ROTORCRAFT APPLICATIONS OF ACTIVE GURNEY FLAP INVESTIGATED WITHIN THE CLEAN-SKY PROJECT COMROTAG

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Abstract

Computational investigations within the EU 7th FWP Project COMROTAG have been carried out. The main goal of the Project is to develop, implement and validate through computational tests the methodology of simulation of the flow around helicopter rotors with blades equipped with the Active Gurney Flaps (AGF). The AGF is a small, flat tab located at lower surface of the blade, near its trailing edge. The tab is cyclically deployed and retracted perpendicularly to the blade surface. When deployed, the tab deflects air stream behind the blade trailing edge downwards, leading to the lift increase, which is especially important on the retreating blade of the rotor. On the advancing blade, the tab is retracted to minimise rotor torque. The AGF may be potentially used for the active control of flow on helicopter-rotor blades. The paper presents results of already finished stages of the COMROTAG project. The initial stage was focused on development of innovative methodology of computational simulation of flight of the helicopter main rotor with blades equipped with AGF. In general, the methodology is based on solution of the Navier-Stokes Equations via Finite Volume Method. The motion of helicopter rotor blades equipped with dynamically deployed AGF is modelled using Deforming Mesh and Sliding Mesh techniques. First stage of validation of the developed methodology concerned quasi-2D investigations of rotor-blade segment equipped with the AGF. The computational results have been compared with experimental data obtained in wind-tunnel tests.

1. INTRODUCTION

The Active Rotor Technology is a dynamically developing sub-domain of Rotorcraft Engineering, focused on the improvement of performance of modern helicopters and their environmental impact, by active control of their rotors. Such active control may refer to several different aspects, but the paper focuses on one of them - the active control of airflow on helicopter-rotor blades. Generally, to control the flow on the blades, two approaches are taken into consideration. The first utilises mechanical solutions, dynamically activated and inactivated blade-rotation cycles. The during alternative approach is based on fluidic devices. The solution presented in this paper belongs to the first group and is named Active Gurney Flap (AGF).

The classic Gurney Flap [1] is a small, 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 lift increase. Solutions using Gurney Flap are applied in many areas. In helicopter rotor applications, instead of static tab, the dynamically deployed Active Gurney Flap is taken into consideration.

To take full advantage of aerodynamic benefits of rotor blades equipped with the AGF, 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 improvement of helicopter-rotor efficiency. Investigations concerning this subject are carried out within the EU 7th FWP Project COMROTAG, titled: "Development and Testing of Computational Methods to Simulate Helicopter Rotors with Active Gurney Flap".

The discusses general background paper concerning rotorcraft applications of the AGF and presents results of already finished stages of the COMROTAG project. The initial stage was focused on development of innovative methodology of computational simulation of flight of the helicopter main rotor with blades equipped with the AGF. In general, the methodology is based on solution of the Navier-Stokes Equations via Finite Volume Method, where the motion of helicopter rotor blades equipped with dynamically deployed AGF is modelled using Deforming Mesh and Sliding Mesh techniques. First stage of validation of the developed methodology was focused on quasi-2D investigations of a rotorblade segment equipped with the AGF. The computational results have been compared with experimental data obtained through wind-tunnel tests.

2. COMROTAG PROJECT

The COMROTAG project is realised within the Green Rotorcraft ITD, a component of the Clean Sky Joint Technology Initiative.

The main objective of the project is to develop, implement and validate through computational tests the computational methods of simulation of the flow around a helicopter rotor with blades equipped with Active Gurney Flaps.

The project is conducted within several stages. The initial stage is focused on development of separate CFD codes dedicated for solution of Navier-Stokes equations describing air-flow around:

- rotor-blade airfoil (2D case)
- rotor-blade section (2.5D case)
- helicopter-rotor blades (3D case)

equipped with operating Active Gurney Flap(s). It is assumed, that the above-mentioned codes will be modified and supplemented during the project realisation, based on results of validation conducted within next stages.

The planned validation studies include:

- low-speed and high-speed wind tunnel test of rotor-blade section
- wind tunnel tests of model rotor
- whirl tower tests of full-scale rotor

A separate stage of the project will be focused on series of blind tests: CFD simulations of forward flight of full-scale rotor.

