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USING OPEN SOURCE SOFTWARE FOR SOLVING AEROELASTICITY CASE FOR WIND TURBINE BLADE

PAVEL S. LUKASHIN[1,2], VALERIIA G. MELNIKOVA[1,2], GEORGY A. SHCHEGLOV[1] AND SERGEI V. STRIJHAK[2]

[1] Bauman Moscow State Technical University
5/1, 2-nd Baumanskaya st., Moscow. 105005, Russia
ski1l@mail.ru, vg-melnikova@yandex.ru, shcheglov_ga@bmstu.ru

[2] Ivannikov Institute for System Programming of the RAS
25, Alexander Solzhenitsyn st., Moscow, 109004, Russia
strijhak@yandex.ru

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Abstract. Due to the development of Wind Energy and construction of new wind farms in the Russian Federation and Europe there is a need for solution of application-oriented problems and development of effective methods for numerical modelling of wind turbine's elements. One of the directions for computational continuous mechanics is connected with problems in aeroelasticity (fluid-structure interaction). The possibility of solving one of the problem in aeroelasticity using a complex program approach on the basis of open source software OpenFOAM and Code_Aster is shown in this article. On the example of the blade for wind turbine, which has 61.5 meters long, the techniques of solving problem for a static and dynamic aeroelasticity in which flow simulation of the blade with a subsonic air flow is done in OpenFOAM library (solvers simpleFoam and pimpleFoam) are considered. The calculation of the stress-strain state of the blade is done in Code_Aster. The flowcharts for four different approaches for solving problems of aeroelasticity are provided in article. The finite-volume mesh consisting hexahedral elements, the total number is about 400000 elements, for simulation of the flow around the blade is created in OpenFOAM library, the finite-element mesh consisting of triangular shell elements of first order, the total number is 7714, for calculation of the stress-strain state is created in Salome-Meca. The results of analysis are provided in the form of pressure and velocities fields; projections of aerodynamic force from time; displacement and stress diagrams; the values of pressure for two points on the surface of the blade and displacement of the tip of the blade from time. The calculations are run using resources of UniHUB web-laboratory ISPRAS.

1 INTRODUCTION

Due to the development of Wind Energy in the Russian Federation and Europe, the design of new wind turbines, wind farms and their operation in different climatic conditions in the vast territory of the Russian Federation and Europe, a number of application-oriented problems arise. One of them is the assessment of dynamic and strength characteristics of the wind turbine blades taking into consideration the wind load. The flexible commercial software are the most suitable for solving such problems. But statistics show that different large and medium-sized enterprises gradually became aware of the advantages provided by Open Source Software (OSS): reduction of costs for software packages, open source code, as well as protection from possible sanctions of foreign right holders. Therefore, the search, modification, improvement of existing and creation of new open source software tools is an actual task nowadays.

Currently, OSS is already successfully used for structure analysis in the field of energy. In particular, we can note the Code_Aster package used by France's largest energy company EDF.

An important advantage of OSS is the ability to create a new software package, based on several packages, in order to solve complex problems of multiphysics. Traditionally the problems of aeroelasticity are referred to as such problems.

The main purpose of the paper is to adjust the methods for solving the conjugate problems of interaction between the deformable structure and the flow based on two open source packages: OpenFOAM and Code_Aster.

The various definitions of the problem of aeroelasticity are possible, based on simplifications and assumptions [1,2]. Based on the analysis of the literature [2-5], it is possible to distinguish two variants of related Fluid-Structure Interaction (FSI) problem:

- The problems of static aeroelasticity: joint consideration of the equations of the theory of elasticity and equations for the steady-state liquid and gas flow;
- The problems of dynamic aeroelasticity: joint consideration of the equations of the theory of elasticity and equations for the transient liquid and gas flow.

The several approaches are highlighted to the FSI problem solution in the paper [6]:

- The one-way coupling: separate sequential integration of the equations of two subsystems at each step of integration, without influence of the body displacement on the flow;
- The two-way coupling: coherent sequential integration of the equations of two subsystems with consideration of the body displacement in the flow.

