Active noise control in turbofan aircrafts: theory and experiments

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This paper presents the activities developed by the authors within the research project M.E.S.E.M.A. funded by the European Commission. A noise and vibration control system using magnetostrictive actuators has been designed and experimentally tested on a fuselage mock-up test article, controlling noise and vibrations between 150 – 500 Hz. The environmental noise and vibration excitation was representative of a small/medium turbofan aircraft. A numerical model of the test article has firstly been developed in MSC/NASTRAN coupling the structural part with the interior acoustic volume. Furthermore the experimental characterisation of the test-article has been carried on. The model, updated by the mean of the experimental results, was employed to derive the required control actuators performances in order to achieve the best control predicted using a well consolidated "feed-forward" approach. Genetic Algorithms have been employed in order to optimise the positioning of the actuators. Dedicated magnetostrictive actuators have been designed together with light power amplifiers meeting the specifications; on each actuator an optoelecronic sensor, based on Bragg grating, has been integrated to optimize the actuator performance. A two-level ANVC system has been designed and tested on a full scale fuselage mock-up. The paper present an overview of the activities developed and achieved results.

1 Introduction

One of the main targets for the MESEMA Consortium consisted in reducing the level of disturbance noise in turbofan aircraft; furthermore this activity is a "natural extension" of those carried out during a previous program named MESA (Magnetostrictive Equipment and Systems for a more electric Aircraft) where an active feedback control system has been designed, realised and tested for counteracting a vibration primary field typical of turboprop families aircraft [4]. The promising results obtained during the past experience convinced the consortium in facing within the new research program with the problem of reducing a "wide frequency band" noise disturbance field. A noise and vibration control system using magnetostrictive actuators has been designed, developed and tested, with the goal of controlling noise and vibrations in a frequency range between 150 – 500 Hz. The environmental noise and vibration excitations has been selected as representative of a small/medium turbofan aircraft case.

Fig.1 Mock-up of the ATR 42 aircraft and constraining structure.

Final results of the task has been represented by a system made up of 42 actuation/sensing devices connected to a system performing control of external disturbances as well as of the devices' intrinsic non linearity. As experimental test article a fuselage mock-up of the ATR42/72 aircrafts family has been chosen available at the acoustic laboratory in the Alenia plant; due to its geometry and overall dimensions it well represents a fuselage section of an hypothetic regional jet (Figure 1). The numerical (finite element) model of the mock-up has been developed, correlated with experimental modal analysis results and updated in order to match the best way possible the experimental reality. This model has then been employed to carry out a deep simulation activity aimed at evaluating the required control actuators performances in terms of force spectra as far as their optimal placement for control purposes. This last activity has been accomplished by means of a dedicated genetic algorithm code developed in MATLAB environment. Dedicated actuation systems has been developed for the scopes of the control system, respecting the demanding constraints in terms of performances/weight; 42 actuators based on the employ of magnetostrictive material and a patented displacement amplification devices have been developed, optimised and mounted on frames and stiffeners of the fuselage section test article. Dedicated "hybrid" amplifiers characterised by low weight have also been developed for all the actuators. The employed control scheme is composed by two nested feedback loops. The inner loop, based on a model following approach [11], usefully exploits the measurement information provided by the optical Bragg sensor integrated into the actuator with the aim of linearizing its behaviour and specifically to fix its resonant frequency. The outer controller resorts to a robust H_∞ optimal control strategy specifically devised to tackle the problem of strong stabilization of a flexible structure [10]. In order to apply such a model-based strategy, a novel identification procedure, based on a subspace approach, has been specifically setup for this project to obtain a dynamic gray-box model suitable for control purposes [12]. Experimental tests and obtained interior noise reduction levels evidenced the effectiveness of the approaches employed for designing the system.

2 The test article: description, numerical modeling, experimental analysis and correlation

In a previous research program an experimental test-article consisting in a fuselage mock-up of the ATR42/72 aircrafts family has been assembled and is still available at the acoustic laboratory in the Alenia plant. It reproduces the real fuselage section in the propeller area and has been used in the “untrimmed configuration”, i.e. without interior furnishing and seats (Figure 1).

