SIMULATION OF TRIMMED FLIGHT OF A HELICOPTER USING THE URANS SOLVER ANSYS FLUENT

Wienczysław Stalewski
wienczyslaw.stalewski@ilot.edu.pl, Łukasiewicz Research Network - Institute of Aviation (Poland)

Wiesław Zalewski
wieslaw.zalewski@ilot.edu.pl, Łukasiewicz Research Network – Institute of Aviation (Poland)

Maximilian Pulfer
maximilian.pulfer@koptergroup.de, Kopter Germany GmbH (Germany)

Frieder Hirsch
frieder.hirsch@koptergroup.de, Kopter Germany GmbH (Germany)

Abstract

The methodology of simulation of a fully trimmed flight of rotorcraft has been developed and applied to simulate a helicopter flight within a range of flight velocities from a hover to fast flight at advance ratio 0.34. The presented approach is based on a solution of Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. In contrast to typical solutions of such problem, in the newly developed methodology, the flight controls corresponding to the trimmed-flight conditions are also determined based on the solution of URANS equations. The methodology is based on coupling of several computational models of Computational Fluid Dynamics and Flight Dynamic. The URANS equations are solved in a three-dimensional region surrounding the flying helicopter, using the ANSYS FLUENT code. The approach is truly three-dimensional, with truly modelled geometry and kinematics of main and tail rotor blades. This applies to modelling of blade flapping, too. The trimming procedure uses six independent parameters (i.e. collective and cyclic pitch of main rotor blades, collective pitch of tail rotor blades, pitch and bank angles of a helicopter) that should be adjusted so as to balance all forces and moments acting on the helicopter. The detailed description of the developed methodology as well as the results of simulation of trimmed hover of the helicopter are presented.

1. INTRODUCTION

In trimmed flight of a helicopter all the forces, aerodynamic, inertial and gravitational, as well as the overall moment vectors are in balance. Keeping the helicopter in trimmed state, needs a precise adjustment of flight controls (i.e. collective and cyclic pitch controls of main rotor blades, collective pitch control of tail rotor blades, etc.) [2]. Computational simulation of such flight state is a very challenging task, especially when flight simulation is conducted using the Navier-Stokes-Equations solver to determine precisely all interactions between the air and helicopter surface. Usually, in such approach, the helicopter flight controls corresponding to the trimmed flight are determined using simplified aerodynamic models of rotors (e.g. Blade Element Theory) and other components of a helicopter (e.g. tabulated, static aerodynamic characteristics of a fuselage, stabilizers, vertical fin, etc.) [3],[4]. Then, these determined in simplified manner flight controls are used in an advanced flight simulator based on the Navier-Stokes Equations. However, this approach can in fact lead to flight states significantly distant from a trimmed flight. The reason may be incompatibilities between simplified and advanced aerodynamic models of a helicopter flight.

The presented research focused on development of methodology of simulation of trimmed flight of a helicopter based on a solution of Unsteady Reynolds-Averaged Navier-Stokes (URANS) equations. In contrast to the approach described above, in the newly developed methodology, the flight controls corresponding to the trimmed-flight conditions are also determined by the solution of URANS equations.

2. METHODOLOGY

A flight of a helicopter has been simulated based on computational methodology schematically presented in Figure 1.

Presented at 45th European Rotorcraft Forum, Warsaw, Poland, 17-20 September, 2019