Based on the nature of the load acting on the wind turbine blade structure, the strength of influence of the body deformation on the flow and the classification presented above, several variants of the calculation procedure were chosen:

1. The quasistatic problem definition - stress-strain behaviour (SSB) analysis of the blade under static pressure loading, obtained as a result of steady-state aerodynamic simulation of the undeformed structure.
2. The dynamic problem definition - analysis of forced oscillations of the blade under dynamic pressure loading, obtained as a result of transient aerodynamic simulation.
3. The coupled quasistatic problem definition - blade's SSB analysis under static pressure loading, obtained as a result of steady-state aerodynamic simulation with consideration of the blade deformation influence on the flow parameters.
4. The coupled dynamic problem definition – analysis of forced vibrations of the wind blade under pressure loading, obtained as a result of unsteady aerodynamic simulation with consideration of the blade deformation influence on the flow parameters.

2 DESCRIPTION OF THE METHODS

2.1 Quasistatic problem definition

The simplest sequential method for solving the problem of aeroelasticity, the flowchart of which is shown in Fig. 1, is permissible to use in case when the flow regime of the blade can be considered continuous and stationary, and the impact of elastic displacements of the structure on the flow and distribution of aerodynamic loads along the blade can be neglected. Also a simplifying assumption is the assumption about compensation of inertial forces by dissipative forces, which makes the problem of the SSB determination a static problem. The method consists of the following stages:

- The steady-state aerodynamic simulation with the finite-volume method in the OpenFOAM package using the simpleFoam solver. As a result, the velocity and pressure fields are determined;
- The transfer of the aerodynamic simulation results from the OpenFOAM package to the Code_Aster package;
- The determination of the structure SSB with finite-element method in the Code_Aster.

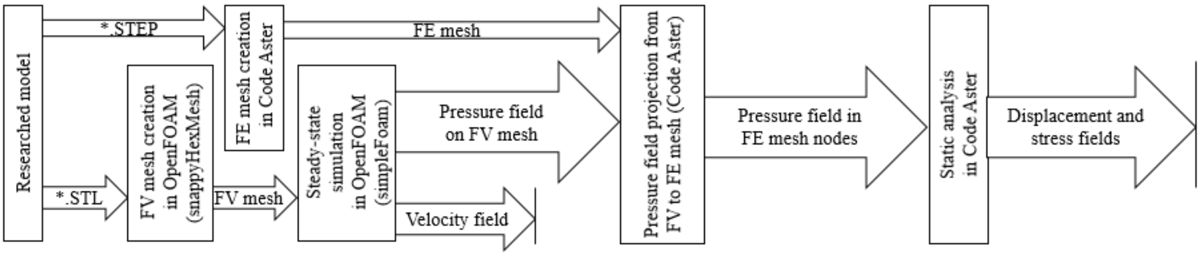

Figure 1: Simulation algorithm at quasistatic problem definition

The key stage to the joint use of packages is the second stage, during which the pressure field obtained in aerodynamic simulation is projected from the finite-volume (FV) to the finite element (FE) mesh, for further use as a load in the SSB analysis.

The data conversion from the *.foam format used in the OpenFOAM to the *.med format used as the input format for the Code_Aster was carried out through the Paraview visualization module built into the Salome-Meca preprocessor. In order to project pressure values from one mesh to another, the Code_Aster PROJ_CHAMP operator was used, in which the collocation method was used. This method determines the position of each node of the new mesh against the elements of projected mesh. When a node is inside an element, the value in it is calculated using the form functions of corresponding element. If a node is not inside an element, then the value in it is defined as the value at the point inside the nearest element. Setting of the maximum distance between the node and this point allows interpolation of the values with specified accuracy.

The disadvantage of described method is exclusion of the impact of inertia forces from consideration, which does not allow to take into account the significant dynamic displacements, deformations and stresses arising during transient modes of motion and structural vibrations.

2.2 Dynamic problem definition

In case where it is necessary to take into account the dynamic load on the blade caused by the forces of inertia and pulsations of the aerodynamic loads, and where the effect of change of the blade shape on the flow pattern can be neglected, it is permissible to use the calculation procedure for forced oscillations of the structure, flowchart of which is shown in Fig. 2. In order to use the method, it is required for the frequencies of the aerodynamic loads and the self-oscillation frequencies of the blade to be strongly differentiated from each other. This technique does not allow the modeling of self-oscillation modes. The method consists of the following stages:

- The aerodynamic nonstationary simulation in the OpenFOAM package using the pimpleFoam solver and determination of the pressure and velocity fields as functions of time;
- The transfer of pressure fields for each time point from FV to FE mesh and determination of nonstationary external loads in the Code_Aster;
- The structure dynamics analysis under the influence of received load in the Code_Aster.

