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SIMULATION OF AERODYNAMICS AND AEROACOUSTICS OF HELICOPTER MAIN ROTOR ON UNSTRUCTURED MESHES

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Abstract. A CFD simulation approach for prediction of aerodynamic and acoustic characteristics of helicopter rotors is presented. The numerical method is based on a finite-volume discretization of Navier–Stokes equations using a higher-accuracy numerical scheme for unstructured hybrid meshes.

1 INTRODUCTION

The choice of the optimal helicopter rotor configuration is a laborious and costly process. The evaluation of rotor characteristics using engineering methods on the base of impulsive, vortex and disk vortex theories is rather cheap and helpful, but not accurate enough especially for complex geometries of rotors and increasing speeds of modern helicopters.

The physical experiments are a very costly process requiring both an expensive production base and high labor efforts. Furthermore, the range of rotor operating conditions that can be reproduced in experiments on the ground and the size of the investigated model are limited by the size of the working zone of the wind tunnel involved in the experiment. All this makes the computational experiment an indispensable tool in the process of aircraft design. Moreover, numerical predictions are becoming more affordable with the growth of power of modern high-performance computer systems and with the development of more accurate and efficient mathematical models and simulation technologies.

The paper presents a simulation approach for evaluation of aerodynamic and acoustic characteristics of a helicopter rotor of a complex geometric shape at different operational conditions. The computational algorithm is built using higher-accuracy numerical methods on unstructured meshes. Besides, the paper analyzes the ways of possible reduction of computational costs needed for performing the corresponding predictions.

The developed approach is used for the simulation of two cases of different rotor configurations: a single main rotor and a shrouded tail rotor.

2 NEAR FIELD MODEL

In this paper, the flow around a rotor rotating at an angular velocity $\boldsymbol{\omega}$ is governed by the system of Navier–Stokes equations in a noninertial coordinate system, written in the form of conservation laws relative to the absolute velocity vector:

$$\begin{aligned}
&\frac{\partial \rho}{\partial t} + \operatorname{div} \rho \left(\mathbf{u} - \mathbf{V}\right) = 0 \\
&\frac{\partial \rho \mathbf{u}}{\partial t} + \operatorname{Div} \rho \left(\mathbf{u} - \mathbf{V}\right) \otimes \mathbf{u} + \nabla p = \operatorname{Div} \mathbf{S} - \rho \left(\boldsymbol{\omega} \times \mathbf{u}\right) \\
&\frac{\partial E}{\partial t} + \operatorname{div} \left(\mathbf{u} - \mathbf{V}\right) E + \operatorname{div} \mathbf{u} p = \operatorname{div} \mathbf{q} + \operatorname{div} \mathbf{S} \mathbf{u},
\end{aligned} \tag{1}$$

where $\mathbf{V} = \boldsymbol{\omega} \times \mathbf{r}$ is the linear speed of rotation of the blade, $\mathbf{q}$ is the heat flux and $\mathbf{S}$ is the stress tensor.

For an observer in a fixed coordinate system, the system of equations (1) describes evolution of conservative variables due to their transport in a medium rotating at a velocity $\mathbf{V}$, a pressure gradient and rotation of the velocity vector by an angle $|\boldsymbol{\omega}|\, t$. In the numerical implementation of this system of equations, the speed of rotation can be interpreted as the speed of the moving mesh. In this form, the system of equations was considered, for example, in [1, 2].

The difference between the system (1) from the Navier–Stokes system, written in a fixed coordinate system, consists only in changing characteristic velocities in the Jacobian matrix of a gas-dynamic flow (the eigenvalues of the Jacobi matrices of systems written in the inertial and non-inertial coordinate systems differ by the speed $-\mathbf{V}$) and the presence of a source term on the right hand side. Therefore, approximation methods for (1) using Godunov-type schemes will remain the same as in case of a fixed coordinate system.

Boundary conditions for the system (1) include characteristic flux-splitting conditions for inflow and outflow surfaces, no-slip and slip [3] conditions for solid surfaces in case of viscous and inviscid flows, respectively. In addition, angular periodic boundary conditions can be used in order to represent the computing domain of a rotor as a sector of a body of revolution with a single blade inside.

The system (1) written in the rotating coordinate system has a natural extension to the turbulent flow models within Reynolds-averaged NavierStokes (RANS), large eddy simulation (LES) and hybrid RANS-LES approaches.

