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DEVELOPMENT AND APPLICATIONS OF A VIRTUAL HYBRID PLATFORM FOR MULTISCALE ANALYSIS OF ADVANCED STRUCTURES OF AIRCRAFT (DEVISU)

E. Carrera[1], U. Galvanetto[6], S. De Rosa[2], P. Gardonio[3], A. Milazzo[4],
R. Vescovini[5], M. Zaccariotto[6]

[1]Department of Mechanical and Aerospace Engineering, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

[2]Department of Industrial Engineering - Aerospace Section, Università degli Studi di Napoli "Federico II", via Claudio 21, 80125 Napoli, Italy

[3]Polytechnic Department of Engineering and Architecture, University of Udine, via delle Scienze, 208, 33100 Udine, Italy

[4]Department of Engineering, Università degli Studi di Palermo, Viale delle Scienze, bldg 8, 90128 Palermo, Italy

[5]Department of Aerospace Engineering , Politecnico di Milano, Via La Masa, 34
20156 Milano, Italy

[6]Department of Industrial Engineering, University of Padova, v. Venezia 1, Padova 35131, Italy

Abstract

This paper outlines the main findings of the project “DEvelopment and applications of a VIrtual hybrid platform for multiscale analysis of advanced StructUres of aircraft” (DEVISU), which deals with failure of composite structures and noise/vibration reduction, along with investigation of new materials for aerospace applications.

Keywords: Aircraft structures, Composites, Failure, Optimization, vibro-acoustic control.

1. Introduction

Damage tolerance in design of metallic structures and aeroelastic control of aircraft are among the most significant accomplishments in the aerospace technology. These two fundamental achievements were due mostly to the work of eminent scientists and engineers whose work has led to the development of multidisciplinary tools and knowledge to control failure of structures (i.e., fatigue behavior, progressive crack growth, non-destructive testing, residual stress evaluation, etc.), and to optimize flying conditions of aircraft (aeroelasticity, loading evaluation/alleviation, and active controls, among the others). Today, we are in a comparable paradigm for a few other and new problems as demonstrated by current trends in research and resource drivers. Modern innovative airplanes are mostly made in composite materials. Safety, comfort and cost-effectiveness are the critical success factors of these airplanes.

The project “DEvelopment and applications of a VIrtual hybrid platform for multiscale analysis of advanced StructUres of aircraft” (DEVISU), supported by the Ministero dell’Istruzione, dell’Università e della Ricerca research funding programme PRIN 2017 (2017ZX9X4K), ambitiously aims at setting new methodologies and design tools to address failure of composite structures and noise/vibration reduction, along with investigation of new materials for aerospace applications. DEVISU will result into an integrated multi-disciplinary (structure mechanics, acoustics, control), multi-fidelity (classical and nonlocal mechanics, advanced theories of structures), multi-scale (from micro-mechanics to global/local analysis of complex structural assemblies) and hybrid approach together with its software tool implementation for the reliable, efficient and computationally effective simulation of aircraft structures.

The focal point of DEVISU will be the development of a hybrid surrogate platform based on advanced theories and this paper collects the main developments from the partners on relevant and different research topics, such as i) advanced structural theories for , ii) meshless methods, iii) non classical mechanics and iv) sensing and control, in view to improve the safety and comfort of aircraft.

2. Multi-scale materials modelling

2.1 Coupled VEM-BEM modelling

The activities described in this section focused on the development of computational tools for micro- and multi-scale analysis of composite and polycrystalline materials, with attention to the initiation and evolution of damage at the micro-scale.

A novel hybrid formulation, based on the conjoined use of the emerging virtual element method (VEM) and the boundary element method (BEM), has been proposed, developed, implemented and tested in [1,2,3], for the effective computational analysis of multi-phase materials, representative of heterogeneous materials such as composite or polycrystalline materials, see Fig.1. VEM can be seen as a generalisation of the finite element method (FEM) and it allows the straightforward employment of elements of general polygonal shape, maintaining a high level of accuracy. For its inherent features, it allows the use of meshes of general topology, including non-convex elements; on the other hand, BEM is nowadays an established technique for the numerical solution of boundary and/or initial value problems that may be formulated in terms of boundary integral equations, employed as the original model of the represented physical problem.

