LATTICE COMPOSITE STRUCTURE DEVELOPMENT FOR SMALL AIRCRAFT; WASIS

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Abstract

An introduction to the EU funded research project WASIS (Wafer design Approach for Safety Increasing in worst case Situations and joints minimizing) is given in this paper, including work performed and results obtained by the whole project consortium. Development of a wafer like structure designed as a fiber reinforced lattice composite is accomplished, aiming to replace a conventional metallic fuselage section of a small airplane with an alternative Carbon Fiber Reinforced Plastic (CFRP). WASIS project aims to achieve the challenge of "More Affordable, Safer, Cleaner and Quieter" aircrafts, developing a composite fuselage structure based on the lattice stiffening concept and optimizing geometrical and mass properties of transition zones of fuselage structural joints. Main project activities covered the full scale fuselage section design based on downscaled prototypes, as well as setting up manufacturing processes for two alternative methods; filament winding and tape placement. Analytical and numerical calculations guide the development process, and are validated through dedicated tests before leading to the final fuselage section design. Besides low weight and automatic manufacturing aspects, safety is a main concern during design, accounting for composite structure performance under several impact load cases. Special attention is given to vibroacoustic performance of test panels and fuselage section, with a dedicated study to virtually assess the acoustic field inside the composite fuselage section under operational conditions.

1. Introduction

The EU funded research project WASIS (Wafer design Approach for Safety Increasing in worst case Situations and joints minimizing) is presented in this paper, covering the work performed by the whole project consortium. WASIS project aims to achieve the challenge of "More Affordable, Safer, Cleaner and Quieter" aircrafts, developing a composite fuselage structure based on the lattice stiffening concept and optimizing geometrical and mass properties of transition zones of fuselage structural joints. After an introduction of the components that are designed and manufactured, a more detailed study of the vibro-acoustic

performance of composite parts including the development of a Statistical Energy Analysis model is covered.

Figure 1. Piaggio Aero P-180. Avanti aircraft with WASIS lattice fuselage section superposed

2. Panel and Fuselage section design

2.1. Test panels design

According to the standard procedure followed in new structures development, test specifications have to be accurately defined before structure design and manufacturing. That is why final parameters of wafer barrel have to be grounded on results of sub-components testing. Before attempting to manufacture the wafer fuselage section, test panels representative of a fuselage part were designed to clarify some structure and manufacturing requirements. Typical representative sub-component for cylindrical fuselage section is panel as a part of full-scale and small-scale barrels with and without opening (illuminator, lid etc) having the same load-carrying structure and radius as real barrel. Therefore possible variants of testing panels' load-carrying schemes and dimensions were developed. Test panel's wafer structure and ribs cross-section geometry within this "working area" correspond completely to the wafer fuselage section design (26º/90º). Two test panel configurations were addressed:

- Regular wafer panel, used to account for generation of wafer structure during the manufacturing stage and test panel joining with specific jig, so that it can be fixed to the test machine grips (reels number and position)

- Wafer panel with opening. Opening configuration and dimensions were selected to ensure optimal loads transfer and distribution within the panel, and continuous generation of lattice structure and opening reinforcing frame.

To ensure test panel manufacturability at ribs intersection, details of fibers intersection at ribs were defined including fillet radii.

2.1. Fuselage section design

From initial wafer design results obtained with analytical models, specific aspects of the wafer structure design were addressed. In particular deep wafer fuselage section analysis including ribs/reels quantity, winding scheme and ribs geometry. Due to budget limitation, instead of manufacturing a full scale fuselage section of 1.8m in diameter and 2m length

(corresponding to the P-180 aircraft), design and manufacturing tasks of the wafer structure are being carried out at two scaled down levels:

- Small prototype design (0.5m diameter): Based on the developed requirements and similarity criteria small-scaled prototype was designed for further wafer section study and testing as well as all possible bottlenecks in integral structure manufacturing identification.

- Large prototype design (1m diameter): Based on detailed analysis of small prototype design, manufacturing and testing, as well as taking into account results of wafer section safety assessment and corrective design measures, large-scale prototype was designed to demonstrate WASIS integral approach of fuselage section development.

