Dynamic Behavior And Performances Determination of DG400 Sailplane through Flight Tests

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SUMMARY

In recent years several general techniques have been developed for the determination of the characteristics of physical systems, based on their measured responses (time histories of some observed variables). The present paper analyzes one of these techniques, known as Maximum Likelihood Method (MLM), and applies to airplane flight data. Given the equations governing the aircraft flight, the MLM allows the "estimation", or extraction, of the parameters included in the mathematical model directly from flight data. The linearized aircraft equations of motion are discussed, as implemented in the performances and dynamic behavior prediction code ***MeMaV***, developed at DPA. Then, as a validation case study, the application of the proposed approach to an aircraft whose flight characteristics are known is performed. Finally, the ***MeMaV*** code is applied to the DG400 sailplane. Details are given on the instrumentation used to acquire flight data. For the prediction of performances and dynamic behavior of the sailplane in flight, specific and detailed maneuvers have been designed and executed in order to excite dynamics modes. Control surfaces deflections, angular rates, accelerations, speed, attitude angles have all been measured and acquired during many test flights performed. All dynamic characteristics and performances of DG400 have been obtained and uncertainty and limits of the applied methods are highlighted and discussed.

Nomenclature

A, B = dynamic matrix, and matrix of inputs
C, D = response matrices
I = moment and/or product of inertia
X, Y, Z = force components
L, D = lift and drag forces
_, M, N = rolling, pitching, and yawing moment
t = time
$X_u, X_w, X_{\delta e}, Z_u, Z_w, Z_{\delta e}, Z_q, Z_{w'}, M_u, M_w, M_q, M_{w'}, M_{\delta e}$
longitudinal derivatives
$Y_v, Y_p, Y_r, Y_{\delta r}, L_v, L_p, L_r, L_{\delta a}, L_{\delta r}, N_v, N_p, N_r, N_{\delta a}, N_{\delta r}$
lateral-directional derivatives
ξ, u = vector of parameters, and vector of inputs
J = cost function
W = weighting matrix
Φ, Ψ = continuous-to-discrete time transformation matrices
p, q, r = rate of roll, pitch, and yaw, respectively
u, v, w= body x-, y-, z-axis wind-relative velocities
w' = time derivative $\partial w/\partial t$
α, β = angle of attack, and of sideslip
δ_e, δ_r = elevator angle, and rudder angle
θ, ϕ, ψ = pitch, rolling, yaw angles

Superscripts
$\cdot$ = (dot) time derivative d/dt

Subscripts
E = Estimated

THE MAXIMUM LIKELIHOOD METHOD

The so-called "parameter estimation methods" have been used in recent years for characterizations of complex physical systems, subject to known inputs, based on the observation of their time evolution. These techniques are of great importance in the prediction of stability and control derivatives of an aircraft. Semi-empirical methods could also be used to this goal [14].

Some of the prediction methods used in the past are based on the observation of free oscillations after given maneuvers and on the evaluation of the time needed for the aircraft to reach the steady state. The analysis of the transient state usually is based on a least square technique. These approaches are applied to simple maneuvers and give a limited amount of information on aircraft dynamic characteristics and their accuracy.

Currently, more advanced approaches couple the estimation of parameters with statistical inference techniques. They have been shown to be capable of good parameter estimations and the determination of their accuracy and confidence interval is possible. The parameter estimation approach presented here belongs to the family of so-called "Maximum Likelihood Methods" (MLM).

The MLM was first introduced by Fischer in 1912, and extended later in a number of papers, see refs. [1,2,3]. The choice of the mathematical model representing the physical system under study is important in the process of parameter estimation. The most general flight dynamic problem is the prediction of one aircraft characteristics according to a non-linear model, taking into account all possible disturbances and errors. The basic idea of this approach is relatively simple. An experiment, like a prescribed maneuver of an aircraft, is assumed to be dependent on a number k of unknown parameters, collected in vector $\xi=\{\xi_1,\ldots,\xi_k\}$. Maximum likelihood estimations ξ_M of parameters are related to a set of m observed values, collected in a vector

z, that coincide with the "most probable" among all of the estimates. Definition of "most probable" is given by the minimization of the so-called "likelihood function", i.e. the conditioned probability density function $P[Z | \xi]$, in a set Z of observations, once ξ is given. A general discussion on the problem of the minimization of function P, based on Kalmann filtering techniques for general non-linear problems, is given in ref. [2]. The minimization is time consuming even in simple scalar problems, especially when all kinds of possible errors are considered. Thus, in the present work where the aircraft motion is the primary interest, a simplified numerical version of the standard MLM is proposed.