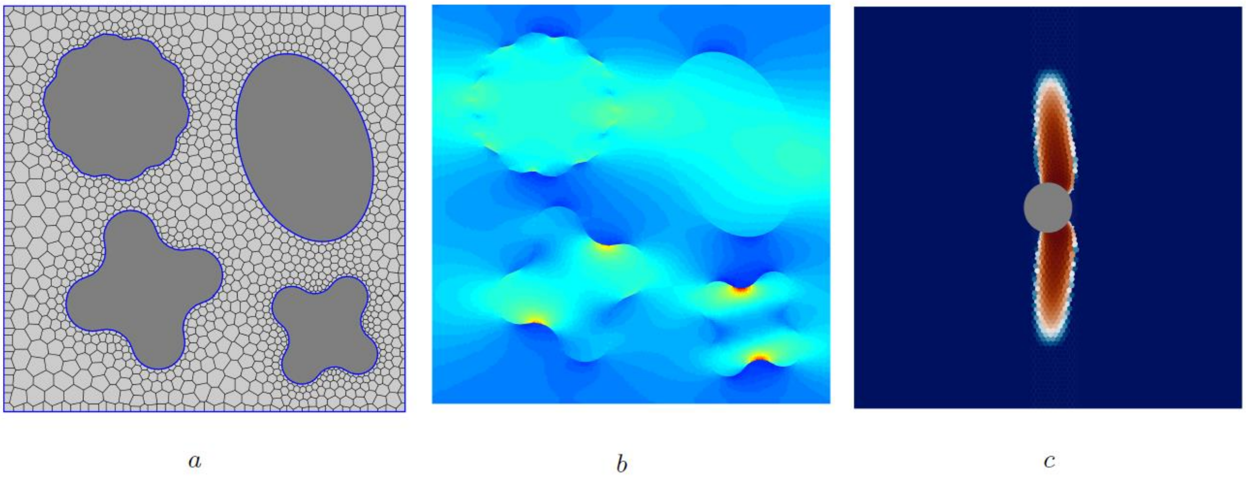


Figure 1 – The hybrid VE-BE technique addresses the analysis of heterogeneous materials domains inheriting the benefits of both VEM and BEM.

In [1, 2, 3], the inherent advantages of VEM and BEM are simultaneously employed for the study of heterogeneous material micro-structures. The method has been applied to the elastic analysis and computational homogenization of fibre-reinforced composite materials and to the analysis of composite unit cells exhibiting matrix isotropic damage. The presented results confirm how the developed technique inherits the generality of VEM and the modelling simplification and accuracy of BEM, ensuring high accuracy and fast convergence and providing a versatile tool for the analysis of multi-phase materials, also including non-linear behavior such as material degradation.

2.2 Coupled FE-Peridynamic models for crack propagation

Crack propagation in structural materials is one of the most common problems in aeronautical applications where cracks are closely monitored on the field. The accurate modelling of damage and fracture phenomena is still an open issue. Approaches based on classical continuum mechanics (CCM) have limitations because they require the use of the partial derivatives of displacement throughout the problem domain, which are difficult to define in the presence of discontinuities. Peridynamics (PD) [4] is a non-local continuum theory able to model discontinuities in the displacement field, such as crack initiation and propagation in solid bodies. Unfortunately, the PD-based methods are not computationally efficient, due to the nonlocal nature of the approach. To reduce the computational cost, it is therefore convenient to divide the problem domain into two zones:

PD-based methods are used only around cracks or in regions where cracks are likely to develop or propagate, and CCM-based methods elsewhere. In the framework of the DEVISU project, methodologies were developed to couple advanced CCM theories of structures, such as one-dimensional high-order finite elements based on the Carrera Unified Formulation (CUF), and Peridynamics, thus obtaining models that make it possible to study components of 3D geometry in which crack propagation phenomena occur [5], see Fig. 2.

