IDENTIFICATION OF THE AEROELASTIC MODEL OF A LARGE TRANSPORT CIVIL AIRCRAFT FOR CONTROL LAW DESIGN AND VALIDATION

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Abstract

Since the introduction of the digital technology into flight control systems the structural behaviour is an important issue of the control law design, firstly to guaranty that no instability of a flexible mode is created by the flight control law. However, if a model of the structural dynamics is in hand, in a form convenient for control design, the flexible mode behaviour can be changed from a constraint into a new objective of the control design, offering a wide range of new benefits for the aircraft : ride quality improvement, passenger comfort augmentation, dynamics load reduction ...

Such models can be derived in the state space form from the flutter theoretical models, but if flight test results are available better models are obtained by a direct identification of this model from flight test data.

This paper presents an identification procedure of an aeroelastic state space model from flight data, for control law design and validation purposes. The procedure is split into a first estimation of the model by the E.R.A (Eigensystem Realization Algorithm) followed by a model refinement using the output-error minimization procedure.. Flight tests results on a large civil transport aircraft are presented.

1. Context and Objectives

Flight mechanics modelizations for control law synthesis have been developed and used industrially for a long time. These models are derived from the non linear flight mechanics equations, and may take into account many refinements: non linear aerodynamics, introduction of static flexibility effects, adjustment of aerodynamic data from wind tunnel tests… In addition to this theoretical modelization process, in-flight identification of the flight mechanics behaviour, with dedicated flight tests, is now a common practise. After this identification, a very high accuracy is usually obtained, offering the possibility to adjust the control law, or to provide a simulation for the training simulators.

With the Airbus A320 and the introduction of the fly-by-wire technology, the structural dynamics has become an important issue of the design of a flight control system of a civil aircraft. On this aircraft the structural dynamics was taken as a constraint of the control law design, by setting specific stability margins at the flexible modes frequencies. This constraint was passed through with a filtering of the control law, which excludes the flexible modes outside of the bandwidth of the controller.

A break in this passive approach was achieved on the Airbus A340, with the first introduction of a flexible mode control through the EFCS in a civil aircraft (CIT, Comfort In Turbulence). This specific function increases the damping of some fuselage modes, providing therefore an improvement of passenger comfort. The active approach will be pushed further on the stretched versions of the A340, with the integration of the structural dynamics objectives inside the whole control law design process, offering optimal handling qualities together with a flexible mode control in the whole flight domain. This last step is now possible thanks to the development in Aérospatiale-Matra-Airbus of control methodology dedicated to flexible aircraft [1], together with progress in flexible aircraft modelization.

When using the active approach the structural dynamics modelization is an important stage of the flight control design process. Today’s state-of-the-art methodologies used in aeroservoelasticity (Finite element models, adjustement on ground vibration test, unsteady aerodynamic computation with doublet lattice or CFD methods, transformation in the state space form of aeroelastic equations) provide theoretical models accurate enough for a first design of flexible modes control.

However, in a way similar to the flight mechanics procedure, significant improvements of the control performance on the structural dynamics aspects can be obtained by an adjustment of the controller on flexible aircraft models identified during flight test.

This paper focuses on this identification question. A methodology for identification of flexible aircraft models for control law design is presented. The link with the usual rigid body identification, and the flight test procedure are addressed.

Then some results of this methodology on flight test results of a large civil test aircraft are shown. Finally, future uses of these identified flexible aircraft models, in addition to the original control law design needs are discussed.

2. Aeroelastic Model Identification Procedure

2.1. Model Identification and Model Adjustment

The identification of the flight mechanics models can be directly transformed into an identification of aerodynamic coefficient. By this relation, the rigid body identification process can be moreover seen as an adjustement of data of the theoretical model. The flight test identification can be used to adjust theoretical models at conditions different from the test conditions (eg different cg positions, aircraft mass, dynamic pressures). Such simple relations between model data (mass, stiffness or aerodynamic data) and model coefficient do not exist on aeroelastic model. Therefore, model identification and model adjustement are two different questions and ask for different methodologies. This paper concentrates on the identification question only : how to extract from flight data only (without any previous theoretical knowledge) aeroelastic models suitable for control law design ? The question of aeroelastic model adjustment is addressed in ref [2].

2.2. General algorithm

The algorithm is divided into two main steps:

1/ identification of the impulse responses of all the outputs excited through all the inputs.

