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Flight Test Oriented Autopilot Design for Improved Aerodynamic Parameter Identification

Matthias Krings, Karsten Henning and Frank Thielecke

Abstract In order to reduce development costs and time, model-based design is widely introduced in the industry leading to a strong need for verified high-fidelity simulation models. An inevitable, but challenging process step to obtain such simulation models for GNC-applications is the aerodynamic parameter identification on the basis of real flight test data. The identification process requires distinct excitation maneuvers in order to constrain the design space to a subset of model parameters reducing the complexity of the identification problem and the correlation within the overall parameter set. Typically, manually flown excitation maneuvers are not exact and fully reproducible concerning the requirements and therefore the amount of rejected data points is significant. In case of remotely piloted aircraft systems, the decoupling of the aircraft and the ground pilot in charge leads to an even less sensitive maneuver control, a further reduced disturbance suppression and even greater difficulties in meeting the initialization requirements. This scenario calls for an automation of aerodynamic parameter identification related flight tests. A practical approach to a flight test oriented autopilot for improved aerodynamic parameter identification is proposed within this paper. The requirements for identification excitation maneuvers and the corresponding design of the autopilot are emphasized and flight test results are presented.

1 Introduction

Increasing automation of aircraft systems introduces a wide variety of complex issues regarding novel system concepts and technologies of prospective aircraft. In order to reduce development costs and time of such technologies, model-based design is widely introduced in the industry leading to a strong need for verified high-fidelity

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simulation models. Especially the development of advanced flight control and envelope protection schemes [1, 2] as well as the development of methods for system diagnosis and monitoring, e.g. loads observer for structural loads analysis and monitoring [3, 4, 5, 6], call for qualified flight mechanical models for evaluation and validation at an early design stage.

Although there is a strong trend towards numerical determination of model parameters, e.g. CAD, CFD, etc., system identification on the basis of real test data is still inevitable, even though it is only for validation of numerical findings. Due to the well known structure of flight mechanical simulation models the identification is often narrowed to the aerodynamic parameters, but can be extended to an identification of mass properties and actuator dynamics. Nevertheless, the effort of identifying the plant properties disproportionally increases with the number of parameters to be considered and with the data quality required. Therefore, distinct excitation maneuvers are required in order to constrain the design space to a subset of parameters reducing the complexity of the identification problem and the correlation within the overall parameter set [7, 8].

In the context of an identification of the aircraft's aerodynamic properties, the definition of these maneuvers shall aim on a separation of longitudinal and lateral motion, on a specific magnitude and timing of the command inputs and on an initialization at a predefined point within the flight envelope. Typically, these manually flown excitation maneuvers are not exact and fully reproducible concerning these requirements and therefore the amount of rejected data points is significant [5, 6]. This problem is further exacerbated by identifying the aerodynamic parameters of a remotely piloted aircraft system. The decoupling of the aircraft and the ground pilot in charge leads to a less sensitive maneuver control, a reduced disturbance suppression and difficulties in meeting the initialization requirements. This scenario calls for an automation of aerodynamic parameter identification related flight tests.

A practical approach to a flight test oriented autopilot for improved aerodynamic parameter identification is therefore suggested within this paper, which is organized as follows. First, a general description of the system identification process and a specification of common maneuvers for identification of aerodynamic parameters are given in Section 2, followed by the flight test oriented autopilot in Section 3. In Section 4 an application example and related flight test results are presented.

2 System Identification and Maneuvers

System identification represents a process of determining a model structure and related model parameter of a dynamic system with known system excitation and response. This general approach is depicted in Fig. 1 and is denoted as *Quad-M* process [7]. Herein, the four elements: maneuver design, measurement accuracy, method and model definition are the key enablers to identification results with high quality and reliability.