3 NUMERICAL METHOD

For the spatial discretization of system (1) we use the original Edge-Based Reconstruction (EBR) scheme of higher accuracy [4] and its WENO version supporting the solutions with sharp gradients and discontinuities [5]. For smooth solutions these schemes provide the accuracy not less than of the second order for arbitrary unstructured meshes, and of the fifth or sixth orders for translationally symmetric meshes (i.e. uniform grid-like meshes). The higher accuracy of the EBR scheme is achieved by quasi-one-dimensional reconstructions of the variables on the extended edge-oriented stencils.

An explicit time integration scheme is restricted to unacceptably small time steps, since spatial mesh steps in boundary layer zones near solid walls are typically very small. For this reason, the time integration is performed using an implicit 2-nd order scheme with Newton linearization, which allows advancing in time with sufficiently big time steps.

The proposed method of numerical simulation is implemented in the in-house code NOISEtte [6] for higher-accuracy computations of aerodynamics and aeroacoustics problems on unstructured meshes.

4 FAR FIELD MODELING

The integral formulation "1A" proposed by Farassat [7] on a base of the Ffowcs Williams – Hawkings (FWH) method has been used for modeling of acoustic characteristics of a helicopter rotor. This "1A" formulation admits use of a control surface of an arbitrary shape but the velocity the points of the control surface is assumed to be subsonic. Otherwise, when passing over the speed of sound, the integral formula contains a singularity that makes it difficult to apply the FWH for a rotating rotor. Solutions for this problem were proposed in [8, 9]. However, their implementation is quite complicated and entails additional computational costs.

A simple to implement modification of the "1A" formulation was proposed in [10]. The key idea of this modification is the parametrization of the control surface in the absolute inertial system associated with the fuselage of the helicopter instead of the rotating coordinate system associated with the rotor. It is assumed that the control surface is a surface of revolution about the axis of the rotor. This assumption keeps the surface undeformable under the proposed parametrization. In addition, the use of a uniform grid in spherical coordinates allows simple interpolation of variables and calculation of the angular derivative at any point on the control surface. As a result, the problem reduces to calculating the surface integral with delay, with the necessary data on the surface, moving translationally with respect to the background flow. This problem is easily solved by using the "1A" formulation.

5 WAYS TO REDUCE COMPUTATIONAL COSTS

5.1 Angular periodic boundary conditions

Imposing periodic boundary conditions in the direction of rotation allows to reduce the problem to modeling of a single rotor blade in a sector of a round cylinder the rotor revolves in (see fig. 1). This approach, denoted as *sector*, is only applicable in hover and in vertical climb and descent modes. In these conditions, a rotor generates the axisymmetric flow, in contrast to the cruise condition characterized by non-zero projections of upstream flow on the plane of rotation. In the latter case, modeling the full multi-blade rotor configuration is required.

Additionally, even for hover, climb and descent modes, only the tonal-noise components of the acoustic characteristics can be accurately predicted. For a proper prediction of a broad-band noise the full rotor configuration must be considered. This is because the complete data on the whole FWH surface is gained by replicating the data of a single

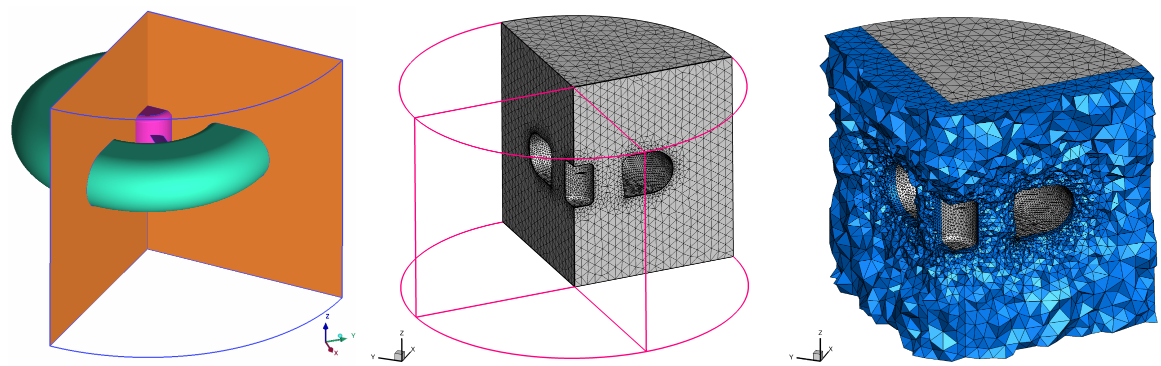

Figure 1: Single rotor blade in a sector of a round cylinder: original configuration (left), sector with a single-blade mesh (center) and single-blade mesh with periodic buffer zones (right)

blade with regard to rotation. As a result, the space and time integration over the FWH surface leads to the simulation of the response from as many correlated acoustic sources as the number of blades. A distorting impact of this artificial correlation is especially noticeable in the regions close to the axis of rotation, where the acoustic pressure levels appear overestimated.

