IDENTIFICATION TECHNIQUES IN VNAV AUTOPILOT DESIGN FOR A LIGHT SPORT AIRCRAFT

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Abstract

This paper describes the application of identification techniques in the design and optimization of a vertical navigation (VNAV) autopilot for a light sport aviation (LSA) high performance aircraft (Flight Design CT 2K). The whole design has been based, to reduce global costs, weight and complexity, on the control of the stabilator trim instead than, as is more common, on the direct control of the stabilator by means of a dedicated servo actuator. This solution, despite the above mentioned advantages, is characterized by some critical aspects due to the introduction of additional delays in the control chain and also to potential safety problems that must be carefully considered. The first design step has seen the construction of an accurate model concerning the aircraft response to the stabilator trim. This model has been obtained by means of identification techniques applied to data sequences collected in specific flights and has been validated by means of simulations performed on data sets concerning different flights. The model has then been used to design and optimize a PID controller whose performance has been tested first in simulation contexts and subsequently, after its implementation into the autopilot, in flight conditions. This design approach has allowed, on the one hand, a sensible reduction of inflight tests and of trial and error procedures and, on the other hand, to obtain a good final autopilot behavior confirmed by all inflight validation tests.

Keywords: System identification, Aircraft models, Autopilots, PID controllers.

Presenting Author's Biography

Roberto Guidorzi holds the chair of System Theory at the University of Bologna since 1980. He has, besides, been Director of the Computer Centre of the Engineering School of Bologna University from 1987 to 1992 and has been, from 1997 to 2006, Director of CITAM (Interfaculty Center for Advanced and Multimedia Technologies). He has been visiting professor and invited speaker in European and American universities and has collaborated with several industries in the development of advanced projects. He is the author of some 200 publications dealing with subjects of a methodological nature as well as applications of system theory methodologies. His present research interests concern errors-invariables identification and filtering, blind channel equalisation, aircraft modeling and control and development of e-learning environments.

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1 Introduction

The fast evolution of microelectronics and, particularly, of the new families of Micro Electro–Mechanical Systems (MEMS) has opened advanced possibilities in many transportation areas and particularly in automotive and avionics. Another parallel evolution concerns the decline, due to increasing costs and bureaucracy, of General Aviation (GA) and the shift towards the category of the so–called ultralight or microlight aircrafts (ULM) i.e. two–seat aiplanes with a maximum take–off weight of approximately 450 Kg. Also in the U.S.A., where general aviation mantains a very important role with more than 160.000 active registered GA piston aircraft, more than 16.000 turboprop and turbojet, approximately 7.000 rotorcrafts and 21.000 experimentals [1], the increasing importance of lighter and less fuel consuming aircraft has been recognized by introducing the Light Sport Aviation (LSA) category that, with a maximal take–off weight of 600 Kg, positions itself between ultralights and GA airplanes. It can also be noted that some ULM and LSA aircraft are characterized by flight envelopes and other features like efficiency and autonomy superior to those of a part of GA airplanes.

The rules applied to these new categories are less demanding than the GA ones; for instance, the instruments and the engines are not conditioned by airworthness certifications. This has allowed the development and diffusion of advanced avionics that can take advantage of the absence of certification costs and of the associated limits. It is thus not uncommon to see ultralights endowed with 1 or 2 axes autopilots that rely, for heading evaluation, on inexpensive GPS units instead than on VOR (VHF Ominidirectionl Range) or mechanical gyros like in more traditional GA versions. Most autopilots are 1 axis units that operate as wing levelers and ground track followers on the basis of the error obtained from a GPS unit. Autopilots that allow mantaining a selected altitude and that can manage the transition between selected flight levels (Vertical Navigation or VNAV) can be installed as stand–alone units or constitute the second axis in 2 axes units; this function is more requiring, for what concerns safety aspects, than GPS navigation or wing leveling.

