RIBES

Radial basis functions at fluid Interface Boundaries to Envelope flow results for advanced Structural analysis

State of the art – Background

The high level of maturity of HPC architectures and simulation tools in several physical fields (fluids, structures, electromagnetism...) allows to reliably and accurately model several behaviours of complex systems using large numerical domains in a multi-disciplinary environments. Several challenges are, however, still open. Multi-physics analyses often require the synchronization of different meshes, i.e. to update each mesh so that the current geometry of the system is properly represented. A topic particularly representative of the described state is aeroelasticity in which FSI (Fluid-Structure Interaction) analysis methods, based on high fidelity numerical solvers, are considered the most accurate strategy to address the phenomenon.

One of the most common approach for FSI problems consists in coupling RANS solvers, with FEM codes in a so-called 2-way procedure (Cella & Biancolini 2012). Several complexities are related to the implementation of such technologies. One of them concerns the technique used to transfer the aerodynamic loads from the wet surfaces of the CFD mesh to the structural domain that, in general, have a non-matching discretization on the common boundaries. The forces computed by the fluid dynamic analysis are, in fact, extracted from the cells of the CFD walls boundaries in the form of vectors positioned on a cloud of points that will typically differ from the FEM grid points on which the loads have to be applied (the grid requirements are, in general, different for FEM and CFD analyses). An interpolation between the two domains is then required with a consequential introduction of an error. The minimization of the uncertainness associated to this process relates to the quality of the mathematical approach adopted to face the interpolation.

Mapping methods needs to fulfil accuracy and flexibility requirements. Forces vectors must be transferred with no loss of magnitude or direction. The methods must be able to handle dissimilar meshes, including the cases fine-to-coarse and coarse-to-fine, on very large models in a reasonably short time.

The following families of load transfer methods are available:

- point-wise interpolation and extrapolation;
- point to element projection schemes;
- area weighted averaging;
- mortar elements method.

A good review about load transfer schemes can be found in the studies by Jaiman et al. (2006). Practical examples dealing with aeronautical meshes are considered by Samareh (2007). A detailed example of mortar method is given in the paper by Hou (2012).

Objectives

The goals of the RIBES project are the development of an accurate loads transfer procedure between fluid and structural domains and the implementation of a structural numerical optimization procedure. An innovative aspects of the research is the adoption of the Radial Basis Function (RBF) mathematical framework. In addition, a significant part of the RIBES project was devoted to the setup of an extensive aeroelastic wind tunnel test campaign on a test article that replicates a typical metallic aeronautical wing structure. The aim is to generate an experimental base of assessment strongly customized to the verification of the FSI numerical methods capability to model complex topologies.

Description of work

The RIBES project is focused on three main topics:

- development of a load mapping procedure;
- setup of an experimental campaign;
- development of a structural optimization tool.

The activities on the first topic dealt with the development of numerical procedures able to perform correctly the load transferring process between CFD and FEM structural models. In the platform developed within the RIBES project, the main tasks are accessible using Text User Interface (TUI) commands. A Graphical User Interface (GUI) for mesh inspection and workflow management was also developed.

The second topic is addressed to the creation of an experimental database to validate aeroelastic numerical analysis tools focusing the attention to the verification of the FSI methods ability to

accurately capture the structural response of a complex mechanical system as a wing box structure. The objective was to create a test case representative of a typical aeronautical design problem.
For the last topic a shape numerical optimization procedure, able to modify the original design, was developed. A direct FEM based approach is used so that the FEM model becomes parametric by means of updating the cards in the solver input file (shape by updating nodal positions, properties by updating relevant fields). An automated DOE approach is adopted for the selection of the optimum.

