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INTERIOR ACTIVE NOISE CONTROL IN TURBOFAN AIRCRAFT: NUMERICAL SIMULATION AND OPTIMAL ACTUATORS POSITIONING USING DEDICATED GENETIC ALGORITHMS

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Abstract

This paper presents the activities developed by the authors within the first year of the research project named M.E.S.E.M.A. (Magnetoelastic Energy Systems for Even More Electric Aircraft) funded by the European Commission within the 6th Framework Program and coordinated by the "Dipartimento di Progettazione Aeronautica" of the University of Naples "Federico II" (DPA). One of the main targets for the MESEMA Consortium consists in reducing the level of disturbance noise in turbofan aircraft. A noise & vibration control system using magnetostrictive actuators will be designed, developed and tested, with the goal of controlling noise & vibrations in a frequency range between 150 – 500 Hz. The environmental noise & vibration excitations will be representative of a small/medium turbofan aircraft case. During the first two years of the project a numerical (Finite Element) model of the test article has been developed in MSC/NASTRAN environment coupling the structural part with the interior acoustic volume. Furthermore a complete experimental characterisation of the test-article has been carried on. Numerical model has been correlated with experimental results, updating it in order to achieve the best fitting in terms of natural frequencies and modes shapes at low frequencies [1]. Then the updated model has been employed to derive the required control actuators performances in order to achieve the best theoretical interior noise control predicted using a well consolidated "feed-forward" approach [2] and Genetic Algorithms have been employed in order to optimise the positioning of the actuators.

INTRODUCTION

This work presents the activities developed by the authors within the Research Project funded by the European Commission within the 6th FP named MESEMA [3]. This project is a technology oriented research program mainly devoted to accomplish

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objectives of the aeronautics and space priority of the EC by implementing “innovative transducer systems based on active materials”. One of the main targets for the MESEMA Consortium consists 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 Sytems 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 & vibration control system using magnetostrictive actuators will be designed, developed and tested, with the goal of controlling noise & vibrations in a frequency range between 150 – 500 Hz. The environmental noise & vibration excitations will be representative of a small/medium turbofan aircraft case. Final results of the task will be represented by a system made up of about 50 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).

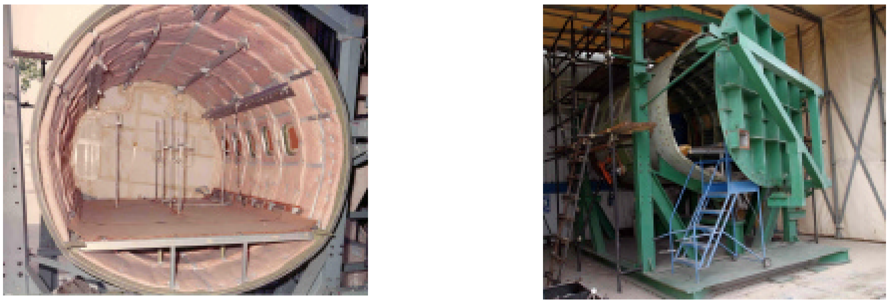


Figure 1: Mock-up of the ATR 42 aircraft and constraining structure

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 to evaluate the required control actuators performances in terms of force spectra as far as their optimal placements for control purposes. This last activity has been accomplished by the mean of a dedicated genetic algorithm code developed in MATLAB environment by the authors.

THE TEST ARTICLE: DESCRIPTION AND NUMERICAL MODELLING

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).

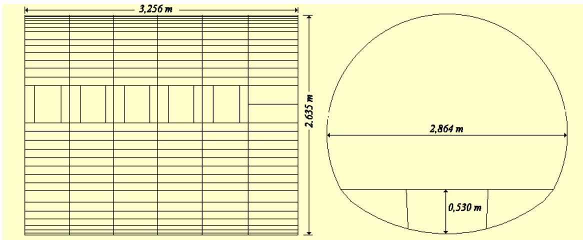


Figure 2: Overall dimension of the fuselage mock-up

The cylinder is closed at the two ends by heavy caps bolted to final flanges, and a proper spring system and fixture connection allow both vibration isolation and free longitudinal deformation of the fuselage section. Figure 2 presents the overall test article dimensions; the mock-up is made of seven frames and six bays. In order to extend the maximum dynamic analysis frequency of the finite element model until at least 1000 Hz, the authors took in account the typical flexural wavefield behaviour of cylinders [4-5], including low frequency beam modes, intermediate frequency cylinder modes, and high frequency plate modes