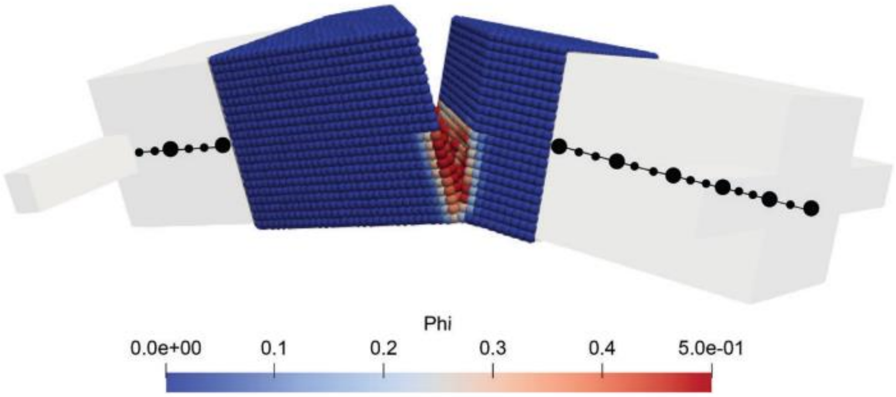


Figure 2 – Coupled CUF-PD model.

Furthermore, the PD formulation has been enriched to simulate the fatigue damage of materials considering high cycle fatigue crack propagation. In the adopted model, the damage status of the material is defined based on a static damage component and a fatigue damage component. Fig. 3 shows the results of a fatigue compact tension test [6] simulated by using the proposed approach. The model provides very good results (compared to experimental data) in terms of both crack path and crack length as the number of cycles increases.

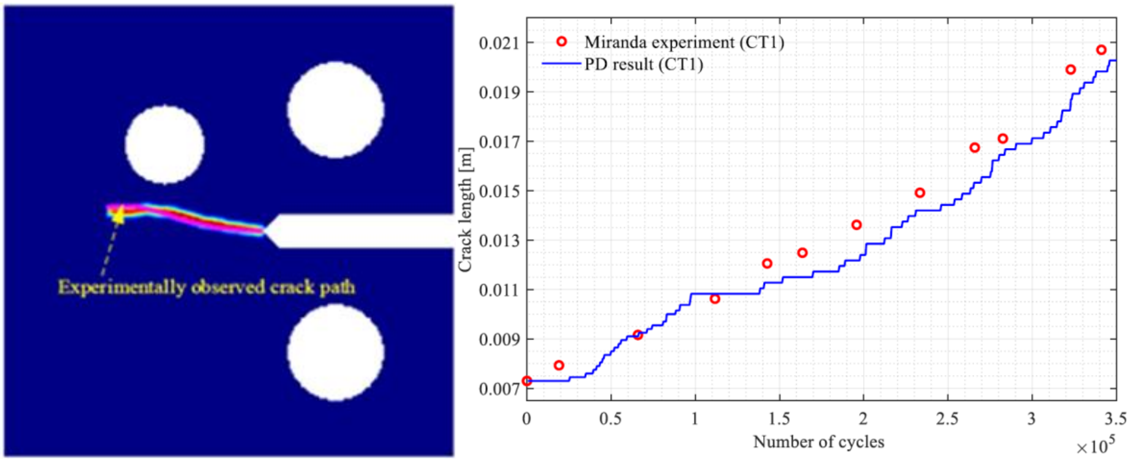


Figure 3 – left: compact tension test model, simulated and experimentally observed crack path are shown; right: experimental data and simulation results of crack length vs. number of cycles.

3. Metamodelling optimization strategy

Given the material and structural models of the previous section, a novel metamodeling technique has been developed for the analysis and optimization of lightweight composite structures.

The method relies upon the use of Physics-Informed Neural Networks (PINN) in combination with Extreme Learning Machine (ELM). On one hand, PINNs allow Neural Networks (NN) to be enriched through the available mathematical models of the structure; this is particularly beneficial as the amount of data for training, commonly relying upon costly experiments or numerical simulations, can be drastically reduced. On the other hand, ELM is a powerful learning algorithm characterized by improved computational time for training. As compared to commonly used Gradient-based Learning (GBL) algorithms, ELM allows the training process to be performed in a single step by solving a least-square problem. This feature leads to fast and effective training of the network, with a required time several orders of magnitudes smaller than traditional approaches.

Another new feature of the proposed technique consists in the application of a domain decomposition strategy, as a powerful mean to study assemblies of plate- and shell-like elements, as typical for aerospace thin-walled structures.