3. METHODOLOGY

Typical AGF mounted on a rotor blade is a small, flat tab located at lower surface of the blade near its trailing edge. The tab is cyclically deployed perpendicularly to the blade surface. When deployed, the tab deflects air stream behind the trailing edge downwards, leading to lift increase, which is especially important on the retreating blade of the rotor. On the advancing blade, the AGF is retracted to minimise rotor torque. Such performance-enhancement application of the AGF is realised in one deployment-retreatment cycle per one revolution of the rotor. Higher frequencies of movement of the AGF are considered for vibrationcontrol purposes. Due to technical limitations, the deployable tab is usually located at a distance of a few percent of the chord from the trailing edge of the blade, as shown in Figure 1, taken from the Patent of Active Gurney Flap [4].



Figure 1. Scheme of implementation of the AGF on helicopter blade taken from the Patent of Active Gurney Flap [4].

3.1. CFD Simulation of Forward Flight of Helicopter Main Rotor

3.1.1. Methodology of Rotor-Flight Simulation

The general scheme of developed methodology of simulation of forward flight of helicopter main rotor is shown in Figure 2. In the presented approach, the simulation of rotor flight consists in the solution of unsteady Navier-Stokes Equations in time-varying domain surrounding the rotating rotor. The Navier-Stokes Equations are solved using the commercial code ANSYS FLUENT [2]. All computational activities concerning specific rotorcraft aspects, including the AGF motion, are realised by the developed code Virtual-Rotor-3D which as compiled module is linked with essential code of the ANSYS FLUENT. Among others, the module Virtual-Rotor-3D is responsible for modelling of:

- forward flight and rotational movement of the rotor
- feathering of the rotor blade, resulting from assumed collective and cyclic pitch controls and pitch-flap coupling
- flap and lag motion of the blades around flap and lag hinges
- cyclic movement of the AGF

Coupled equations of flap and lag motion of the blades are solved simultaneously with the solution of Navier-Stokes Equations, taking into account effects of dampers and springs (or elastomeric bearing), if any. The flap-and-lag motion is described by the system of four ordinary differential equations of the first order. There are four unknown functions in this system: $\beta(t)$, $\zeta(t)$, $\beta(t)$, $\zeta(t)$, where β is the blade-flap angle, ζ is the blade-lag angle, $\dot{\beta} = d\beta/dt$, $\dot{\zeta} = d\zeta/dt$. The system of ordinary differential equations is solved separately for each blade, using explicit, three-step Adams–Bashforth method [5].

The collective and cyclic pitch controls may be changed during the simulation which is used when trimming the rotor, i.e. establishing the collective and cyclic pitch controls so as to obtain required thrust and moments generated by the rotor.

The input data defining computational case of simulation of forward flight of helicopter rotor, consist of computational mesh and three data sets describing: flight conditions, flight control parameters and rotor data. In the presented approach, the computational mesh is divided into several sub-domains. Around each blade, the cylinderconical volume zone is defined, as it is shown in Figure 3. Such zones are embedded in a cylindervolume zone which is embedded in a far-field, cuboid zone. Complete topological structure of computational mesh is presented in Figure 4. During the rotor flight simulation, the mesh surrounding each blade is moving together with the blade.



Figure 2. The general scheme of developed methodology of simulation of flight of helicopter main rotor with blades equipped with AGF.

This movement is a combination of feathering, flapping and lead-lag motion of the blade. Additionally the mesh surrounding each blade is rotating together with the cylindrical zone, around the rotor-rotation axis.

The movement of meshes surrounding the blades relative to the cylindrical zone is realised by the use of Dynamic Mesh and Sliding Mesh techniques implemented in the ANSYS FLUENT solver. Similarly, the rotational movement of the cylindrical zone inside the stationary far-field zone is also realised by the use of the Sliding Mesh technique. stretched on it. During retraction of the AGF, similar deformation is performed in inverse direction. Presented method of simulation of the AGF movement was developed specially for purposes of COMROTAG project. The method ensures high quality of the deformed mesh (including preserving high-quality of boundary-layer mesh of Y^+ ~1) as well as full repeatability of deformations. Presented approach is an alternative to the Overlapping Grid Methods [2], usually utilised in such cases.



Figure 3. Structure of computational mesh: the cylinder-conical zones surrounding each of the rotor blades.

During the rotor flight simulation, the mesh surrounding each blade is locally deformed so as to model a movement of the AGF. Sequential stages of such deformation are presented in Figure 5. During gradual deflection of the AGF, the mesh is gradually



Figure 4. Overall structure of computational mesh.



Figure 5. Sequential stages of 3D-mesh deformations during the deployment of the AGF.