For many relevant flight conditions, the choice of a linear model is appropriate, such as

$$\dot{x}(t) = A\, x(t) + B\, u(t) \tag{1}$$

where $x = \{x1,\ldots,x_r\}$ is the state vector, $x(0)=x0$ is an assigned initial state, $u = \{u_1,\ldots,u_c\}$ is the vector of inputs, i.e. the prescribed maneuver, A, the so-called "dynamic matrix", and B, the "matrix of inputs", are matrices containing the unknown parameters. When external disturbances, such as gusts, are neglected, equation (1) describes perfectly the aircraft evolution. Generally, disturbances are present and are called here "process errors". They are collected in a vector $w(t)$, and taken into account adding a term $\Gamma w(t)$ to the right-hand side of (1), where Γ is an error distribution matrix. When flight data are considered, also measure errors are involved, collected in a vector v. Moreover, data are not continuous in time but sampled with a given frequency $1/\Delta t$. Thus, the vector z of measured quantities is a discrete function of time given by

$$z(i) = C\, x(i) + D\, u(i) + v(i) \tag{2}$$

where i, or $t_i=t_0+i\Delta t$, is the ith instant, C and D are transformation matrices. In the following expressions the response vector z is assumed to coincide with $x+v$, i.e. $C=I$, and $D=0$.

The small perturbation equations of motion of an aircraft can be generally written like the linear equation (1), where the state vector x is a perturbation of the state variables in the mathematical model chosen, and the vector of inputs u is an assigned maneuver. In the linearized case, the longitudinal and lateral-directional motions are decoupled. For the longitudinal motion, the state vector is given by $x=\{\Delta u,\Delta w,\Delta\vartheta,\Delta q\}$ ($m=r=4$, $c=1$). Matrices A(4x4) and B(4x1) are given in appendix A. The unknown vector of parameter is, for this case, $\xi = \{X_u, X_w, X_{\delta e}, Z_u, Z_w, Z_{\delta e}, Z_q, Z_{\dot{w}}, M_u, M_w, M_q, M_{\dot{w}}, M_{\delta e}\}$ (k=13). For the lateral-directional motion, $x=\{\Delta v,\Delta p,\Delta r,\Delta\phi\}$ ($m=r=4$, $c=2$), and matrices **A**(4x4) and B(4x2) are given in appendix A. The vector of parameters is, for this case, $\xi = \{Y_v, Y_p, Y_r, Y_{\delta r}, L_v, L_p, L_r, L_{\delta a}, L_{\delta r}, N_v, N_p, N_r, N_{\delta a}, N_{\delta r}\}$ (k=14).

The state vector for the discrete time case can be approximated by

$$x(t_{i+1}) = \Phi \cdot x(t_i) + \Psi \cdot \tfrac{1}{2}\left(u(t_i) + u(t_{i+1})\right) \tag{3}$$

where the matrices Φ and Ψ are given by the following

$$\Phi = e^{(\Delta t\, A)} = \sum_{n=0}^{\infty} \frac{(\Delta t)^n A^n}{n!} \tag{4}$$

$$\Psi = \int_0^{\Delta t} e^{(A\tau)} d\tau\, B \tag{5}$$

formulas

$$\Psi = A^{-1}\left(\Phi - I\right)B \tag{6}$$

For linear systems with a dynamic matrix A not depending on time, matrix Ψ is simply given by

and Φ by the summation (4) with n from 0 to a finite value.

MLM consists of an iterative procedure of estimation of parameters ξ. It needs an initial estimation ξ_0, for successive estimations z_E, estimated responses, to be compared with time histories. An error function, called here the "cost

$$J = \frac{1}{2}\sum_{i=1}^{N}\left(z(t_i) - z_E(t_i)\right) \cdot W \cdot \left(z(t_i) - z_E(t_i)\right)^{\mathrm{T}} \tag{7}$$

function" J, gives the difference between the estimated aircraft evolution quantities and the measured ones. It is thus defined according to the following expression

where W is a diagonal weighting matrix, and N the number of acquisitions.

Minimization of the function J is the goal of the iterative procedure that updates the values of parameters.

$$\frac{\partial \Phi}{\partial \xi_j} = \Delta t\, \Phi \frac{\partial A}{\partial \xi_j} \tag{8}$$

$$\frac{\partial \Psi}{\partial \xi_j} = \frac{\partial A^{-1}}{\partial \xi_j}(\Phi - I)B + A^{-1}\left(\frac{\partial(\Phi - I)}{\partial \xi_j}\right)B + A^{-1}(\Phi - I)\left(\frac{\partial B}{\partial \xi_j}\right) \tag{9}$$

Minimum search is done by a Gauss-Newton algorithm and requires the calculation of derivatives of matrices Φ and Ψ with respect to parameters ξ's. In case of time independent dynamic matrix one has

for j=1,...,k.