An overview of the procedure is presented in Fig. 4, where a description of the logical steps is provided. A single hidden layer NN is considered, where the internal parameters are initialized randomly. The evaluation of the network parameters is conducted by solving a least-square problem, obtained by accounting for the structural model and numerical simulation available.

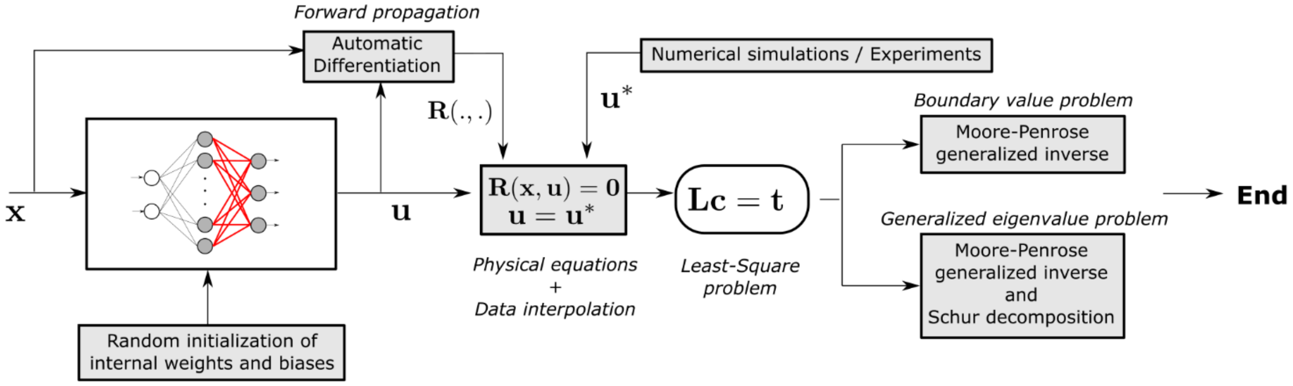


Figure 4 – Overview of the optimization procedure.

The framework has been successfully applied for the analysis of different kind of structures. Specifically, the static, buckling and free vibration analysis of a composite plate with cutout is presented in Fig. 5.

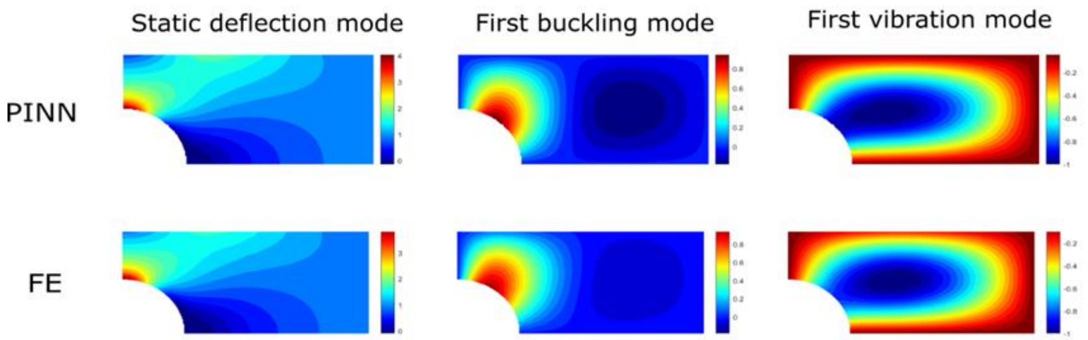


Figure 5 – Static, buckling, and free vibration analysis of a composite plate with cutout.

4. Vibration and Acoustics

4.1 Vibration band gaps by Finite Element Analysis

Periodic structures have found a big interest in engineering application because they introduce frequency band effects due to the impedance mismatch generated by periodic discontinuities in the geometry, material, or boundary conditions. Adding periodicity to structures leads to wave mode interaction, which generates pass- and stop-bands. The frequencies at which stop-bands occur are related to the periodic nature of the structure. Numerical studies on different beams are done to compare band gaps position at different periodic sequences. First, a FE model of a beam has been developed to predict the frequency range in which band gaps. Periodicity effects can be realized in several ways: by geometric impedance, material impedance, etc..

4.1.1 Geometric impedance

For finite structures, vibrations levels are calculated by the frequency response function (FRF) [7,8].