Results

The workflow of the developed load mapping procedure consists in decomposing the original datasets in small overlapping subdomains in which the field is locally interpolated by RBF. The error in the equilibrium between source and target field is compensated by introducing corrective coefficients that locally force the equivalence between the resultants of the source and target subdomains. A GUI, used to load, manage and visualize the process, was developed. The procedure has been assessed using the HIRENASD test case for which both CFD and FEM grids are available. The errors obtained on moments (errors on forces are zero for definition) are below 0.3% along all directions.
The RIBES experimental test case was setup with the aim to accomplish the task of being significant for a realistic wing design problem and of being suitable to be experimentally verified in a low speed wind tunnel under steady flow conditions. A straight wing 1.6 meters wide was selected as the final configuration. The wing box is a typical aeronautical structure with two C-shaped spars and ten ribs (Figure 1). The model was instrumented with 81 pressure taps along 6 sections. The stress state of the structure under load was verified by twenty-five strain gauges installed on the most significant locations of the wing model. The tests were performed in the low speed facility of the university of Naples “Federico II”. Figure 2 evidences the model installation in the wind tunnel test section.
A 2-way and a modal FSI analysis procedures was setup and validated against measurements. The technologies derive from tools developed within the EU RBF4AERO project in which the University of Rome “Tor Vergata” was involved (Bernaschi et al. 2016). The workflow of the 2-way procedure is synthesized in Figure 3. The RIBES mapping procedure is applied to transfer the aerodynamic loads to the FEM model. The CFD domain is adapted to the FEM solution using RBF mesh morphing. The modal approach for FSI analysis consists in modelling the geometric deformation by a combination of a limited number of structural natural modal shapes. The aim is to avoid the iteration between CFD and FEM analysis by the development of a fluid dynamic model that, with an opportune parametrization of the mesh, becomes intrinsically aeroelastic. The 2-way and the modal FSI configurations gave extremely similar solutions. Figure 4 reports a detail of the FEM solution in the root region of the wing obtained by the 2-way procedure. Good agreement of stress state with measurements was observed in regions far from the wing root. Some disagreements became evident in the areas close to the junctions at the wing root where higher gradients are present.
The structural optimization procedure developed within the RIBES project is based on routines that manage the geometric parameters, update the model, perform the FEM analysis and drive the optimization starting from a Nastran model. The optimum selection criterion is based on filling a DOE (Design Of Experiment) table and on the computation of a Response Surface (RS) on which to apply the search algorithm. The University of Rome “Tor Vergata” developed a Response Surface metamodel based on the Radial Basis Functions using various kernels. The possibility to perform both a shape and thickness optimization was implemented by two different strategies. Thickness is introduced as variable of design directly taking the control of the bulk data file by the management of the property labels in the ASCII file. The shape change is applied to the topology directly on the numerical domain by mesh morphing techniques (Figure 5). The complete workflow of the structural multi-objective optimization procedure is sketched in Figure 6. The parameters that is possible to extract to be used to compute the objective functions and/or implement constraints are the maximum stress, the maximum displacement, the total mass and the Maximum Failure Index (FI) of composite structures. The full process can be controlled by a set of opportunely developed GUI. The efficiency of the tool was demonstrated against a test case consisting in a composite rib provided by the project Topic Manager in which the optimization variables were: rib thickness, depth of holes, clews depth ant diameters of holes. The objective functions were the total weight and the structural strength. Figure 7 visualize the FEM analysis of the optimized solution.

a) Timeline & main milestones

The main activities for the generation of the load mapping tool were the developments of the core procedure and the development of a Graphical User Interface. The procedure was subjected to deep testing and debugging that progressed along

the whole duration of the project. A user manual was prepared and made available with the software.
The activities related to the experimental tests were divided in two work packages. One related to the model design and FSI validation and the other to the model manufacturing and wind tunnel measurements. The WT model was designed and verified in operating condition. This process took a significant part of the project. The final part of the numerical activity was dedicated to the validation of the coupled CFD-CSM FSI analysis method, using the developed mapping procedure, against the measurements on the designed wind tunnel model. The performance of the FSI analysis method, based on modal superposition approach, was also verified in this contest.
The development, debugging and application activities of the structural shape optimization tool were performed during the first year and progressed independently from the other activities of the project.

b) Environmental benefits

The increasing demand of aircraft travel will increase output of undesirable emissions, such as carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), sulphur dioxide (SO2), hazardous air pollutants (HAPs), unburned hydrocarbons and particulate matter. The new methodological concept presented in the RIBES project is very much promising in this sense as it will allow to reduce the weight of the structures. In particular, successful exploitation of the RIBES Project outcomes it expected to produce the following advantages:

1. providing a reliable and validated predictive methodology to accurately mapping load acting on the aircraft structure to optimise shape, reduce weight and so improve the overall efficiency;
2. constituting a valid mean to reduce fuel consumption and consequently pollutants emissions.