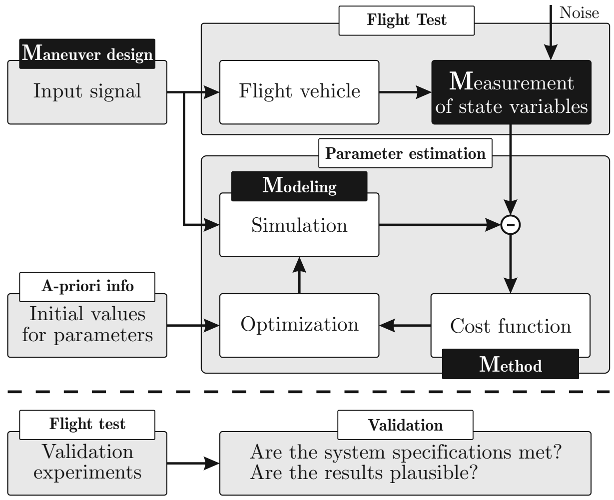


Fig. 1 General process flow (Quad-M process acc. to Ref. [7])

Among other a gray box approach is chosen defining a physically motivated model structure of the flight dynamics. The classical representation, which can be found in Ref. [9], comprises the 6DOF equation of motion and a polynomial representation of the aerodynamic properties. Actuator dynamics might be also taken into account. The unknown model parameters are quantified by comparison of the model and the measured aircraft system response. This procedure, widely known as the output error method, is described in detail in several Ref. [5, 6, 7].

While the mass properties and the actuator dynamics are identified within laboratory test, e.g. weighing, the aerodynamic derivatives are determined on the basis of flight tests. During these flight tests the designated aircraft is excited by well-defined input signal sequences, which form the basis for an efficient, unambiguous solution of the identification problem. Therefore, the input signal sequences are subject to certain conditions, in particular [5, 6]:

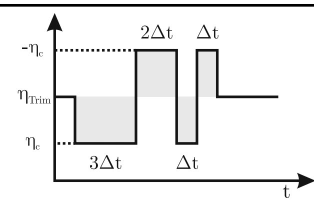
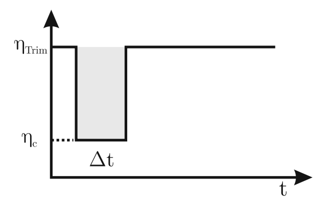
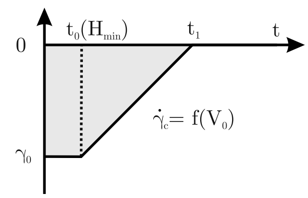
- the cause variables of the aerodynamic model shall be excited,
- the excitation shall allow an identification of the parameters without correlation,
- the maneuvers shall be initialized based on a steady straight symmetric flight,
- the data basis shall contain at least one set of measurements for identification as well as one for validation and
- the maneuvers shall be repeated with variable excitation magnitude and initial flight condition in order to capture nonlinearities due to viscosity effects.

One might optimize the input signal sequences on the basis of the estimation error criterion used within the identification process [7, 10, 11]. However, the optimality of these input sequence heavily depends on the fidelity of the model and thus, in an early phase of the identification process, these excitation maneuvers are quite often not suitable [12]. Considering small and/or slow aircraft the circular-

ity problem in defining optimal input sequences might be hard to resolve. Due to the low Reynolds numbers the preliminary numerical findings from classical CFD methods are relatively poor and hence, the initial model might be inappropriate to break the circularity problem. Therefore, the input design technique must be robust to unknown errors in the a priori model. Here, a practical approach is suggested, which comprises the well-known multistep input sequences with a low number of design parameters and a good traceability of aircraft's response.

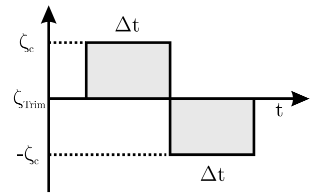
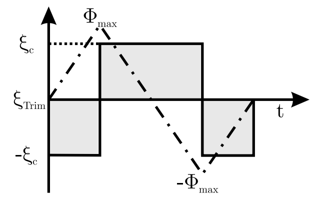
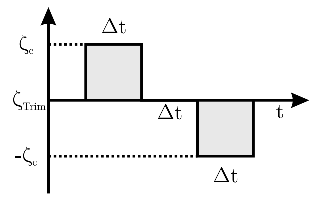
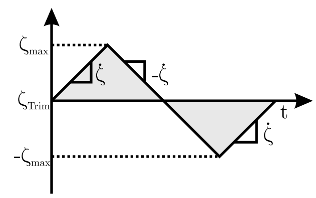
In order to identify the full parameter set of the longitudinal and lateral aerodynamics and the corresponding coupling effects seven maneuvers are recommended in Ref. [5, 6, 7]. The maneuvers and their major properties are listed in Tab. 1 and Tab. 2.