Derivatives of matrices A and B depend on the problem

$$z_E(t_{i+1}) = \Phi \cdot z_E(t_i) + \Psi \cdot \left(u(t_i) + u(t_{i+1})\right)/2 \quad (10)$$

$$\frac{\partial z_E(t_{i+1})}{\partial \xi_j} = \frac{\partial \Phi}{\partial \xi_j} \cdot z_E(t_i) + \\ + \Phi \cdot \frac{\partial z_E(t_i)}{\partial \xi_j} + \frac{\partial \Psi}{\partial \xi_j} \cdot \left(u(t_i) + u(t_{i+1})\right)/2 \quad (11)$$

to be solved, i.e. longitudinal or lateral-directional motion.

$$z_{E0} = z_E(0)\,, \quad \left(\frac{\partial z_E(t_i)}{\partial \xi_j}\right)_0 = \frac{\partial z_{E0}}{\partial \xi_j} \quad (12)$$

By assigning the initial attempt vector ξ_0, one can calculate the estimated response z_E and its derivatives from the following formulas

for j=1,...,k. Also the last given quantities have to be initially predicted by assigning the initial values

At each time instant t_i the gradient matrix $\nabla_\xi z_E$=[∂ $(z_E)i$

$$\nabla_\xi J = -\sum_{i=1}^{N} \left(z(t_i) - z_E(t_i)\right) \cdot W \cdot \nabla_\xi z_E(t_i) \quad (13)$$

$$\nabla_\xi^{\,2} J = \sum_{i=1}^{N} \nabla_\xi z_E(t_i)^{\mathrm{T}} \cdot W \cdot \nabla_\xi z_E(t_i) \quad (14)$$

/ $\partial \xi_j$], i=1,...,r and j=1,...,k, enable the correction of param-

$$\xi_{s+1} = \xi_s - \omega \nabla_\xi^{\,2} J^{-1} \cdot \nabla_\xi J^{\mathrm{T}} \quad (15)$$

eter values until the minimum of J is reached. For each correction step, the vector ξ is updated and a new estimated response is evaluated. In Gauss-Newton method of correction, the cost-function gradients has to be constructed, i.e. the vector

and matrix

The updated vector of parameters at step s+1 of the minimization procedure is given by

where w is a relaxation factor. The iteration stops when the cost function value J(ξ_s+1) is lower than a prescribed threshold value.

THE *MEMAV* CODE

The method presented in the previous section has been implemented in a code developed at DPA. It is written in FORTRAN language, and named ***MeMaV***. The code has been developed and validated with well-known case-study aircraft. The aim of validation has also been the identification of maneuvers that, combined with the proposed numerical method, give a better approximation of parameters.

SIMULATION FOR THE NAVION AIRCRAFT

As a first application of the code it has been considered the parameters estimation of longitudinal flight derivatives of the NAVION aircraft. Geometric and mass characteristics of this airplane are reported in ref. [4]. For a fixed flight condition, the cited reference gives also the values of the stability derivatives, enabling the simulation of the aircraft response to a prescribed maneuver. Simulations have been carried out by a Matlab program. In fig. 1 it is reported one of the simulated maneuvers. In the same figure it is also shown the longitudinal motion as estimated by the ***MeMaV*** code, and the initial curve selected for the parameter estimation procedure. The assigned initial values in this example have been generated supposing that they would have been affected by errors up to the 250% with respect to the ones given by the simulation. As one can see from the graph, the estimated response is perfectly coincident with the simulated one. It can be seen from table 1, where the aircraft estimated stability derivatives are compared with the exact ones taken from ref. [4], that the maximum percentage error is around 9.5% among all possible parameters for the maneuver considered.

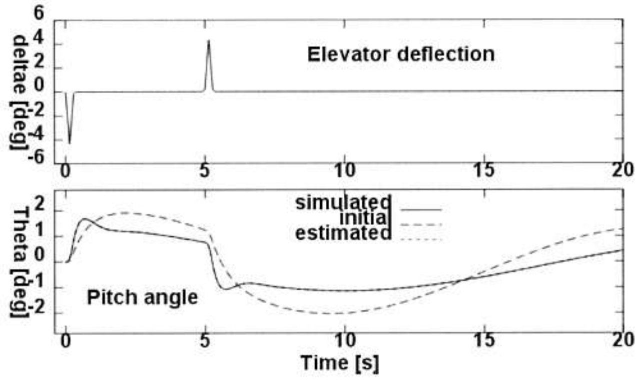


Figure 1: output of a ***MeMaV*** code estimation for the NAVION aircraft; example of longitudinal motion maneuver.