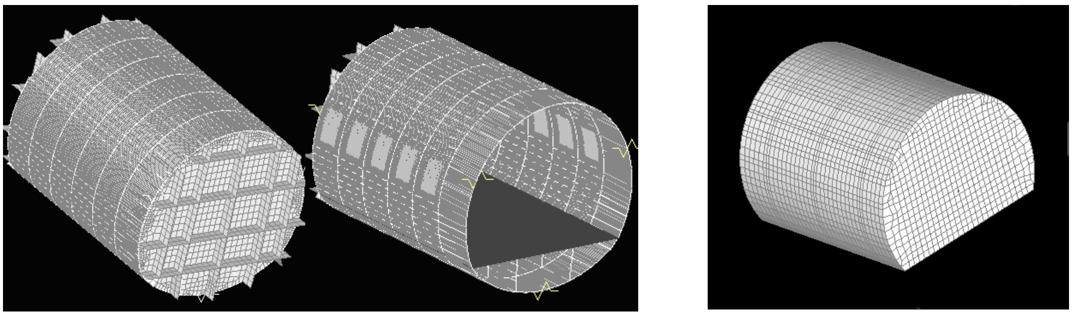


Figure 3: Mock up structural and acoustic F.E. model

According to this preliminary analysis the structural part of the F.E. model is composed by 42595 grid points and 55552 elements. After realized the structural model, the fluid part representing the cabin cavity has been modelled still dimensioning the "acoustic" mesh in order to permit maximum analysis frequencies of the acoustic model up to 1000Hz. The fluid part of the model consisted in 20165 grid points and 18288 elements.

THE EXPERIMENTAL ANALYSIS, CORRELATION WITH NUMERICAL MODEL AND ITS UPDATING

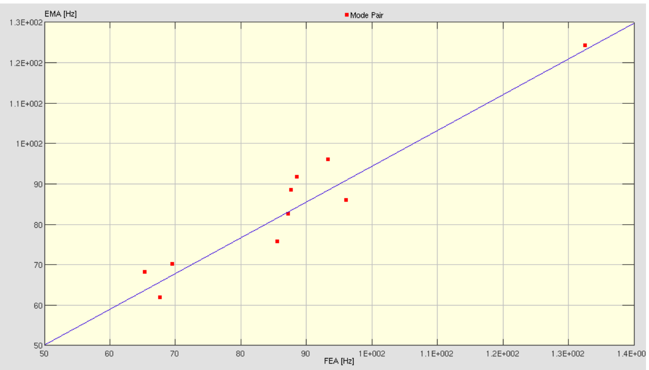
The experimental tests were aimed to extract modal parameters of both structure and acoustic volume in order to permit the numerical-experimental correlation and the updating of the model. The structural natural frequencies and modes shapes where extracted from the experimental measurements up to 300Hz, but it was not possible to classify all the extracted modes since above 120 Hz the local panels dynamics is dominant over the global mode shapes and the geometric description of the global modes becomes more difficult. In order to choose the best modelling solution the numerical analysis results have been compared with those coming from experimental tests. The correlation has been carried out taking in account results of numerical and experimental modal analysis performed. The common results of modal testing is a set of modal parameters (resonance frequencies, damping and mode shapes), which characterise the linear dynamics of the structure. Different methodologies for the correlation analysis exist. 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. The following equation is used:

$$MAC(\{\psi_n\},\{\psi_e\}) = \frac{\left|\{\psi_n\}^t\{\psi_e\}\right|^2}{(\{\psi_n\}^t\{\psi_e\})(\{\psi_e\}^t\{\psi_n\})} \tag{1}$$

where $\{\psi_n\}$ and $\{\psi_e\}$ are respectively the numerical and experimental eigenvectors (mode shapes). The initial model did not well represent the dynamic behaviour of the real structure for what concerns the natural frequency parameters. Hence it was chosen to consider one “evolution” of the original model, in particular by reconsidering the stiffness of the boundary conditions. It was required to perform a “sensitivity analysis” by the mean of sensitivity coefficients. A differential sensitivity coefficient is the slope of the response Ri with respect to parameter Pj, computed at a given state of the parameter. When this differential is computed for all selected responses with respect to all selected parameters, the sensitivity matrix [S] is obtained:

$$[S] = S_{ij} = \left[\frac{dR_i}{dPj}\right] \tag{2}$$

where i: 1..N are the Responses and j: 1..M are the selected Parameters. The sensitivity analysis brought to the decision of updating the presented model by modifying the stiffness coefficient of the boundary springs. The objective of model updating is to adjust the values of selected parameters such that a reference correlation coefficient is minimized.