Table 1 Longitudinal aerodynamic parameter identification maneuvers

Maneuver name	Maneuver requirements	Maneuver commands
Short-period mode maneuver (SPM)	no lateral motion, constant thrust lever position	
Phugoid maneuver (PM)	no lateral motion, constant thrust lever position	
Level deceleration maneuver (LD)	no lateral motion, constant thrust lever position, constant speed break settings	

The input signals as well as the corresponding aircraft response are measured with high-precision. The recorded system response is then compared to the response of the simulation model, based on the same input signal sequence. Due to the initial, insufficient knowledge of the model parameters, the response of the simulation model differs considerably from the response of the real aircraft. A cost function, defined by the principle of maximum likelihood estimation [7], and hence, the output error, are minimized by manipulation of the uncertain model parameters. Detailed information regarding implementation and specific optimization algorithms for system identification problem formulations can be found in Ref. [5] to Ref. [8].

Table 2 Lateral aerodynamic parameter identification maneuvers

Maneuver name	Maneuver requirements	Maneuver commands
Dutch roll maneuver (DR)	remaining motivators in trim position	
Bank-to-bank maneuver (BTB)	remaining motivators in trim position	
Steady heading steady sideslip maneuver (SHSS)	maintaining track by means of aileron deflection, maintaining speed by means of elevator deflection, constant thrust lever position	
Wings level sideslip maneuver (WLS)	maintaining zero bank angle by means of aileron deflection, maintaining constant speed by means of elevator deflection, constant thrust lever position	

3 Flight Test Oriented Autopilot

The flight test oriented autopilot, presented in this paper, is required to provide three different modes of operation:

- improving the flying qualities in manual flight mode,
- guiding the aircraft on the basis of predefined flight path parameters and
- performing identification maneuvers corresponding to Tab. 1 and Tab. 2.

Despite the multiple utilization and the implementation on various aircraft types the autopilot itself is required to have an easy-to-handle design with lean overhead structures. A cascaded control strategy was selected with inner flight control loops improving the flying qualities and the outer flight guidance loops regulating the aircraft rigid body motion on the basis of predefined flight path parameters. With regard to the previously defined identification maneuvers, the global controller struc-

