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Engineering Notes

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In-Flight Structural Modes Identification for Comfort Improvement by Flight Control Laws

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Introduction

HIGH-CAPACITY, long-range, large aircraft are necessary to meet the growing demands of increasing air traffic volume. Such large aircraft with flexible structures pose new technological challenges. For flight control systems, flexibility increases the interaction between control laws and structural dynamics, particularly as the frequency of such modes is reduced. Two ways to cope with this problem are 1) a passive approach to avoid coupling with the control laws by filtering the flexible modes sensed by the flight control system and 2) an active philosophy aimed at controlling the structural modes. It has been shown that the second approach seems to be more convenient for the handling qualities[1] and simultaneously allows improvement of passenger comfort by decreasing fuselage accelerations through an active control.[2] Design of efficient active control laws needs a set of accurate aeroelastic models.[3] The objective of this Note is to describe the process applied at Airbus Industries to obtain some refined aeroelastic models for designing active structural control laws.

Flight Control Law Design

The general objective of the flight control laws integrated in a fly-by-wire system is to improve the natural flying qualities, in particular stability, control, and flight envelope protection. The basic philosophy of the flight control system has not changed; that is, for longitudinal control, stick position is translated into vertical load factor, whereas lateral control is achieved through roll rate or sideslip objectives. Static stability is restored at the limits of the flight regime through activation of specific protections like angle of attack and high speed.

Increased aircraft size, however, leads to increased flexibility and can result in interaction with the flight control system. The sensors used by the control laws measure not only the flight path but also the structural modes, which can be amplified by the flight control system. Moreover, turbulence may excite the structural modes, generating uncomfortable vibrations. To improve the damping of these structural modes, and thus to decrease the level of accelerations, it is necessary to control them without degrading the handling qualities. Thus, an integrated design is necessary. Active control, possible through a fly-by-wire system, achieves these objectives while controlling the structural modes at the same time.

Structural Modes Identification

The goal of the in-flight structural identification process is to provide the control law designers with a set of flexible models valid over 1) a large number of flight conditions, like approach (with high lift device deployed), climb at subsonic regime, cruise, and maximum operational Mach number and speed and 2) sufficient mass configuration cases including those for which a particular mode shows an adverse characteristic (minimum damping). For a better performance in terms of comfort improvement using active control, the flight domain explored is, generally, limited to normal operation. To ensure robustness and optimal performance of control laws, high-accuracy models are required to meet these objectives.

In spite of the significant advances in the theoretical models over the past years, their accuracy can not reach that provided by the identified model, notably on gain and phase on transfer function of acceleration to control surface deflections. As a consequence the theoretical model needs extensive tuning, which is not simple and involves a lot of time and effort. Nevertheless, such models are useful for certification purposes, to evaluate the behavior of nontested mass configurations and flight points, to evaluate the influence of design change (weight saving) and to deal with some critical failure cases that are difficult to experiment.

On the other hand, system identification techniques supported by good-quality tests are efficient and achieve these objectives of accuracy within a very short time interval.[4] It is possible to obtain higher accuracy models through in-flight identification of modal characteristics. As a result, the identified models allow the control laws designer to assess efficient laws very early in the flight-test period.[5] In this Note details are provided for the identification process that applies an eigensystem realization algorithm (ERA) to analyze flight data.

Eigensystem Realization Algorithm

ERA, introduced in the 1980s by Juang,[6] can be considered an extension of the Ho–Kalman algorithm to noisy measurement data. It is based on the system Markov parameters and takes advantage of the excellent numerical properties of the singular value decomposition (SVD). For a linear time-invariant nth-order system represented by

$$X_{k+1} = AX_k + Bu_k, \qquad Y_k = CX_k + Du_k$$

the (α, β) Hankel matrix of the system is defined as

$$H_{k-1;\alpha,\beta} = \begin{bmatrix} Y_k & Y_{k+1} & \cdots & Y_{k+\beta-1} \\ Y_{k+1} & Y_{k+2} & \cdots & Y_{k+\beta} \\ \cdots & \cdots & \cdots & \cdots \\ Y_{k+\alpha-1} & Y_{k+\alpha} & \cdots & Y_{k+\alpha+\beta-2} \end{bmatrix}$$

where Y_k are the Markov parameter (impulse response values); X_k the states; u_k control inputs; and A, B, C, and D are the system matrices. $H_{k;\alpha,\beta}$ can be factored as

$$H_{k;\alpha,\beta} = O_\alpha A^k C_\beta$$

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where

$$O\alpha = [C \quad CA \quad CA^2 \quad \cdots \quad CA^{\alpha-1}]^T$$
$$C_\beta = [B \quad AB \quad A^2B \quad \cdots \quad A^{\beta-1}B]$$

are extended controllability and observability matrices, respectively. In particular, $H_{0;\alpha,\beta} = O_\alpha C_\beta$. If the system is controllable and observable, O_α and C_β and, hence, $H_{k;\alpha,\beta}$ have the rank n.