As a reference, optimised metallic fuselage sections were calculated, weighting:

- Monocoque: 73.63 kg for aluminium alloy and 101.44 kg for titanium alloy.

- Semi-monocoque: 60.15 kg for aluminium alloy and 169.2 kg for titanium alloy

Thus variant of aluminium monocoque section was selected as reference prototype for further comparison because it is the lightest and more realistic. For the composite wafer structure three alternative rib winding patterns were compared, changing the number of mandrel revolutions per stroke of laying device. For those three design patterns, ribs orientation angles and ratio between layers having different orientation angles, (i.e. package stacking sequence) were taken into account. Eventually a trapezoidal cross section shape of spiral and hoop ribs was designed, and its geometrical parameters optimised. For each prototype scaled version, ribs/reels quantity, winding scheme and ribs geometry was obtained. Ribs cross-section geometry was achieved balancing between manufacturing requirements (trapeze angle is critical for wafer structure extraction from silicon mould) and uniform distribution of load, transferred from rib to reels, fixed on attachment frame. As result – ribs cross section with trapeze angle 5° was found as optimal. The final design versions before validation tests passed a final checking, using typical limitations of material ultimate strength (60% of knocking down factors) and deformations (less than 3000 microstrains maximum deformation in the 1st direction). Once the fuselage section design was closed, floor fittings for floor attachment were designed.

3. Manufactured prototypes

3.1. INEGI test panel

Upon completion of the real scale wafer-structure design based on predefined requirements, guaranteed its manufacturability and considered respective setups to different scales, INEGI proceeded with its implementation. In order to have a preliminary assessment of manufacturing difficulties, understanding and results about the match between the expected behaviour and the one resulted from tests INEGI manufactured a wafer Test Panel, which is a section of the real scale wafer-structure.
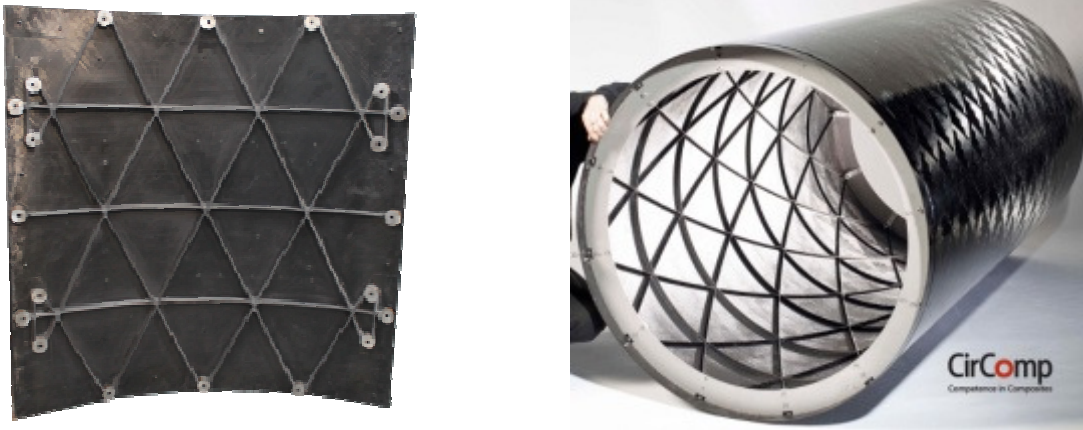
Figure 2. Test panel on the left side and fuselage section on the right hand

3.2. CIRCOMP fuselage section

The larger prototype, a demonstrator manufactured by CirComp for proving of the concept of filament winding, is a fuselage section of 1m diameter and 2m length. It includes technological advances of the project and will be used for non destructive static testing. In contrary with the test panel, fuselage section is not real scale, and will not be implemented for real use. The main purpose for being manufactured is to validate the designed technologies and the manufacturing processes with their respective toolings, and test the prototypes afterwards, including vibro-acoustic characterisation. The main work was related to the wafer section manufacturing design, specially the manufacturing process set up. Parts of the set-up of the manufacturing process had been carried out. The filament winding set up of the machine with the special tooling to integrate the common manufacturing of skin and ribs together had been performed.