3.1.2. Preliminary Tests of Rotor-Flight Simulation

Discussed in this Section preliminary tests of developed code Virtual-Rotor-3D were conducted for the 4-blade model rotor, which blades of chord 0.09 m were build based on partially modified airfoil NACA0012. The rotor of radius $R_{MAX} = 1.1$ m was fully articulated, with coincident flap and lag hinges.

Flights tests of the rotor have been conducted for the following flight conditions:

- Mach number: 0.132 (flight velocity: 45 m/s)
- rotor angle of attack: -2 deg
- rotor rotational speed: 1600 rpm
- atmosphere: ISA Sea Level

During the flight simulation, the rotor-blade pitch angle θ was changing according to the formula:

(1)
$$\theta(\Psi) = \theta_0 - \theta_S \cdot \sin(\Psi) - \theta_C \cdot \cos(\Psi) -\beta(\Psi) \cdot \tan(\delta_3)$$

where Ψ is the azimuthal position of the blade, θ_0 , θ_S , θ_C are the collective and cyclic components of blade-pitch control, β is the current flap angle and δ_3 is the pitch-flap coupling angle (δ_3 =12.5 deg). In conducted test simulations, the components of blade pitch were set to: θ_0 = 5 deg, θ_S = 5 deg, θ_C = 0 deg.

The forward-flight tests of the model rotor were conducted twice in the same flight conditions, for two following configurations:

- 1. clean rotor blades
- 2. rotor blades equipped with oscillating AGFs

In the latter case, the following AGF-deployment schedule was assumed as a function of the blade azimuthal position Ψ :

(2) $h_{agf}(\Psi) = H_{max} \cdot 0.5 \cdot [1 - \sin(\Psi)]$

where the maximum AGF height (H_{max}) was 2% of the blade chord. The spanwise range of the AGF zone was from 53.5% to 68.5% of the rotor radius.

In conducted CFD simulations of forward flight of the model rotor, the following model of flow has been applied:

- unsteady
- compressible, air model: ideal gas
- URANS, model of turbulence: k-ω SST

General view of investigated four-blade model rotor is presented in Figure 6. The same Figure shows flow velocity-magnitude contours in cylindrical crosssection of the flow region. These contours illustrate considerable differences between flow-velocity fields around the advancing and retreating blade. Figure 7 presents vorticity magnitude contours in a middle cross-section of the AGF zone of the blade, for blade azimuthal positions: Ψ = 0, 90, 180, 270 deg.



Figure 6. Forward flight of four-blade model rotor with blades equipped with the AGFs. Velocity-magnitude contours in cylindrical cross-section of flow region.



Figure 7. Vorticity magnitude contours in the middle cross-section of the AGF zone, for selected azimuthal positions (Ψ) of the blade.

Momentary pressure-coefficient (C_P) distributions in a middle cross-section of the AGF zone are presented in Figure 8.

Both the vorticity-magnitude contours and pressurecoefficient distributions were analysed for the case of rotor with blades equipped with the AGFs oscillating according to the dependency (2). Qualitatively, these results correctly reflect physical aspects of the modelled phenomena. Quantitative validation will be possible after the completion of experimental research in the wind tunnel.

Figure 9 - Figure 18 compare selected aerodynamic properties for two model-rotor configurations:

- "AGF off" the rotor with clean blades
- "AGF on" the rotor with blades equipped with the AGFs, oscillating according to the function (2)

The aerodynamic characteristics were obtained for both compared configurations as results of CFD simulations conducted in the same flight conditions.

Figure 9 presents the time-variable thrust coefficient (C_T) obtained for two compared configurations. The configuration of rotor with blades equipped with the AGFs ("AGF on") has approx. 9.0% higher average thrust coefficient than the clean configuration ("AGF off"). Similarly, Figure 10 shows, that the "AGF on" configuration has approx. 7.2% higher average torque coefficient (C_Q) than the clean configuration ("AGF off"). Finally, the configuration "AGF on" has approx. 1.6% higher average Power Loading (the ratio of thrust to power) than the configuration "AGF off".



Figure 8. Pressure-coefficient (C_P) distributions in the blade cross-section, in the middle of the AGF zone, for selected azimuthal positions of the blade.



during one period of rotor rotation.

Figure 11 presents azimuthal changes of blade-flap angle (β) for two compared rotor configurations. In the discussed case, both compared dependencies β vs. Ψ are very similar, though slightly higher flapping amplitude was observed for the "AGF on" configuration.

