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Improved aeroelastic design through structural optimization

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Abstract. The paper presents the idea of coupled multiphysics computations. It shows the concept and presents some preliminary results of static coupling of structural and fluid flow codes as well as biomimetic structural optimization. The model for the biomimetic optimization procedure was the biological phenomenon of trabecular bone functional adaptation. Thus, the presented structural bio-inspired optimization system is based on the principle of constant strain energy density on the surface of the structure. When the aeroelastic reactions are considered, such approach allows fulfilling the mechanical theorem for the stiffest design, comprising the optimizations of size, shape and topology of the internal structure of the wing.

Key words: fluid-structure interaction, biomimetics, structural optimization.

1. Introduction

Nowadays, to design an aircraft structure the coupled fluid-structure interactions (FSI) simulations are crucial. On the other hand, for the structural optimization techniques have to be used [1, 2]. There are many examples of using optimization techniques to design the structural elements of an aircraft [1–5]. In the resent years, especially the topology optimization method has been introduced to the designing processes. A good industrial example is here the structure of the Airbus A380 wing. The structural elements of the wing were designed in two designing steps. First, the optimal material distribution was defined using the topology optimization – the SIMP method. Then, after extraction of geometry from the topology optimization results, the model for size and shape optimizations was derived. The size and shape optimization were the next step in the wing designing process. Splitting the topology and then size and shape optimizations is necessary, due to completely different optimization methods used in each case.

2. The bio-inspired optimization method

While examining biological structures, we often realise that they are optimal from both mechanical and mathematical optimality perspectives. The trabecular bone is here an excellent example. Wolff's law [6], formulated in 19th century assumes that bone is capable of adapting to mechanical stimulation and optimizing energy expenditure to keep tissue in good condition. This aspect could be useful when issues of structural optimization are discussed. Healthy tissue of trabecular bone has very sophisticated shape. The tissue forms a network of beams called trabeculae. This structure is able to handle a wide range of loads being continually rebuilt. The phenomenon of trabecular bone adaptation, called remodelling, has two important attributes. First, mechanical stimulation is necessary to conserve rebuilding balance. In many numerical models of trabecular bone remodeling strain energy density (SED) is used to measure the level of mechanical stimulation [7, 8]. Second, the process of resorption and formation occurs only on the bone surface. In this way the bone reacts to external forces and the process of remodeling leads to mechanical adaptation [7–12]. It is interesting, that SED, as energy measure, is also emphasized in optimization research, distant from biomechanical studies [13–16], where one can find the theorem, that for the stiffest design the energy density along the shape to be designed must be constant.

Based on these assumptions the biomimetic optimization system was created [17] and the optimization results were compared to the standard topology optimization method. The obtained optimization results are the same as it is in case of SIMP topology optimization method [18]. In the example presented in Fig. 1, the starting configuration is as simple as possible – the stick connecting the bending force and possible support area. Instead of support definition, there is a clumped wall, as a surface, on which during the optimization procedure supports are defined.

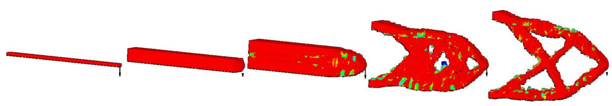

Fig. 1. The optimization results of the cantilever beam bending – from the left to the right: selected simulation steps

To design an aircraft structure, coupled fluid-structure interactions simulations are necessary as well as for the structural design the optimization techniques must be used. Combining both fluid-structure interactions simulations and structural optimization it is possible to obtain an improved solution. The most important element of the structural optimization in case of FSI computation is multiple load case problem. It is because every step of FSI analysis is, in fact, a different load case. For the classical optimization approach each load case has to be analysed separately. The used here biomimetic optimization method is able to treat different load cases as a one optimization task. As an example of multiple load case simu-

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lation the same starting configuration (stick) was studied. Two different load cases were examined. First, identical with the study presented in Fig. 1, and the second, with the same definition of boundary conditions and horizontal bending force. The optimization results for these two configurations treated separately are depicted in Fig. 2.