4. Development of fuselage section vibroacoustic model

Composite structures represent today a valid alternative to conventional metal airframe architecture thanks to both the high stiffness to weight ratio and to manufacturing advantages in terms of parts saving. Unfortunately, despite these known benefits, its application could be limited due to drawbacks related to the poor vibro-acoustic performances. Indeed, it is known that high stiffness and low weight of such structures could result in supersonic propagation of bending and shear waves at low frequencies and high frequencies, respectively, finally resulting in a severe decrease in transmission loss properties. So far, although much research has been performed on the conventional composite fuselage to reduce the interior noise level of the cabin, it is very rare to find a scientific literature referred to composite fuselage with geodesic stiffening approach. Then, on the basis of these considerations a deeper investigation on vibro-acoustic performances of such fuselage design approach will be conducted and then compared with conventional metal architecture based on aluminum skins and frames stiffening. Thus the aim of this comparative study is to gain understanding on the vibro acoustic performance of composite fuselage with lattice structural architecture with respect to conventional metal airframe with frame stiffening as that adopted by Piaggio P.180 business aircraft. To reach this goal both numerical and experimental activities were accomplished. The dynamic performance of a structure is primarily determined by its weight, bending stiffness and loss factors. The acoustic properties like sound radiation ratio and sound

transmission loss are determined by the dynamic properties and dimensions of the structure. For the validation of any theoretical model for the prediction of the acoustic properties of a structure all its basic dynamic properties must be known. Once these parameters have been determined through experimental measurements any theoretical model predicting the acoustic properties of more complicated structures can be validated. On these premises, at first a method to model composite wafer structures with the Statistical Energy Analysis (SEA) method was developed and validated through correlation with experimental measurements carried out both on a single test article of a composite wafer panel and then on a composite wafer fuselage section. Besides, two full scale SEA models based on the fuselage section of a P.180 aircraft were developed aiming to characterize its vibro acoustics behavior. In particular, the former numerical test rig represents a conventional metal structure with frame stiffening while the latter is a full scale, structurally equivalent, composite fuselage with lattice stiffening. Finally, a conclusive assessment, highlighting advantages and disadvantages of each design approach is presented. Next a detailed description of numerical and experimental activities is described.

4.1. Model development

Both a Finite Element and a SEA models of wafer stiffened curved test panel have been developed to simulate its behavior over the full frequency range of interest in the ESI VAone simulation environment for vibro-acoustic analysis and design. At first, the right modeling approach has been verified through numerical comparison against results of another refined FE model developed in NASTRAN and then the Hybrid FE-SEA models validated through correlation with experimental outcomes of laboratory tests for dynamic characterization carried out on the test panel at CIDAUT facilities. For that purpose, basic design parameters were extracted from Catia drawings of the wafer test panel in order to develop the refined FE model which consisted of 34530 degrees of freedom. The skin of the panel was modelled in the commercially available program Patran with 2-dimensional CQUAD4 elements, whereas the rib configuration was modelled with 1-dimensional CBAR elements. Meshing was considered in a way as to efficiently capture the wavelength of the highest frequency of investigation in our structure. Material properties were drawn from laboratory measurements carried out on test specimens and used to feed MAT8 and PCOMP cards. Next step, was the creation of a FE model with smeared properties through the NASTRAN equivalent process.
The new equivalent FE model was characterized by rib properties introduced as an isotropic material and PSHELL with equivalent bending, membrane, coupling and transverse shear stiffness for simulating the two ply configuration of the skin. This step was necessary to import the model in VA One. Finally, the check of modal behaviors between refined and equivalent FE models resulted to match well.
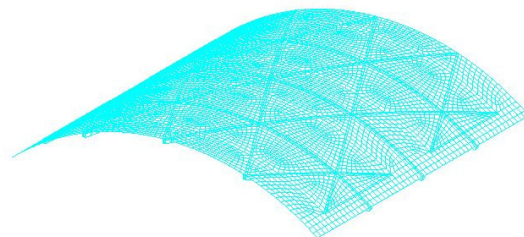