2/Calculation of the aeroelastic state space model from the impulse responses using the ERA (Eigenspace Realization Algorithm) [3] method.

A flexible model of the structure is obtained, which included a participation of rigid modes of the aircraft. The next paragraph will show how this interference from the rigid body movements is managed.

Now let us detail the two steps :

1/Calculation of impulse responses

Each impulse response is calculated individually for any input/output through this process:

The convolution product of the term of the impulse response g_l with the input u gives the output y :

$$y_j = \sum_{l=0}^{k} g_l * u_{j-l}$$

This equation in the matrix form is:

$$\begin{bmatrix} y_0 & y_1 & \dots & y_M \end{bmatrix} = \begin{bmatrix} g_0 & \dots & g_k \end{bmatrix} \begin{bmatrix} u_0 & u_1 & \dots & u_M \\ 0 & u_0 & \dots & u_{M-1} \\ \dots & \dots & \dots & \dots \\ 0 & \dots & 0 & u_{M-k} \end{bmatrix}$$

this overdetermined system is solved with a Singular Value Decomposition (SVD) algorithm.

2/Calculation of state space model

With all the impulse responses for all the input/output it is possible to build a Hankel matrix of the system and then through the ERA process calculate the state space model. A chart of this method is presented in fig 2. A description of the Hankel matrix used is given as well as the expression of A,B,C,D (the matrix of the state space system) from this Hankel matrix is given below:

The impulse response Y_k of a discrete state space system can be expressed as:

$Y_0=D$, $Y_1=CB$ $Y_2=CAB$, $Y_k=CA^{k-1}B$

The form of the Hankel matrix is:

$$H(k-1) = \begin{bmatrix} Y_k & Y_{k+1} & \dots & Y_{k+\beta-1} \\ Y_{k+1} & Y_{k+2} & \dots & Y_{k+\beta} \\ \dots & \dots & \dots & \dots \\ Y_{k+\alpha-1} & Y_{k+\alpha} & \dots & Y_{k+\alpha+\beta-1} \end{bmatrix}$$

if k=1 we have:

$$H(0) = \begin{bmatrix} Y_1 & Y_2 & \dots & Y_\beta \\ Y_2 & Y_3 & \dots & Y_{1+\beta} \\ \dots & \dots & \dots & \dots \\ Y_\alpha & Y_{1+\alpha} & \dots & Y_{\alpha+\beta-1} \end{bmatrix}$$

Identifying with the impulse response of a discrete state space system the Hankel matrix can be expressed as:

$$H(k-1) = P_\alpha A^{k-1} Q_\beta \quad (1)$$

Where :

$$P_\alpha = \begin{bmatrix} C \\ CA \\ CA^2 \\ \dots \\ CA^{\alpha-1} \end{bmatrix}$$

$$Q_\beta = \begin{bmatrix} B & AB & A^2B & \dots & A^{\beta-1}B \end{bmatrix}$$

P_α: Controllability matrix

Q_β: Observability matrix

Applying eq (1) with k=1 gives:

$$H(0) = P_\alpha Q_\beta$$

$H(0) = R_n \Sigma_n S_n^T$ result of the SVD of H(0)

where $R_n R_n^T = S_n S_n^T = I_n$

with I_n matrix (n,n)identity

A solution for P_α and Q_β may be:

$$P_\alpha = R_n \Sigma_n^{1/2} \qquad Q_\beta = \Sigma_n^{1/2} S_n^T \qquad (2)$$

from (1):

$$H(1) = P_\alpha A Q_\beta$$

With P_α, Q_β evaluated in (2) ; so

$$H(1) = R_n \Sigma_n^{1/2} A \Sigma_n^{1/2} S_n^T$$

The solution for the matrix A is then :

$$A = \Sigma_n^{-1/2} R_n^T H(1) S_n \Sigma_n^{-1/2}$$

B and C are given by :

$$B = \Sigma_n^{1/2} S_n^T E_r$$
$$C = E^T_m R_n \Sigma_n^{1/2}$$

Where :

$$E^T{}_m = [I_m \quad O_m \quad \dots \quad O_m]$$

$$E^T{}_r = [I_r \quad O_r \quad \dots \quad O_r]$$

m number of output and r number of input,
with I_i identity matrix of order i
O_i null matrix of order i

H(1) and H(0) are evaluated through the impulse responses calculated with the method described before.