c) Maturity of works performed

The tools proposed in the RIBES Project presents several advantages. The RIBES mapping procedure can be easily automatized and integrated in 2-way FSI workflows to create optimization design environments. Furthermore, the RIBES FEM tool capability to parametrize and update the structural properties, combined with the CFD mesh adaptation to the FEM deformation in a closed loop, provides the possibility to create a shape design method that combines aerodynamic and structural optimizations in a single environment. Such a tool can be adopted to face static and dynamic aero-structural design enabling multi objective/multi physics optimisation in which performances coming from different solutions are pursued steering the same common reference geometry. The RBF mesh morphing approach, on which the FSI methods (derived from the RBF4AERO project) are based, demonstrated its efficiency in facing several industrial engineering problems (Biancolini et al. 2016 and Costa et al. 2014).
All measurements, geometries, numerical models and solutions of numerical/experimental activities performed within the RIBES project will be soon available on line to the scientific community. A web portal (www.ribes-project.eu) is under development with the wish the RIBES test case to constitute an enhancement for information sharing between scientists and a framework for further discussions, research activities, proposals and collaborations.

References

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Picture, Illustration

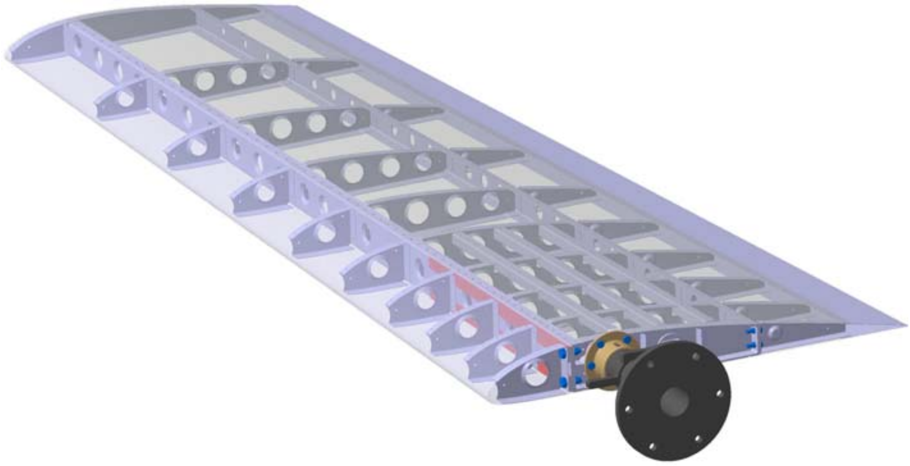

Figure 1: CAD model of the RIBES test article.

Figure 2: Detail of wind tunnel model installation.

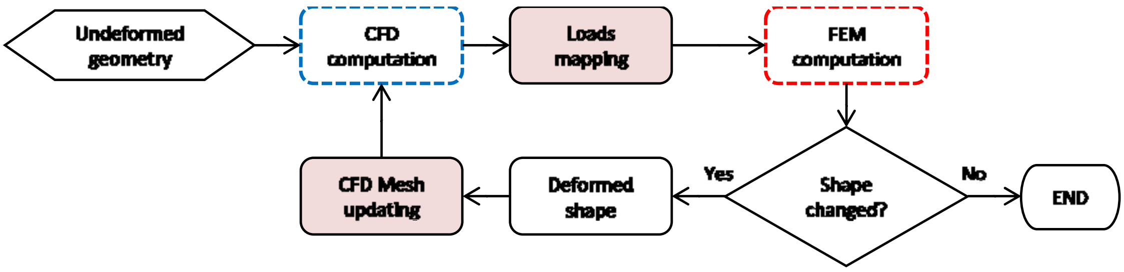

Figure 3: Workflow of the 2-way FSI analysis.

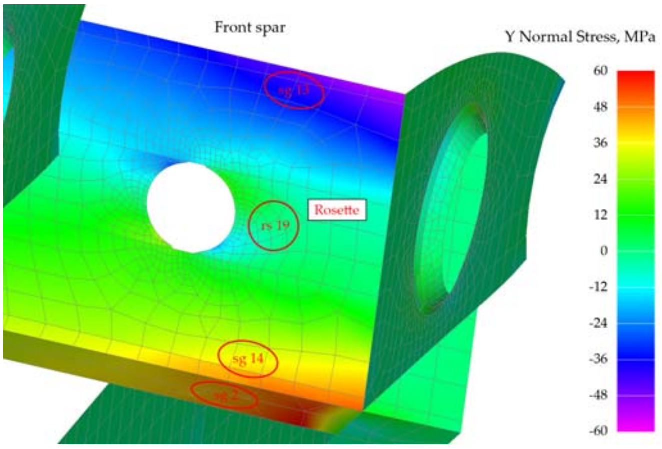

Figure 4: FEM solution of the 2-way FSI analysis in the wing root region and location of strain gauges.