This paper describes some aspects of the design of a VNAV autopilot for a LSA aircraft, performed on the basis of a dynamic model of the aircraft response to vertical trim variations obtained by means of identification techniques [2]. Operating directly on the stabilator trim tab instead than on the elevator or stabilator surfaces is not a common practice in autopilot design because of the additional delay inserted in the control chain and of some possible safety hazards. Despite these drawbacks, this solution has been adopted in this design to reduce weight, costs and complexity at the price of a more difficult design procedure and of the adoption of redundant hardware and software safety measures.

The content of the work is organized as follows. Section 2 concerns the design considerations and the eventual data collection setup. Section 3 describes the identification procedure that has been followed to obtain a dynamic model of the aircraft response and its validation. Section 4 deals with the design of the autopilot controller and with the simulation and fly performance that has been obtained. Some short concluding remarks are finally given in section 5.

2 Design considerations

The horizontal stability of an aircraft can be defined as the tendency of an aircraft to return to its initial pitch after the application of some disturbance on its pitch attitude. An aircraft consisting only in a wing or in wing and fuselage would be inherently horizontally unstable. The horizontal stabilizer, also known as the horizontal tail, is essentially a reduced surface wing whose (positive or negative) lift relies on a much longer arm, with respect to the aircraft center of gravity, than the wing lift. It is thus possible to balance the respective torques and achieve pitch stability [3].

The elevator is a mobile part of the horizontal stabilizer. It can be deflected up or down to produce a change in the lift produced by the horizontal tail; such a deflection forces the nose to pitch upward or downward and is used to control the aircraft. The stabilizer/elevator combination can be substituted by a single larger control surface called stabilator. A stabilator can allow the pilot to generate greater pitching moment with the same amount of effort resulting in an improved maneuverability but also in a greater risk of a stall; for this reason stabilators normally contain an anti-servo tab that deflects in the same direction of the stabilator, making it more difficult to move suddenly.

In order to keep a plane in a steady, level orientation, the elevator usually has to be deflected by some small amount and it would be very tiring for a pilot to physically hold the control stick in position to keep the elevator at that deflection angle for an entire flight. The elevator (or the stabilator) is thus fitted with a small "tab" that creates that deflection automatically. The trim tab can also be seen as a "mini-elevator" whose deflection up or down, increases or decreases the downforce created by the elevator and forces the elevator to a certain position. The pilot can set the deflection of the trim tab which will cause the elevator to remain at the deflection required to keep the desired pitch attitude (or, more properly, angle of attack) and consequently, according with the actual propeller thrust, the desired cruise speed.

Any variation of the trim tab position will lead to a different deflection of the elevator and to a different angle of attack and pitch that will be associated to a different wing lift and overall aircraft drag; the final result, in absence of thrust variations, will be an increase of speed and altitude loss or a decrease of speed and altitude gain. We can thus modify the vertical speed of an aircraft without modifying the propeller thrust either by acting directly on the elevator (by means of the stick) or on the trim tab; this second option requires less energy (the trim surface is remarkably smaller than the elevator or stabilator ones) but concerns a more complex kinematic chain and longer delays.

Moreover, a fault in the trim control chain could, in absence of proper safety measures, require the application to the stick of forces beyond the pilot's capabilities to mantain a proper pitch attitude. The design lines chosen to carry out the project have been the following:

1) Acquisition of a substantial amount of data concerning the response of the aircraft, during standard flight conditions to persistently exciting input signals applied to the trim control. The input has been generated by means of a microcontroller and measured by means of a potentiometer connected to the trim cable in order to reduce as much as possible the errors due to mechanical hysteresis. The output (aircraft altitude) has been measured by means of a Freescale MPX4115 transducer. The sampling time has been taken equal to 0.4 s as a compromise between the use of a reduced order model and the model capability to describe the actual delay in the control action.

2) Identification and validation of a dynamic model of the process.

3) Design of a PID controller for the implementation of the altitude transition and altitude hold functions and calibration of its parameters by means of simulations.

4) Implementation of the algorithm and of safe control range limitations in the controller. Implementation of suitable hardware limitations on the trim excursion on the aircraft.