5.2 Using less expensive simulation approaches

Direct numerical simulation (DNS) of a helicopter rotor in real operating conditions by solving the Navier-Stokes equations (1) requires very high mesh resolution in order to represent all the relevant scales of motion, which leads to an unaffordable computing cost.

Among the potentially affordable alternatives, the scale-resolving approaches, in particular, hybrid RANS-LES methods such as DES, are sufficiently accurate for all the flight regimes. However, these approaches are still too expensive for serial computations in the process of industry-oriented engineering design. In some particular operating conditions less compute-intensive models for the flow description in the near field can be applied depending on the target characteristics.

In hover, vertical climb and slow vertical descent modes, the aerodynamic characteristics can be well predicted using the RANS equations. Moreover, to estimate the thrust, which depends only on normal components of aerodynamic forces, the viscosity impact can be neglected and the Euler equations (EE) can be sufficient. At the same time, the torque depends on longitudinal components so the prediction can not be correct without a careful consideration of viscous effects.

In descent mode with a big enough vertical velocity the interaction of tip vortices with the blades can present a significant impact. Although an acceptable accuracy can be achieved by RANS, the more expensive DES model can be preferable since it better describes a complex phenomena formed by interactions of vortices of different scales.

In cruise condition, the interaction of blades with blade-tip vortices and wakes also requires a careful mathematical description. The RANS equations may still be applicable, however, the scale-resolving approaches such as DES are in great demand.

From the standpoint of acoustic characteristics, the near-field region represents a dis-

Flight mode	Properties	Sector	EE	RANS	DES
Hovering, vertical climbing, slow descent (with negligible blade-vortex interaction effects)	Thrust	+	+	+	+
	Torque	+	−	+	+
	Tonal noise	+	+	+	+
	Broadband noise	+	−	−	+
Descent	Thrust	+	+	+	+
	Torque	+	−	+	+
	Tonal noise	+	+	+	+
	Broadband noise	±	−	−	+
Cruising flight	Thrust	−	+	+	+
	Torque	−	−	+	+
	Tonal noise	−	+	+	+
	Broadband noise	−	−	−	+

Table 1: Roadmap of models

tributed acoustical source. Therefore, the model used in the near field determines the far fields acoustics and its spectrum. For instance, if capturing only a tonal noise due to loading and displacement is sufficient, the EE and RANS approaches can produce acceptable results. For accurate prediction of the noise emission from a helicopter rotor, including broadband components, the use of scale-resolving models is of crucial importance.

Table 1 summarizes the flight regimes and simulation approaches for a proper evaluation of helicopter rotor characteristics. Additionally, applicability of the sector approach with periodic boundaries is indicated.

5.3 Linear solver configuration

In case of a Newton-based implicit time integration scheme, an optimized configuration of a linear solver for the Jacobi system is of major importance. Firstly, an appropriate linear solver for a large sparse system must be chosen. Then, in case of an iterative solver, an appropriate residual tolerance level must be determined. On one hand, insufficient accuracy may result in a slower convergence of the Newton process. On the other hand, after a certain residual level, a rather expensive increase in accuracy is not affecting the Newton convergence. Then, for a given solver and a given tolerance, the solver configuration must be properly adjusted, such as the choice of the preconditioner, etc.

In our code we use a preconditioned Bi-CGSTAB [11] solver for a block sparse matrix. The block size is equal to the number of flow variables. The solver tolerance is adjusted by monitoring with a certain interval the effect of residual criterion variation on the Newton process convergence. This allows to adapt the solver accuracy for different time step sizes.

Then, the preconditioner is chosen depending on the actual convergence properties. The most simple one, the block Jacobi preconditioner, is used in a baseline configuration.