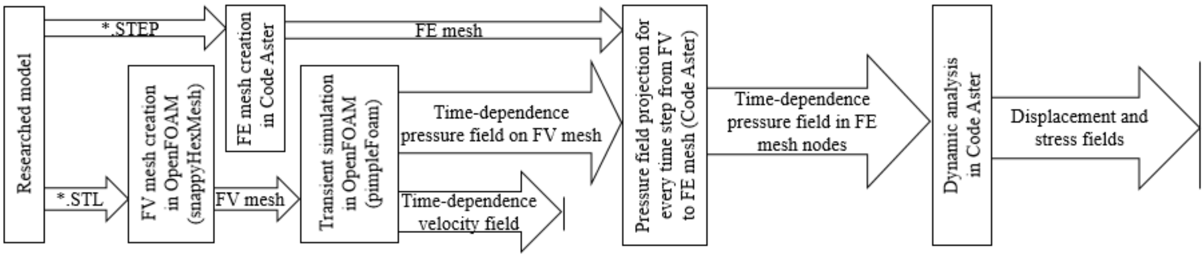

Figure 2: Simulation algorithm at dynamic problem definition

2.3 Quasistatic problem definition taking into account body deformation influence on the flow

In case when it is possible to neglect the dynamics of the blade motion and consider the flow regime of the blade as continuous and stationary, but simultaneously required to take into account the influence of the elastic displacements of the blade on the conditions of the flow, it is necessary to determine the new equilibrium position of the deformed structure in the flow. In that case, it is necessary to use a more complicated method, which uses the iteration cycle shown in Fig. 3. One iteration of searching for a new equilibrium position consists of the following stages:

- The steady-state aerodynamic simulation with the finite-volume method in the OpenFOAM package using the simpleFoam solver. As a result, the velocity and pressure fields are determined;
- The transfer of the aerodynamic simulation results from the OpenFOAM package to the Code_Aster package;
- The determination of the structure SSB with finite-element method in the Code_Aster;
- The transfer of the displacement field of the structure surface from the Code_Aster to the OpenFOAM for replotting or deformation of the mesh.

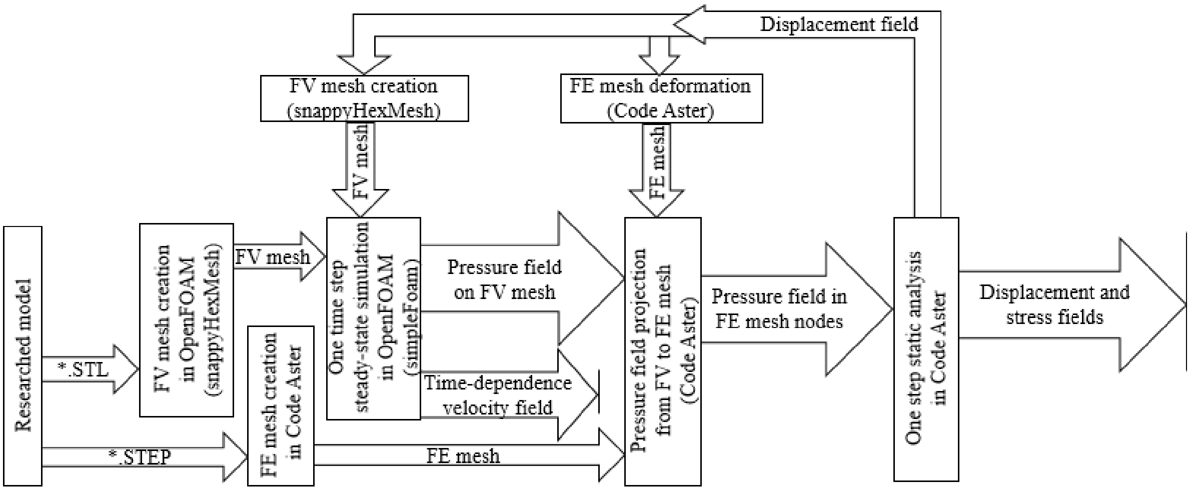

Figure 3: Simulation algorithm at quasistatic problem definition taking into account body

2.4 Dynamic problem definition taking into account body deformation influence on the flow (two-way weak coupling)

This simulation procedure is applied when it is necessary to consider influence of change of the blade's form on the flow, and also the change of the blade's load caused by forces of inertia and fluctuations of aerodynamic forces.