Next Figures compare azimuthal changes of aerodynamic moments acting on the single blade. The comparison concerns:

- the coefficient (C_{mθ}) of aerodynamic moment relative to feathering axis - Figure 12
- the coefficient ($C_{m\beta}$) of aerodynamic moment relative to flap hinge Figure 13
- the coefficient (C_{mζ}) of aerodynamic moment relative to lag hinge - Figure 14

All three compared aerodynamic moments properly indicate (at least qualitatively) the effects of application of the AGF on the rotor blades.

Figure 15 - Figure 18 show spanwise distribution of coefficient (C_N) of out-of-plane bending loads acting on the blade, for four selected azimuthal positions of the blade, respectively: Ψ = 0, 90, 180, 270 deg. In this case, the effects of application of the AGFs on helicopter-rotor blades, also seem to be correct, at

least from qualitative point of view. The highest differences in bending loads, occur in the AGF zone of the blade span and on azimuths close to retreating blade, where the deployment of the AGF is the highest.







Figure 12. Coefficient (C_{m_0}) of blade-moment relative to feathering axis versus blade azimuthal position (Ψ).



Figure 13. Coefficient ($C_{m\beta}$) of blade-moment relative to flap hinge versus blade azimuthal position (Ψ).











Figure 16.Distribution of out-of-plane-bending-load coefficient (C_N) along the blade span. Azimuthal position of the blade: Ψ =90 deg.



Figure 17. Distribution of out-of-plane-bending-load coefficient (C_N) along the blade span. Azimuthal position of the blade: Ψ =180 deg.



Figure 18. Distribution of out-of-plane-bending-load coefficient (C_N) along the blade span. Azimuthal position of the blade: Ψ =270 deg.

3.2. Methodology of Solving 2D and 2.5D Computational Problems

According to general objectives of the project COMROTAG, separate codes dedicated to solving 2D and 2.5D computational problems have been developed. These codes are in a sense simplified versions of fully-3D code Virtual-Rotor-3D.

The 2D and 2.5D versions of the code, named respectively "Vitual-Rotor-2D" and "Vitual-Rotor-2.5D", solve computational problems consisting in determination of unsteady flow around the blade airfoil/segment equipped with periodically moving AGF. Additionally, the blade airfoil/segment may oscillate by performing:

- harmonic oscillations of angle of attack α, to simulate effects of feathering of the rotor blade,
- downward-upward oscillations, to simulate effects of flapping of the rotor blade,
- forward-backward oscillations, to simulate leadlag motion of the rotor blade or effect of changeable relative flow velocity around the rotor blade if forward flight of the helicopter.

The above-mentioned components of blade airfoil/segment kinematics are not obligatory and may be freely switched off and on.

In both variants of the code: 2D and 2.5D, the AGF movement is simulated in the same manner as in a case of 3D code described in Section 3.1.

The 2D variant of the code solves typical problems concerning the flow around the airfoil equipped with oscillating AGF. Figure 19 shows exemplary results of such simulations. In this case, several configurations of airfoil equipped with the AGF were investigated in regard to different chordwise positions of the AGF. During each simulation both the angle of attack and free-stream Mach number were changed harmonically. The AGF also was moving harmonically. Its maximum deployment was synchronised with maximum of angle attack and minimum of free-stream Mach number. Among others, Figure 19 shows that developed method of movement of the AGF, is applicable even for the chordwise position of the AGF at 100% of a blade chord.

In general, the 2.5D variant of the code solves typical problems concerning the 3D flow around the blade segment of finite span. The 2.5 code may be seen as simplified version of the 3D code, where simplification consists in neglecting the effect of rotational motion of the rotor blades and all effects of fluid-structure interaction (i.e. flapping, lead-lag motion, etc.).

Unlike the 2D code, version 2.5D can also analyse the flow around the blade segment, where the span of the AGF is less than the span of the whole segment, as shown in Figure 20.

Selected cases of first stage of validation of the developed codes 2D/2.5D are discussed in the Chapter 4.



Figure 19. Vortex shedding visualised through Turbulent-Kinetic-Energy contours, for three different chordwise positions of the AGF. Snapshots taken at the moment of maximum deployment of the AGF. Results of 2D simulation.

4. VALIDATION OF THE METHODOLOGY AGAINST 2D WIND TUNNEL TEST DATA

The first stage of validation of the developed methodology concerned the quasi-2D investigations of a rotor-blade segment equipped with the AGF. The experimental data were obtained during the wind-tunnel-test campaign conducted at University of Twente. The subject of the investigations was the blade segment NACA0012 with thickened trailing edge. In the WTT, the angle of attack of the segment was fixed during every run, while the AGF was cyclically deployed. The same conditions were modelled in CFD simulations, including modelling of





Figure 20. Snapshots of contours of vorticity magnitude in the plane of symmetry of the rotor-blade segment equipped with the AGF of less span, taken for selected angles of attack α = 0deg, 5deg (α -growth phase), 10deg, 5deg (α -drop phase).