For a moderate time step size it can give fast enough convergence. If the baseline solver needs 10 – 20 iterations, the block symmetric Gauss-Seidel preconditioner (SGS) is used instead, which is still cheap at the setup stage, but is more compute-intensive at the solution stage. It can speedup the solution of Jacobi system by a factor of 2-3, since it notably reduces the number of iterations. If the convergence is even slower, the block version of the incomplete LU factorization (LIU0) is used as a preconditioner. It accelerates further the convergence, but has a more expensive setup part. The benefit about 1.5 – 2 times compared to the SGS can be observed when the time step is big enough. This simple set of preconditioners is far from being exhaustive, but it illustrates the importance of the appropriate solver configuration. Further details about the mentioned preconditioners can be found in [12].

5.4 Accelerating transition to a statistically stationary mode

Another important issue is a reduction of computing cost on achieving statistically stationary flow state. It usually takes very long integration time until the global flow structure induced by the rotor is developed. This transition time interval is several times bigger than the target integration period, in which the flow statistics is accumulated. For this reason in DES simulations a preliminary RANS calculation on the same mesh is used in order to accelerate the formation of the major flow structure including tip vortices. When DES mode is enabled the fine-grained flow structures are quickly developed and captured. Since RANS mode admits orders of magnitude bigger time steps, it allows to significantly reduce the overall calculation time.

5.5 Wall functions

The use of wall functions allows to increase the first wall-normal mesh step in a boundary layer zone near solid walls by an order of magnitude. Such functions use universal wall laws in order to restore near-wall flow parameters without fully resolving the boundary layer, including viscous sublayer. Details can be found, for instance, in [13].

This coarsening of the mesh in wall-normal direction results in notable savings in terms of number of nodes, typically 20–40% of of the overall mesh size. In addition, it results in a many times bigger time step for the same CFL condition. This is crucial, of course, in case of an explicit scheme, but it also gives benefits in case of an implicit Newton-based scheme, since it speeds up the convergence of the linear solver.

6 NUMERICAL RESULTS

6.1 Caradonna & Tung rotor

The first validation case considered was the Caradonna&Tung [14] rotor, which is a two-blade rotor in an axial flow mode rotating at 650 RPM. Its blades are installed at 8° angle. The blade surface is formed by the NACA-0012 airfoil without twist. The Reynolds number, $\mathrm{Re} = 1.01 \times 10^6$, is based on the chord of the blade and the blade tip velocity. A RANS approach with the Spalart–Allmaras model [15] has been used in the simulation on a hybrid tetra-dominant mesh with $7M$ nodes and $37.5M$ elements.

Comparison of numerical and experimental results for the pressure coefficient distribution at different sections of the blade surfaces is shown on fig. 2. The numerical results appeared to be in good agreement with the experimental data.