The analysis represents the solution of the equations of two subsystems on an integration step taking into account the movement of the body's boundary. On each temporary step occurs:

- The unsteady aerodynamic simulation with finite-volume method in OpenFOAM package using pimpleDyMFoam solver. The fields of velocity and pressure are result;
- The transfer of pressure field from an OpenFOAM package to Code_Aster;
- The solution of the dynamics equations in Code_Aster. The fields of displacements, velocity and accelerations are result.
- The transfer of displacement field of the structure surface from Code_Aster to OpenFOAM
- The deformation of a finite-volume mesh.

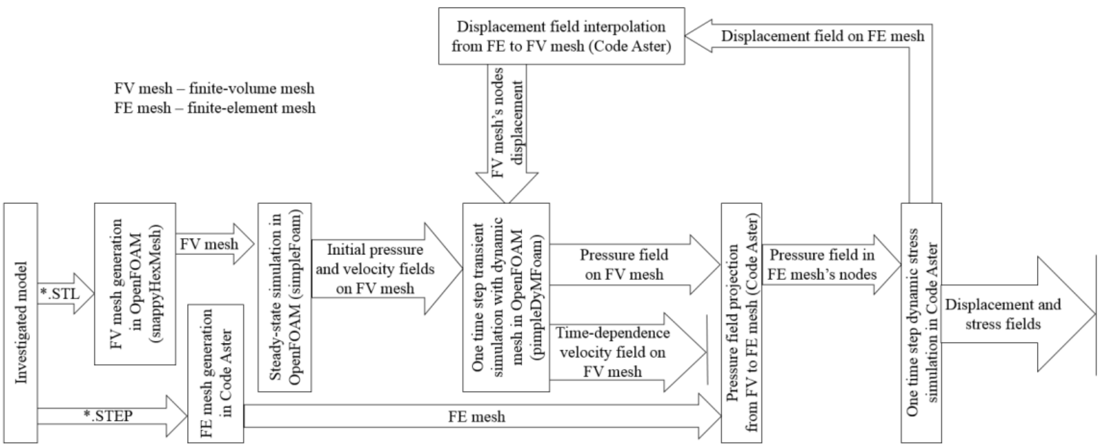

Figure 4: Simulation algorithm at two-way weak coupling problem definition

3 APPLICATION OF METHODS FOR WIND TURBINE BLADE ANALYSIS

3.1 Researched model

As the research model (Fig. 5), a blade for a 5 MW wind turbine was selected [7, 8]. The blade length is 61.5 meters. The blade has a variable cross section, consisting of 6 different profiles. The cross-sectional area decreases from the root section to the top with a maximum ratio of 74.2. Also, the blade has an initial swirling with a smooth increase in the section angles of incidence from the top to the root. The maximum angle of swirling is ≈ 13.3 degrees. The design of the blade is a shell, reinforced with stiffening ribs along the entire length.

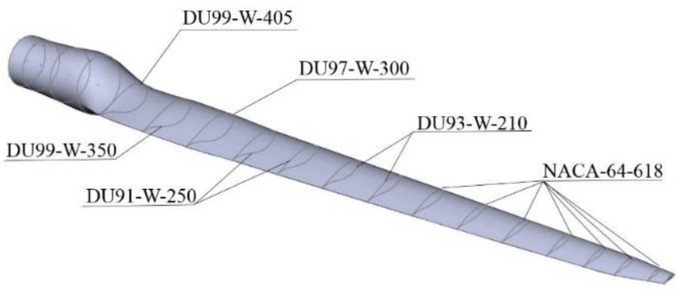

Figure 5: Researched blade of the wind turbine

In practice, the composites are used for production of wind turbine blades, including glass-carbon fabrics, combined reinforced materials, honeycomb plates, etc., the analysis of the strength of structures made of such materials is rather complicated and is one of the directions for further studies. Since the main attention in this paper was paid to the method of coupling packages for the solution of aeroelasticity problem, in the analysis a simplified structure model was considered in which an isotropic material with the following mechanical characteristics was used: modulus of elasticity $E=0.68*10^{11}$ Pa, density p=2700 kg/m^3, Poisson's ratio n=0.3. The wall thickness was d=1.5 mm.

3.2 Blade quasistatic analysis

The simulation of the flow around a blade in the OpenFOAM package was performed on an unstructured hexahedral mesh of 400 thousand elements with 4 levels of mesh thickening.