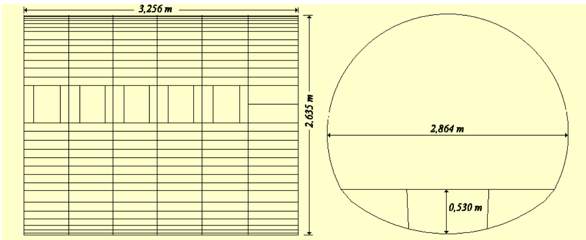

Fig.2 Overall dimension of the fuselage mock-up

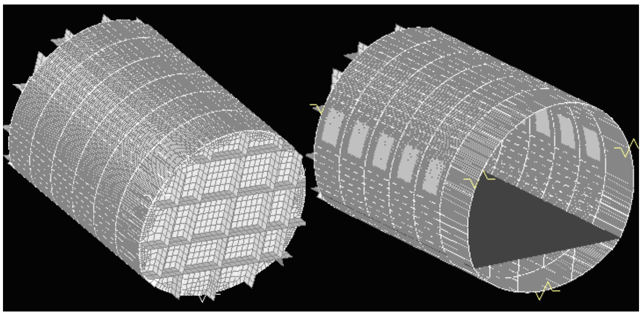

Fig.3 Mock up structural and acoustic F.E. model

Figure 2 presents the overall test article dimensions; the mock-up is made of seven frames and six bays. Figure 3 presents the F.E. models of the test article. The experimental tests were aimed to extract modal parameters of both structure and acoustic volume in order to permit the numerical-experimental correlation and the updating of the model. The structural natural frequencies and modes shapes where extracted from the experimental measurements up to 300Hz. Within this work the Modal Assurance Criterion (MAC) has been used: it compares all mode shapes in the numerical database with all mode shapes in the experimental database.

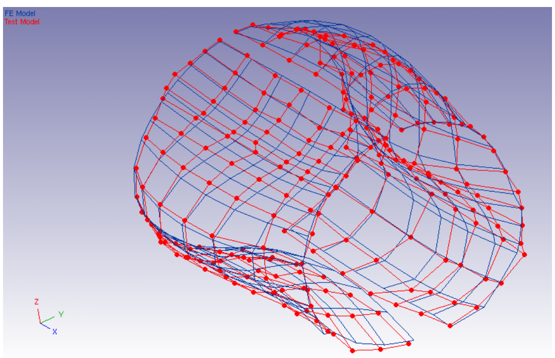

Fig.4 Mode shape pair comparison - FEA 67.6Hz - EMA 61.94Hz - MAC 76%

By the mean of a “sensitivity analysis” an updating of the FE model permitted to achieve good correlation results as presented in Figure 4.

3 Active control simulation

Two control strategies have been simulated: the first one consisting in an Active Structural Acoustic Control (ASAC) aimed to reduce interior noise by controlling the corresponding structural vibrations on the fuselage section; the second one consisting in an Active Noise Control (ANC) aimed at reducing directly interior noise actuating the structural components, but without attempting necessary to reduce vibrations levels [7-8]. For what concerning the simulation of the actuators actions on the structure, the initial basic idea has been to focus on inertial actuators able to provide concentrated forces in their application point.As a consequence they have been modelled as simple point force acting on the selected nodes of the F.E. model. It has been chosen to optimize actuation locations and obtain required forces for each one of them contemporarily employing the well known optimization (pseudo-inverse) approach proposed by Fuller et alii [8] and based on the minimization of the cost function J (see next equations) in selected control points.

$$J = \sum_{n=1}^{N} \left| w_n(\omega) \right|^2 = \underline{w}^H \cdot \underline{w} \qquad (1)$$

The previous formula reports the cost function J, where wn represent the response in terms of noise or vibration of the n-th control point. The response vector w is represented by the linear combination of the primary and control fields, that is:

$$\underline{w} = \underline{w_p} + \underline{\underline{R}}\,\underline{F_s} \qquad (2)$$

where wp is the vector of the complex response due to the primary field; the product defines the complex response vector due to the contribution of M secondary forces. If the number of control points (N) is bigger than the number (M) of the force sources, the optimum control force vector FS is reported in the following equation [8]:

$$\underline{F_S} = -(\underline{\underline{R}}^H \underline{\underline{R}})^{-1} \underline{\underline{R}}^H \underline{w_p} \qquad (3)$$

Employing this approach is possible, then, to evaluate the maximum “response reduction” in the selected control points and for each configuration the complex force spectra required to each actuator in order to reproduce the “controlled response level”.

