Improved aeroelastic design through structural optimization

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Abstract

The paper presents results of coupled multiphisics computations. The presented procedure shows the concept and presents some preliminary results of static coupling of structural and fluid flow codes as well as biomimetic structural optimization. The biological phenomenon of trabecular bone functional adaptation was here a model for the biomimetic optimization formula. The 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 mechanical theorem for the stiffest design, comprising the optimizations of size, shape and topology of the internal layout of the wing structure.

Keywords: 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 design optimization techniques have to be used [2, 10]. There are many examples of using optimization techniques to design the structural elements of an aircraft [2, 9, 10, 11, 19]. In the resent years, especially the topology optimization method has been introduced to the designing processes. A good industrial example is the structure of the Airbus A380 wing. The structural elements of the wing were designed in two design steps. First, the optimal material distribution was defined using the topology optimization - the SIMP method. Then, after the extraction of the geometry from the topology optimization results, the model for size and shape optimizations was derived. The size and shape optimizations 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 a good example. Wolff's law [21], 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 studying issues of structural optimization. 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 has two important attributes. First, mechanical stimulation is necessary to conserve rebuilding balance. 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 healing leads to mechanical adaptation [1, 6, 7, 8, 13, 14]. It is interesting, that SED, as energy measure, is also emphasized in optimization research, distant from biomechanical studies [4, 12, 17, 20], 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 [16]. The obtained optimization results are the same as it is in case of SIMP topology optimization method [3]. In the example presented in Figure 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.

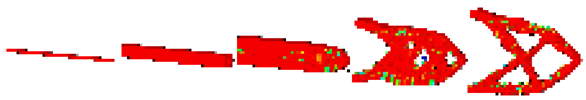

Figure 1: The optimization results of the cantilever beam bending – from the left to the right: selected simulation steps.

To design an aircraft structure, coupled fluid-structure interactions (FSI) simulations are crucial. On the other hand, 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 problems. 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 simulation the same starting configuration (stick) was studied. Two different load cases were examined. First, identical with the study presented in Figure 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 Figure 2.

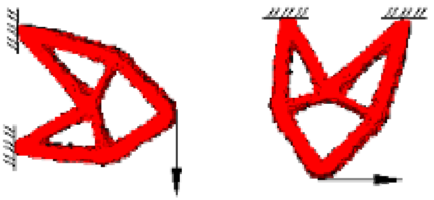

Figure 2: The optimization results for the same starting configurations (stick) and different direction of the bending force: left – vertical bending, right – horizontal bending force.

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.

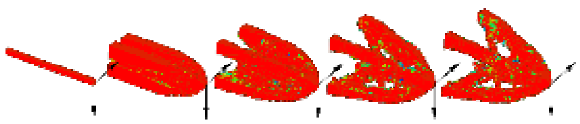

Figure 3: The result of the multiple load study (altering vertical and horizontal bending force).

The obtained solution is radically different from the ones obtained for each of the load cases shown in Figure 2, nor is their superposition. Due to the unique features of 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 cases of loading, when homogenisation of SED on the surface of the structure guarantees optimality of solution.

3. The computational environment

The biomimetic optimization system was implemented into the FSI 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 simulation system consists of Finite Element Mesh generator, decision block setting criteria for structural adaptation and the Finite Element Analysis in a parallel environment. The presented in the paper design problem can be defined as a determination of the internal structural layout of the wing. 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 was coupled with the FSI environment [17]. The performed algorithm contains coupled flow code TAU (Deutches Zentrum fuer Luft und Raumfahrt) [5, 18], structural code Abaqus and specialized procedures like mesh deformation tool AE_Tools. Pressure distribution resulted from the FSI a calculation of the static coupling was applied on the wing surface and this was the base for the load definition for the optimization procedure.

Figure 4 depicts the algorithm for coupling aeroelastic analysis with structural optimization. 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.

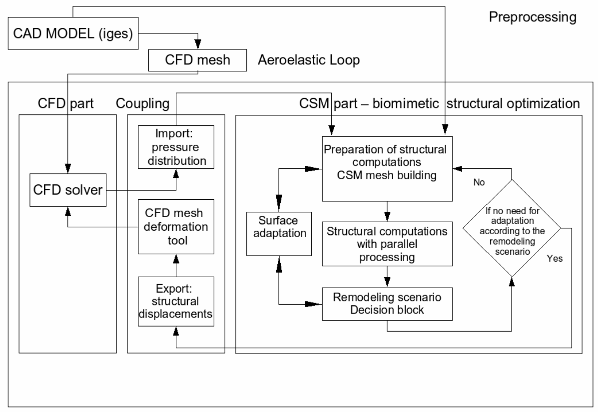

Figure 4: The algorithm for aeroelastic analysis coupled with the biomimetic structural optimization

The multiphisics simulation starts on the CFD site. The flow solver computes the distribution of pressure on the outer surface of the analysed wing. Then, the information about the pressure distribution is translated to the CSM site. 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 stopped when there was no need for further adaptation and the SED on the surface was between the assumed limits. Now, in turn, the structural deflections are translated to the CSM part, where after the mesh deformation computations the next flow analysis is performed.