As the boundary conditions on the blade, the conditions for a rigid impermeable wall are set (for pressure - zeroGradient, for velocity - noSlip), and for the lateral faces of computational domain the free flow conditions are set (for pressure - freestreamPressure, for velocity - freestream with a value of 12 m/s). The Reynolds number, calculated from the largest of the profile chords was $4.37 *10^6$.

The simulations are performed using a simpleFoam steady-state solver for an incompressible viscous medium. The parameters of the medium correspond to the air parameters at 20 ^{0}C (density of 1.204 kg/m^3 and kinematic viscosity of $1.51*10^{-5}$ m^2/s). In order to model the turbulent flow, the Spalart-Allmaras turbulence model was used. The turbulent viscosity in the free flow is 0.14 m^2/s, on the surface of the blade - 0. All physical quantities in the computational domain were determined at the center of the calculated cell. Approximation of the terms in the original equations was carried out with a second order accuracy in time and space. Equations for relation between velocity and pressure were solved using the iterative SIMPLE algorithm [9].

The obtained fields of pressures and velocities of the medium are shown in Fig. 6 and 7. It can be seen from the figures that when the flow collides with a blade, it slows down and changes the direction of motion, flowing around it. At the same time, there is an area with increased air pressure around one face of the blade, and there is an area with a lowered air pressure near the opposite face. The difference in pressure is ≈ 190 Pa. Because of the difference in pressure on the blade, the aerodynamic force begins to act.

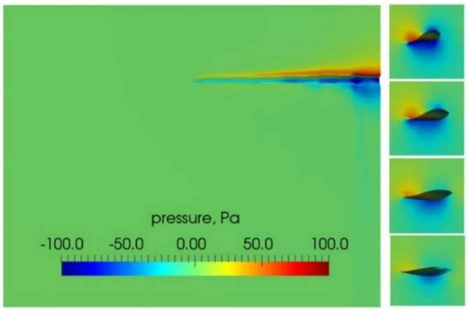

Figure 6: Pressure field at steady-state solution Sections (from top to down) x = 12 m, x = 24 m, x = 36 m, x = 48 m

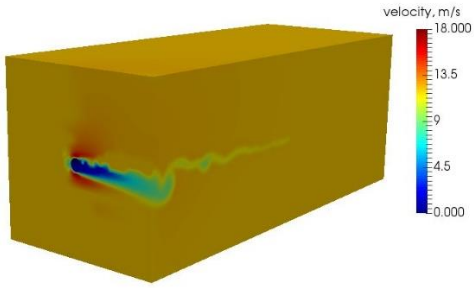

Figure 7:Velocity field at steady state-solution

The distribution of the pressure on the faces of finite-volume mesh is shown in Fig. 8.

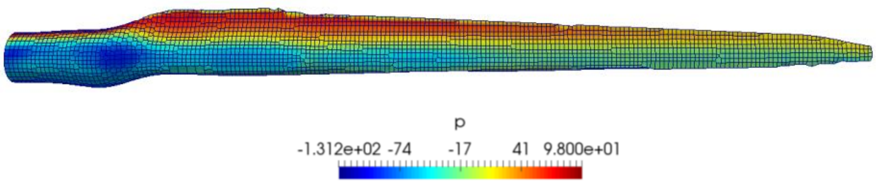

Figure 8: Aerodynamic pressure in the FV at the blade surface

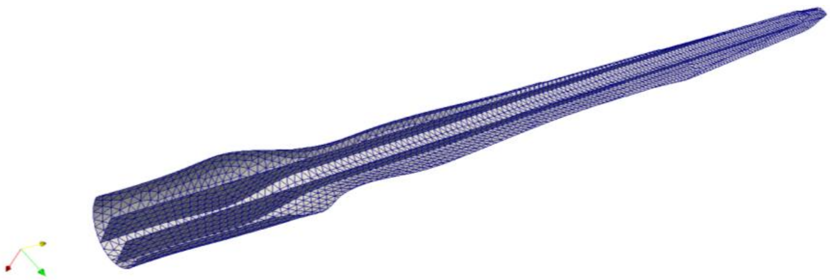

Figure 9: Finite element mesh of the blade (longitudinal section)

In order to determine the SSB of the blade, a finite element model consisting of first order triangular shell elements was used. The mesh size was 7714 elements (1774 of them were stiffening ribs). The appearance of this mesh is shown in Fig. 9.