5) Flight test of the autopilot performance in presence of various turbulence levels.

3 Model identification

The first family of models that has been tested concerns simple ARX ones, i.e. equation error models of the type

$$y(t) = \sum_{i=1}^{n} \alpha_i\, y(t-i) + \sum_{i=1}^{n} \beta_i\, u(t-i) + e(t) \quad (1)$$

where n denotes the model order (memory of the process) and $e(t)$ denotes a white process uncorrelated with the input sequence $u(t)$. On the basis of performance comparisons and of *a priori* knowledge about the process and of the sampling time that had been selected ($T = 0.4$s) it was decided to use models with order $n = 10$. Figure 1 shows the input sequence (elevator trim) used to perform the identification of the model. The corresponding output sequence (aircraft altitude) and the model prediction (dotted line) are reported in Figure 2; they are very close and look like a single pattern. A plot of the prediction error (innovations) is reported in Figure 3. Despite the excellent behavior of the obtained model, also other classes of models, like NARX, have been tested. These nonlinear models consider also terms of the type $y(t-i)y(t-j)$, $u(t-i)u(t-j)$ and $u(t-i)y(t-j)$ i.e. have a general

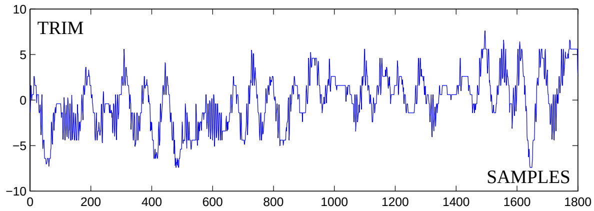

Fig. 1 – Input sequence

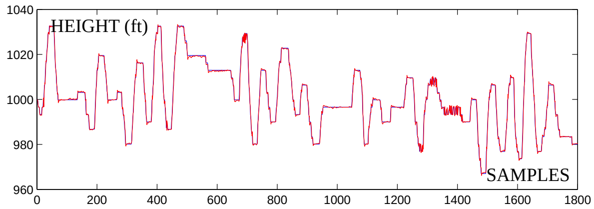

Fig. 2 – Output sequence and model prediction

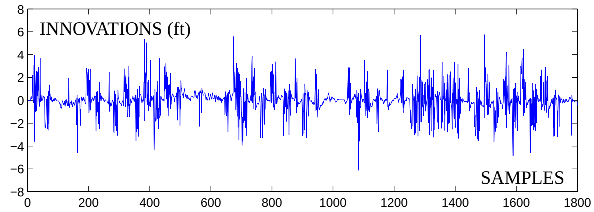

Fig. 3 – Order 10 model prediction error

structure of the type

$$\begin{aligned} y(t) &= \sum_{i=1}^{n} \alpha_i\, y(t-i) + \sum_{i=1}^{n} \beta_i\, u(t-i) \\ &+ \sum_{i=1}^{n}\sum_{j=1}^{n} \gamma_{ij}\, u(t-i)u(t-j) \\ &+ \sum_{i=1}^{n}\sum_{j=1}^{n} \delta_{ij}\, u(t-i)y(t-j) \\ &+ \sum_{i=1}^{n}\sum_{j=1}^{n} \zeta_{ij}\, y(t-i)y(t-j) + e(t) \quad (2) \end{aligned}$$

where the total number of terms actually inserted in the model is limited by a preassigned complexity and the terms to be inserted are discriminated against the excluded ones by a suitable cost function usually given by the sum of the squares of prediction errors. The performance improvement has been marginal and the greater complexity has not been considered, in this case, as balanced by the increase in performance. This does not imply, of course, that NARX models cannot play a significant role in modeling aircraft dynamics as shown, for instance, in [4] where the considered models describe the aircraft behavior also in take–off and landing situations that are of no interest in the context considered in this paper (during take–off and landing autopilots must be disengaged).