4. The numerical example

As the numerical example the computations were performed for inviscid flow of symmetric NACA0012 airfoil with the following flow conditions: Mach number = 0.30, angle of attack = 4 degrees. The structural grid with 6’500’000 tetrahedral elements was used with the farfield of 20 times long as a chord length. The CFD computational mesh is schematically depicted in Figure 5.

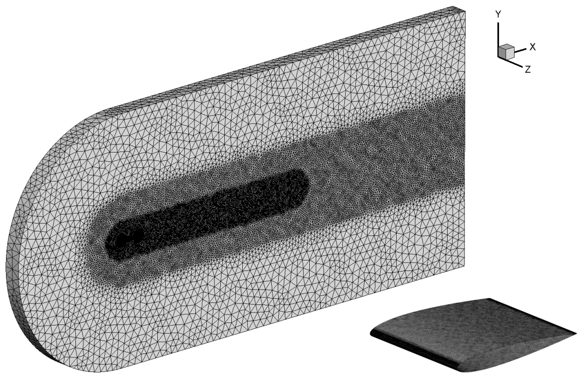

Figure 5: The numerical example - the structural grid for inviscid flow of symmetric NACA0012 airfoil (Mach number = 0.30, angle of attack = 4 degrees, farfield of 20 times long as a chord length).

The finite element method unstructured tetrahedral grid of 200'000 to 300'000 elements was used for structural optimization purpose. The results of coupled aeroelastic and optimization procedures are depicted in Figure 6. The selected simulation steps are presented from top to down where the starting domain was an empty domain – the internal area of the airfoil. The outer shape of the wing remains its form during the whole simulation process.

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

5. Conclusions

The computational scheme of coupled aeroelastic analysis and biomimetic optimization has been presented. 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 cases of loading, when homogenisation of SED on the surface of the structure guarantees optimality of solution. The solution, as a proposed material distribution can help engineers in process of designing a practical implementation of internal wing structure.

The above presented approach allows to comprise the optimizations of size, shape and topology without the need of parameters definition. 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.

Future development of the presented method will concentrate efforts on use of larger finite element method mesh sizes. 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 should be parallelised.

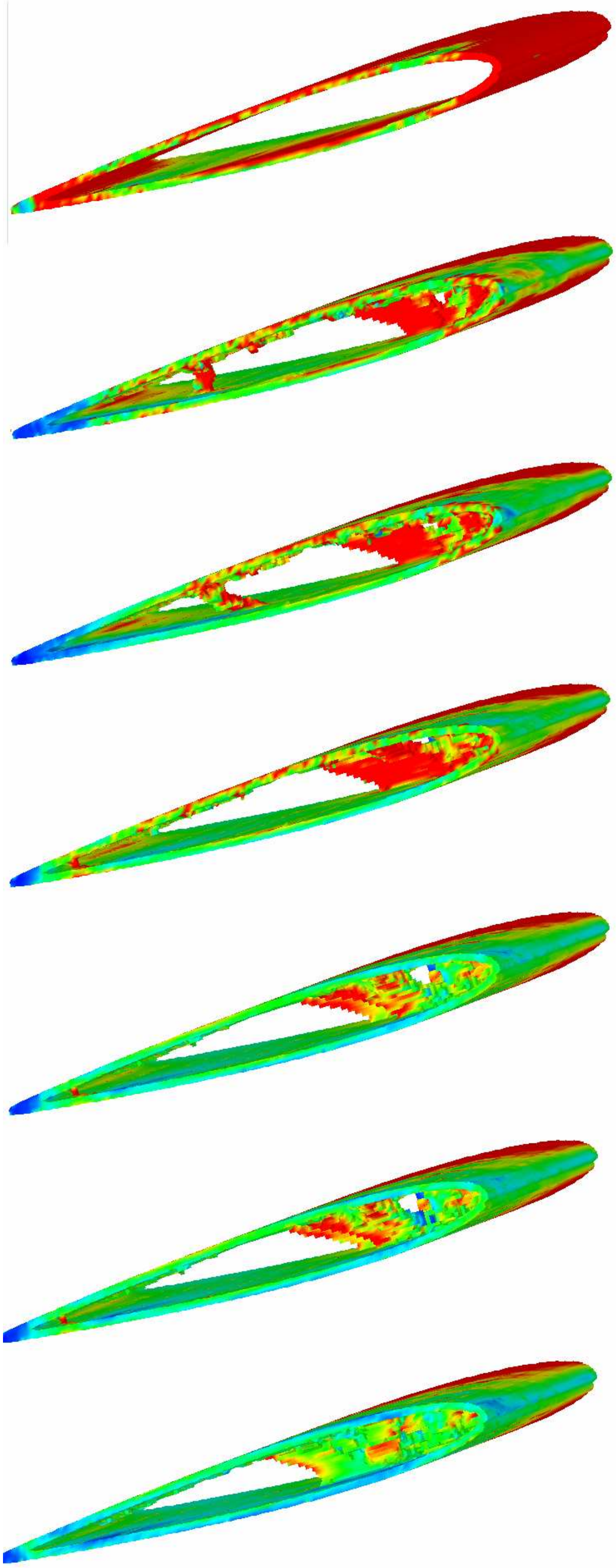

Figure 6: The results of coupled aeroelastic and optimization procedures– from top to down: selected simulation steps.

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