Fig. 2 and table 2 refer to the same maneuver of fig. 1 but with an additional noise, characterized by Gaussian distribution and zero mean, which simulates the presence of a measure error. Even in this example of parameters estimation, it can be observed the perfect coincidence of the estimated response with the mean of the simulated one. Also

Table n. 1: results of parameter estimation for the maneuver of fig. 1.

Dimensional Derivatives			
Parameter	Exact	Estimated	% error
X_u [1/s]	-0.0451	-0.0451	-0.1508
X_w [1/s]	0.0361	0.0363	0.5978
Z_u [1/s]	-0.3700	-0.3715	0.4025
Z_w [1/s]	-2.0262	-2.0340	0.3838
Z_q [m/s]	1.4919	1.6342	9.5395
$Z_{\delta e}$ [m/s^2]	8.6108	8.6319	0.2444
M_w [1/m·s]	-0.1645	-0.1645	0.0098
M_q [1/s]	-2.0872	-2.0874	0.0129
$M_{w'}$ [1/m]	-0.0170	-0.0170	-0.1197
$M_{\delta e}$ [1/s^2]	-11.9497	-11.9502	0.0040
Non-dimensional Derivatives			
Coefficient	Exact	Estimated	% error
C_L	0.4101	0.4117	
C_D	0.0500	0.0499	
$C_{L\alpha}$	4.4406	4.4579	
$C_{D\alpha}$	0.3300	0.3312	
$C_{m\alpha}$	-0.6831	-0.6832	
$C_{m\dot{\alpha}}$	-4.3606	-4.3554	
C_{Lq}	3.8005	4.1631	
C_{mq}	-9.9614	-9.9627	
$C_{L\delta e}$	0.3551	0.3559	
$C_{m\delta e}$	-0.9231	-0.9232	

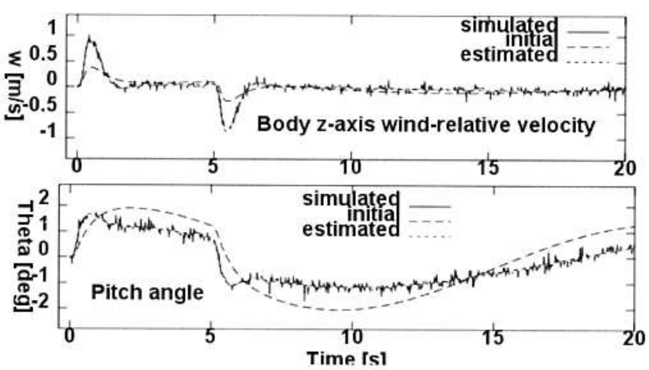
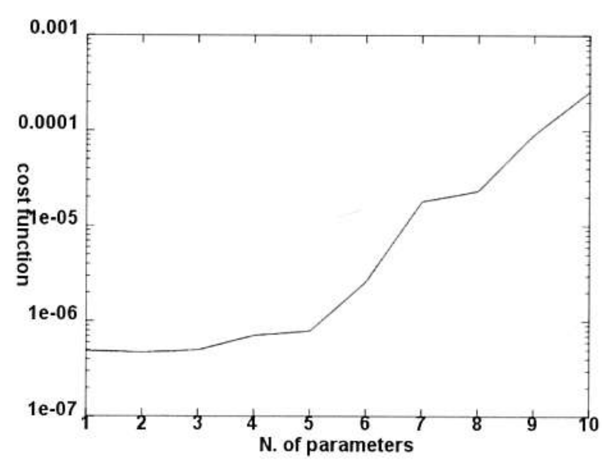


Figure 2: output of a ***MeMaV*** code estimation for the NAVION aircraft; example of longitudinal motion maneuver with initial noise.

Table n. 2: results for the maneuver of fig. 2 with noise.

Dimensional Derivatives			
Parameter	Exact	Estimated	% error
X_u [1/s]	-0.0451	-0.0451	0.1495
X_w [1/s]	0.0361	0.0363	0.6349
Z_u [1/s]	-0.3700	-0.3715	0.4001
Z_w [1/s]	-2.0262	-2.0337	0.3718
Z_q [m/s]	1.4919	1.6355	9.6242
$Z_{\delta e}$ [m/s^2]	8.6108	8.6314	0.2390
M_w [1/m·s]	-0.1645	-0.1645	0.0144
M_q [1/s]	-2.0872	-2.0875	0.0145
$M_{w'}$ [1/m]	-0.0170	-0.0170	-0.0973
$M_{\delta e}$ [1/s^2]	-11.9497	-11.9490	-0.0060
Non-dimensional Derivatives			
Coefficient	Exact	Estimated	% error
C_L	0.4101	0.4117	
C_D	0.0500	0.0499	
$C_{L\alpha}$	4.4406	4.4574	
$C_{D\alpha}$	0.3300	0.3312	
$C_{m\alpha}$	-0.6831	-0.6832	
$C_{m\dot{\alpha}}$	-4.3606	-4.3564	
C_{Lq}	3.8005	4.1663	
C_{mq}	-9.9614	-9.9629	
$C_{L\delta e}$	0.3551	0.3559	
$C_{m\delta e}$	-0.9231	-.9231	