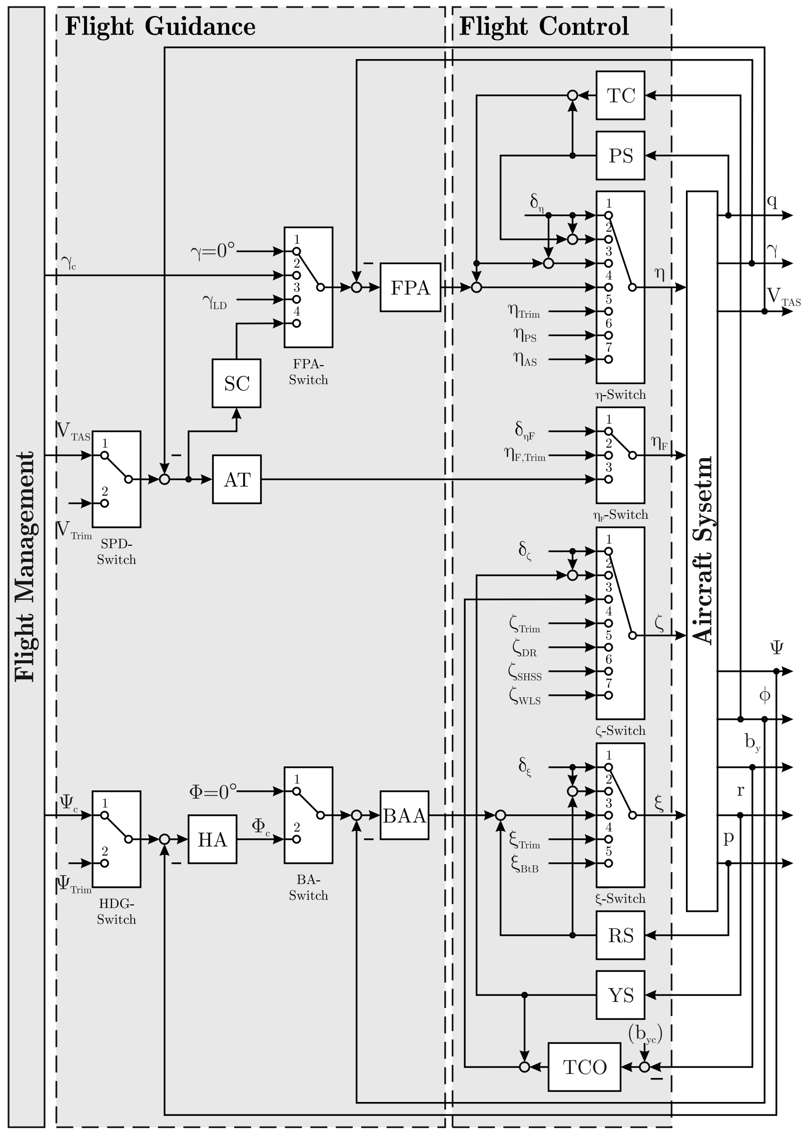


Fig. 2 Autopilot structure

ture has a clear dissociation of longitudinal and lateral control tasks, as depicted in Fig. 2.

The inner control loops comprise not only stability augmentation systems (PS, RS, YS) but also a turn coordination (TCO) and a turn compensation (TC). The guidance part of the autopilot comprises on the one hand a flight path angle displacement autopilot (FPA) and an autothrottle function (AT) occupying the lon-

gitudinal motion, and on the other hand a bank angle displacement (BAA) and a heading autopilot (HA) occupying the lateral motion of the aircraft. An alternative in regulating the airspeed is inevitable due to the aerodynamic parameter identification requirement of a steady straight descent with constant thrust lever position. Therefore a speed controller (SC) is introduced in order to regulate the airspeed via elevator deflections. The regulators of the inner loops are chosen to be proportional only, whereas the regulators of the outer loops are designed as proportional-integral controller. In conjunction with the chosen maneuver input sequences the overall concept aims on an intuitive design of a minimal set of parameters and hence, leads to reduced complexity and good traceability throughout flight testing. A minor performance compared to more advanced controller structures and maneuver design methods is therefore to be accepted.

A distributed state machine, depicted in Fig. 3, takes on the management of the overall GNC-system not only controlling the mode switching solely but also monitoring the current flight and sensor conditions. In dependence on the available sensor data and command channels, the requested system modes are executed. A transient-free mode switching is ensured by a trimming routine capturing the current flight condition and motivator commands. The general structure of the state machine reflects the structure of the overall GNC framework. Its modular design enables an easy augmentation of the existing system with additional modes and control laws. Alongside other, already existing control laws, e.g. a *Default* mode, which keeps the motivators in neutral position, a *RC Teacher* mode, which is the safety pilot mode,