Conversely, assuming $H_{0;\alpha,\beta}$ to be the estimated Hankel matrix, where α and β are chosen to exceed the largest expected system order, starting from this point the ERA proceeds in two steps: 1) select the system order and 2) estimate the system matrices A, B, C, and D.

The key feature is the SVD factorization of $H_{0;\alpha,\beta}$:

$$H_{0;\alpha,\beta} = USV^T$$

where U and V are orthogonal matrices and the diagonal matrix S contains the singular values in nonincreasing order. In the case of noisy impulse response measurements, $H_{0;\alpha,\beta}$ is a full-rank matrix and it is required to decide how many singular values can be neglected, which determines the system order n. Estimates of extended controllability and observability matrices are given by

$$O_\alpha = U_n S_n^{\frac{1}{2}}, \qquad C_\beta = S_n^{\frac{1}{2}} V_n^T$$

where U_n and V_n are submatrices formed from the first n columns of U and V and the diagonal matrix S_n contains the n principal singular values. The system matrices are now derived from O_α and C_β as follows: 1) B and C are the first block row of C_β and the first block column of O_α, respectively; 2) D is given by Y_0 (first estimated term of the Markov parameter); and 3) A is obtained using the shifted-block Hankel matrix $H_{1;\alpha,\beta}$ by solving

$$H_{1;\alpha,\beta} = O_\alpha A C_\beta$$

Besides singular values, other indicators (modal amplitude coherence, mode singular value) have been developed to evaluate the validity of the models provided by ERA and especially to give information about the accuracy of the estimated modes. They help to arrive at the best model order by comparing several models. The modal amplitude coherence, based on the pulse responses of "measured" and identified modes, has been extended to take into account the behavior with respect to inputs as well through the controllability matrices. These new modal coherence indicators, which range from 0 (no coherence) to 1 (full coherence), must be stuck at each mode for each tested order and plotted on a stabilization diagram, which provides the modal frequencies for different selected orders and allows evaluation of the modal frequencies stability. The indicators allow quick assessment of the effect of increasing or decreasing the system order.

Application of the ERA requires selection of α and β that determines the size of the Hankel matrix. Using a simplified model of a flexible aircraft, it was found that, for a given number of pulse response measurement data, a square Hankel matrix is preferable to reduce the noise influence. An undesirable characteristic of the ERA method is to yield extraneous modes that are not present in the system. These modes, which seem sensitive to the built-up Hankel matrix, have significant coherence indicators and well-stabilized frequencies. Hence, it is difficult to separate those from the physical modes and to suppress them just by looking at the stabilization diagram. Nevertheless, to not affect the further identification procedure, they must be eliminated. The overall model-building process is depicted in Fig. 1.

Markov Parameter Estimation

The response y of a linear causal discrete-time system to an arbitrary input u can be expressed as the discrete convolution

$$y_k = \sum_{l=0}^{k} h_{k-l} u_l$$

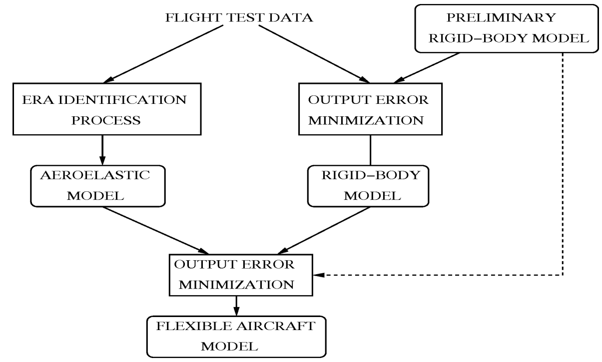

Fig. 1 Block schematic of model building.

where y denotes the system Markov parameters. Conversely, the first $k+1$ Markov parameters can be determined from input and output measurements by deconvolution.