Figure 3: dependence of cost function *(J)* minimum values on the number of unknown parameters, for a fixed maximum allowed error.



in this case, the maximum error on parameter values is around 9.5%.

A number of other maneuvers has been investigated for this case study aircraft, with essentially the same results in terms of the estimated responses and parameters. Fig. 3 reports the converged minimum values of the cost function J against the number of parameters considered unknown, for a fixed maximum error of the initial values given to the estimation iterative procedure.

SIMULATION FOR THE ASW24 SAILPLANE

Results presented in previous section refer to a specific flight condition, i.e. to fixed values of speed and angle of attack that satisfy the equilibrium dynamic equations of motion at the beginning of the motion. In the present section, an example of parameters estimation for varying angle of attack is reported. For each flight condition, the linearized equations of motion have been considered in order to apply the linear model implemented in the present code. The linear equations are applied to the successive equilibrium flight conditions assumed as initial conditions of the prescribed maneuver. In this framework, the maximum amplitudes of the maneuvers and of the relative time responses have to be small enough to satisfy the small perturbation hypothesis. Once the estimated parameters are known at each angle of attack, stability derivative curves are given point by point.

The case study chosen is the ASW24 sailplane, whose geometric and mass characteristics are given in ref. [5]. Stability derivatives for the simulated responses are calculated by using the ***AEREO*** code implemented by the authors, see ref. [6,7,8]. Maneuvers considered are the same chosen for the simulation of the last section.

In fig. 4, are reported the lift and polar curves, as calculated using the prediction code ***AEREO*** (in the figure referred as "numerical") and "estimated" by the ***MeMaV*** code. These examples show that the estimation code results are good as compared to the predicted ones, even at high angles of attack in proximity of stall conditions, although the model is linear.

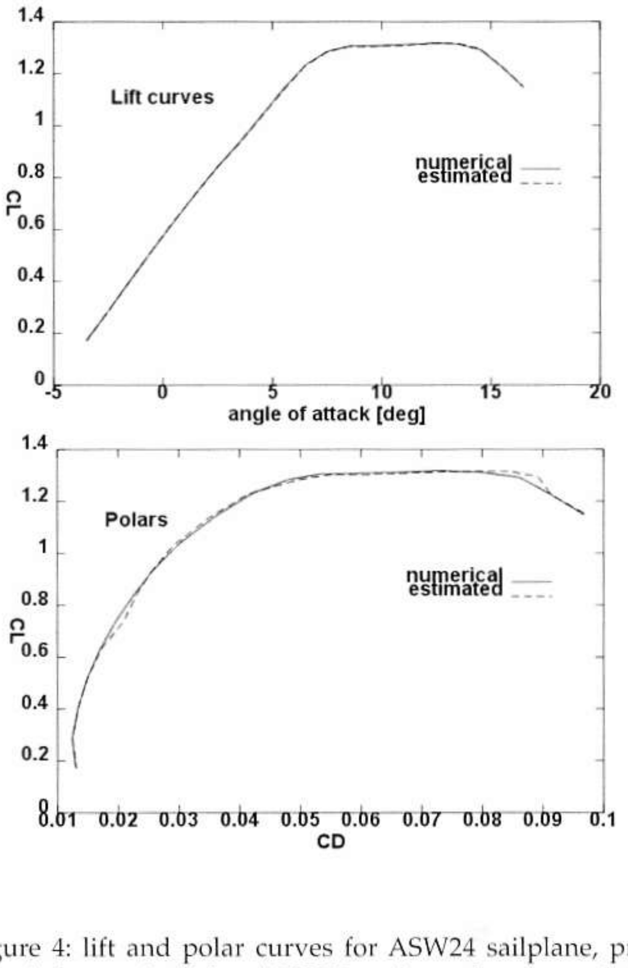


Figure 4: lift and polar curves for ASW24 sailplane, predicted (numerical) by ***AEREO*** code and estimated by ***MeMaV*** code.

PARAMETER ESTIMATION OF THE DG400 SAILPLANE

Arising from the authors' past experience in flight test of light aircraft, see for example ref. [9], the last application of the parameter estimation technique presented here is that related to the DG400 sailplane flight tests, see fig. 5. The geometric and mass data relative to this single-pilot self-launching sailplane are given in ref. [10].

