Journal of KONES Powertrain and Transport, Vol. 21, No. 2 2014

ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1133905
DOI: 10.5604/12314005.1133905

COMPUTATIONAL INVESTIGATIONS OF ACTIVE FLOW CONTROL ON HELICOPTER-ROTOR BLADES

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Abstract

The paper presents results of the first stage of the research conducted within the frames of Active Rotor Technologies, which is the dynamically developed sub-domain of Rotorcraft Engineering. The research concerned a computational modelling and investigations of new solutions aiming at improvement of performance of modern helicopters and their environmental impact, by active control of operation of their rotors. The paper focuses on one of such solutions applied for the active control of airflow around helicopter-rotor blades. This solution is the Active Gurney Flap – a small, flat tab located at a pressure side of rotor blade near its trailing edge, which is cyclically deployed and stowed during rotation cycles of the blade. The Active Gurney Flap seems to be very promising solution which will enable helicopters to operate with reduced power consumption or reduced main rotor tip speed whilst preserving current flight performance capabilities, especially in terms of retreating blade stall.

The newly developed methodology of computational modelling of active-flow-control devices, like Active Gurney Flap, applied for enhance a helicopter performance and improve its environmental impact, has been presented. Development of the methodology was the challenging task, taking into account strongly unsteady character of modelled phenomena and large differences of scales in both the space and time domain, where very small, dynamically deflected tab strongly influences the flow around rotating, large main rotor. Exemplary CFD simulations, presented in the paper, have been conducted to validate developed methodology.

Keywords: *rotorcraft, rotor aerodynamics, active flow control, Active Gurney Flap, URANS, ANSYS FLUENT*

1. Introduction

Helicopters are the means of transport being still under development and improvement. Contemporary rotorcraft engineers have to cope with new challenges and growing requirements of the market. While traditional rotorcraft technologies are approaching to their limits, the new technologies are being the subjects of interest and hope of further progress. Among these new approaches, the Active Rotor Technology seems to be especially promising when going to improve main drawbacks of helicopters: low/moderate cruise speeds and high emission of noise.

The Active Rotor Technology is the dynamically developed sub-domain of Rotorcraft Engineering, which is focused on the improvement of performance of modern helicopters and their environmental impact, by active control of work of main rotors. The active control of helicopter rotor may concern several different aspects, but the paper focuses on one of them – the active control of airflow on helicopter-rotor blades. Generally, to control the airflow on the rotor blades, two approaches are being applied: mechanical and fluidic. The former approach utilises small mechanical devices e.g. flaps, tabs, etc. dynamically deflected during blade-rotation cycles or even whole morphing blades changing their shape to adjust themselves to current flow conditions. The latter approach is based on fluidic devices like micro-nozzles, usually influencing the flow around the blades by blowing/suction of air. The solution presented in the paper belongs to the group of mechanical devices, and it is named Active Gurney Flap.

The classic Gurney Flap [2] flat tab located at a pressure side of lifting surface near its trailing edge. The tab deflects the air stream behind the trailing edge downwards, leading to increase of the lift-force. The solutions using Gurney Flap have been applied in many areas. In rotorcraft engineering, instead of static tabs, applications of dynamically deployed Active Gurney Flap (AGF) are widely explored. According to the definition, the Active Gurney Flap is a fully retractable structure protruding perpendicularly to chord line on the lower blade surface at the trailing edge. The kinematics of the flap consists of continuous, prescribed, vertical motion achieved through a mechanism mounted inside the rotor blade. Possible applications in helicopter rotors include lower frequencies of deployment (1 deployment per revolution) applied for performance enhancement and higher frequencies of deployment applied for vibration control. It is expected that application of the Active Gurney Flap will enable helicopters to operate with reduced power consumption or reduced main rotor tip speed whilst preserving current flight performance capabilities, especially in terms of retreating blade stall.