A first study is carried out on 1D beams of fixed length L=1.2 m and made of aluminum (E=73 GPa, ν=0.33, ρ=2700 kg/m³). The base structure is divided in 12 cells of equal length, each cell is modelled on finite element (FE) in 3 beams element. To obtain the normalized response, the entire structure is loaded with a flexural load on extreme point of 1N. To consider the physics of the problem, a 1% damping is also considered. No constraints have been placed on the structure which therefore has free-free boundary conditions. To compare the answer between the various analyses a constant mass of 5 kg is set for each beam and the height of the individual cells is obtained. The solution is evaluated considering the mean energy value in dB that pass thought the structures. The reference case has cells of equal height. The first periodic structure analyzed is that with two periodic cells: A, B. The unit cells, that are repeated all over the structures are: AB and BA. Two different cases of their height's ratio h_a/h_b are considered to analyze the effects of the impedance on bandgaps: case 1 with h_a/h_b =2.6 and case 2 with h_a/h_b =1.6.

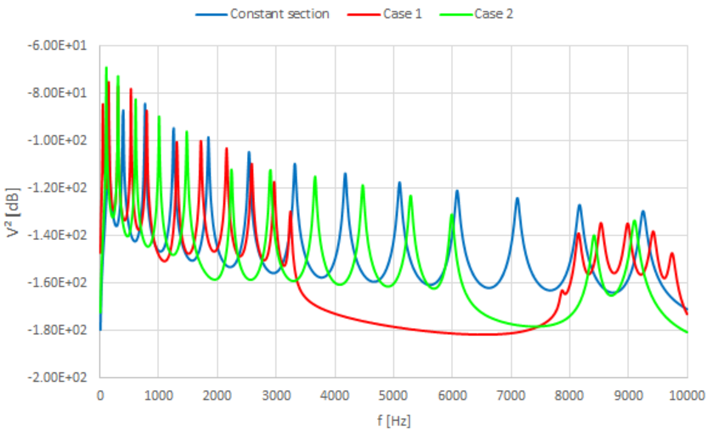


Figure 6 – Mean value of the squares of velocities (AB cells).

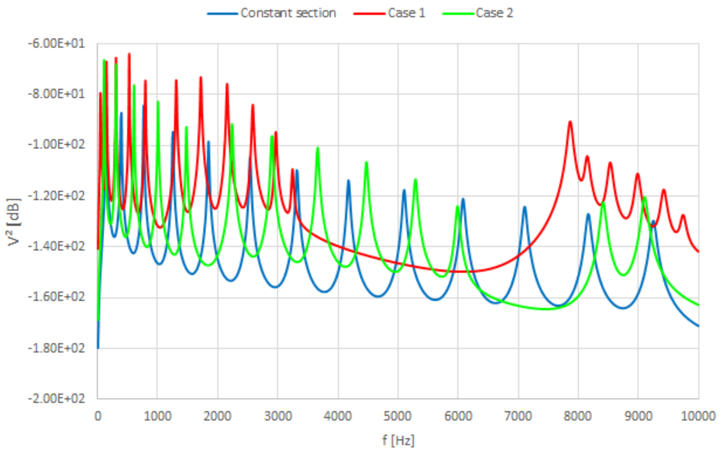


Figure 7 – Mean value of the squares of velocities (BA cells).

As expected, the higher is the impedance mismatch, the higher is the frequency range in which the bandgap appears. In AB sequence (Figure 6), the bandgap is in the same frequency range of the BA one (Figure 7), the only difference being the lower energy level, because the load is applied on B cell. This allows more energy to enter in the structure.

4.1.2 Material impedance

Impedance mismatch generated by material is now analyzed: aluminum (cell A) and steel (cell B, E=210 GPa, ν=0.26, ρ=7800 kg/m³) are chosen.