4 Optimal control actuators placement by genetic algorithms

In order to select among the many possible set of control actuator configurations an optimisation activity was required. The used optimisation method is based on "genetic" algorithms [9, 14]. For this analysis 126 actuators potential locations were selected on frames or stiffeners of the two middle bays of the mock-up. The authors developed the genetic algorithm code in MATLAB framework. Following are presented the results obtained considering as primary disturb a noise pattern provided by Alenia Aeronautica and extracted from in-flight testing: it is a typical noise spectra due to local aerodynamic phenomena and variable with flight parameters. The ASAC approach has been employed and a final comparison between the best obtainable results employing ASAC and ANC approach has been carried out. The main results related to the 30 control actuators configuration are reported .

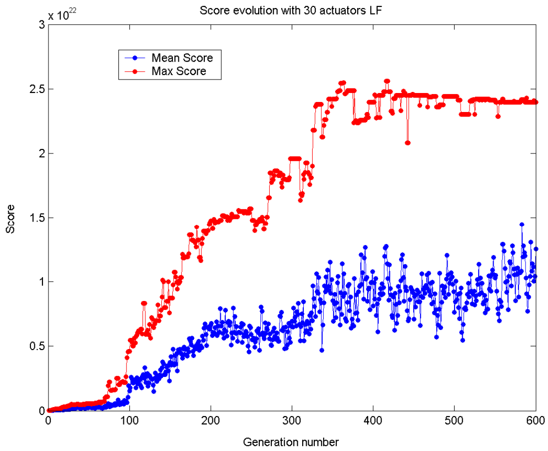

Fig.5 "Score" for ASAC approach

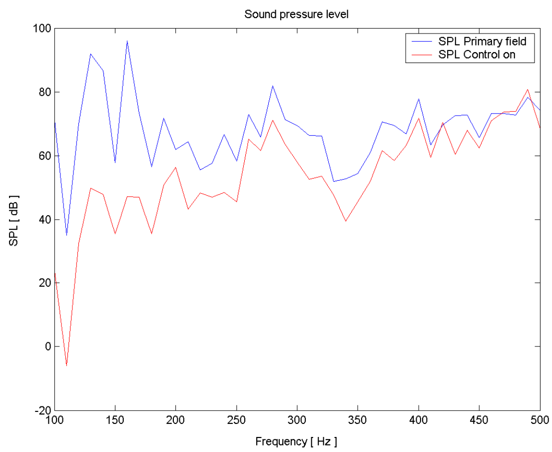

Fig.6 Mean interior noise reduction for the optimal actuators configuration

It is possible to notice the good predicted performances in terms of noise reduction related to the final control actuator configuration selected by the optimisation algorithm up to 400Hz. Next figure present control forces values for each one of the 30 control actuators placed in their optimal locations. Part of the analysis results was obviously the optimal actuators placement configuration and their distribution among stiffeners and frames of the fuselage mock-up.

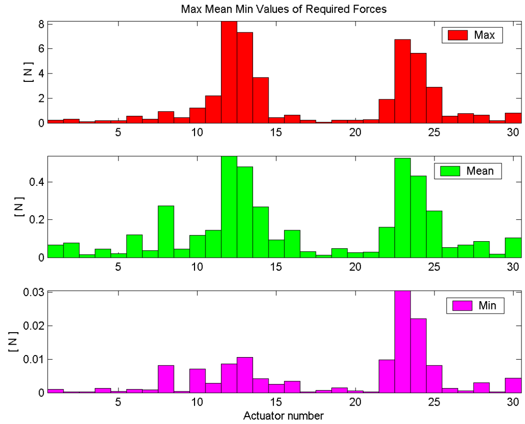

Fig.7 Required control force values for the control actuators in their optimal configuration

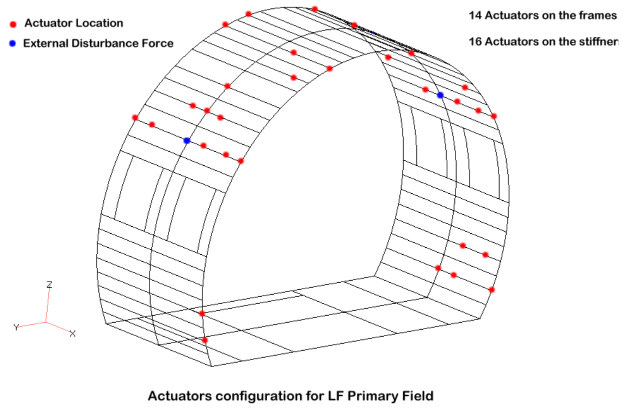

Fig.8 Optimal actuators placement configuration – low frequency disturb force field