To take full advantage of aerodynamic benefits of rotor blades equipped with AGFs, it is necessary to gain knowledge about physical phenomena that occur in the flow around such configurations. It is also desirable to find geometric and kinematic parameters of the AGF, optimal from the point of view of improving helicopter-rotor efficiency. The presented paper concerns such research, carried out based on Computational Fluid Dynamic (CFD). The study was accomplished within the EU 7th FWP Project COMROTAG (Development and Testing of Computational Methods to Simulate Helicopter Rotors with Active Gurney Flap). The paper refers to the first stage of the project, within which the innovative methodology of computational modelling of flight of helicopter rotor with blades equipped with the AGF has been developed. Although the presented methodology was originally developed to support research concerning the AGF, the methodology may be adapted to modelling and investigations of other devices, both the mechanical and fluidic, controlling the airflow around the helicopter-rotor blades.

2. Methodology of Computational Modelling of Flight of Helicopter Rotor with Blades Equipped with the AGF

The subject of the research is the helicopter rotor, which blades are equipped with the AGF. The segment of such a blade is presented Fig. 1.

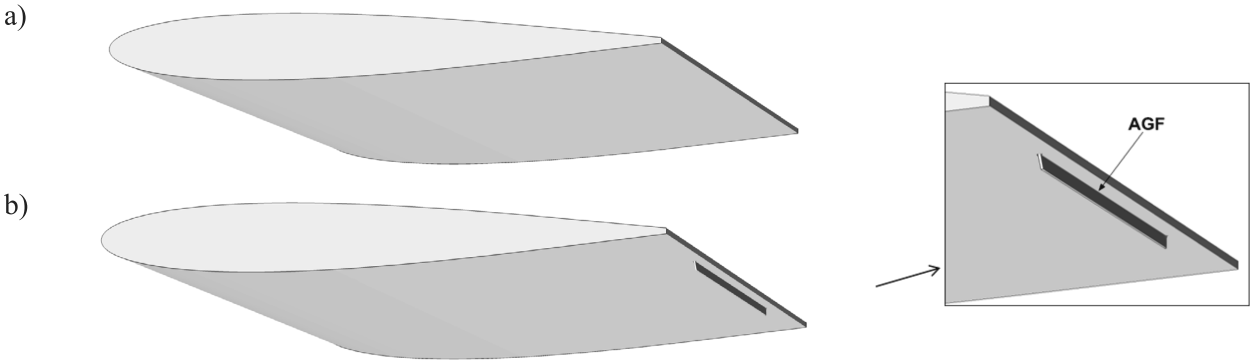

Fig. 1. The segment of the rotor blade equipped with the Active Gurney Flap, (a) AGF fully retracted , (b) AGF fully deployed

The flow around investigated configuration is considered fully unsteady, taking into account following phenomena:

- forward flight of the rotor,
- rotation of the rotor around the rotation axis,
- time-variable pitch of rotor blades – the movement resulting from given collective and cyclic pitch controls as well as from pitch-flap coupling,
- flapping of rotor blades around a flapping hinge,

- lead-lag motion of rotor blades around a lead-lag hinge (if any),
- aero-elastic deformations of rotor blades.
- cyclic deployment and retreat of the Active Gurney Flaps mounted on the rotor blades.

In general, the proposed methodology of modelling of defined the described above motion of the rotor, consists in the solution of unsteady Navier-Stokes Equations in time-varying domain surrounding the rotating blades. General scheme of the methodology is shown in Fig. 2. It is assumed that the Unsteady Navier-Stokes Equations are solved in the in time-varying domain using the software ANSYS FLUENT [1]. It is commercial, general-purpose CFD code for the solution of the Euler/Navier-Stokes equations by Finite Volume Method. The software provides computational schemes: it implicit in space domain up to 3rd order inclusive and implicit in time domain up to 2nd order inclusive. Compressible flows may be modelled in subsonic, transonic and supersonic flow regimes. Viscous flows may be modelled as laminar, transitional or fully turbulent, with wide spectrum of both the statistical and scale resolving models of turbulence.

In presented in the paper CFD simulations, the FLUENT code was used to solve URANS (Unsteady Reynolds-Averaged Navier Stokes) equations, taking into account unsteady, compressible, viscous model of the flow, with SST k-ω model of turbulence. Computational mesh used in simulations was of high quality and resolution, especially within the regions of boundary layers, aerodynamic wakes and in proximity of the AGF.