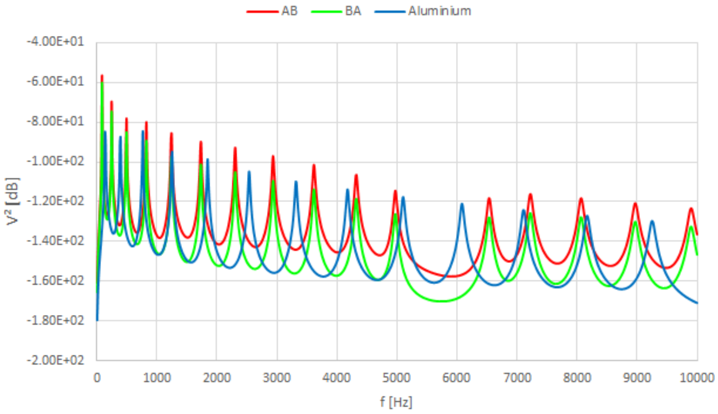


Figure 8 – Mean value of the squares of velocities (material impedance effect).

No extended bandgaps are generated, and only one between 5000-6000 Hz is visible (Figure 8). As expected, loading the aluminum cell, more energy enters through the system.

4.2 Vibration band gaps by unit cell approach

The advantage of dealing with periodic configurations is that it is possible to study the base cell by applying the periodic boundary conditions, thus reducing computational costs. A one-dimensional base cell is considered, and the dispersion curves are obtained. A study is then carried out with the COMSOL software. The results are compared with those obtained with the Carrera Unified Formulation (CUF) method [9]. The reference wave guide is shown in Fig. 9 along with the proposed analyses.

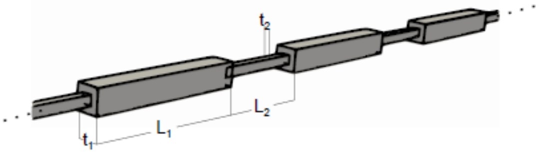
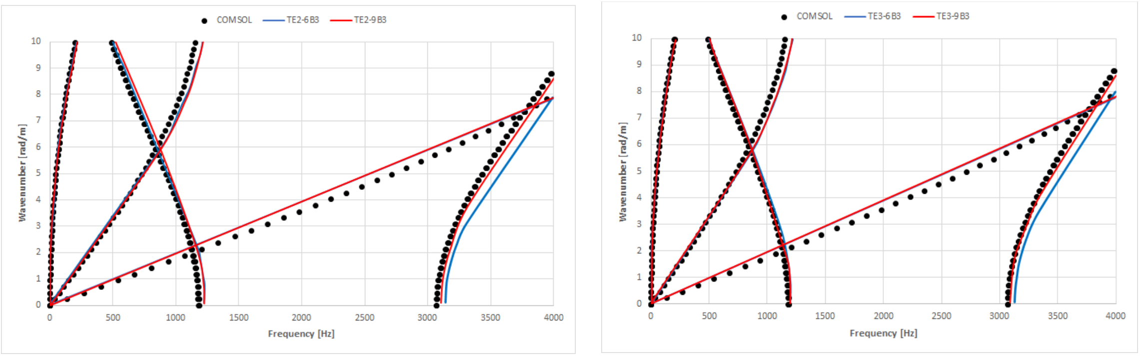


Figure 9 – Multi-section wave guide and dispersion curves.

The geometric characteristics are: L_1=0.17 m, L_2=0.1 m, t_1=0.025 m and t_2=0.01 m. Material characteristics are: Young modulus E=210 GPa, Poisson ratio ν=0.30, density ρ=7850 kg/m³. For the first analysis, the unit cell is discretized in three Lagrangian elements considering a first case with 3 nodes for each portion of segment, and a second case with 4 nodes. The second analysis is made with the software COMSOL and the geometry is discretized with 373 triangular and tetrahedral elements. Periodic boundary conditions of Floquet-Bloch are applied [10,11].