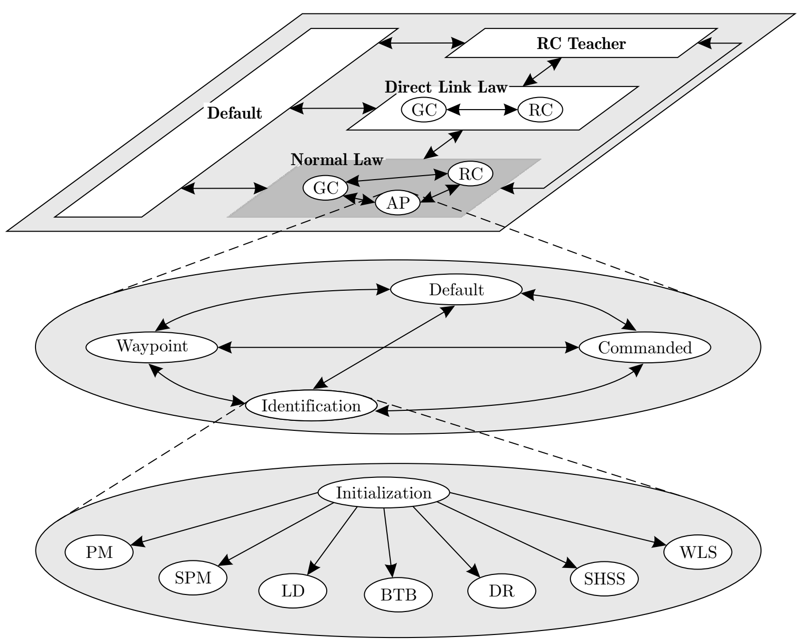


Fig. 3 Autopilot state machine

and a *Direct Link Law* mode, which is a direct feed-through of joystick (GC) and remote control (RC) commands, the *Normal Law* mode accommodates the proposed autopilot scheme. The *Normal Law* mode reflects the two stage approach of the preceding paragraph: a manual flight control part (GC and RC) and an automated flight guidance part (AP). The latter part is divided into a *Default* mode capturing and maintaining the current flight condition (airspeed, flight path angle and heading), a *Commanded* and a *Waypoint* mode providing an interface to a manual and an automated set up of the flight path parameters, and an *Identification* mode comprising the automated identification process (initialization and identification maneuvers).

4 Application Example and Comparative Flight Test Results

A first application case of the flight test oriented autopilot represents the unmanned flight test platform ULTRA-Dimona, which is the most visible aspect of the ULTRA-project founded by the TUHH-Institute of Aircraft Systems Engineering. A simulation model of this aircraft, e.g. required for software-in-the-loop and hardware-in-the-loop simulations, comprises a preliminary set of aerodynamic parameters derived by vortex lattice methods. In order to enhance the fidelity of this simulation model, identification flight test campaigns are required to determine more accurate parameter sets.

This section briefly introduces the ULTRA-project environment and the unmanned flight test platform ULTRA-Dimona. The subsequent presentation of flight test results indicates the reliability and performance of the basic autopilot functions for aerodynamic parameter identification. Due to uncertainties within the aerodynamic modeling, these results should be seen as a preliminary evaluation of the overall autopilot performance.

4.1 Unmanned Low-cost Testing Research Aircraft at TUHH

Increasing automation of aircraft systems introduces a wide variety of complex issues regarding novel systems concepts and technologies of prospective manned aircraft. Facing these issues, the Institute of Aircraft System Engineering at Hamburg University of Technology founded the project ULTRA [1] (Unmanned Low-cost Testing Research Aircraft). Establishing flight test capabilities, the ULTRA-project conducts a representative framework for research and education adopting industry standard software and hardware components. This framework includes not only the ability of flight testing with the cost-effective, scaled, unmanned motorglider ULTRA-Dimona (see Fig. 4), but also capabilities of a laboratory infrastructure, enabling software-in-the-loop and hardware-in-the-loop simulations.

[1] ULTRA-Project: www.fst.tu-harburg.de/ultra

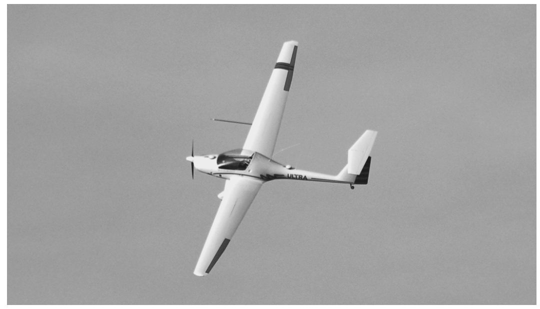


Fig. 4 Unmanned flight test platform ULTRA-Dimona

The ULTRA-Dimona is equipped with a precise navigation platform enabling highly accurate measurements of the rigid-body motion. Air data sensors as well as measurements of control surface positions and motor speed complete the instrumentation of the unmanned flight test platform providing an ideal basis for aerodynamic parameter identification. An on-board *dSPACE* real-time system provides the capability of easily implementing, tuning and executing flight guidance and control algorithms.