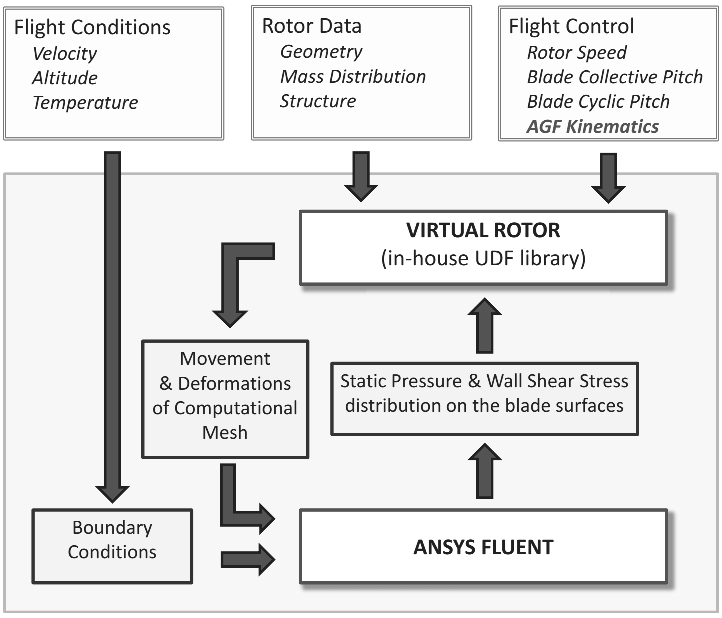

Fig. 2. *General scheme of the proposed methodology of computational simulation of flight of helicopter rotor with blades equipped with the Active Gurney Flaps*

In the presented methodology all computational activities concerning the updating of time-varying computational mesh, specific to rotorcraft applications, are realised by the in-house code VIRTUAL ROTOR written in the C programming language as the module of User Defined Functions linked with the FLUENT solver. The code VIRTUAL ROTOR has been originally developed by Institute-of-Aviation team to support Polish National Project [3] concerning designing of new five-blade main rotor for the helicopter PZL W-3A SOKOL manufactured by PZL Swidnik. Within the frame of research presented in the paper, the VIRTUAL ROTOR code was considerably improved and developed so as to model effects of active-flow-control devices (e.g. AGF) mounted on the rotor blades.

As it is shown in Fig. 2, in the presented approach the input data consists of the initial computational mesh and three data sets describing flight conditions, flight control parameters and rotor data. While the flight conditions define directly external boundary conditions necessary for the FLUENT solver, the rotor data set and flight control parameters are utilised by the VIRTUAL

ROTOR code which, based on these and other parameters deforms the computational mesh. The computational mesh has special structure, and it is divided into several sub-domains as it is shown in Fig. 3. Around each rotor blade, the cylinder-cone shape volume mesh zone is defined. Such zones are embedded the cylinder-shape volume zone surrounding whole rotor and rotating together with the rotor around its rotational axis. Inside the cylinder zone, the cylinder-cone zones surrounding blades may rotate around the pitch axes. This movement is realised using the sliding-mesh technique while the blade rotations are controlled by the VIRTUAL ROTOR based on assumed collective and cyclic pitching control of the blades. The cylinder-cone zones may also rotate around the blade flapping and lead-lag hinges. This movement is determined step-by-step during the simulation by integration of system of ordinary differential equations describing flap-lead-lag motion, which is done using the Adams-Bashforth method. In the case when flap-lead-lag motion of blades is resolved, the mesh inside the cylinder zone is deformed using the Dynamic Mesh technique implemented in FLUENT code. As it is shown in Fig. 3, the cylinder zone is embedded and rotating inside the external, motionless zone modelling far-flow region.

Inside every zone surrounding the single blade, structural mesh of high quality and resolution is generated. During the flight, simulation this mesh may be deformed according to modelled bending and torsional deformations of the blade and first of all to model dynamic deployment and retreat of the Active Gurney Flap. The proposed solution of such mesh deformation is presented in Fig. 4. In this approach, during gradual deflection of the Gurney flap, the computational mesh is gradually stretched on the flap, maintaining the coherence and the high quality of the mesh cells. During retraction of the Gurney flap, similar deformations are performed in inverse direction. This is the innovative approach adapted in the FLUENT solver. Usually, such kind of movement in CFD codes is realised using Overlapping Grid Method [4], which is not accessible in the FLUENT code.