The result of application of the pressure projection operations is shown in Fig. 10. It should be noted that in this model only the aerodynamic load was considered, and forces of another nature (centrifugal, own weight of the blade) were not taken into account.

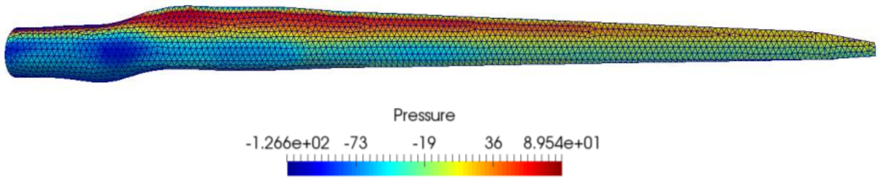

Figure 10: Pressure field interpolated to the FE mesh

The obtained pressure field was used as an external load in determining the SSB of the blade fixed at the left end. The results of calculation of the values of node displacements and stresses are shown in Fig. 11, 12.

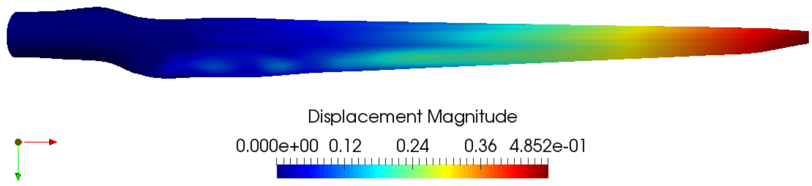

Figure 11: Plot of the displacement

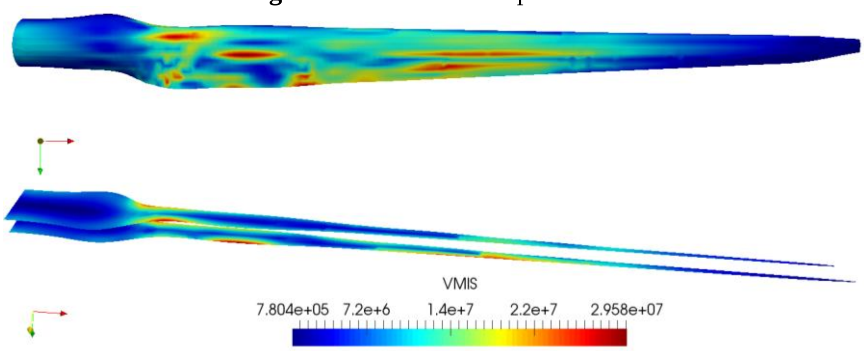

Figure 12: Plot of the stress (Von Mises): top - shell, bottom - longeron

Based on the simulation results, it can be concluded that, for a given flow rate of 12 m/s, maximum displacements at the end of the blade are about 0.49 meters, and in the blade structure of isotropic material there are no stresses leading to destruction.

3.3 Blade dynamic analysis

When solving the nonstationary flow problem in the OpenFOAM, the calculations were performed using a transient pimpleFoam solver for an incompressible viscous medium. As initial fields of pressure, velocity and turbulent viscosity, the results of stationary calculations were used. The time step was selected automatically from the condition for the value of the

Courant number Comax < 0.9. The typical value of the time step is 0.005 seconds. The calculation time for a transient mode of 10 seconds was 2 hours on 1 core (Intel (R) Xeon (R) CPU X5670, 2.93GHz). The open cloud service UNIHUB provided by ISP RAS was used for calculations [10].

As an example for two points lying near the surface of the blade, Fig. 13 shows the graphs of pressure dependency on time.