Figure 5: the DG400 sailplane.

FLIGHT TESTS

Flight tests on DG400 took place on October 2001 in the province of Salerno (Italy). The height of the airport is 458 *m* above sea level. The weather was warm, with temperatures from 25 to 27 Celsius degrees.

THE INSTRUMENTATION USED

The sailplane was equipped with the following data acquisition devices: *(i)* an inertial platform, see fig. 6, for the measure of roll and pitch angles, ϕ and θ, and for the angular rates p, q, r with respect to the body axes, and of linear accelerations along the longitudinal axis x and transversal axis y; *(ii)* a vertical accelerometer for the measure-

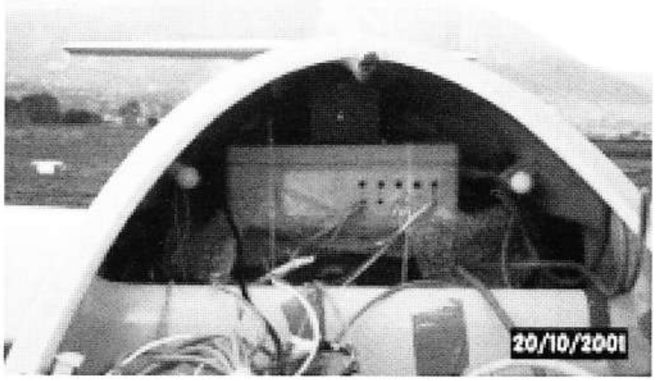


Figure 6: the inertial platform mounted on DG400 sailplane.

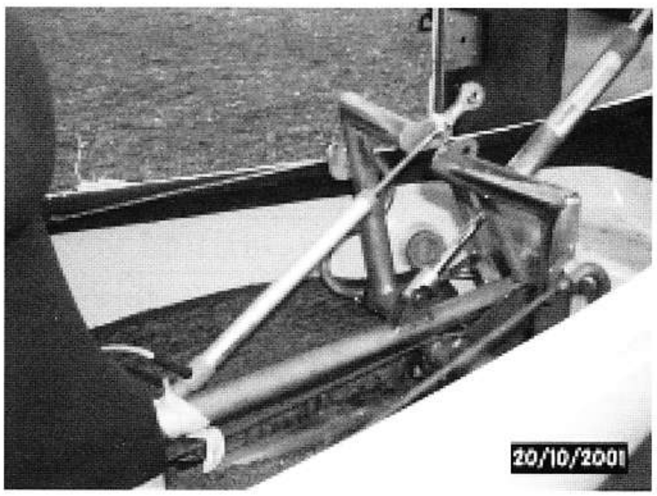


Figure 7: the potentiometer for the measure of rudder angular deflections.

ment of the load factor N; *(iii)* a temperature probe; *(iv)* potentiometers, see fig. 7, for the measure of elevator, ailerons and rudder angular deflections, δ_e, δ_α, δ_r; *(v)* pressure probes, connected to the sailplane own instrumentation, for the acquisition of velocity and altitude.

FLIGHT TEST RESULTS

Manoeuvres performed by the sailplane pilot did not always satisfy the small perturbation hypothesis. Although the prescribed manoeuvres were designed to excite only one type of motion at a time, the longitudinal and lateral-directional motions were always coupled: for example, for a typical longitudinal manoeuvre the pilot had to adjust the sailplane flight with rudder, or, for a typical lateral manoeuvre, elevator adjustments could not be avoided.

For the lack of wind tunnel or numerical data on the DG400 sailplane, initial vectors for the parameter estimation procedure were derived in this case from numerical simulations.

A complete description of all manoeuvres performed during the test flight and parameter estimations can be found in ref. [11]. Below are shown some examples.

LONGITUDINAL MOTION

One of the performed longitudinal motion manoeuvres is shown in fig. 8 as elevator deflection (top graph; dots), together with that prescribed to the pilot (top graph; continuous line). As it can be inferred from the same figure, although sailplane estimated responses (continuous line,

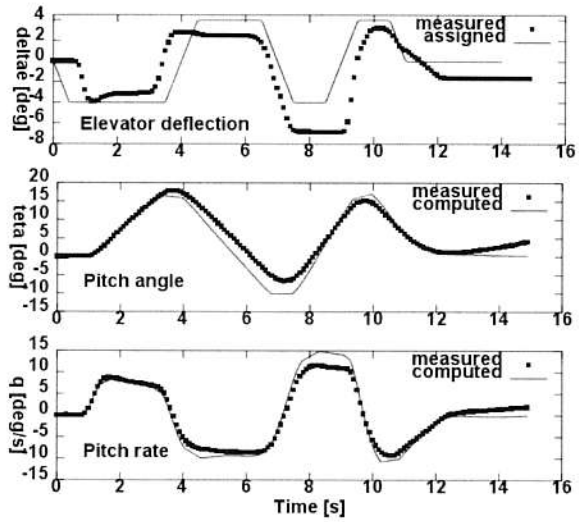


Figure 8: an example of manoeuvre for the longitudinal motion. Here computed stands for "estimated".