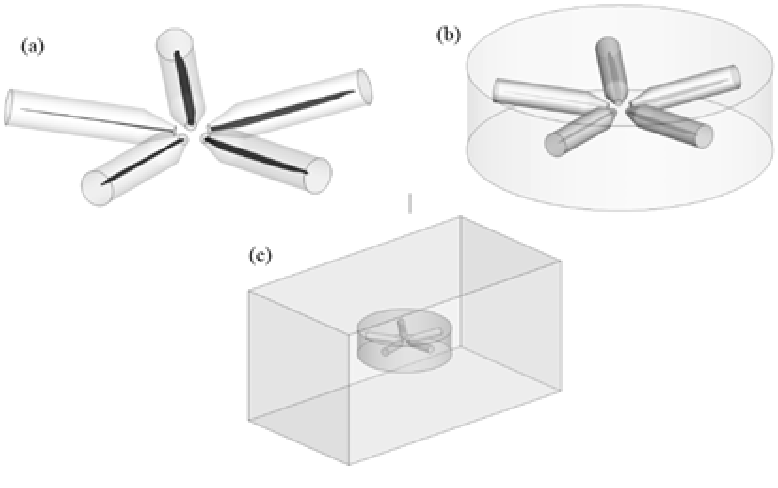

Fig. 3. Structure of computational mesh: (a) cylinder-cone zones surrounding each blade, (b) cylinder-shape zone, (c) far-flow-field zone

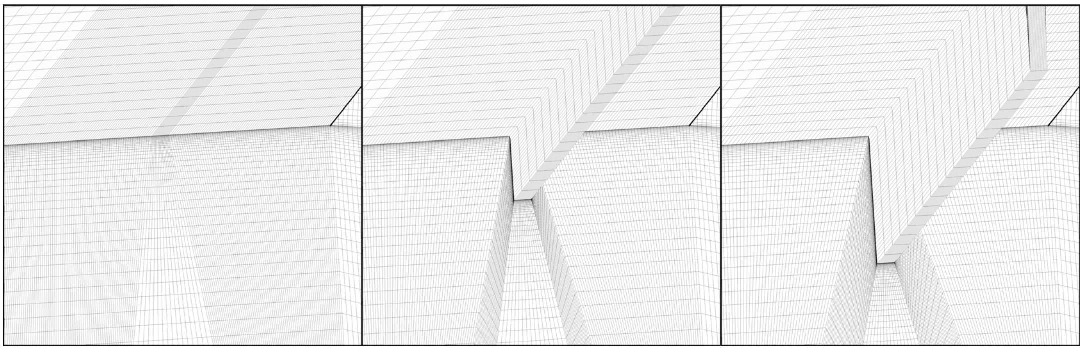

Fig. 3. Stages of 3D-mesh deformations during deployment of the AGF

3. CFD Simulations of Flow around the Blades Equipped with the AGF

Exemplary simulations of flow around the blade segment shown in Fig. 1 were conducted to validate the developed methodology. In the example presented below, instead of full kinematics of rotor blade, the 2.5D simulation of flow around the oscillating blade segment equipped with the AGF was conducted. In the simulation, the assumed free-stream Mach and Reynolds numbers were $M=0.1$, $Re=1164800$. Blade-segment pitching amplitude was 5 deg, average pitch was 5 deg and reduced frequency was $k=0.231$. Harmonic movement of the AGF was consistent in phase with pitching of the segment. Maximal deployment of the AGF was 1.5% of the segment chord. The assumed time changes of the angle of attack (α) and relative height of the AGF (H_{agf}/C) are presented in Fig. 5. Similar computational case, with non-active and hidden AGF, was chosen as a reference configuration. The flow simulations were conducted using the ANSYS FLUENT solver, assuming the flow model 3D, unsteady, compressible, viscous, with Shear-Stress Transport k-ω turbulence model. The computational mesh was of high quality and resolution ($Y+\approx 1$).

Figure 6-8 compare global aerodynamic characteristics (C_L - lift coefficient, C_D - drag coefficient, C_m - pitching moment coefficient as functions of angle of attack α) obtained for cases of active and non-active AGF. Analysis of these figures may lead to the conclusions, that in presented simulation, for higher angles of attack, the dynamic deployment of the AGF influenced:

- approx. 17.5% increase of maximal lift coefficient (C_L) of the blade segment,
- approx. 27.5% increase of maximal drag coefficient (C_D) of the blade segment,
- shifting of pitching moment coefficient (C_m) towards negative values of approx. 0.04.