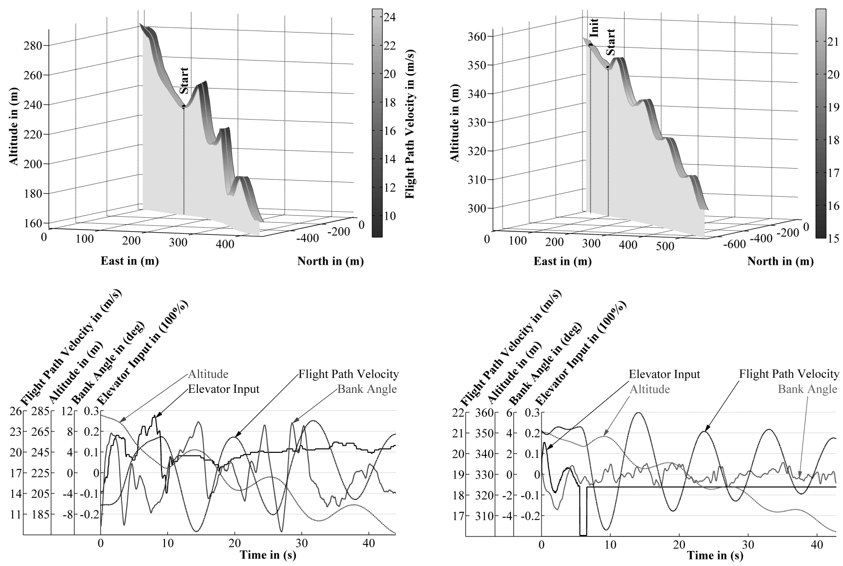
The flight test oriented autopilot approach for improved system identification was implemented on this target system and first tested within a hardware-in-the-loop simulation. The design of the controller parameters was based on a preliminary system model, where the mass properties of the flight test platform as well as the motivator dynamics were already identified throughout laboratory tests and the aerodynamic properties were determined on the basis of vortex lattice methods and slightly adapted in order to match the experience of manually controlling the real aircraft.

4.2 Flight Test Scenario for Aerodynamic Parameter Identification

A typical flight test scenario for identification of the aerodynamic system parameters is divided into manually and automatically flown parts. A safety pilot flies the aircraft to a starting position characterized by a desired airspeed, altitude and heading. Whereas the airspeed and altitude are defined by a specific flight point within the envelope of the aircraft, the heading is typically chosen as the wind direction. At this initialization position the aircraft is handed over to the autopilot. The current airspeed and heading are captured and define the steady straight descent representing the trim condition of the identification maneuver. During this flight phase the thrust lever position is kept constant and the airspeed is controlled by means of elevator deflections. The actual identification maneuver is accomplished out of this trim condition. The point of maneuver completion, a predefined altitude threshold or the range of vision respectively define the point in time, when the aircraft is handed back to the safety pilot. A subsequent repetition of this procedure might be carried out.

4.3 Flight Test Results

The autopilot was tested throughout two flight test campaigns in 2012 according to the previous procedure definition and the identification maneuvers defined in Tab. 1 and Tab. 2. Comparative identification maneuvers were flown manually. Representative for the enhancement of the flight test data quality two different identification maneuvers, the phugoid maneuver (Fig. 5) and the bank-to-bank maneuver (Fig. 6), are discussed hereinafter in detail.