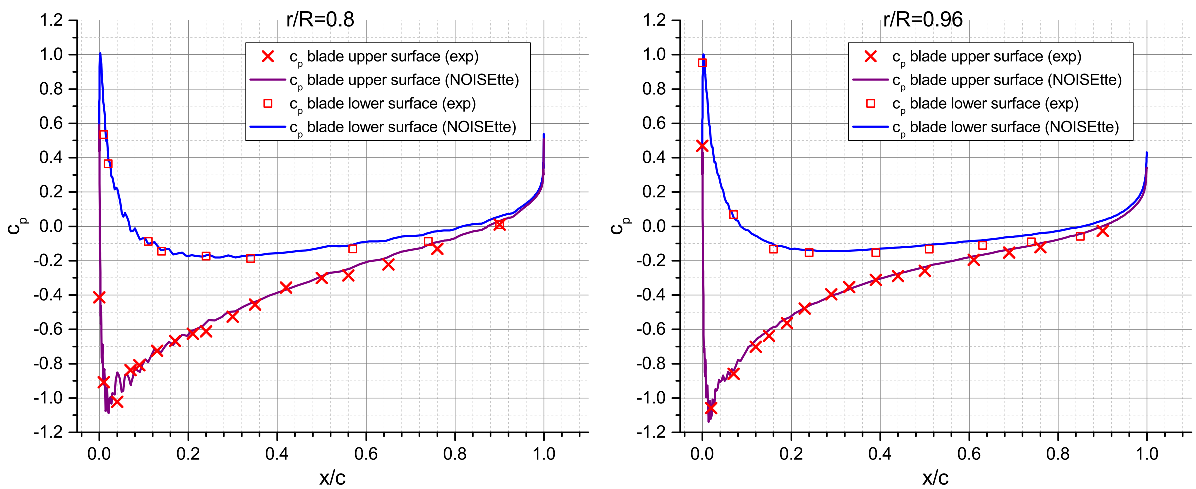

Figure 2: Caradonna & Tung rotor: pressure coefficient distributions

6.2 Flow over a shrouded rotor

The next validation case is a tail shrouded rotor, which includes both rotating and stationary components. The geometry of the model under consideration is based on an actual experimental setup representing a shrouded four-blade tail rotor. The channel (ring), where the rotor rotates, represents an axisymmetric body of revolution. The central body is in the shape of a cylinder with rounded end faces (see Fig.3, left).

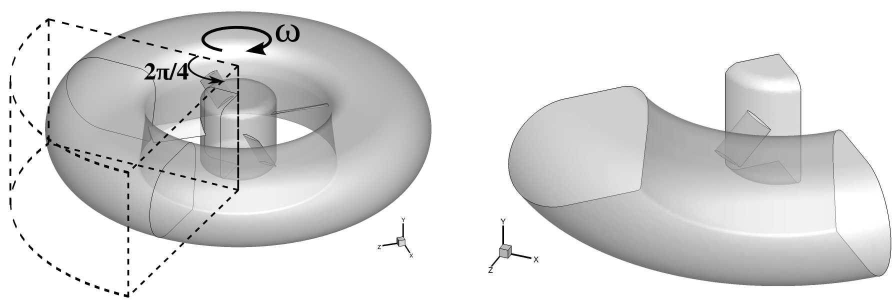

Figure 3: The model shrouded rotor geometry: original configuration (left) and single sector with blade (right)

The spatial symmetry of this configuration without external flow allows to apply angular periodic boundary conditions. Thereby, the problem was reduced to a simulation of a single rotor blade in a $\pi/2$ sector (see Fig.3, right).

The blade surface is based on the TsAGI SV-11 airfoil with the linear twist. We consider the rotor rotation velocity 1166.4 RPM; the pitch angle of the blade can take the values of 10°, 15°, 20°, 30°, and 40°. The Reynolds number is determined by the blade chord and the tip velocity and takes the value $\mathrm{Re} = 6.28 \times 10^5$.

Simulations using RANS approach were carried out on meshes with about $2.5M$ nodes and $15M$ elements. Comparison of the obtained aerodynamic characteristics with the experimental data is shown in Fig. 4. It can be seen that the numerical results are in good agreement with the experiments.

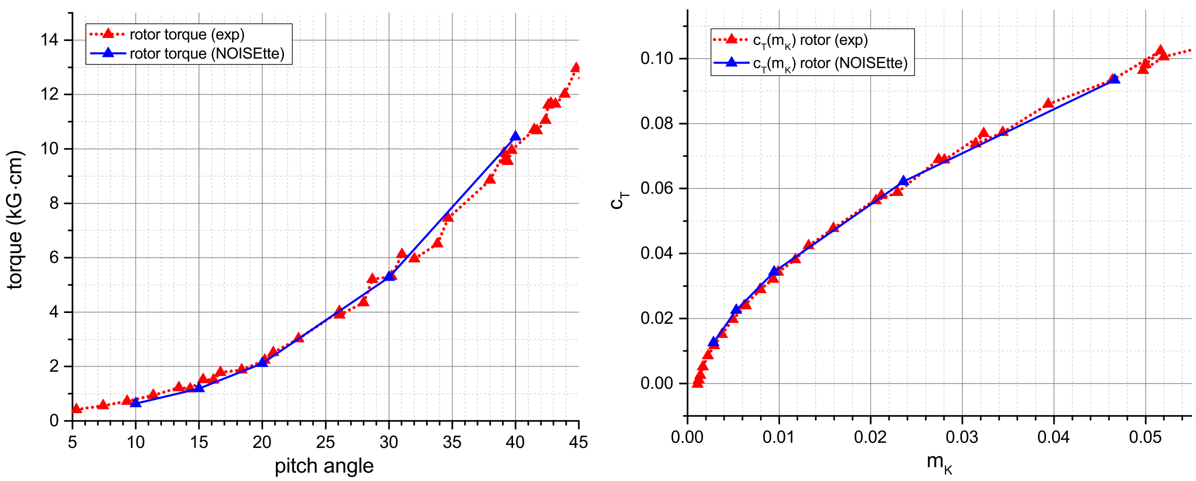

Figure 4: The model shrouded rotor torque(left) and polar curve(right)

The acoustic parameters of the shrouded rotor were analyzed using the integral FWH-approach described above. The results of the calculation are represented in Fig. 5. The directivity diagrams for the overall sound pressure level (OASPL) at a distance 150 m were carried out for the three different FWH-control surfaces (see Fig. 5, left). The overall intensity of the sound radiation increases with the pitch angle, while its peak is displaced into the jet flow region behind the rotor (see Fig. 5, center, right).