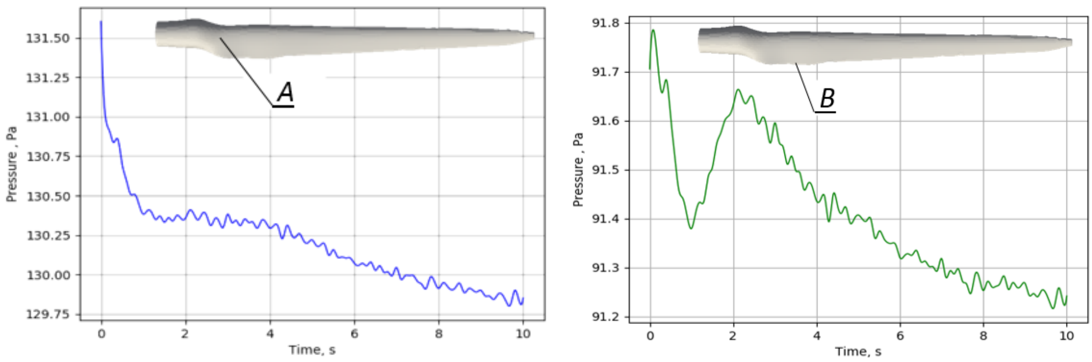

Figure 13: Pressure plots for two points (A and B) near the surface of the blade

The pressure fields obtained as a result of the aerodynamic calculation for each time point were projected onto the FE mesh, and an external load vector was compiled for each time point. Dynamic calculation of the transient mode of the blade oscillation was carried out for the same model as the static one. In this case, Rayleigh damping was introduced with the coefficients α=β=0.05.

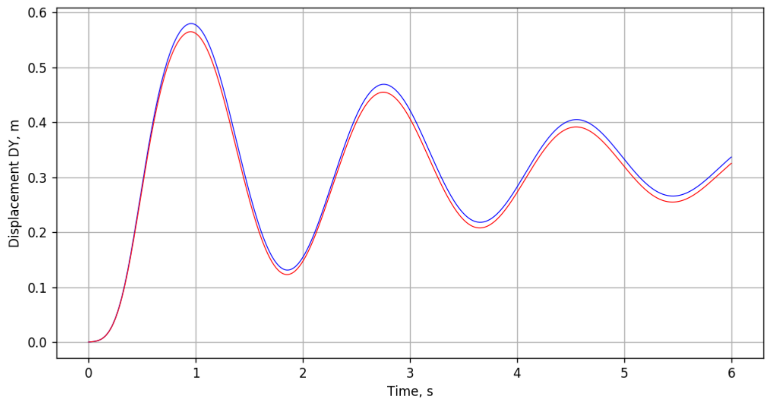

Figure 14: Displacement of the tip of the blade

As a controlled parameter, the Y-component of the displacements of the point lying on the free end of the blade was chosen. For this point, a graph of displacements was plotted for the time interval of 0...6 seconds. The integration step of 0.1 seconds was selected. Fig. 14 shows a comparison of the transition modes for two cases. In the first case (blue), the external load was nonstationary (varied at each integration step), and in the second case (red) the load was constant, suddenly applied at the initial time point.

As can be seen from the graph in Fig. 14, in the considered case, taking into account the nonstationarity of the aerodynamic load of the pressure field has practically no significant effect on the parameters of the transient process. This can be explained by the fact that the self-frequencies of the blade (the lowest self-frequency is 0.56 Hz) are significantly lower than the frequencies of the change in external load (3.0...4.0 Hz). The maximum displacement of the end of the blade in the transitional mode was about 0.58 meters (which is 18% more than the static displacement in the previous calculation), while the displacement in the new static equilibrium position, to which the transition mode tends, is approximately 0.32 meters, which is 30% less than the displacement in the first method calculation.

Further calculation can be carried out with eddy-resolving modeling, using the large-eddy simulation method, in order to obtain instantaneous velocity and pressure components [11].

3.4 Blade quasistatic analysis taking into account the structure deformation influence on the flow

For the same model, according to the flowchart of the algorithm shown in Fig. 3, five iterations (internal cycles) were carried out. The graph of displacement of the free end of the blade is shown in Fig. 15. It is seen that taking into account the influence of blade deformations significantly affects the parameters of its flow, since in this case the maximum displacement was approximately 0.53 meters, which is 10% more than in the first method quasistatic analysis.

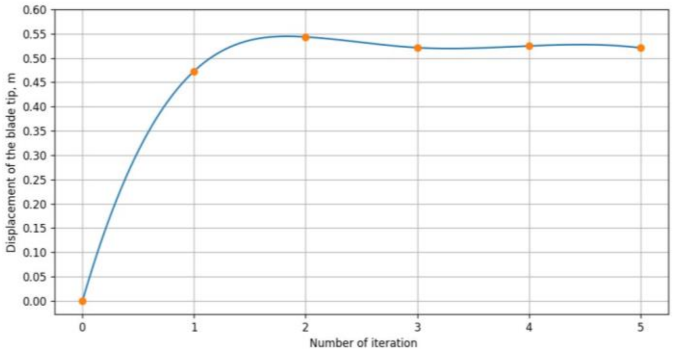

Figure 15: Displacement of the tip of the blade

3.5 Blade dynamic analysis taking into account the structure deformation influence on the flow

At the solution of unsteady problem the simulations were carried out in OpenFOAM by means of a solver with a dynamic mesh pimpleDyMFoam for the incompressible viscous flow. As initial fields of pressure, velocity and turbulent viscosity results of steady-state simulation were used.