Figure 3. FE model of the lattice configuration panel

A SEA model was later developed with 42 SEA "composite plates" of "orthotropic material", joined together with 17 SEA isotropic "beam" subsystems having the same properties as equivalent FE NASTRAN model.
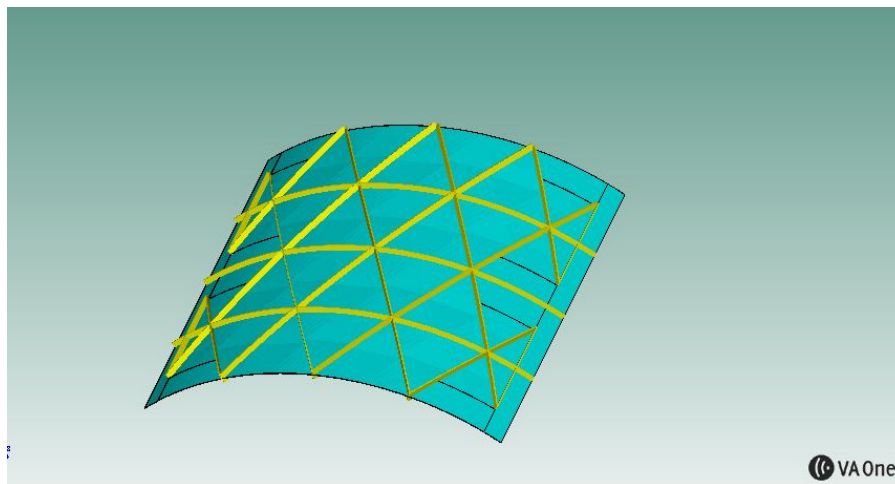

Figure 4. SEA model of the lattice configuration panel

4.1. Vibroacoustic characterisation tests

Vibro Acoustic characterization of the composite panel. The composite wafer panel developed and manufactured previously in WASIS was tested. Experiments on that panel included modal analysis aimed to identify resonance frequencies, modal shapes, structural damping loss factor and bending stiffness of the structure. In addition a number of frequency response functions (FRFs) were determined. Panels manufactured by the consortium corresponds to two different manufacturing methods, the one from INEGI is manufactured with filament winding while the one from IVW was made with automatic tape placement. The one from INEGI was selected for the study because the manufacturing method is shared between both panel and fuselage section. The panel study started with frequency response functions (FRF) in order to identify first natural frequencies of the panel corresponding to its modes of resonance and what the modal density of the panel is. According to the dimensions of the panel, its stiffness and weight, it was highly probable that its first resonances were at higher frequencies than its equivalent metallic counterpart. The composite panel FRF consisted of 5 excitation points and 8 measurement points. The panel was hanged with elastic ropes to reproduce free boundary conditions. The structure was excited by an impact hammer in 5 points and the response was registered with accelerometers and a laser vibrometer, being the 8 measurement points evenly distributed over the sample surface. After that the panel radiation properties where characterized through the panel radiation factor. In this test the panel, still with free boundary conditions, was excited by a shaker. In order to represent the actual use conditions, i.e. excitation equivalent to flight loads, loads were introduced through the external surface (corresponding to the shell, namely, the airplane external side) and the emitted noise was measured in the inner side (where the lattice structure is facing the interior of the airplane). To calculate the radiation factor the sound power and the vibration energy of panel were measured. Eventually the last test on the INEGI panel is the measurement of its transmission loss (TL). Depending on the modal behavior of the panel, two alternatives were proposed: (1) if first panel resonance is found at "high" frequency, the TL is measured between a small reverberant chamber (loading the panel with a diffuse sound field on one side) and an hemi-anechoic chamber (to allow sound radiation in free field conditions on the opposite side). Figure 5 shows the small reverberant chamber used to measure TL.

Figure 5. Small reverberant chamber used for composite panel transmission loss characterisation.