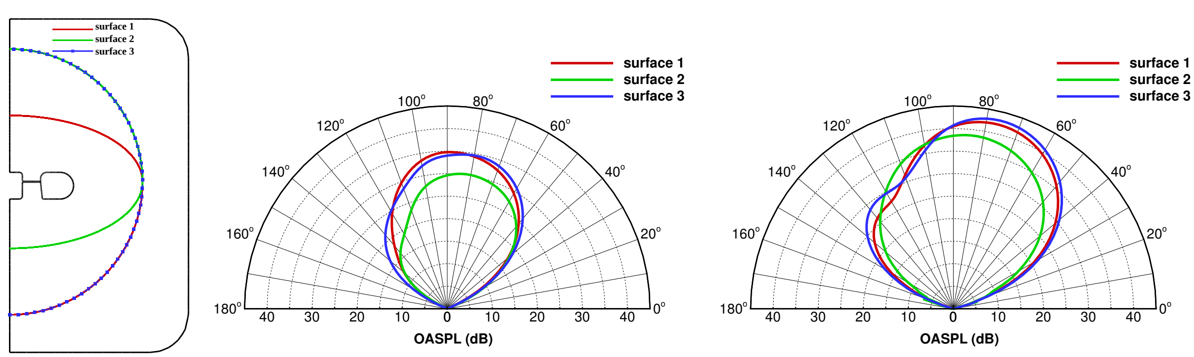

Figure 5: FWH control surfaces (left) and OASPL directivity diagrams for pitch angle 15° (center), 40° (right)

6.3 Flow over four-blades main rotor

Finally, after the validation cases were solved, a main rotor with blades of a complex shape has been simulated. The rotor consists of four rectangular planform blades. Each blade is composed with a piecewise-linear twist using 5 unsymmetrical airfoils of TsAGI and a swept tip. The pitch angle of the blades is 8°. Axial flow around the rotor has been simulated at 584.5 RPM, which corresponds to Mach number 0.35 at blade tips. The Reynolds number based on the blade's chord and the tip velocity is $\mathrm{Re} = 1.4 \times 10^6$.

A hybrid unstructured mesh of 99M elements and 19M nodes has been used for a single-blade sector. The full mesh for the four blades consists of 392M and 75M nodes, respectively. RANS(SA) and DES models have been used in simulations. The obtained flow fields are shown in Fig. 6. The acoustic results are depicted in Fig. 7 and Fig. 8.

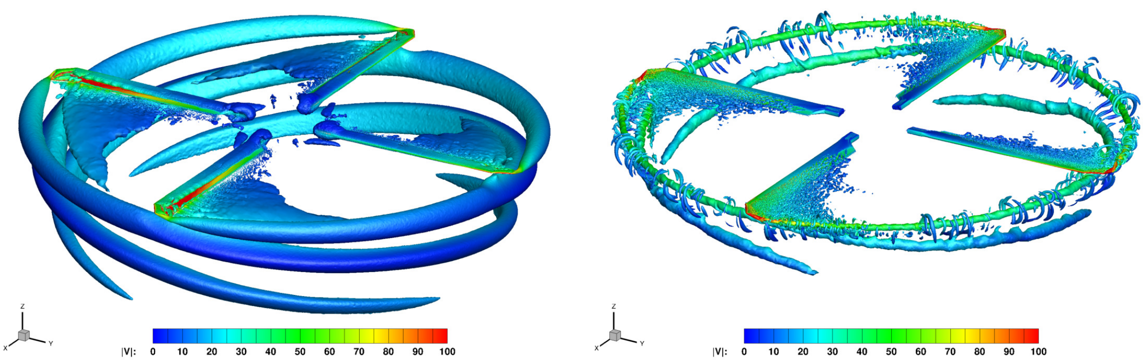

Figure 6: The turbulent structures (Q-criterion) resolved using RANS-SA (left) and DES (right)