FEA	Hz	EMA	Hz	Diff. %	MAC
6	65.34	6	68.20	-4.20	43.1
7	67.60	4	61.94	9.15	76.0
8	69.47	7	70.29	-1.15	40.5
12	85.56	10	75.85	12.81	29.0
15	87.18	12	82.62	5.52	42.6
16	87.65	14	88.56	-1.03	45.5
19	88.57	15	91.86	-3.59	47.8
27	93.29	16	96.11	-2.94	37.7
31	96.03	13	86.04	11.61	33.4
94	132.5	24	124.25	6.67	28.6

Figure 4: Exp. and num. modal parameters: correlation results – Updated F.E. model

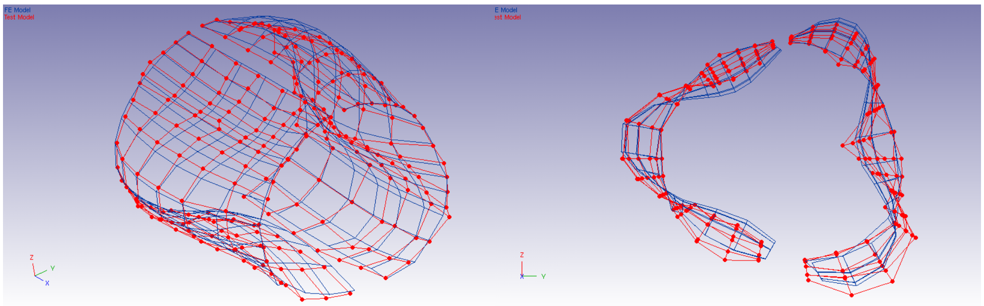


Figure 5: Mode shape pair comparison - FEA 67.6Hz - EMA 61.94Hz - MAC 76%

THE PRIMARY DISTURB FIELD DESCRIPTION

As mentioned before the research project was primary oriented to solve the problem of interior noise inside “turbofan” aircraft; for these vehicles the main noise sources come from [6]: TBL induced vibrations on the fuselage exciting the skin panels; Structure-borne sound due to vibrations originated on the engines; Local aerodynamic phenomena due to interactions between airflow and structural connections and/or specific arrangements. The last type of disturbance can introduce noise patterns characterised by some hundreds Hz frequency extension with or without a fundamental tone in the middle of the frequency band. The main concern of Alenia Aeronautica was focused on disturbances having some local aerodynamic origins and characterised by a frequency pattern concentrated in the low-medium frequency range where passive control solutions (damping and soundproofing materials) are not really effective. Alenia Aeronautica requirements were to design and test a control system devoted to attenuate a primary noise field originating at the flap channels and measured during in-flight noise measurements carried on their aircraft. The levels of sound pressure into the aircraft have been acquired during the in-flight measurements; they permitted to recognise, beyond the three well known BPFs, a so called “bump” noise (Figure 6) due to the aerodynamic effect described above, particularly the channel separating the wing from the flap. It is possible to notice the “bump” noise pattern in the frequency range between 100 and 200Hz; furthermore the same phenomenon has been observed at higher frequency bandwidths depending from the values of the trim velocity of the aircraft. It was also possible to notice how the “bump” noise pattern results correlated to a similar vibration pattern measured on the reference frame. Since no experimental measurements were available on the frame connecting fuselage and wings, the updated mock-up F.E. structural model described above was employed to carry on an “inverse” analysis of the acoustic-structural response inside the selected fuselage section obtaining a vibrational pattern to assign to the load in order to get as analysis results the noise and acceleration spectra measured during in-flight tests within the two frequency ranges 100-200Hz (l.f.) and 300-400Hz (h.f.). The two obtained force spectra represented the vibration fields generating the two chosen primary noise field that it was decided to control.