2.3. Link with the flight mechanics model

In the identification process it is supposed that a rigid model response and a structural model response are summed together to correctly represent the global response.

At this moment the aeroelastic model identified contains both the rigid and the structural part of the response of the aircraft. To have a pure structural model, the rigid body movement participation must be removed. An output-error minimization method is carried out on the aeroelastic model together with a flight mechanics model to remove the bias due to rigid body movements. Either a rigid model identified from flight tests at the same flight point, or a theoretical model may be used for this process. During the output error minimization process, the parameters of the aeroelastic model only are adjusted to stick to flight data. The integration of this step is explained in the overall chart of the identification procedure given in fig 1.

2.4. Flight test process

To get the flight data necessary to the method describe above, the aircraft is excited with all the inputs used by the controller. Rigid body tests are performed at the same flight point to provide an accurate flight mechanics model. Sine sweeps excitations in the frequency range of the first structural modes are used to identify the structural dynamics. Different flight conditions and mass cases are flight tested to provide the control law designer with the sufficient number of models for control law tuning and robustness checks.

3. Example of flight test results

Results of the identification of a large civil aircraft in landing configuration are shown in appendix. This flight point can be considered as a very difficult one, due to a very noisy environment induced by separation on the high lift devices. Time domain flight test results with all the inputs are shown in fig 4, whereas an example of comparison between test results and time domain simulation with the identified model is given in fig 5. The mode selection is guided by the hankel matrix singular values plot and the stabilization diagram, shown in fig 3. One can see in fig 5 that a very good fit between test and simulation results is obtained; A further check is offered by the analysis of the error signal (column 4) that is decorrelated from the excitation. The mathematical form, size and accuracy of the identified aeroelastic model fulfil the requirements of the design of an active control of the structural dynamics through the flight control system.

4. Conclusions. Additionnal uses of identified aeroelastic models

The need for an identification of the structural dynamics has grown in Aérospatiale Matra Airbus with the development of the “flexible aircraft flight control laws”, that insure a control of the flexible modes dynamics as well as the flight mechanics mode. It has been shown in this paper that aeroelastic state space models relevant for control law design can be extracted from flight test data, providing the possibility to improve the structural mode control during the flight test campaign.

In addition to the control law synthesis, such models allow other applications in the field of aeroservoelasticity. Once the control law is designed, identified models can be used during the validation step : aeroservoelastic stability, performance of the flexible mode control, comfort evaluation can be carried out in some cases with identified models, completing the validation performed with theoretical models.

Such applications of identified aeroelastic models do not mean that the theoretical model is forgetten when the identification has been carried out. It remains the first modelization for stability and performance demonstrations of the flight control system with respect to flexible modes issues. Identified models are limited to the specific flight and mass conditions flight tested. Moreover, the identification procedure provide only “black box” models, without any understanding of the dynamic behaviour, or help in the search for improvement. For these reasons, progress in flexible aircraft modelization is still of first importance in aeroservoelasticity, and is complementary of flight test aeroelastic model identification.

References

[1] F Kubica. New flight control laws for large capacity aircraft. Experimentation on Airbus. ICAS, 1998.

[2] S Prudhomme, C Blondeau, M Humbert, A Bucharles: *An unsteady aerodynamics identification procedure for flutter prediction.* International forum on aeroelasticity and structural dynamics 1999, Williamsburg

[3] Jer-Nan Juang. *Applied system identification*.