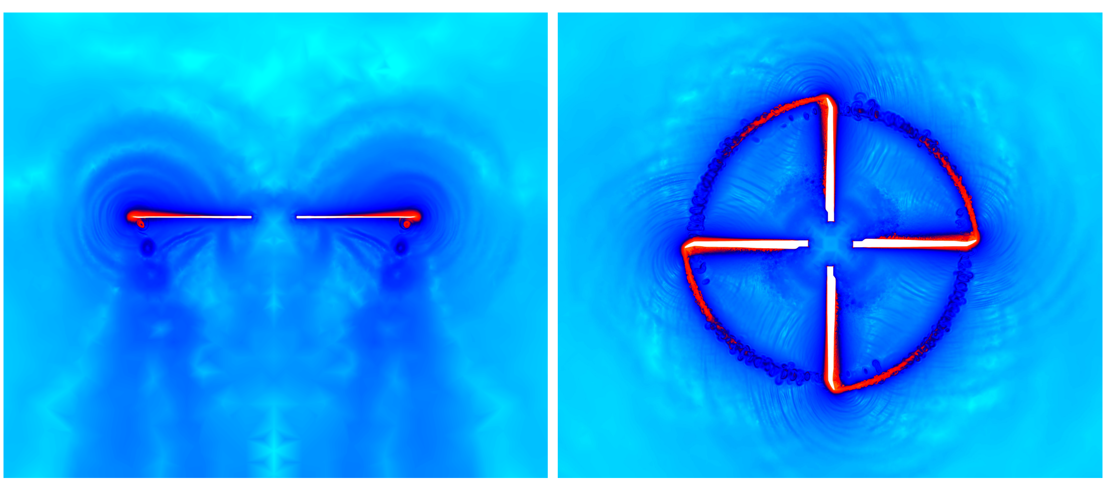

Figure 7: The absolute values of density gradient ("numerical Schlieren") on plane sections

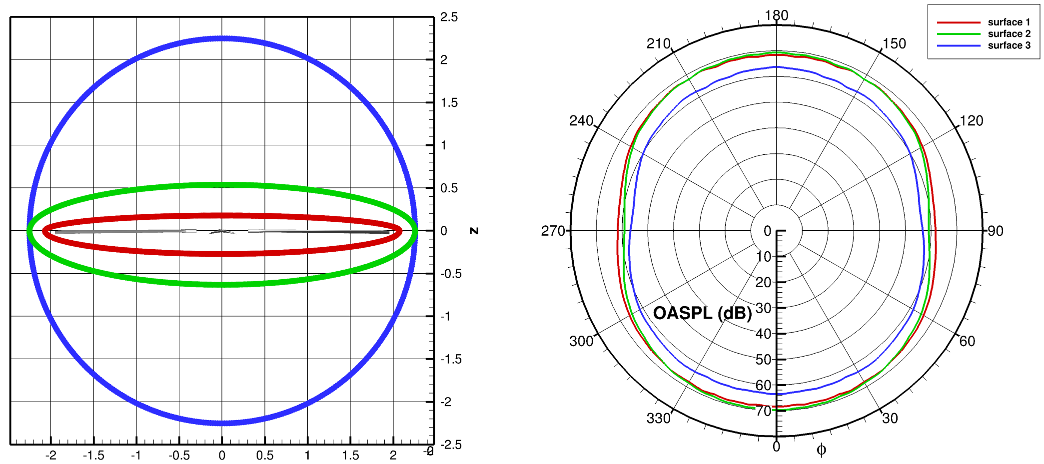

Figure 8: FWH control surface (left) and OASPL directivity diagram(right)

7 CONCLUSIONS

The paper presents an approach to predict aerodynamic and acoustic characteristics of helicopter rotor. This approach implies the numerical simulation of a compressible flow governed by the Navier–Stokes equations written in the noninertial coordinate system. The numerical algorithm is based on the higher-accuracy EBR schemes for unstructured meshes. The far field acoustics is evaluated using the FWH method with the control surfaces of axisymmetric shapes considered in the fixed coordinate system. It has allowed to avoid singularities in the FWH integral caused by the transonic transition. An attention has been paid to the possible ways to reduce the computational costs within the developed approach. The future investigations are aimed at the extension of the developed approach to multi-rotor configurations under retention of reasonable computational costs.

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