It should be mentioned, that in presented case, the span of the AGF was twice smaller than the segment span, which weakened an impact of AGF activity on global aerodynamic characteristics of the segment in comparison to the case when both spans are the same.

Snapshots of the flow state in a plane of symmetry of the segment are presented in Fig. 9 (velocity-magnitude contours) and Fig. 10 (vorticity-magnitude contours). The drawings visualise vortex shedding from the deployed AGF and from the trailing edge of the blade segment. The effects of vortex shedding are also visible in Fig. 6-8 as local oscillations of global aerodynamic characteristics (C_L, C_D, C_m), which are considerable especially in a case of the pitching moment coefficient. Further computational investigations confirmed the rule, that the higher is the maximal deployment of AGF, the higher is amplitude of observed oscillations of global aerodynamic coefficients.

The flow simulations were performed to demonstrate computational possibilities of the developed methodology. The methodology of the AGF movement may be directly expanded on cases of simulation of flow around real rotor blades e.g. in forward flight of helicopter. This will be the subject of future works, which will be taken within the next stage of mentioned project COMROTAG.

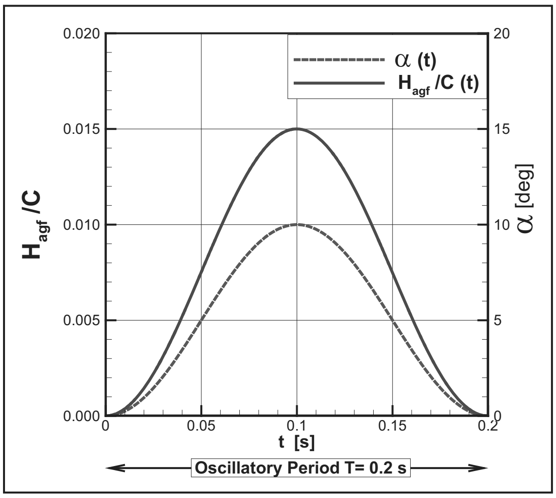

Fig. 5. Assumed oscillations of angle of attack (α) and relative height of AGF (H_{agf}/C)