By assuming that the number of measurements is higher than the impulse response length, Markov parameter estimates H are obtained by the least-squares solution of an overdetermined system $Y = UH$, where U is a Toeplitz matrix built from successive input values and Y contains the output values. However, the result is not very satisfactory in the presence of noise. It can be strongly improved by the use of SVD: all singular values of the input matrix U, smaller than a selected threshold, are set to zero before computing the pseudoinverse of U.

Application to A340-600 Aircraft

The A340-600 aircraft is a derivative of the basic A340 family. This airplane has some major changes compared to its predecessor, the A340-300: 10-m-longer fuselage, higher weight [maximum takeoff weight (MTOW) increased by 100 tons], and 20% increased wing surface. These modifications lead to a higher flexibility, requiring modification of the flight control system architecture. The most significant changes are the use of 1) dedicated sensors whose locations are optimized with respect to flexible modes characteristics, 2) active flight control laws to control handling and structural modes at the same time, 3) electrical rudder to improve bandwidth and resolution, and 4) minimization of time delays between sensors and control surfaces by integrating autopilot inner loop and manual flight control laws in the same computer.

Before the first flight, a preliminary flight control system architecture is defined and a first set of active control laws is designed, limiting the performance of the control laws for safety reasons. Subsequently, once the aeroelastic models are identified in flight, the efficiency of the control laws can be increased. During the A340-600 flight-test campaign the process of identification was performed for five different mass configurations. The objective was to evaluate the influence of outer tank filling, trim tank filling, and payload, thereby covering the complete range of normal operation from MTOW to empty weight. At each flight point, a sine sweep is used to excite the structural dynamics, using all available symmetrical and antisymmetrical control surfaces. Proper care is taken to perform the flight tests and gather data with a minimum amount of noise, because the turbulence has detrimental effects on quality results.

The tests are monitored in a telemetry ground station, and a test is repeated, if necessary, to achieve high-quality data. As an example, Fig. 2 shows time histories of four typical accelerometers (lateral acceleration at front and rear fuselage as well as vertical acceleration on outer engines), obtained with a sine sweep from 0.5 to 6 Hz on an antisymmetrical outer aileron.

Based on the precise identified models, the locations of the flight control system sensors (gyros and accelerometers) are optimized to achieve the best compromise between handling qualities and comfort control laws. Most of the sensors are located in the fuselage, but some accelerometers are also placed in the outboard engines. With this optimized architecture, some active control laws are designed to reduce the level of acceleration in all parts of the fuselage to improve comfort. These control laws use the elevators for longitudinal control

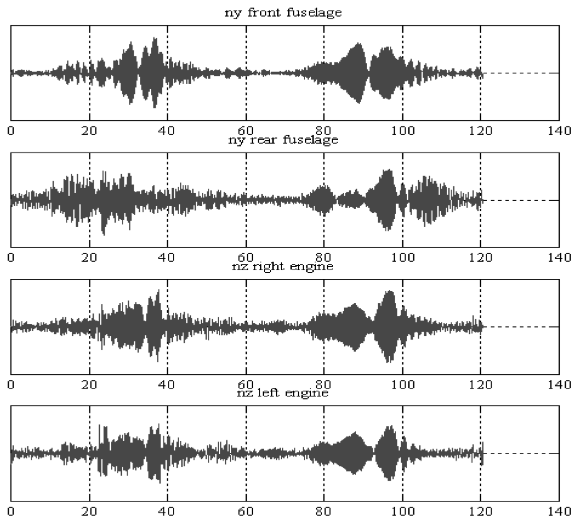

Fig. 2 Example of flight data for aileron sine sweep input.

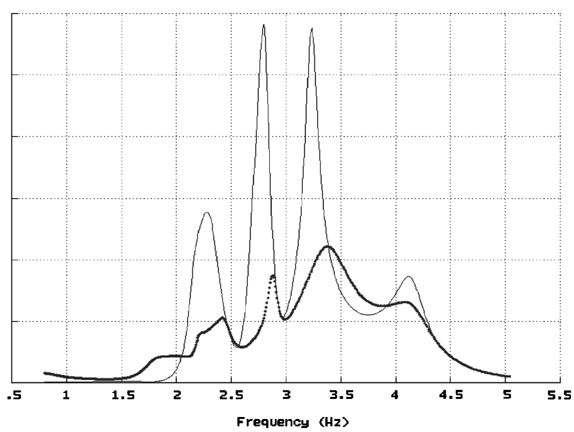

Fig. 3 Transfer function with aileron at front fuselage.