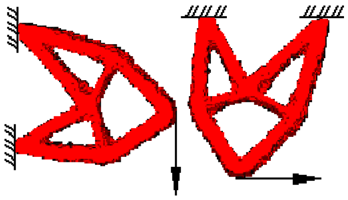

Fig. 2. The optimization results for the same starting configurations (stick) and different direction of the bending force: left – vertical bending, right – horizontal bending force

The solutions have identical form, but rotated according to the direction of applied force. Figure 3 depicts the result for the same starting configuration but including multiple load cases. The direction of applied force was switched every two simulation steps from the vertical to horizontal one and vice versa.

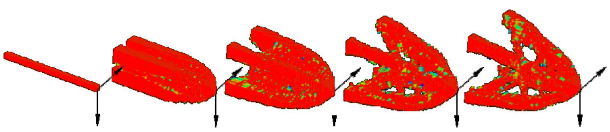

Fig. 3. The result of the multiple load study (altering vertical and horizontal bending force)

The obtained solution is radically different from the ones obtained for each of the load cases shown in Fig. 2, nor is their superposition. Due to the unique features of the biomimetic structural optimization process discussed above, the evolution of the structure ran stable, despite the changes in load definition. The method allows efficient performance of the optimization process for several load cases, when homogenisation of SED on the surface of the structure guarantees optimality of the solution.

3. The computational environment

For the structural optimization purposes the biomimetic system based on the principle of constant strain energy density on the surface of the structure was prepared. The biomimetic optimization system was implemented into the FSI environment. One of the important elements of the optimization system is the finite mesh generator called Cosmoprojector. The tool was originally dedicated to mesh creation and evolution simulations where a biological entity was an object. Since the visualization for biological entities is based on the digital images, the input to the system is based also on the collection of the 2-dimensional images. After some graphical operations the images are directly used for building of the 3-dimensional finite element mesh. The information about nodes and elements is stored in a special data base and translated into Abaqus finite element system input file. The presented in the paper design problem can be defined as a determination of the material layout within the wing internal domain. The outer profile of the wing must remain its form because this form satisfies aerodynamic constrains. In the presented method the optimization of the internal wing structure is coupled with already existing FSI environment.

The computational environment contains coupled elements: flow code TAU (Deutches Zentrum fuer Luft und Raumfahrt) [19], structural code Abaqus and other specialized procedures like mesh deformation tool AE_Tools, developed in frame of Taurus project [20]. The algorithm for coupling aeroelastic analysis with structural optimization is depicted in Fig. 4. The approach presented here is based on the assumption, that different codes will be used separately for each part of simulation field. But the main coupling process still concerns two blocks: CFD for the fluid flow computations and the CSM for the structural deflections computations. The structural biomimetic optimization is performed inside the CSM block. The multiphysics simulation starts on the CFD site. The flow solver computes the pressure distribution on the outer surface of the analysed wing. Then, the information about the pressure distribution is translated to the CSM block. The information is exchanged on the coupling surface. The coupling surface is defined for interpolation purposes and geometrically corresponds to the outer surface of the wing. The next step is performed on the CSM site and it is the optimization task. If the SED value in the structure is higher than the assumed level, surface adaptation occurs adding the material on the surface. If the SED value in the structure is lower than another assumed level, surface adaptation occurs again, but this time, removing the material. If the SED value is between the two levels described above, no adaptation occurs. But the outer shape of the wing must remain its form. For this purpose a procedure of shape control was implemented. After each step of optimization the outer shape of wing is controlled, and the shape changes resulting from optimization procedure are undone for this area. The optimization process stops when there is no need for further adaptation and the SED values on the surface of the internal wing structure are between the assumed limits. Now, in turn, the structural deflections are translated to the CSM part, where after the CFD mesh deformation procedure the next flow analysis step is performed.