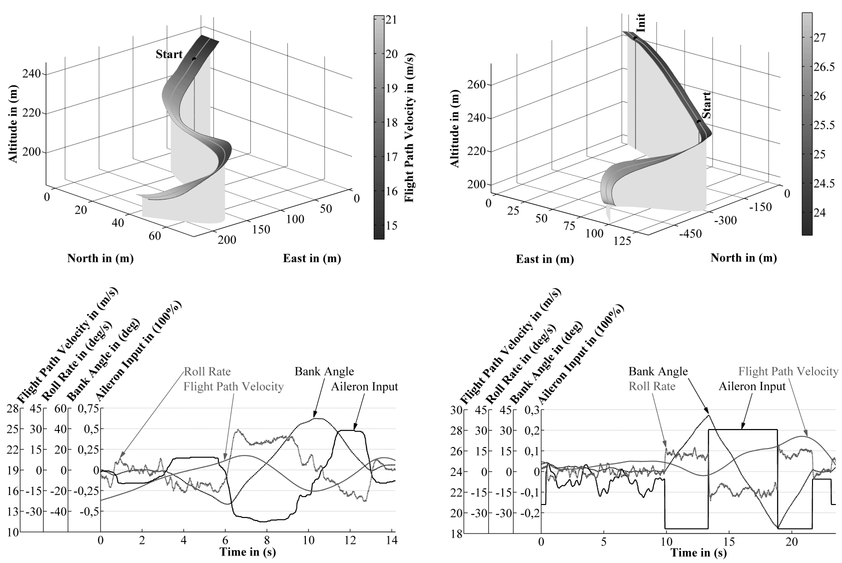


(a) manually flown (b) automatically flown

Fig. 5 Flight trajectory and selected quantities of phugoid identification maneuver

Generally, the phugoid eigenmotion is easy to stimulate and hence, the phugoid maneuver is one of the less complex maneuvers. Nevertheless, Fig. 5 shows significant differences in manually and automatically flown phugoid maneuvers. One can emphasize two decisive points: 1) the capability of establishing a steady straight descent during the initialization phase and 2) the capability of successfully suppressing any lateral movement of the aircraft during the maneuver phase. Due to the decoupling of the aircraft and the pilot in charge, the indirect and delayed estimation of the velocity as well as the aircraft attitude leads to significant deviations compared to the automatically performed identification maneuver. In the manual case a steady straight descent was not achieved (flight path velocity increase of about $10m/s$), whereas the autopilot is capable to keep the velocity within a $1m/s$ band. Due to the use of the autopilot, the bank angle variation is minimized around factor ten compared to the manually flown maneuver.

The comparison of manually and automatically flown bank-to-bank maneuvers, depicted in Fig. 6, highlights another aspect. There is no clear indication to the pilot, like a mechanical stop at the remote control, whether the input command is kept at a predefined steady amplitude or not. As a result of this lack of information it is hardly possible to keep the roll rate constant during different legs of the maneuver. Furthermore, the probability of over excessive or too cautious maneuver inputs and therefore, the probability of gathering unusable identification data is reasonable. That this is not the case in automatically performing the identification maneuver illustrates the right-hand side of Fig. 6.



(a) manually flown (b) automatically flown

Fig. 6 Flight trajectory and selected quantities of bank-to-bank identification maneuver

Particularly with the lateral maneuvers the autopilot suppresses not only disturbances but also regulates distinct flight conditions, e.g. steady heading or steady bank angle. The performance of the flight test oriented autopilot is therefore inversely proportional to the modeling uncertainties and thus dependent on the accuracy of the controller design. Hence, an iterative process, compromising controller design and aerodynamic parameter identification, has to be carried out in order to achieve an optimal performance level. The evaluation of the automatically flown test campaigns suggests, however, that the automation of identification maneuvers will help to increase the reproducibility, reliability and accuracy of the overall aerodynamic parameter identification process at an early stage.

5 Conclusion

A flight test oriented autopilot design for improved aerodynamic parameter identification has been presented. The distinct requirements on identification maneuvering and resulting design rules have been discussed. Based on this analysis a generic autopilot scheme with easy-to-handle design and lean overhead structure was derived. Comparative flight test results have shown the reliability and functionality of the proposed autopilot scheme suggesting that the automation of identification maneuvers will help to increase the reproducibility and accuracy of the overall aerodynamic parameter identification process.

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