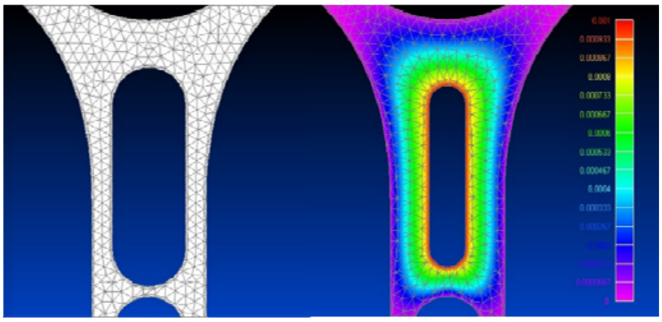

Figure 5: Example of structural shape parameterization based on mesh morphing.

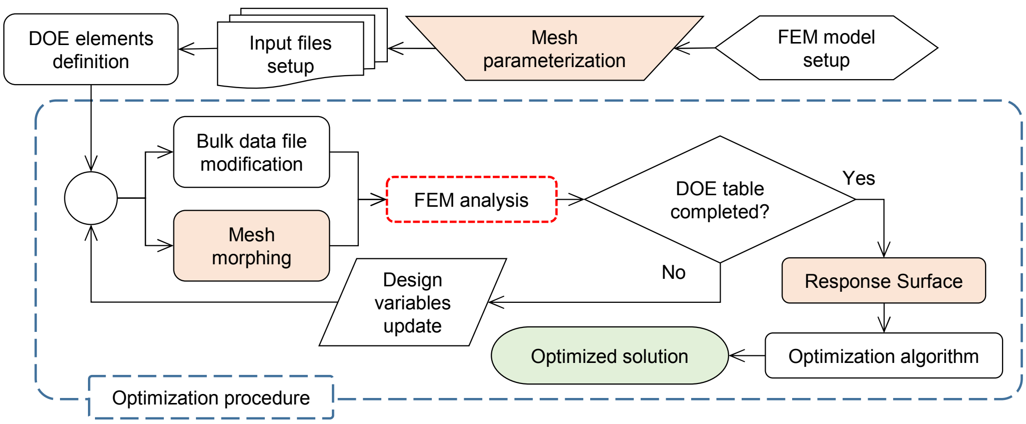

Figure 6: Structural optimization workflow.

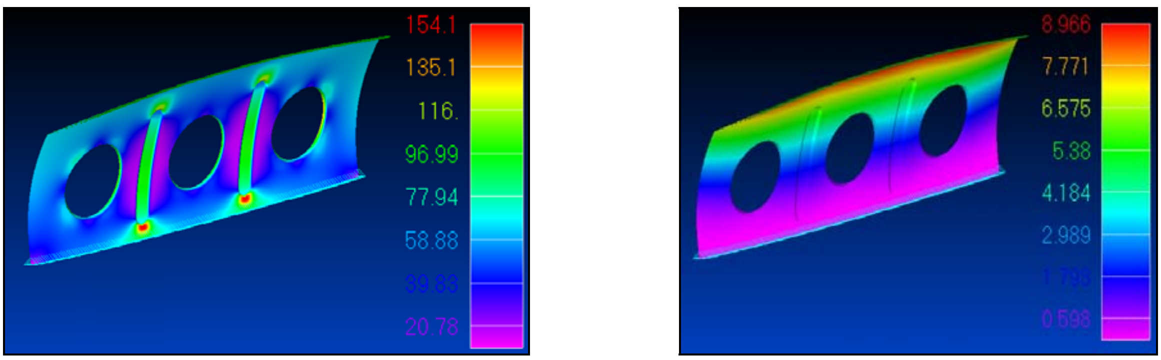

Figure 7: FEM equivalent stress (left) and total displacement (right) of the optimized composite rib.

Project Summary

Acronym:	RIBES
Name of proposal:	Radial basis functions at fluid Interface Boundaries to Envelope flow results for advanced Structural analysis
Web site:	www.ribes-project.eu
Technical domain:	Research and Technology Development Projects
Involved ITD:	Green Regional Aircraft
Grant Agreement:	632556
Instrument:	Clean Sky JU
Total Cost:	292,000
Clean Sky contribution:	219,000
Call:	SP1-JTI-CS-2013-02
Starting date:	1st December 2014
Ending date:	1st December 2016
Duration:	24 months
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