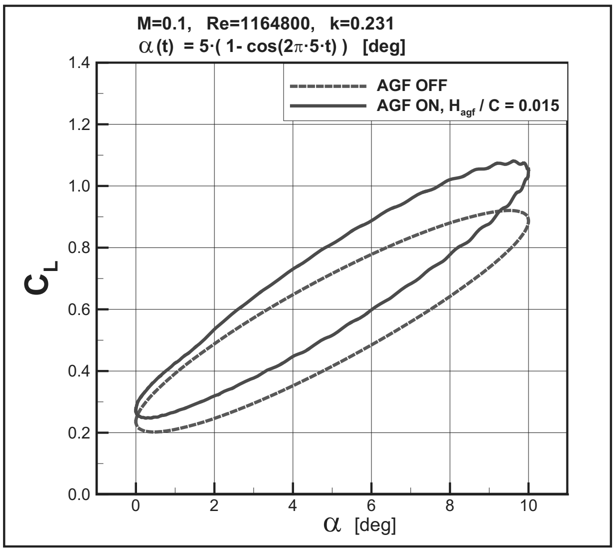

Fig. 6. Comparison of dependencies C_L vs. α for active and inactive AGF

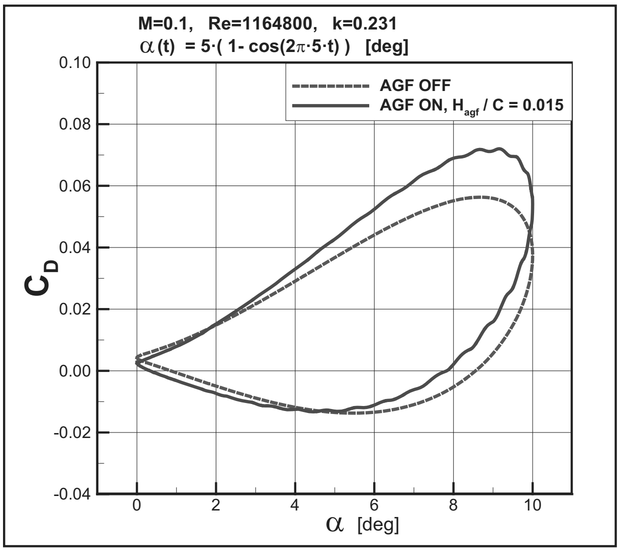

Fig.7. Comparison of dependencies C_D vs. α for active and inactive AGF

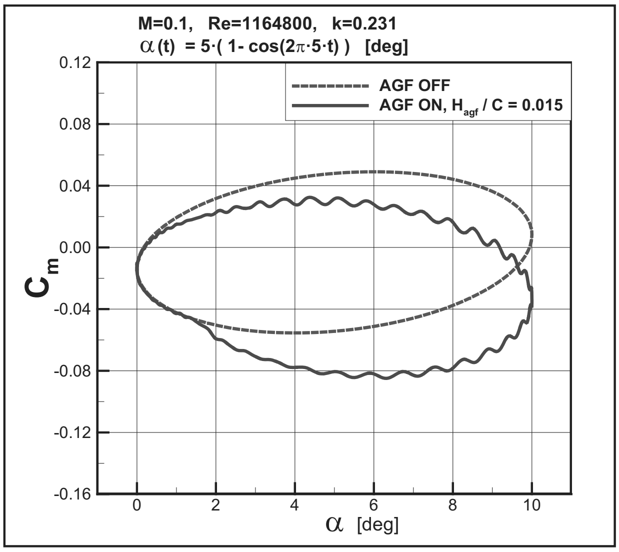

Fig. 8. Comparison of dependencies C_m vs. α for active and inactive AGF

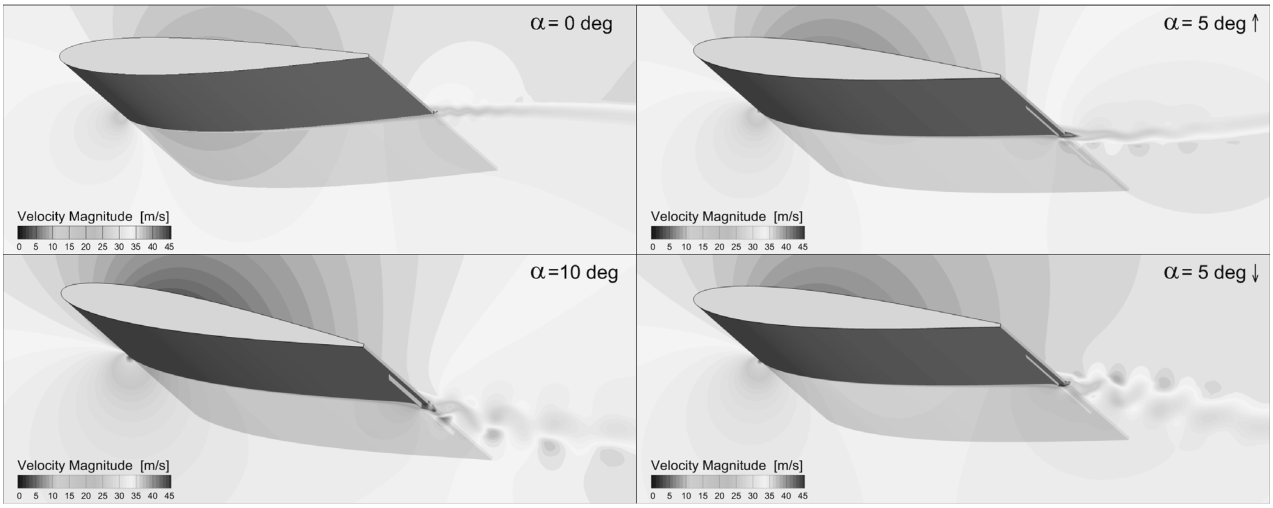

Fig. 9. Contours of velocity magnitude in a plane of symmetry of the rotor-blade segment, for selected angles of attack (α): 0 deg, 5 deg (leading-edge-pitching-up phase), 10 deg, 5 deg (leading-edge-pitching-down phase)