Table n. 3: average estimated parameters for DG400 sailplane over different longitudinal motion maneuvers.

Coefficient	Estimated
$C_{L\alpha}$	5.70
$C_{L\dot{\alpha}}$	0.59
$C_{m\alpha}$	-0.44
$C_{m\dot{\alpha}}$	-2.82
C_{Lq}	4.45
C_{mq}	-10.70
$C_{L\delta e}$	0.17
$C_{m\delta e}$	-0.77
I_y [kg m^2]	570

"computed") in terms of pitch angle (middle) and pitch rate (bottom) are not perfectly coincident with the actual ones (dots), the time development of these curves is cor-

	Mean value
Phugoid period [s]	21,61
Phugoid frequency [Hz]	0,047
Phugoid damping ratio	0.024
Short period [s]	3,60
Short period frequency [Hz]	0,28
Short period damping ratio	0,75

Table n. 4: estimated phugoid and short period motion characteristics.

rect. Differences between measured data and estimated responses, particularly important at minima and maxima, can be explained considering that the linear model does not take into account the aeroelastic effects. Average values of estimated longitudinal motion parameters over a set of manoeuvres are reported in table 3 below.

In addition to the parameter estimation, the frequencies

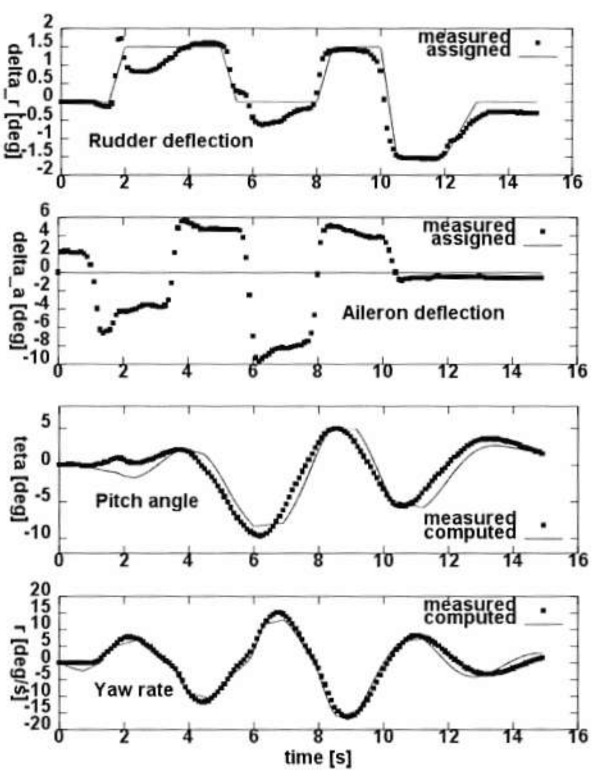


Figure 9: an example of manoeuvre for the lateral-directional motion.

Table n. 5: average estimated parameters for DG400 sailplane for different lateral-directional motion maneuvers.

Parameters	
$C_{Y\beta}$	-0.45143
C_{Yp}	-0.01857
C_{Yr}	0.00015
$C_{Y\delta r}$	0.24289
$C_{\_\beta}$	-0.02016
$C_{\_p}$	-0.28117
$C_{\_r}$	0.00023
$C_{\_\delta a}$	-0.17038
$C_{\_\delta r}$	0.01345
$C_{n\beta}$	0.02885
C_{np}	-0.00988
C_{nr}	-0.11566
$C_{n\delta a}$	0.00077
$C_{n\delta r}$	-0.01933
I_x [kg m^2]	1839.46800
I_z [kg m^2]	2545.24100

Table n. 6: estimated Dutch roll and Spiral motion characteristics

	Mean value
Dutch roll period [s]	5.48
Dutch roll damping ratio	0.293
Spiral time to half [s]	7.24

and the damping factors of the characteristic "phugoid" and "short period" motions, which are related to the eigenvalues of the dynamic matrix A, have been calculated according to standard theories [12,13]. Average values are reported in table 4 below. The small value of the damping ratio, i.e. nearly unstable, of the phugoid motion has been effectively observed during test flights for impulsive and particularly intense maneuvers: in this case a fast and conscious control by the pilot was necessary.

