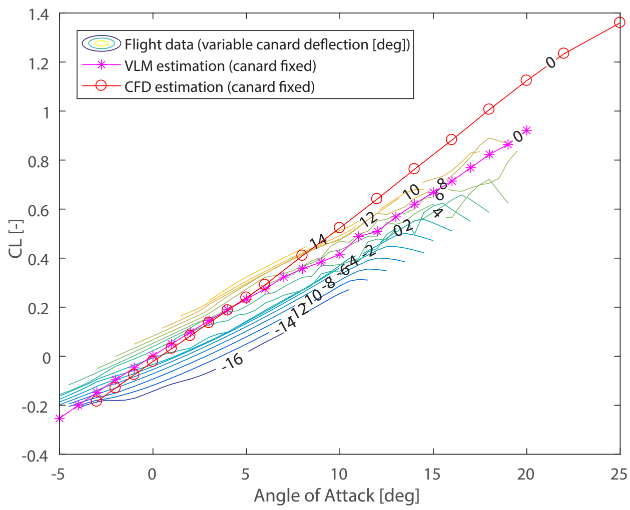

Fig. 11 Example of performance data obtained during a single flight with dynamic manoeuvring.

3.2 Identification of Flight-Mechanical Characteristics

Results from a real flight with the GFF are given in Fig. 12. A test run using a multisine input is compared with one using a double pulse.

The top three rows show the input signals and the estimated parameters in the *B*-matrix in (1) over time. In the same way, the output signals and the estimated parameters in the *A*-matrix are shown in the lower three rows. The estimated parameters are shown as red circles for the multisine using the instruments and in black for the double pulse without the instruments. The verti-

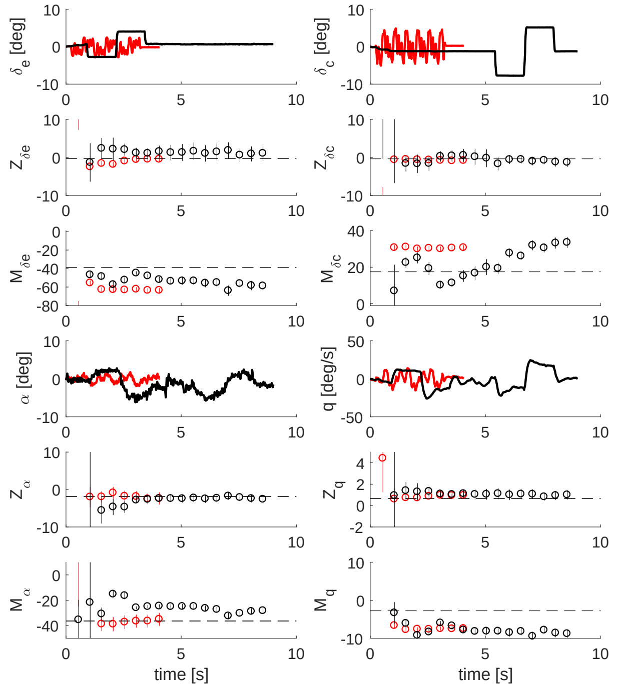

Fig. 12 Estimated parameters shown as red circles for the multisine input using the instruments, and in black for the double pulse without the instruments. The model used as instruments in the estimation is given as dashed lines.

cal bars are estimated uncertainty measure of two standard deviations. The model (3), based on previous flight test data, is shown as dashed lines. As can be seen, the elevator and canard efficiency, M_{δ_e} and M_{δ_c}, are better and also, the pitch damping M_q is larger than previously estimated. The presence of turbulence can clearly be seen in the noisy angle-of-attack signals.

Table 4 shows the correlation for the multisine input and Table 5 for the double pulse input. The expected results from the inputs simulated earlier are confirmed: the correlation for the multisine is much lower than for the double pulse.

The resulting models from the identification are given in (4) for the multisine case and (5) for the double pulse case. These two are not the same, but similar. To test the validity of the models a third data set is used: an aborted test run.

As can be seen there are differences, but in general both models give a good agreement with the new test run. It should be noted that for the use of the multisine this result was acquired using

Table 4 Absolute value of correlation between regressors for the multisine input.

	δ_e	δ_c	α	q
δ_e	1.00	0.05	0.01	0.40
δ_c		1.00	0.34	0.22
α			1.00	0.08
q				1.00

Table 5 Absolute value of correlation between regressors for the double pulse input.

	δ_e	δ_c	α	q
δ_e	1.00	0.00	0.57	0.58
δ_c		1.00	0.50	0.71
α			1.00	0.67
q				1.00

half the flight time compared to the double pulse input. This shows that using multisine input with the suggested on-line monitoring method given in [29] gives an effective evaluation process for this type of flight testing.

$$\dot{x}(t) = \begin{bmatrix} -2.38 & 0.94 \\ -35.08 & -7.45 \end{bmatrix} x(t) + \begin{bmatrix} -0.50 & -0.82 \\ -63.57 & 30.69 \end{bmatrix} u(t)$$
$$y(t) = \begin{bmatrix} 1.00 & 0.00 \\ 0.00 & 1.00 \end{bmatrix} x(t) \tag{4}$$

$$\dot{x}(t) = \begin{bmatrix} -2.60 & 1.00 \\ -28.27 & -8.80 \end{bmatrix} x(t) + \begin{bmatrix} 1.06 & -1.31 \\ -58.27 & 33.53 \end{bmatrix} u(t)$$
$$y(t) = \begin{bmatrix} 1.00 & 0.00 \\ 0.00 & 1.00 \end{bmatrix} x(t) \tag{5}$$

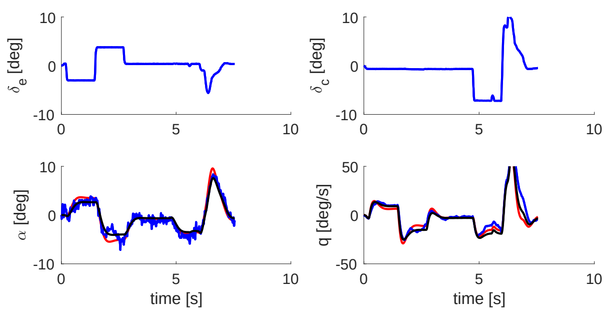

Fig. 13 Validation data in blue, multisine input in red and double pulse input in black.

4 Conclusions

This investigation has been focused on finding solutions that could improve performance evaluation and system identification of fixed-wing RPA flying within VLOS at VLL, aiming at minimum complexity and low implementation cost.

After several flight-test campaigns, mainly with the GFF platform, it is believed that the proposed concept of operations and the use of optimised manoeuvres have improved not only safety but also the efficiency of the tests in terms of relevant data versus total flight time.

The presented method for commanding precise pre-programmed excitation manoeuvres by using a novel application installed in the radio-control transmitter has undoubtedly played an important role in this improvement. This tool effectively reduces pilot workload and it has also enabled experimentation with complex signals such as multisine inputs.

It has been shown with experimental data that the multisine approach can reduce significantly the excitation time needed for the identification of flight-mechanical characteristics. The use of simultaneous uncorrelated inputs seems an important advantage for this kind of scenario, considering the very limited time available during flight within VLOS. The efficiency of data acquisition and its evaluation could be improved further by incorporating an on-line monitoring method as suggested before.

It is also probable that some of the techniques presented here could perhaps present similar benefits in other kinds of flight testing such as flight testing beyond visual line-of-sight or even full-scale flight testing.

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