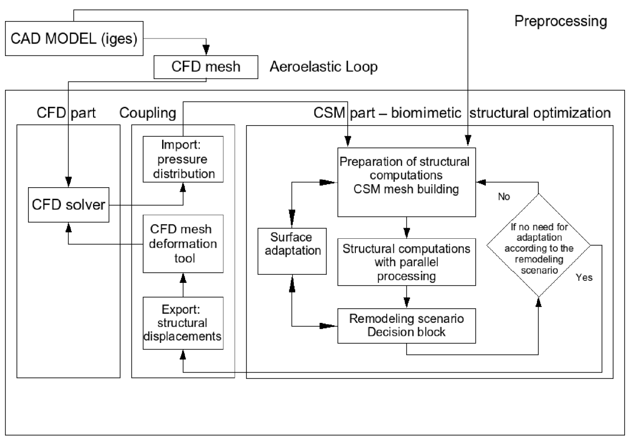

Fig. 4. The algorithm for aeroelastic analysis coupled with the biomimetic structural optimization

The strain energy density computations are realized in the parallel environment, what is a condition to solve larger problems. But the same question concerns mesh generation, especially if the mesh elements number is the order of 10^6. To increase the capabilities of the optimisation system the mesh generation tool Cosmoprojector was parallelised. The scheme of the parallel mesh generation procedure is shown in Fig. 5. Because the mesh generation procedure is based on the collection of 2-dimensional cross-sections of the 3-dimensional geometry of the analysed structure [21], in the natural way the mesh generation for the whole domain can be divided into independent tasks. The only change is the modification of input data necessary to define the overlapping areas. The aim of overlapping areas is to ensure that the slice by slice mesh creation procedure is independent of the number of processors used in the computation.

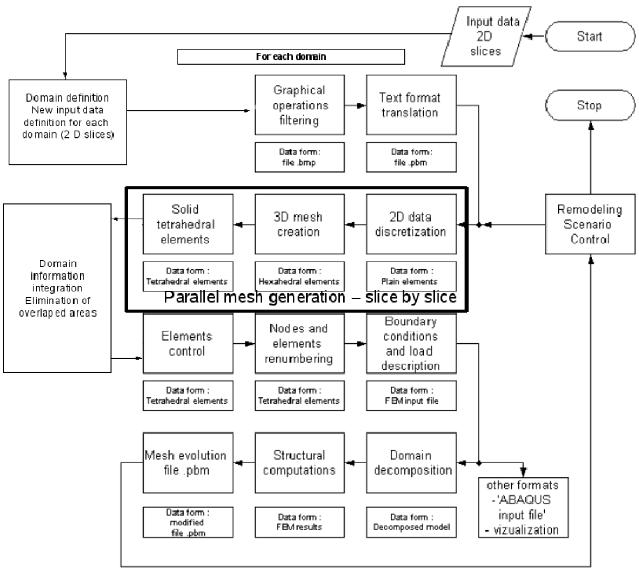

Fig. 5. Cosmoprojector – the parallel mesh generation procedure

4. The numerical example

The numerical example is the study of optimal structural wing configuration for the inviscid flow of symmetric NACA0012 airfoil with the following flow conditions: Mach number = 0.30, angle of attack = 4 degrees. The CFD computational mesh with 6'500'000 tetrahedral elements and the farfield of 20 times long as a chord length is schematically depicted in Fig. 6.

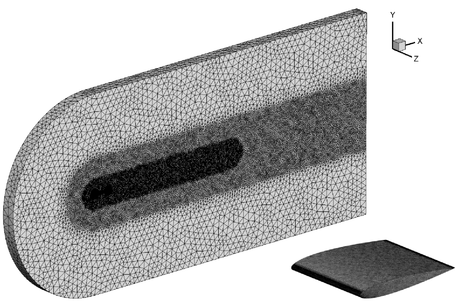

Fig. 6. The numerical example – the structural grid for inviscid flow of symmetric NACA0012 airfoil (Mach number = 0.30, angle of attack = 4 degrees, farfield of 20 times long as a chord length)