Fig 1 : GENERAL CHART OF THE IDENTIFICATION PROCEDURE

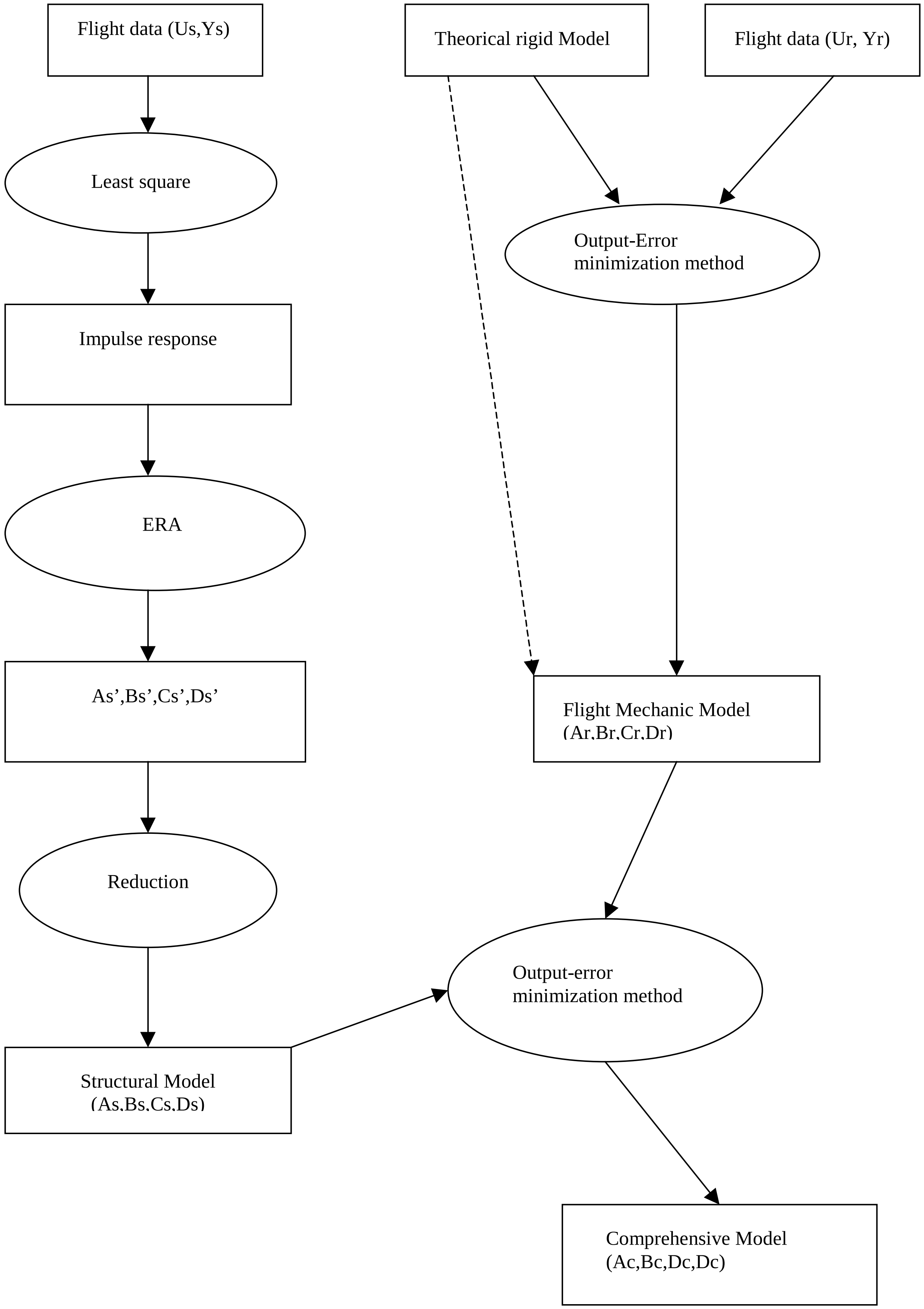

Fig 2 : CHART OF THE ERA METHOD