Another family of linear models that can give a remarkable improvement over simple ARX ones is that of the so–called "ARX+noise" models where the observations

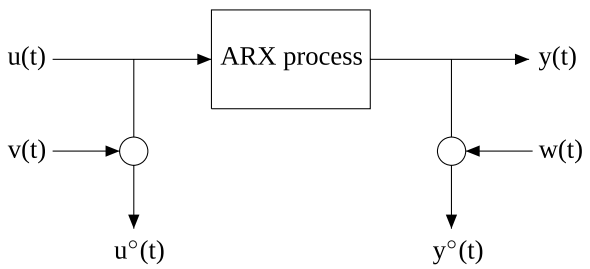

Fig. 4 – Structure of ARX+noise models

of the input and output of an ARX process are assumed as affected by unknown amounts of white additive noise (see Figure 4). ARX+noise models cannot be identified by means of usual least-squares algorithms; a possible approach consists in mapping their identification into an Errors–In–Variables identification problem and in using EIV identification algorithms as has been done in [5]. In this case ARX+noise models have led to results almost equal to those of standard ARX models because a very limited amount of observation noise was present on the data.

It was eventually decided to use the identified ARX model [7, 8], whose parameters are:

$$
\begin{aligned}
\alpha_1 &= 1.2607 & \beta_1 &= -0.1343\\
\alpha_2 &= -0.2801 & \beta_2 &= 0.0192\\
\alpha_3 &= 0.0984 & \beta_3 &= -0.0901\\
\alpha_4 &= -0.0432 & \beta_4 &= -0.0646\\
\alpha_5 &= -0.0389 & \beta_5 &= 0.0158\\
\alpha_6 &= -0.0102 & \beta_6 &= -0.0099\\
\alpha_7 &= 0.0081 & \beta_7 &= 0.0570\\
\alpha_8 &= 0.0015 & \beta_8 &= -0.0084\\
\alpha_9 &= -0.0065 & \beta_9 &= 0.0065\\
\alpha_{10} &= -0.0297 & \beta_{10} &= 0.0933
\end{aligned}
$$

4 Model validation

The capability of the identified model to describe adequately, at least in a predictive environment, the behavior of the considered dynamics has been tested by means of a validation based on the use of data collected during a different flight.

The process input concerning this cross–validation is reported in Figure 5. The comparison between the observed data and the model prediction (dotted line) is reported in Figure 6. Also in this case the patterns are very close and can be hardly distinguished; a plot of the prediction error is reported in Figure 7.

5 Controller design and flight tests

The PID controller to be implemented in the autopilot has been designed starting from the traditional empirical rules [6] relying on simulations performed by means of the identified model for the final calibration. The simulations have been performed by introducing both a realistic amount of observation noise and disturbances on the altitude of the simulated path of the aircraft. The parameters eventually implemented were $K_p = 0.1$, $K_i = 0.08$ and $K_d = 0.08$.

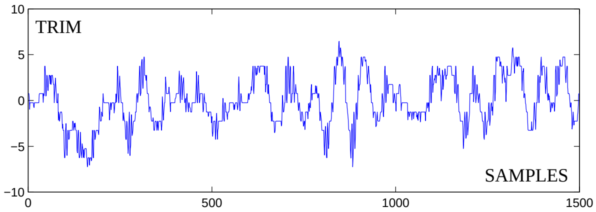

Fig. 5 – Input sequence (validation)

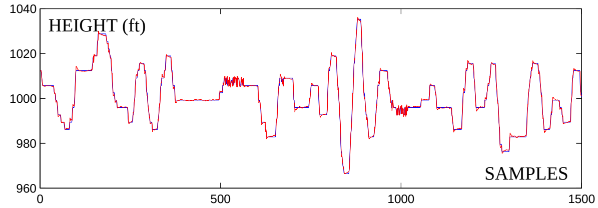

Fig. 6 – Output sequence and model prediction (validation)