LATERAL-DIRECTIONAL MOTION

One of the performed lateral-directional motion manoeuvres is shown in fig. 9 (top two graphs; dots), together with that prescribed to the pilot (top two graphs; continuous line). For this manoeuvre, the pilot was not able to control the sailplane without using the rudder. Also in this case the sailplane estimated responses, now in terms of pitch angle and yaw rate, are not perfectly coincident with the actual ones, but the time development of these curves is correct. Average values of estimated longitudinal motion parame-

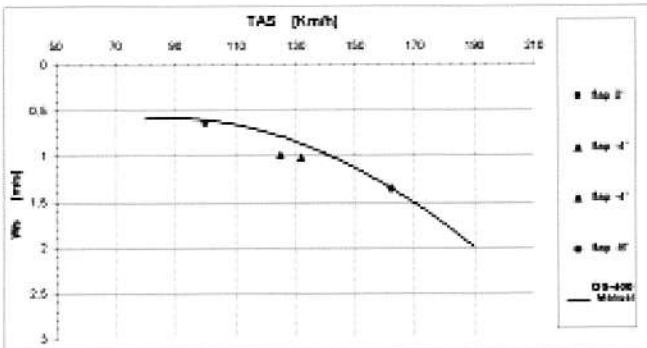


Figure 10: Performance polar of DG400 sailplane, TAS vs. sink rate (*Ws*).

ters over a set of manoeuvres are reported in table 5 below.

PERFORMANCES

In fig. 10 below, the polar curve (continuous line) taken from the DG400 flight manual: TAS [*km/h*] versus sink rate (W_S) [m/s] is shown. At each point of this curve the manual assumes that flap deflection is set at the optimum performance value. In the same figure the symbols represent the values measured in flight and their corresponding flap deflection.

CONCLUSION

In this work, flight tests performed on DG400 sailplane have been presented. A numerical procedure, based on Maximum Likelihood Method, has been set up to predict all aerodynamic and stability derivatives for this sailplane starting from flight test data. ***MeMaV*** code has been developed to this aim and it has been validated with the help of ***AEREO*** code applied for airplanes for which mass and inertia data were available. Longitudinal and lateral-directional dynamic behavior of the DG400 sailplane has been predicted and the reconstructed maneuvers match very well with those measured in flight. Comparison of measured quantities with those numerically predicted with ***AEREO*** and ***JDynasim*** codes will be presented in a future paper.

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APPENDIX A: Dynamic Matrices

Longitudinal motion

$$A = \begin{bmatrix} X_u & X_w & g\cos\vartheta_0 & 0 \\ \dfrac{Z_u}{1-Z_{w'}} & \dfrac{Z_w}{1-Z_{w'}} & \dfrac{-g\sin\vartheta_0}{1-Z_{w'}} & \dfrac{u_0-Z_q}{1-Z_{w'}} \\ 0 & 0 & 0 & 1 \\ M_u+\dfrac{M_{w'}Z_u}{1-Z_{w'}} & M_w+\dfrac{M_{w'}Z_w}{1-Z_{w'}} & \dfrac{M_{w'}g\sin\vartheta_0}{Z_{w'}-1} & M_q+\dfrac{M_{w'}(u_0+Z_q)}{1-Z_{w'}} \end{bmatrix}$$

$$B = \begin{bmatrix} X_{\delta e} \\ \dfrac{Z_{\delta e}}{1-Z_{w'}} \\ 0 \\ M_{\delta e}+\dfrac{M_{w'}Z_{\delta e}}{1-Z_{w'}} \end{bmatrix}$$

Lateral-directional motion

$$A = \begin{bmatrix} Y_v & Y_p & -(u_0-Y_r) & g\cos\vartheta_0 \\ L_v+a\dfrac{N_v+bL_v}{1-ab} & L_p+a\dfrac{N_p+bL_p}{1-ab} & L_r+a\dfrac{N_r+bL_r}{1-ab} & 0 \\ \dfrac{N_v+bL_v}{1-ab} & \dfrac{N_p+bL_p}{1-ab} & \dfrac{N_r+bL_r}{1-ab} & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & Y_{\delta r} \\ L_{\delta a}+a\dfrac{N_{\delta a}+bL_{\delta a}}{1-ab} & L_{\delta r}+a\dfrac{N_{\delta r}+bL_{\delta a}}{1-ab} \\ \dfrac{N_{\delta a}+bL_{\delta a}}{1-ab} & \dfrac{N_{\delta r}+bL_{\delta r}}{1-ab} \\ 0 & 0 \end{bmatrix}$$