5 Actuators and power electronics

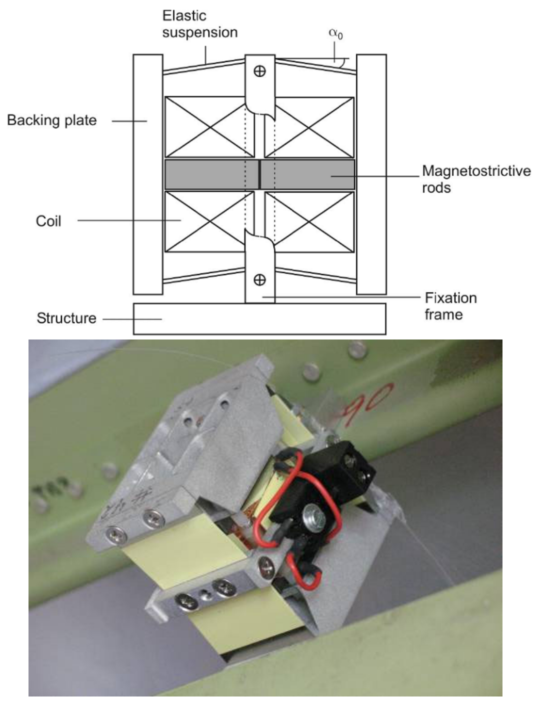

Fig.9 Actuator (with integrated optical sensor) schematic and actual installation on a fuselage stringer

Figure 9 shows the fundamental construction inside the smart auxiliary mass damper [15]. It consists of magnetostrictive rods surrounded by two coils. The coils are on two backing plates that are connected with the stiff frame via two elastic suspensions arranged in parallel. The frame itself is mounted to the vibrating mechanical structure. Due to the magnetostrictive effect a magnetic field caused by a driving current in the coils produces a small extension in the magnetostrictive rods in the horizontal direction. This extension is transformed by the elastic suspensions to a significantly larger motion of the total mass –consisting of the magnetostrictive rods, the coils and the backing plates– in the perpendicular direction. The displacement amplification decisively depends on the angle of the elastic suspension at the working point α0 of the mechanical construction (see Fig. 9) and is greater the smaller this angle α0 is chosen. As a result of Newton's second law, the total moved mass produces an inertial force that has an effect on the vibrating mechanical structure. To drive the actuators, special light power amplifiers (in Fig. 10 some of the characteristics are also reported) have been designed based on a hybrid (analogue/switching) solution to maximize the efficiency in the power conversion and minimize the harmonic distortion in the current waveform feeding the actuator coils.

Fig.10 Light hybrid amplifier: Supply voltage 16…30 V, Input voltage range: 0…4 V, Output current range: 0…4 A, Operating frequency range: 0…15 kHz, -3° phase shift at 1.1 kHz

6 Noise and vibrations control algorithm

As mentioned before, the actuator nonlinearity causes a dependence of the structural frequency response on the amplitude of the driving current, that makes the actuator difficult to use in the noise and vibration control system. Therefore, the low-level control objective is to reduce alterations of the structural response due to variations of the input current level. The adopted control strategy is based on a model-following approach [11] and the overall control scheme is reported in Fig. 11, as the subsystem inside the orange frame. The characteristic of the model-following algorithm consists in preserving the nature of the input signal which has to be computed by the outer control loop. This makes the use of the actuator more transparent in the higher level control system computing the reference current as a result of an outer feedback loop (green frame). For the high-level control algorithm a model based optimal H∞ controller has been designed. In the actual implementation low frequencies must be filtered out, otherwise the very low frequency components of the measured signal would saturate the actuators, thus resulting in a very poor control performance. In the application at hand the low frequencies components are due to the rigid-body dynamics, that is immaterial in vibration control and is obviously sensed by an accelerometer, or noise frequencies below 20Hz, to which the human ear is insensitive. This specific characteristic of the controller can be obtained by suitably selecting the weighting matrices of the H_∞ control problem leading to a strong stabilizing bandpass controller (for more details see [10]).