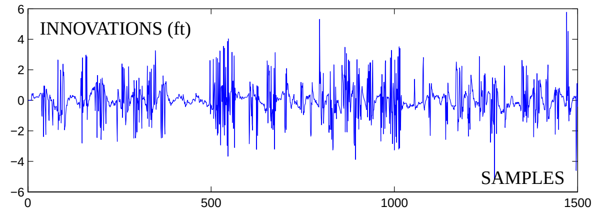

Fig. 7 – Order 10 model prediction error (validation)

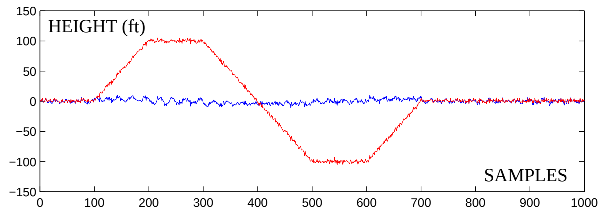

Fig. 8 – Aircraft altitude with and without autopilot control

Fig. 9 – The Flight Design CT 2K during the autopilot tests

The performance of this controller can be observed in Figure 8 that compares the aircraft altitude in presence of 100 ft simulated disturbances (dotted line) with the remarkably lower variations observed when the autopilot is inserted; note the residual disturbances due to observation noise. The final validation of the autopilot has been performed by installing on the same Flight Design CT 2K aircraft (see Figure 9) previously used to collect the data a prototype of the autopilot and by performing flight tests during which the whole aircraft behavior was managed, with the obvious exclusion of take–off and landing procedures, by the autopilot.

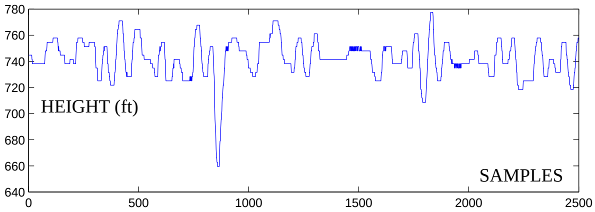

Fig. 10 – Aircraft altitude (first test flight)

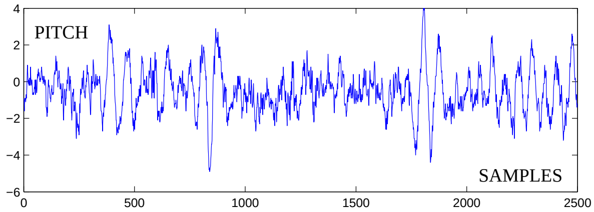

Fig. 11 – Aircraft pitch (first test flight)

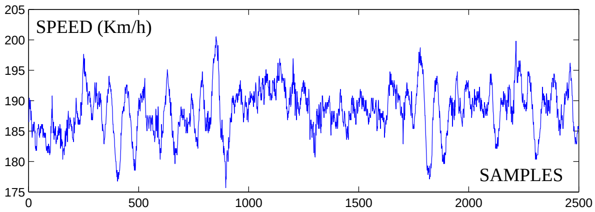

Fig. 12 – Aircraft speed (first test flight)

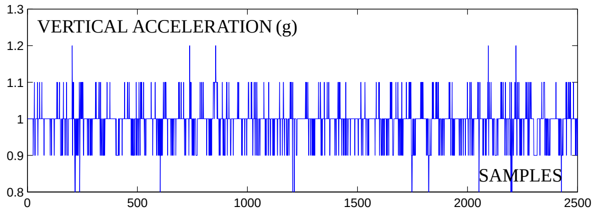

Fig. 13 – Vertical acceleration (first test flight)

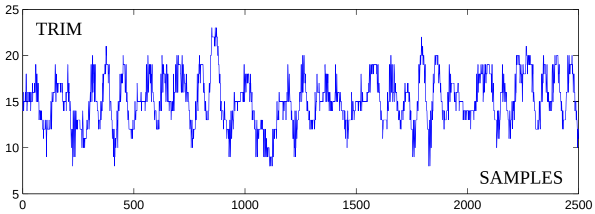

Fig. 14 – Control action (first test flight)

The altitude variations observed during the first test flight can be observed in Figure 10 that shows very limited excursions arount the selected altitude value (740 ft). The control action is reported in Figure 14 that shows how it remains always within the safety limits implemented into the control algorithm (variations of ± 16 with respect to the initial value). The effects of the control on the aircraft pitch, speed and vertical acceleration are reported in the Figures 11, 12 and 13 that show quite acceptable values. This first flight has been performed with the flaps set at $-12°$ which correspond to the high speed configuration of the CT; a second test flight has been performed with the flaps set at $0°$.