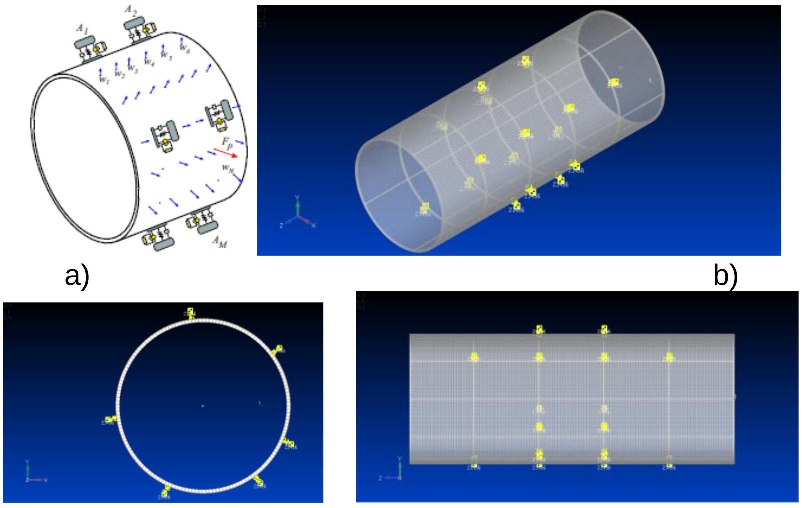
a) b)

Figure 10 – Dispersion curves (COMSOL and TE2 - TE3).

Figures 10 a and b show the results of the dispersion curves. About CUF method, the solutions are indicated with the acronym TEN, where N is the polynomial order. Instead, the notations 6B3 and 9B3 indicate respectively the case with 3 and 4 nodes for each portion of segment. The numerical results show that two stopbands are generated. These are 210-480 Hz and 1200-3090 Hz. Both theories predict approximately the same position and length of the stopbands and as the degree of the polynomial increases, the solutions tend to overlap with those obtained with COMSOL analysis.

4.3 Electro-mechanical Tuneable Vibration Absorbers

This section presents a simulation study on the flexural vibration control of a stiffened cylinder, simulating an aircraft fuselage section, equipped with electro-mechanical tunable vibration absorbers (EM-TVA). The study considers a scaled model of a 5 bays real fuselage section, which encompasses the axial longerons-stringers and circular rings structures wrapped by the thin skin panels (Fig. 11). The electro-mechanical vibration absorbers are formed by a coil-magnet seismic transducer connected to a tunable resistive-inductive shunt, which is used to set the natural frequency and damping ratio of the fundamental axial mode. The control of both tonal and broad-band disturbances is investigated.



a) b)

c) d)

Figure 11 – (a) Schematic model of the fuselage scaled model with EM-TVAs and (b-d) different view of Finite Element model of the fuselage equipped with EM-TVAs.

The study reveals that to guarantee a global control of the flexural vibration of the fuselage structure, the electro-mechanical tunable vibration absorbers should actually be slightly detuned from the structure tonal excitation frequency or from the target resonance frequency of the structure exposed to a broad-band excitation frequency (Fig. 12). Furthermore, in view to guarantee the electro-mechanical tunable vibration absorber works in the typical low frequency range of interest for aircraft fuselage structures, the shunt should encompass a negative resistance and, eventually, a negative inductor too to be effective at low frequencies.

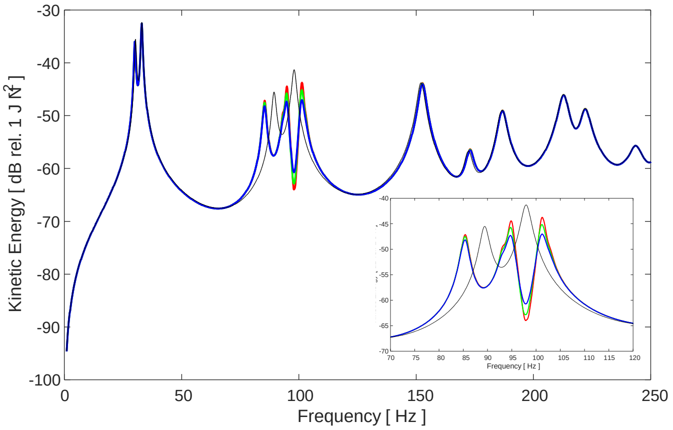


Figure 12 – Spectra of the time-averaged flexural kinetic energy of the fuselage with the EM-TVAs set to control a tonal disturbance at 90 Hz and to control the resonant response of the mode resonating at 90 Hz to a stochastic excitation.

5. Conclusions

This paper has briefly discussed the main outcomes of the project DEVISU, which has introduced innovative models for aircraft materials and structures. These models have been verified to be effective for solving several problems, including structure optimization and acoustic emission control.

6. Contact Author Email Address

Mailto: erasmo.carrera@polito.it

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