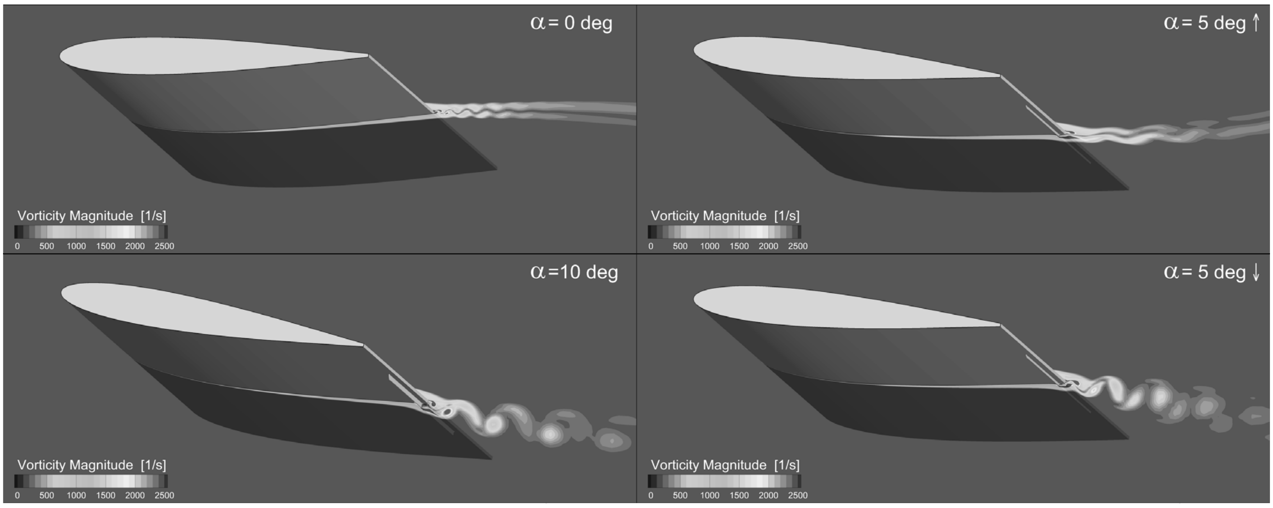

Fig. 10. Contours of vorticity magnitude in a plane of symmetry of the rotor-blade segment, for selected angles of attack (α): 0 deg, 5 deg (leading-edge-pitching-up phase), 10 deg, 5 deg (leading-edge-pitching-down phase)

4. Summary and Conclusions

The newly developed methodology of computational modelling of active control of flow around the helicopter rotor blades has been presented. The methodology was originally developed to support research concerning the Active Gurney Flap - a small, flat tab located at a pressure side of rotor blade near its trailing edge, which is cyclically deployed and retreated during rotation cycles of the blade. The device seems to be very promising solution which will enable helicopters to operate with reduced power consumption or reduced main rotor tip speed whilst preserving current flight performance capabilities, especially in terms of retreating blade stall.

The developed methodology, in general consists in the solution of unsteady Navier-Stokes Equations in time-varying domain surrounding the rotating blades, which is done by application of the software ANSYS FLUENT. Another computational module – VIRTUAL ROTOR is responsible for all computational activities concerning the deformations and updating of time-varying computational mesh, specific to rotorcraft applications. The VIRTUAL ROTOR is the in-house code written in the C programming language, linked with the FLUENT solver. The essence of the developed methodology is developed by the authors of the paper innovative approach to modelling of computational mesh deformation aiming at simulation of dynamic deployment active-flow-control devices like Active Gurney Flap.

Exemplary CFD simulations, presented in the paper, have been conducted to validate developed methodology. They were presented also to explain basic features and possibilities of the developed methodology, which will be further developed and utilised in researches realised within the European Project COMROTAG.

Acknowledgements

The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) for the Clean Sky Joint Technology Initiative under grant agreement no CSJ-GA-2013-619627, within the project COMROTAG.

Computational research presented in the paper was conducted in Polish Interdisciplinary Centre for Mathematical and Computational Modelling, based on the Computational Grant No. G55-4.

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