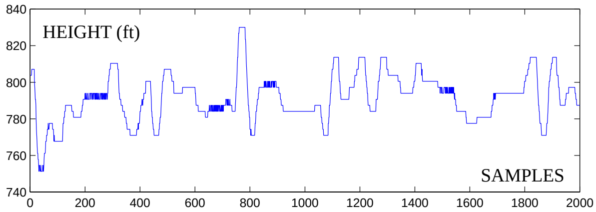

Fig. 15 – Aircraft altitude (second test flight)

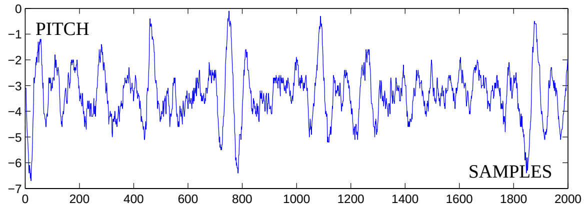

Fig. 16 – Aircraft pitch (second test flight)

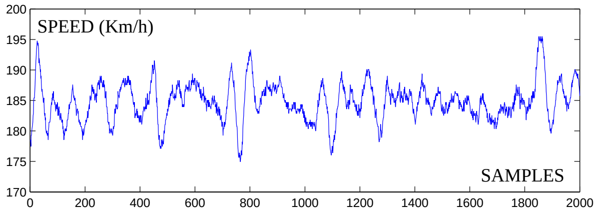

Fig. 17 – Aircraft speed (second test flight)

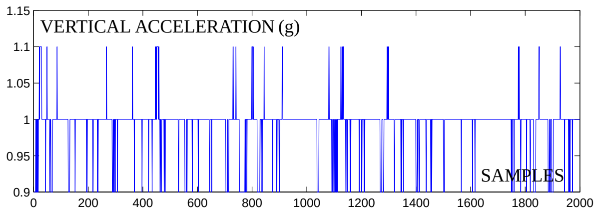

Fig. 18 – Vertical acceleration (second test flight)

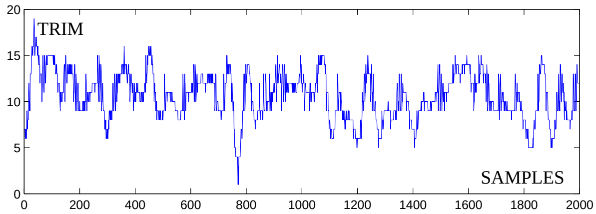

Fig. 19 – Control action (second test flight)

The different attitude of the aircraft due to this different setting of the flaps can be clearly observed by comparing the pitch values reported in Figure 16 with those of

Figure 11. The altitude variations observed during the second test flight are reported in Figure 15 and are of the same order as those of the first flight (the turbulence conditions were, in fact, comparable). The amount of control action (Figure 19) and the associate variations of speed (Figure 17) and vertical acceleration (Figure 18) were, however, slightly lower.

6 Concluding remarks

This paper has described the design and implementation of the altitude hold section of a VNAV autopilot designed for a Light Sport Aviation aircraft. This design acts directly on the stabilator trim instead than directly on the stabilator and, consequently, does not require a specific servoactuator. This solution saves weight and complexity but requires a more careful design to take into account the larger control delay and some possible safety considerations that impose a well defined limit on the control action. The results obtained during test flights performed in moderate turbulence conditions can be considered as quite satisfactory.

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