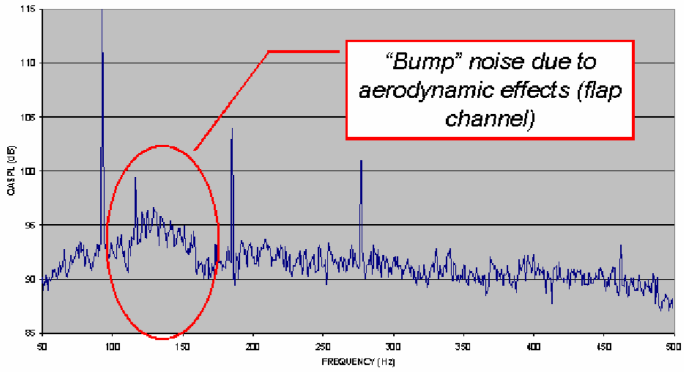


Figure 6: Typical external noise spectrum

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.

$$J = \sum_{n=1}^{N} \left| w_n(w) \right|^2 = \underline{w^H} \cdot \underline{w} \qquad (3)$$

The previous formula reports the cost function J, where w_n 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:

$$\underline{w} = \underline{w_p} + \underline{\underline{R}}\,\underline{F_s} \qquad (4)$$

where w_p is the vector of the complex response due to the primary field; the $\underline{\underline{R}}\,\underline{F_S}$ product defines the complex response vector due to the contribution of M secondary forces. Finally, if the number of control points (N) is bigger than the number (M) of the force sources, the optimum control force vector $\underline{F_S}$ is reported in the following equation [8]:

$$\underline{F_S} = -(\underline{\underline{R}}^H \underline{\underline{R}})^{-1} \underline{\underline{R}}^H \underline{w_p} \qquad (5)$$

Employing this approach is possible, then, to evaluate the maximum "response reduction" in the selected control points corresponding to a fixed primary disturb field and actuators positions configuration. Furthermore to each configuration it will be associated the complex force spectra required to each actuator in order to reproduce the "controlled response level".

OPTIMAL CONTROL ACTUATORS PLACEMENT EMPLOYING 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: it is well known that they represent a quite fast, not deterministic approach for selection among many possible solutions of a problem whose effectiveness can be measured by a "score" [9]. 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. The number of possible actuators location defines the "genetic code" that is therefore represented by the integer numbers range between 1 and 126; each actuator represent a gene and each chromosome is a combination of a fixed number of genes. The number of genes constituting a chromosome represents the number of control actuators we want to employ in our system. The score chosen for the scopes of this work has been defined as:

$$Score = \frac{1}{\left| \{p\}^T \{p\} \right|} \tag{6}$$

where {p} represents the vector of the controlled interior noise field in the selected control points. The vector {p} is obtained as combination of noise disturb field (primary field) and noise field produced by the control actuators:

$$\{p\} = \{p_p\} + [P]\{F_S\} \tag{7}$$

where [P] is the pressure transfer function matrix obtained as mentioned in the previous chapter and $\{F_S\}$ are the optimal control forces evaluated using the pseudo-inverse approach for the selected chromosome. The values of control forces vector $\{F_S\}$ are obtained by employing the eq. (5); within that formulation the matrix $\underline{\underline{R}}$ will be represented by the acceleration or noise Frequency Response Function evaluated in the selected structural or acoustic nodes respectively if an ASAC or ANC approach has been selected. As mentioned above the performance indicator employed as the genetic algorithms score maintains the same formulation whatever control approach has been chosen, since the final goal remains the reduction of interior noise. Following are presented the results obtained considering as primary disturb the one described above. For each disturb field 30 and 50 control actuators configurations have been investigated to be selected among the 126 locations considered within the two middle bays of the mock-up. The ASAC approach has been employed and a final comparison between the best obtainable results employing ASAC and ANC approach has been carried out. Following the main results related to the 30 control actuators configuration are reported since no main advantages in terms of interior noise reduction have been found employing 50 actuators.