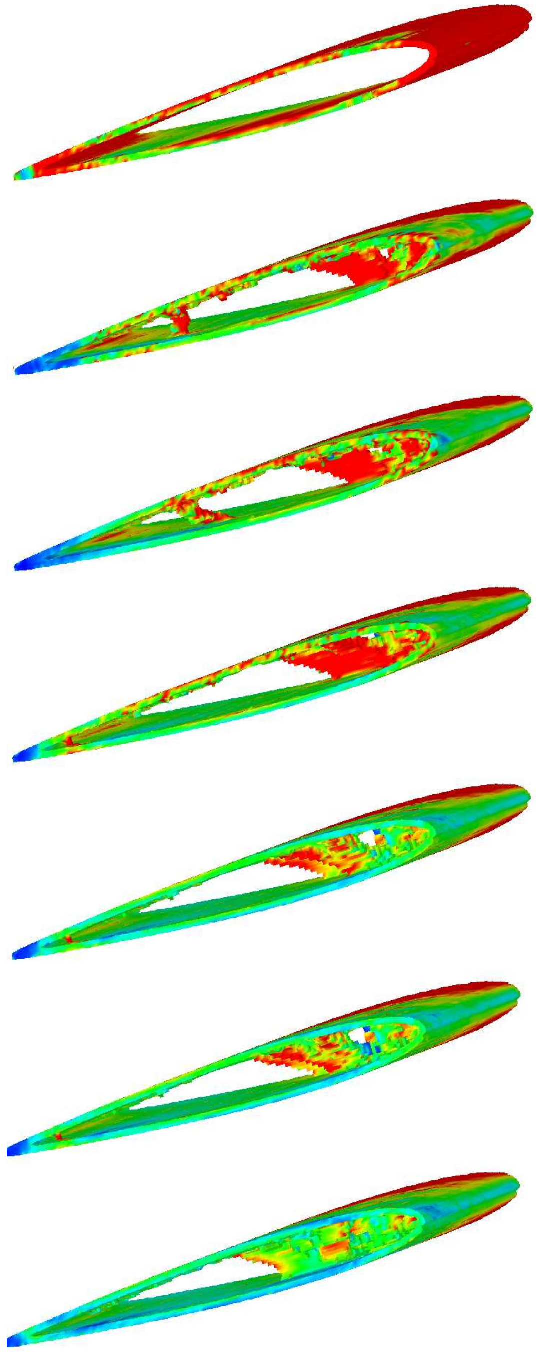

Fig. 7. The results of coupled aeroelastic and optimization procedures – from top to down: selected simulation steps

For the biomimetic optimization purpose the unstructured tetrahedral grid was generated with use of Cosmoprojector mesh generator. The multiphysic analysis contains aeroelastic simulation steps treated as outer loop and the structural optimization steps treated as internal loop. The starting point was the wing configuration with the thin material layer only, according to the outer wing shape, empty inside. The results of the coupled aeroelastic and optimization procedures are depicted in Fig. 7. The presented pictures represent subsequent steps of the static aeroelastic analysis coupled with the biomimetic structural optimization. Selected steps of structural optimization illustrate the change of the internal shape of the analysed wing configurations during the multiphysics analysis. Colors indicate SED distribution on the structural surface (blue – the lower and red – the higher SED value within assumed range). During the simulation, the biomimetic adaptation to external forces leads to the equalization of SED on the structural surface, what is a condition of the stiffest design.

Observing the geometrical form of the solution, one can see parts of the structure which can be interpreted as stiffeners or ribs.

5. Conclusions

In the paper the computational scheme of coupled aeroelastic analysis and biomimetic optimization was presented. The considered here aeroelastic design problem seems to be similar to the bone mechanical adaptation phenomenon. The presented biomimetic approach allows the mechanical structure to adapt to mechanical loads, like the bone adapts to mechanical signals.

The numerical procedures can efficiently merge the process of structural optimization and aeroelastic analysis. Due to the unique features of biomimetic structural optimization the method allows efficient performance of the optimization process for several load cases, when homogenisation of SED on the surface of the structure guarantees optimality of the solution. The solution, as proposed material distribution can help engineers in the practical design of a form of internal wing and other elements of the aircraft structure. The presented method needed the development of specialized numerical environment. The strain energy density computations realized in the parallel environment together with the parallelization of mesh generation and evolution allow solving practical problems. The above presented approach comprising the optimization of size, shape and topology with no need for parameters defining.

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