Figure 21. Computational model of the blade segment equipped with the AGF, investigated in the test chamber of wind tunnel.

For the quasi-2D simulations, a simplified version of the developed software, named Virtual-Rotor-2.5D, was applied.

The CFD simulations of flow inside the test chamber, around the blade segment equipped with AGF, have been conducted utilising the following model of flow:

- unsteady
- compressible, air model: ideal gas
- URANS, model of turbulence: k-ω SST

In all computational simulations the final, fine time step was set to 0.00002 sec though in initial phases of calculations it was 0.0001 sec.

All presented below results refer to wind tunnel tests conducted for the flow velocity V=60m/s and 5Hz frequency of deployment of the AGF.

The first discussed experimental case was run for the angle of attack of 4 degree and the schedule of the AGF movement presented in Figure 22.



Figure 22. Changes of momentary height of the AGF (h_{agf}) during one period of AGF deployment-retraction cycle.

Figure 23 compares the computational and experimental, time-dependent lift coefficient C_L measured during one period of the AGF deployment-retraction cycle. While the time averaged computational and experimental values of C_L are similar, the computational result indicates strong oscillations, especially in the phase when the AGF is fully deployed. Such phenomenon is not observed in experimental results. Similar behaviour of computational and experimental pitching moment coefficient C_m , is presented in Figure 24.

Looking at the frequency-domain analysis of timevarying pitching moment coefficient (C_m), presented in Figure 25, one may conclude that the dominant frequency of oscillations of computational global aerodynamic coefficients is approximately 545 Hz. This frequency is close to 566 Hz - the dominant frequency of vortex shedding observed in computational results in the static case with fully deployed AGF, V=60m/s, α =0deg (not presented in this paper). Additionally, Figure 25 indicate dominant (but much weaker) frequency of C_m oscillations 1100 Hz, which is close to 1123 Hz - the dominant frequency of vortex shedding observed in computational results in the static case with fully retracted AGF, V=60m/s, α =0deg (not presented in this paper).



Figure 23. Changes of lift coefficient (C∟) during one period of AGF deployment-retraction cycle. Comparison of CFD and WTT results.



Figure 24. Changes of pitching moment coefficient (C_m) during one period of AGF deployment-retraction cycle. Comparison of CFD and WTT results.

Unfortunately, the frequency-domain analysis of the experimental results do not indicate any dominant frequencies neither in proximity 592 Hz nor in proximity 1075 Hz, despite that these dominant frequencies were observed previously in WTT results in the static cases with both the AGF fully deployed and fully retracted. This is quite surprising, especially since the PIV results confirm the occurrence of vortex shedding in the discussed wind-tunnel-test case. One of possible explanation of this incoherence of WTT results in presented case is that the pressure-measuring signals were filtered, so the higher frequencies have been cut.



Figure 25. Frequency-domain analysis of pitching moment coefficient C_m. Comparison of CFD and WTT results.

Examples of comparison of PIV results obtained in WTT and analogous results of CFD simulation are presented in Figure 26 in respect of velocity-magnitude contours, in Figure 27 in respect of vorticity magnitude contours and in Figure 28 in respect of Q-criterion contours.



Figure 26. Velocity-magnitude contours at a moment of fully deployed AGF. Comparison of CFD (top) and WTT-PIV (bottom) results.



Figure 27. Vorticity-magnitude contours at a moment of fully deployed AGF. Comparison of CFD (top) and WTT-PIV (bottom) results.



Figure 28. Q-criterion contours at a moment of fully deployed AGF. Comparison of CFD (top) and WTT-PIV (bottom) results.

The second discussed experimental case was run for angle of attack of 12 degree and the schedule of the AGF movement similar to utilised previously (see Figure 22). Figure 29 compares computational and experimental time-dependent lift coefficient C_L measured during one period of AGF deploymentretraction cycle. The values of computational and experimental coefficient $C_{\rm L}$ are similar. The same concerns the time dependant pitching moment coefficient $C_{\rm m}$, which is shown in Figure 30. Additionally, in the presented case, the CFD and WTT results indicate similar amplitudes and frequencies of oscillations of the coefficients $C_{\rm L}$ and $C_{\rm m}.$



Figure 29. Changes of lift coefficient (C_L) during one period of AGF deployment-retraction cycle. Comparison of CFD and WTT results.