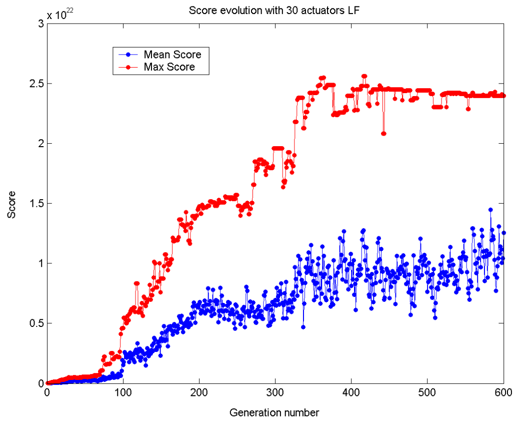


Figure 7: "Score" for ASAC approach – low frequency disturb force field

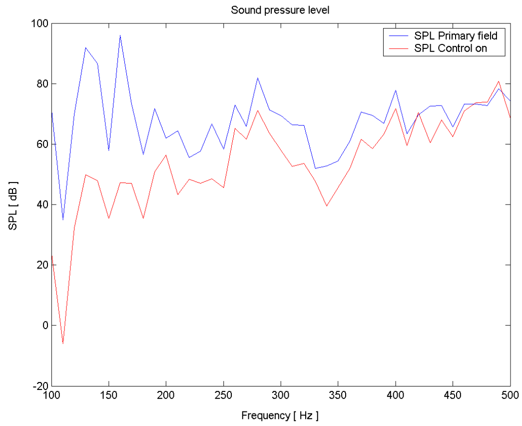


Figure 8: Mean interior noise reduction for the optimal actuators configuration – l. f. disturb force field

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. A very important parameter representing one of the main targets that the authors had to meet was the maximum control force value required from the actuators: this parameter represent in fact a key point of the design of the actuators that will be developed within the MESEMA consortium. Next figure present these 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.

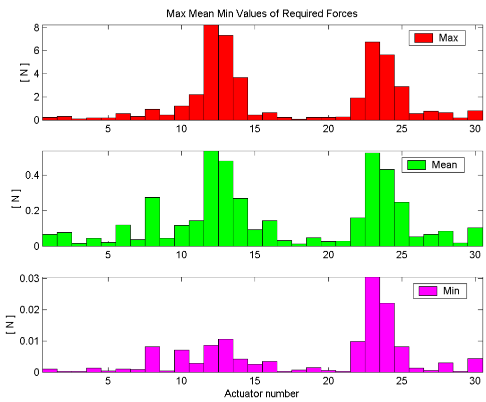


Figure 9: Required control force values for the control actuators in their optimal configuration

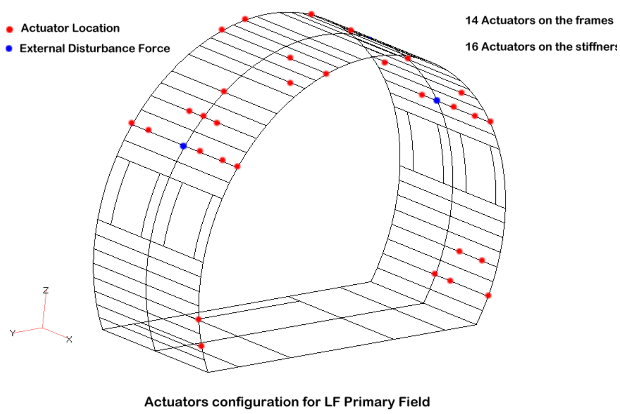


Figure 10: Optimal actuators placement configuration – low frequency disturb force field

CONCLUSIONS

The paper has presented the main results obtained by the authors simulating an active interior noise control system by the mean of a validated F.E. model and genetic algorithms for investigating the best control actuators placement, their requirements in terms of control forces and the best control strategy. The simulations have been carried out for two primary disturb fields characterised by lower and higher noise frequency spectra related to a typical aerodynamic noise source at different aircraft flight speeds. Results of the simulation activity permitted to fix the number of required actuators (30 instead of the original number of 50) in order to achieve the best theoretical performances reducing the overall system weight. Furthermore the optimal placement configurations were investigated associated to the control force values; it was demonstrated that reducing the number of actuators did not affect negatively their required performances that remained almost unmodified. Many of these results were expected, since they are strictly related to the patterns of noise and vibration fields within cylindrical structural as far as to their characteristics wavelength, but the presented study permitted to quantify the control parameters based on the availability of a reliable numerical model.

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