The main feature of this simulation was using of hybrid unsteady turbulence model like Detached Eddy Simulation (DES) based on RANS Spalart-Allmaras turbulence model. The time step was selected automatically of a condition for Courant number Comax < 0.9. The characteristic size of time step was 0.005 seconds.

The dependence of pressure from time for the point lying near the surface of the blade is provided on Fig. 16.

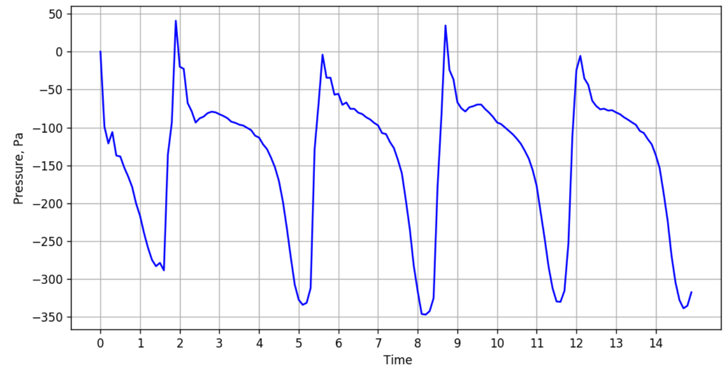

Figure 16: Pressure plots for point A near the surface of the blade

At this approach on each temporary step the loading from external aerodynamic pressure is transferred to FE solver where fields of movements are calculated. The received fields of movements are transferred to OpenFOAM for FV mesh deformation.

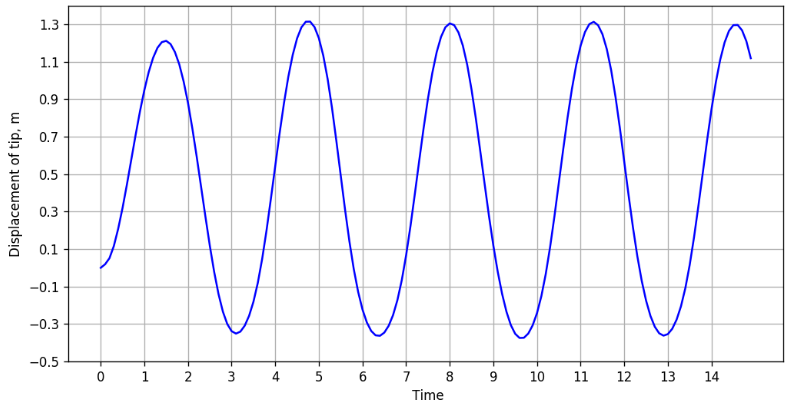

Figure 17: Displacement of the tip of the blade

The dynamic analysis of the transitional mode of blade's fluctuations has been carried out for the same model, as static. At the same time damping according to Rayleigh with coefficients α=β=0.25 has been entered. The step of interface of the equations of subsystems has been chosen 0.1 seconds. In Fig. 17 the graphic for movement of the end of the blade is shown. From the drawing it is visible that fluctuations have the established character.

The simulation time of the transitional mode lasting 15 seconds was 11 hours on one core (Intel(R) Xeon(R) CPU X5670, 2.93GHz).

4 CONCLUSIONS

The paper allows to conclude that the free software packages OpenFOAM and Code_Aster in combination with the Salome-Meca preprocessor have all the necessary tools to use them as a basis for creation of a single software package for solving static aeroelasticity problems and to study small forced oscillations of the wind turbine blade in a viscous medium flow.

The four simple methods for coupling of these two packages proposed and tested on the model problem, based on the transfer of results between the FV and FE meshes, show the stability of the count and the adequacy of obtained results. However, the values of deflections obtained by different methods differ significantly, which requires further verification. In the future, the presented methods can be used to solve more complex verification problems using known experimental data. Also, the obtained results are the basis for implementation of the method for solving completely related aeroelasticity problems on the basis of free software.

5 ACKNOWLEDGEMENTS AND REFERENCES TO THE GRANTS

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