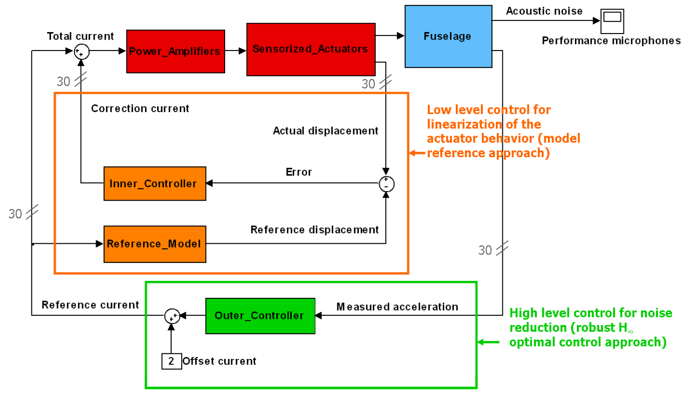

Fig.11 Overall noise and vibration control scheme (30 control channels)

7 Experimental results

The experimental presented hereafter have been evaluated both for the low-level control loop and for the high-level control loop, comparing the control-on case to the control-off one.

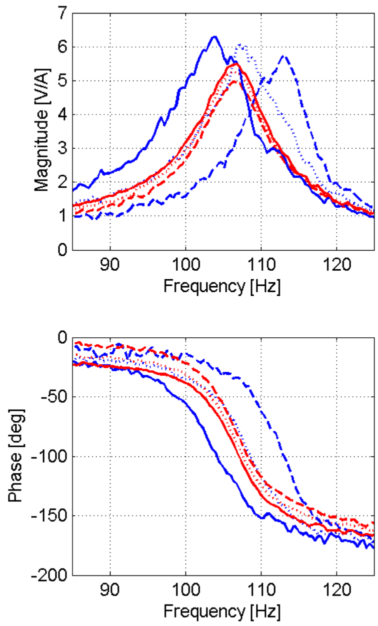

Fig.12 : Actuator behaviour at different current: control off (blue), control on (red)

In Fig. 12, the blue lines represent the actuator frequency response function measured at three different input currents without the low level control. In the same figure, it is possible to see the positive effects of the low level control on the actuator behaviour since the red lines represent the same FRFs measured with the control loop activated, and they all exhibit the same resonant frequency, resulting in a phase shift almost insensitive to the input current amplitude.

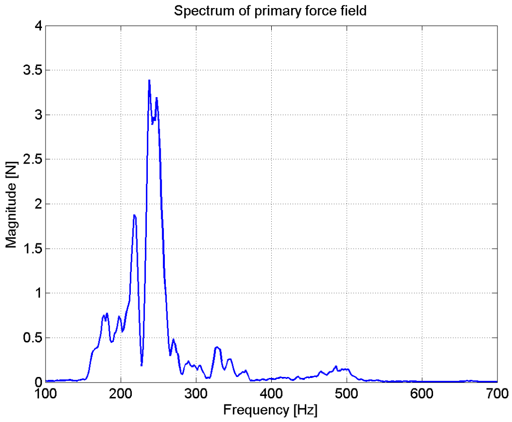

Fig.13 Primary force field from specifications

The effectiveness of the active noise control system has been tested in different conditions. First of all, it is important to state that since the total number of working control channels was limited to 21 and only 4 couples have been mounted on the frames, low controllability of frequencies below 150 Hz is expected and therefore, in agreement with the end-user, a primary force fields at a medium frequency range [200,600] Hz was selected. The spectrum of this primary force field as measured by one the two load cells installed on the shakers is reported in Fig. 13. An experiment has been made with this primary disturbance field generated from two symmetric shakers as requested from the specs. The performances of the control loop, measured from the microphones #1 and #3, are shown in Fig. 14. Also, a 4.1dBA reduction of the overall levels of SPL has been measured.

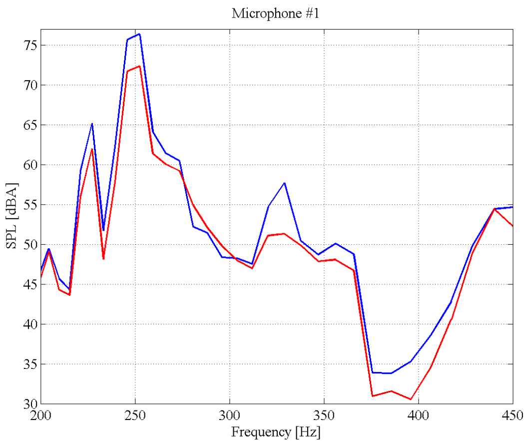

Fig.14 Primary field from specs: control off (blue), control on (red)

Acknowledgments

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