Figure 30. Changes of pitching moment coefficient (C_m) during one period of AGF deployment-retraction cycle. Comparison of CFD and WTT results.

This similarity is confirmed when comparing the frequency-domain analyses of time-varying pitching moment coefficient (Cm), presented in Figure 31. The graphs show lack of high dominating frequencies in both the CFD and WTT results. It is likely, that lack of strong vortex shedding of high frequencies, is a results of weak separation of flow on the upper surface of the blade segment, which may occur at angle of attack of 12 degree. In a presence of flow separation, the vorticity flowing

from the upper surface of the blade at its trailing edge is much weaker. This leads to weakening of the effect of counter rotating vortices flowing from upper and lower part of the blade trailing edge. Thus, the effect of high-frequency vortex shedding is significantly reduced in this case.



Figure 31. Frequency-domain analysis of pitching moment coefficient C_m. Comparison of CFD and WTT results.

Computational and experimental distributions of pressure coefficient (C_P) on the airfoil surface are compared with each other for selected time moments corresponding to the AGF fully retracted and full deployed, in Figure 32 and Figure 33 respectively.



Figure 32. Chordwise distribution of pressure coefficient (C_P) at time moment t/T=0.000. AGF fully retracted. Comparison of CFD and WTT results.



Figure 33. Chordwise distribution of pressure coefficient (C_P) at time moment t/T=0.250. AGF fully deployed. Comparison of CFD and WTT results.

The agreement of computational and experimental results is satisfactory in discussed case.

5. SUMMARY AND CONCLUSIONS

Several stages of EU 7th FWP Project COMROTAG have been carried out. The paper has presented results of two already finished stages. The main goal of the first stage was to develop methodology and implement it in a form of computer codes. Finally, three independent codes were developed, each dedicated for solution of Navier-Stokes equations describing air-flow around:

- rotor-blade airfoil (2D case)
- rotor-blade section (2.5D case)
- helicopter-rotor blades (3D case)

equipped with Active Gurney Flap/Flaps.

The preliminary validation of each of these codes confirmed their fidelity in respect to modelled physical phenomena, at least in qualitative terms. So far, the quantitative validation has been carried out only in respect to the 2.5D code. The validation concerned the wind tunnel test of the segment of the blade equipped with the oscillating AGF.

The validation of the 2.5D variant of the computational method was focused on all accessible experimental data obtained during the wind-tunnel-test campaign, including time-dependent pressure distributions, aerodynamic forces and moments and flow field analysis based on the PIV technique. The unsteady computational and experimental results were analysed in both the real-time domain and in the frequency domain.

Summarising presented stages of validation of the developed codes, it may be concluded, that developed computational methodology gives reliable results in case of quasi-two-dimensional flow around the rotor-blade segment equipped with the Active Gurney Flap. Further validation studies as well as blind tests of forward flight of full-scale rotor are in a progress.

SYMBOLS

С	blade chord
C.	lift coefficient
C.	nitching moment coefficient
C .	blade-moment coefficient
Cmθ	relative to feathering axis
C	blade-moment coefficient
U _{mβ}	relative to flan binge
<u> </u>	blade moment coefficient
U _{mζ}	relative to log binge
C	out of plane bending lead coefficient
C _N	
C _P	torque coefficient
	torque coefficient
С _Т	momentery beight of ACE
п _{agf} ப	morine height of ACE
n _{max}	Mash number
	$\sim 10^{10} \text{ mach number}$
Q	$Q = \frac{1}{2} (\omega ^{-} - S ^{-})$
	s-symmetric, ω - antisymmetric
D	components of flow-velocity gradient VV
к D	Deter reduce
R _{MAX}	Rotor radius
t T	time
	period of rotor rotation
V	velocity
X _{agf}	chordwise position of the AGF
α	angle of attack
β	blade-flap angle
ζ	blade-lag angle
θ	blade-pitch angle
θ_0	collective component of blade-pitch control
θ_{S} , θ_{C}	cyclic components of blade-pitch control
δ_3	pitch-flap coupling angle
Ψ	azimuthal position of rotor blade:
	advancing blade: Ψ = 90deg
	retreating blade: Ψ =270deg

ACRONYMS

AGF	Active Gurney Flap
CFD	Computational Fluid Dynamic
PIV	Particle Image Velocimetry
WTT	Wind Tunnel Tests

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