To measure TL with this facility a grid of microphones on the receiver side is set up, with which sound power radiated by the panel is calculated, while emitted sound power inside the small reverberant chamber is measured as well. (2) if the panel vibration behavior shows that the aforementioned hypothesis is not correct, TL is measured between a larger reverberant room and the hemi-anechoic chamber. Figure 6 shows the facility proposed to measure TL between an hemi-anechoic chamber and a diffuse chamber.
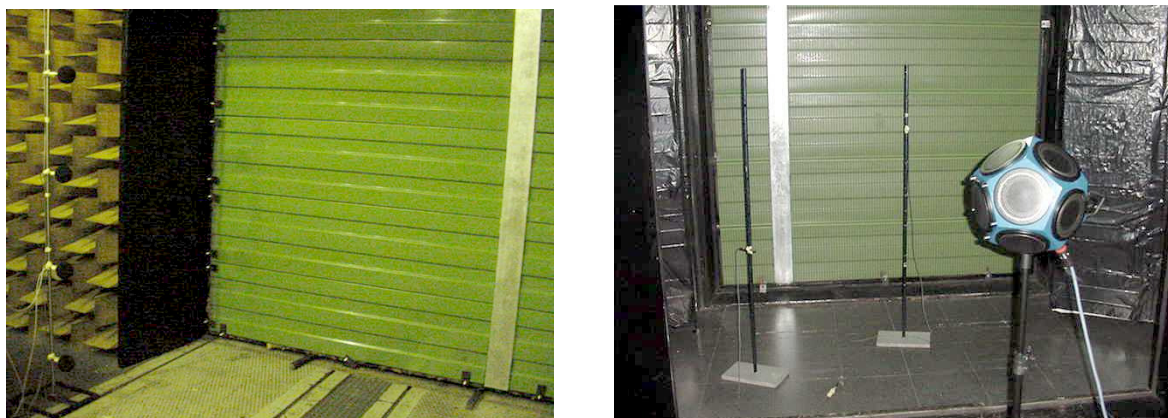

Figure 6. In the left side, we can see an specimen (not the composite panel) in the test window, as seen from the hemi-anechoic side together with a grid of microphones. In the right side the diffuse chamber.

TL is tested in two configurations, changing the receiver and emitting surfaces, in order to investigate whether the transmission properties of the sample are symmetrical or not. The aim of this study is to investigate which configuration is more convenient for the equivalent characterisation of the barrel. If the composite panel behaves equally in terms of sound transmission regardless the receiver and emitter side, then the preferred set up to characterise the transmission of sound performance of the composite barrel is to create a reverberant field outside and measure the transmitted sound inside. Otherwise it is the opposite

Vibro Acoustic characterization of the Wafer Fuselage barrel. The half scale composite fuselage barrel with wafer stiffening manufactured in WASIS was hanged through its metallic attachment frame with suitable suspenders in the hemi-anechoic chamber to simulate free boundary conditions, in a similar fashion as it was done with the composite panel. Two suitable wooden caps were manufactured to create a closed volume with the purpose of allowing acoustic loading and measurements. In order to characterize the vibro acoustic behavior of this component, its main acoustic properties like sound transmission loss, sound radiation ratio and loss factor are determined. In addition a number of FRFs are measured while the fuselage barrel is acoustically excited with loudspeakers and mechanically with shakers. The component dynamic response is measured with microphones and accelerometers, then recorded signals are analyzed to provide baseline for correlation with numerical outcomes. Thus tests on the fuselage section start with FRFs, in which the same setup as the one described for the panel tests is used. Then the fuselage section radiation performance is characterised. In this case, adding a couple of wooden caps, a closed volume is obtained inside the barrel cavity. Then we assume the hypothesis that this interior cavity behaves as a reverberant chamber, which is necessary to calculate the barrel radiation coefficient. After that the fuselage section TL is measured. As explained before, depending on the results of the sound transmission in the panel, two alternative set ups were foreseen. If the panel behaves equally in terms of sound transmission from both sides, then the TL test is done introducing an acoustic source in the barrel cavity and measuring the sound power outside. This test is carried out in the hemi-anechoic chamber. But if the sound transmission is found to be different depending on the emitter and receiver sides, the best way to simulate the real loading condition is to reproduce a diffuse sound field outside the barrel. In doing so the test is carried out in a reverberant chamber, and the sound transmitted to the interior is measured.

5. Conclusions

An introduction to the design and manufacturing process carried out in the WASIS project for composite parts for aeronautic application is shown. Apart from the mechanical performance, a study is presented to characterize the vibro-acoustic performance of such components.

6. Acknowledgments