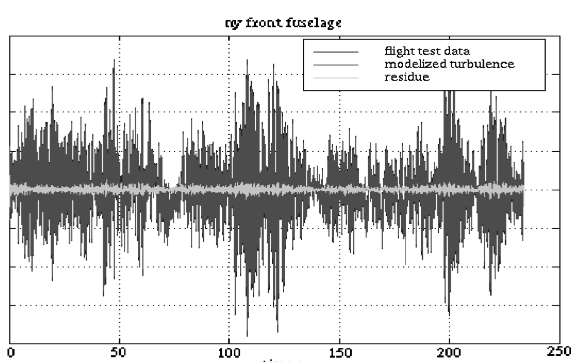

Fig. 4 Lateral acceleration at the front fuselage due to in-flight turbulence described with the identified model.

and the rudder, inboard ailerons, and outboard ailerons for lateral control. Significant reduction in the lateral acceleration, and thereby improved comfort, was achieved for all the mass configurations investigated. As a typical example, Fig. 3 shows the transfer function for the antisymmetrical aileron input, showing pronounced reduction for the mass configuration tested here, namely, the light aircraft configuration, which is the one most critical for the comfort aspect.

The performance and efficiency of the designed control laws incorporating in-flight identified structural modes is demonstrated in actual flight under turbulent conditions. For that purpose we have used flight-test data coming from a flight dedicated to a flight control system (FCS) robustness check during which we have encountered turbulence. Figure 4 shows in-flight measured lateral acceleration

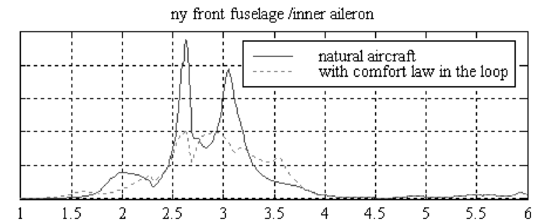

Fig. 5 Transfer function with aileron input.

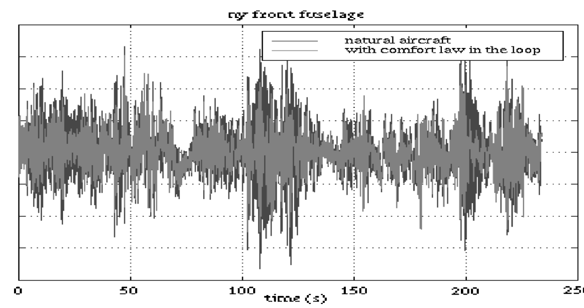

Fig. 6 Lateral acceleration at the front fuselage due to measured in-flight turbulence described with the identified model in closed loop and open loop.

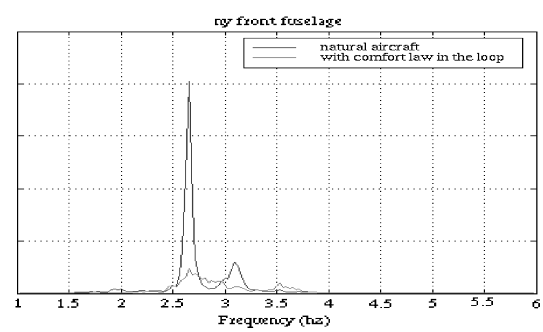

Fig. 7 PSD of lateral acceleration at the front fuselage due to in-flight turbulence in open loop and closed loop.

due to turbulence superimposed with simulated turbulence thank to the identified model, the (srnall) residue (difference between the simulated and measured acceleration) is also shown.

Because the identified model allows us to replay the acceleration due to turbulence it is then possible to close the loop in the FCS (the FCS performance for this flight condition is given in Fig. 5) and to see the effect of the FCS on the aircraft dynamics at the front fuselage. Figure 6 shows the FCS performance in the time domain. The acceleration due to turbulence at the front fuselage is clearly alleviated, and sharper peaks are decreased. The same analysis can be performed in the frequency domain through a PSD in Fig. 7, bringing out a more dramatic effect due to the square factor present in PSD.

Conclusions

This paper describes the process used at Airbus to derive accurate aeroelastic models required to design structural active control laws. The performance in terms of comfort improvement are demonstrated in the A340-600 flight-test data. This process enabled us to achieve a high level of handling qualitiy and comfort for this large aircraft in spite of its high flexibility. The related work and the results presented in this paper establish that the active control laws incorporating in-flight identified structural modes can be successfully implemented to improve comfort on a serial aircraft. It sets the standard for future aircraft like the A380.

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