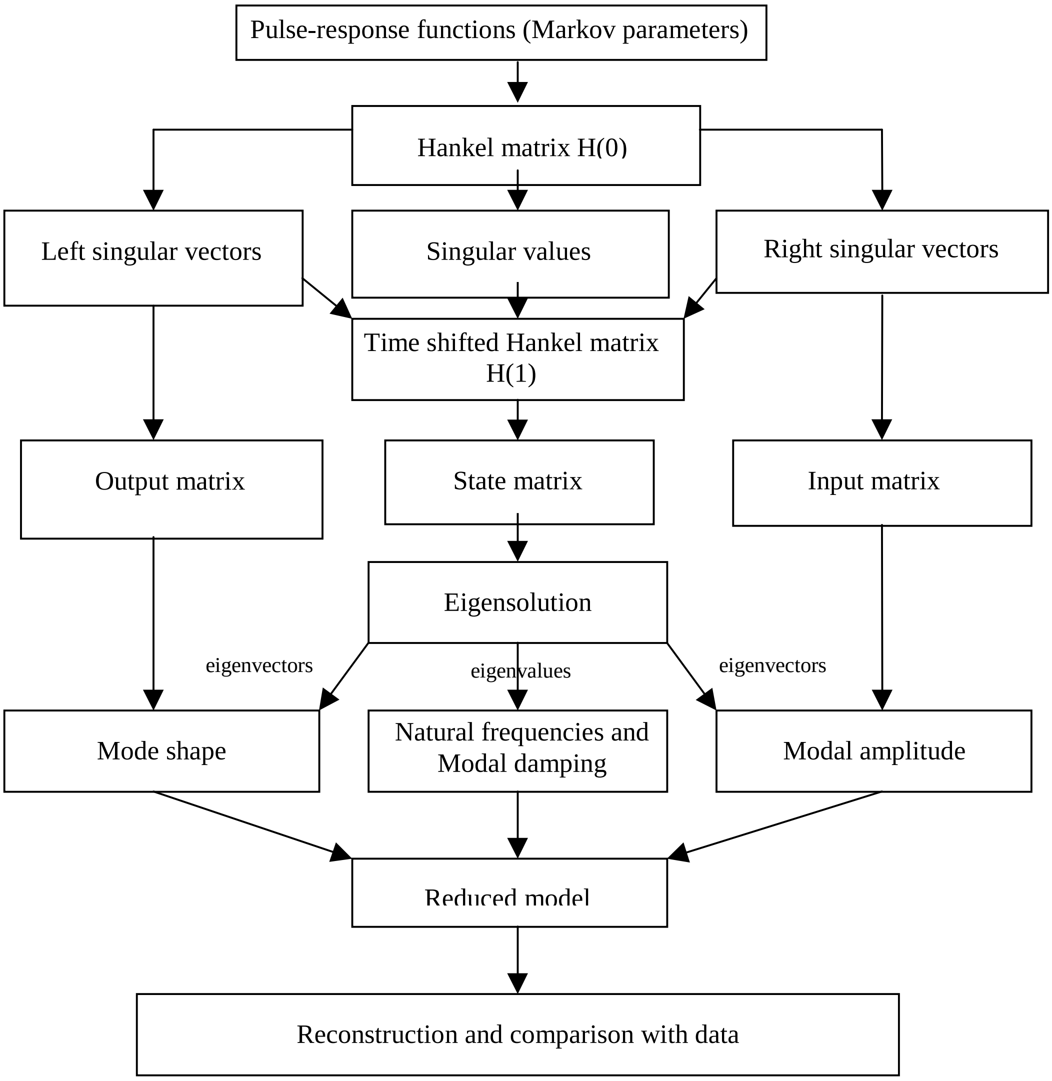

Fig 3 : STABILIZATION DIAGRAM

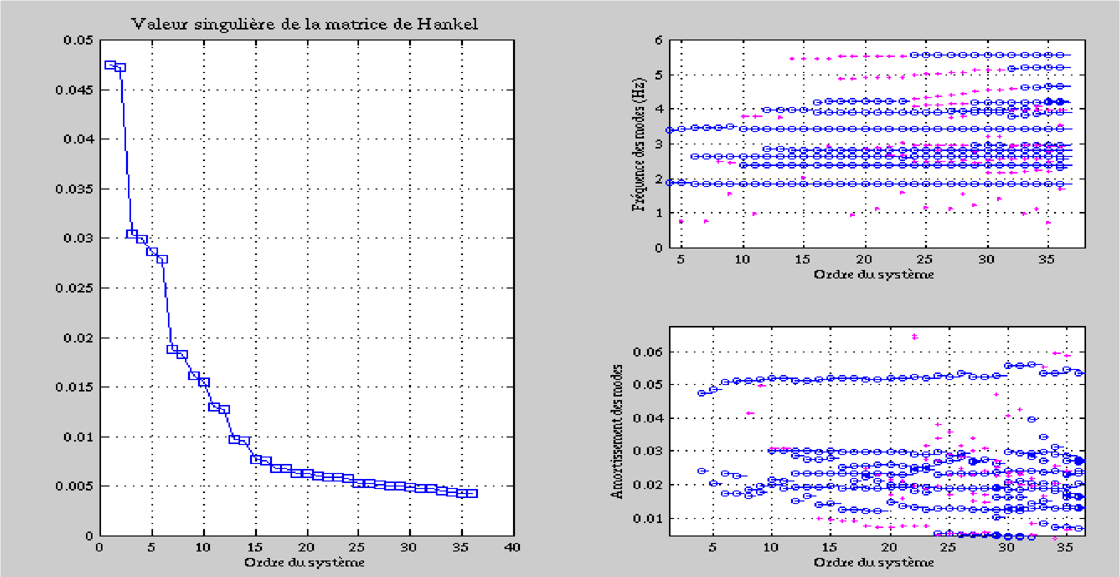

fig 4 : FLIGHT TEST DATA

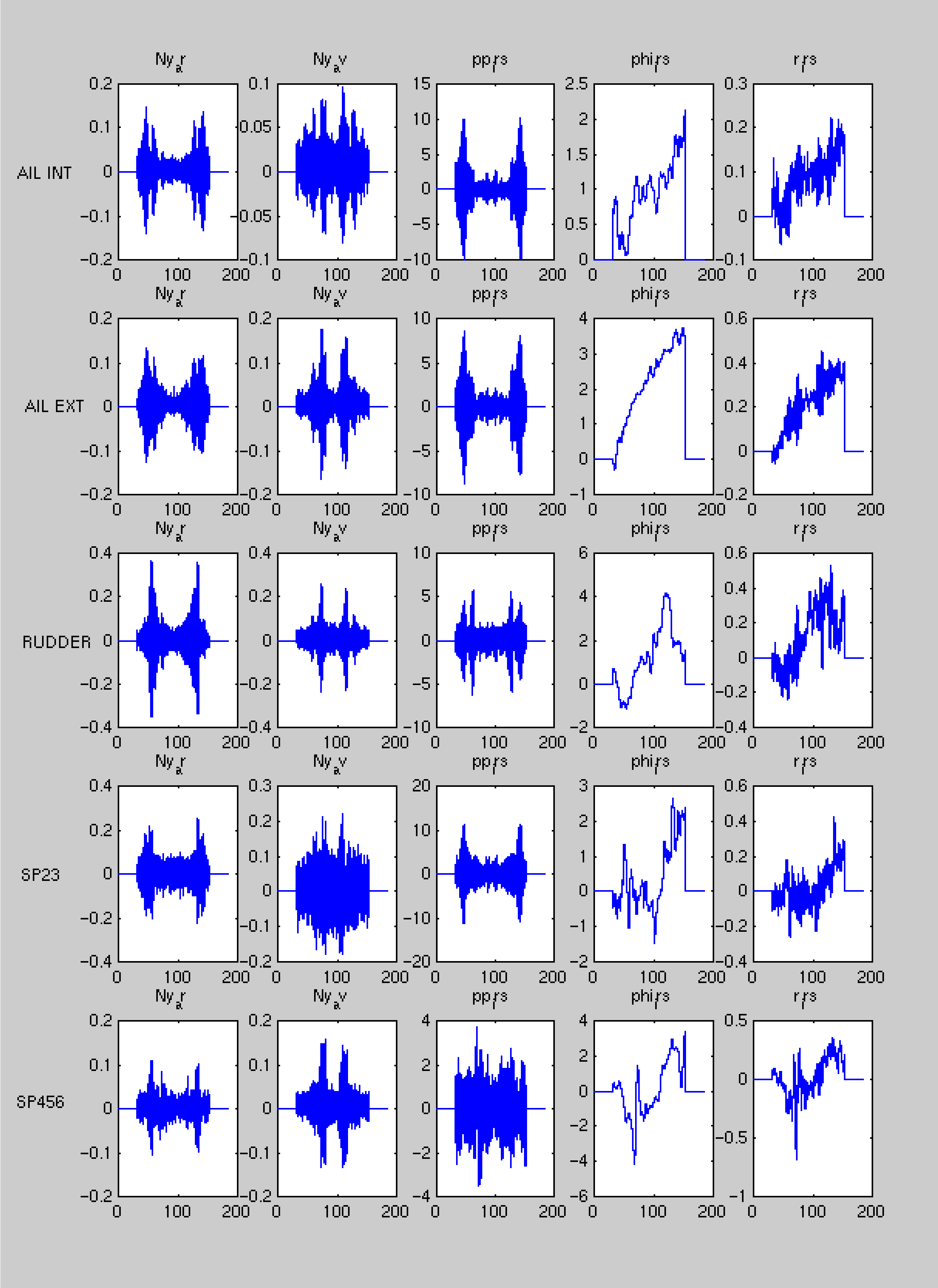

Fig 5 : COMPARAISON BETWEEN FLIGHT TEST RESULTS
AND IDENTIFIED AEROELASTIC MODEL
(inner aileron excitation)