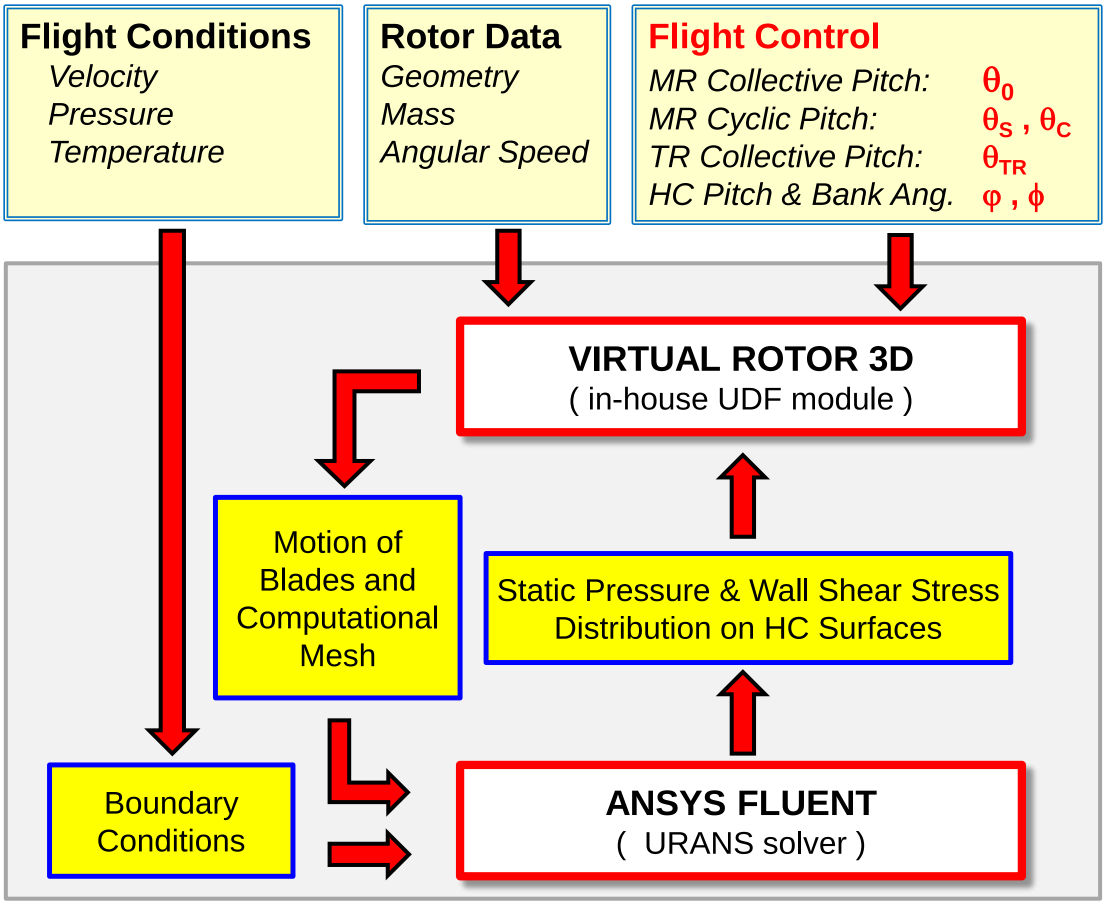

Figure 1. The general scheme of developed methodology of simulation of trimmed flight of helicopter.

The flight simulation consists in the solution of URANS equations in the domain surrounding the helicopter. The URANS equations are solved using the ANSYS FLUENT [1] code. All specific rotorcraft activities are realised by developed in-house UDF-module Virtual-Rotor-3D. This module is responsible for modelling of rotation of the main and tail rotors, blade feathering and flap-and-lag motion that is determined independently for each blade of the main rotor through a solution of ordinary differential equations simultaneously with the solution of URANS equations. The structure of computational mesh is shown in Figure 2. The motion of main-rotor blades is modelled by the Overset Method (computational-mesh overlapping) while the tail-rotor-blade motion is modelled based on Sliding Mesh Method.

In the presented approach the pitch angle (θ) of the main rotor blades is controlled by three angles: θ_0, θ_S, θ_C according to the following formula:

(1) $\theta = \theta_0 - \theta_s \cdot \sin(\Psi + \varphi_s) - \theta_c \cdot \cos(\Psi + \varphi_s) - \tan(\delta_3) \cdot \beta$

where:

φ_S - swash plate phase angle
δ_3 - pitch-flap coupling angle "Delta 3"
β - blade flap angle
Ψ - azimuthal position of the blade

The tail rotor blade pitch remains constant across all azimuths of the blade and is equal θ_{TR}. Thus, in general the helicopter-flight control is conducted using the following parameters:

- collective pitch of main-rotor blades (θ_0)
- components of cyclic pitch of main-rotor blades (θ_S, θ_C)
- collective pitch of tail-rotor blades (θ_{TR})
- pitch and bank angles of a helicopter (φ, ϕ)

The above parameters may be changed smoothly during the simulation of helicopter flight, which is used when trimming the helicopter. In the presented approach, the helicopter trimming procedure consists in establishing the flight-control vector: $\overline{\Theta} = [\theta_0, \theta_S, \theta_C, \theta_{TR}, \varphi, \phi]$, so as to obtain required dimensionless forces and moments: $\overline{T} = (C_{L-W}, C_D, C_S, C_l, C_m, C_n)$ acting on the complete helicopter including the main and tail rotors, where:

- $C_{L\text{-}W}$ - lift-weight-imbalance coefficient, (dimensionless difference between the resultant lift force acting on the helicopter and the helicopter weight),

- C_D - drag coefficient,
- C_S - side force coefficient,
- C_l - rolling-moment coefficient,
- C_m - pitching moment coefficient,
- C_n - yawing moment coefficient.

In the presented helicopter-flight simulation the moment reference point coincided with the centre of gravity of the helicopter. For given flight priority, in the fully trimmed flight corresponded to the following requirement:

(2) $$\mathrm{C_{L-W}} = \mathrm{C_D} = \mathrm{C_S} = \mathrm{C_l} = \mathrm{C_m} = \mathrm{C_n} = 0$$

The problem of helicopter trimming was expressed in mathematical terms as minimisation of function in general defined as follows:

(3) $$\Phi(\overline{\Theta}) = \sqrt{W_{L-W} \cdot \mathrm{C_{L-W}}^2 + W_D \cdot \mathrm{C_D}^2 + W_S \cdot \mathrm{C_S}^2 + W_l \cdot \mathrm{C_l}^2 + W_m \cdot \mathrm{C_m}^2 + W_n \cdot \mathrm{C_n}^2}$$

where $W_{L\text{-}W}$, W_D, W_S, W_l, W_m, W_m are weights (non-negative numbers) describing importance of balancing of given components of forces and moments acting on a helicopter. For example, in helicopter-flight simulations presented in this paper it was assumed:

(4) $$W_{L\text{-}W} = W_D = W_l = W_m = W_n = 1,$$
$$W_S = 0$$

which meant, that the balance of all forces and moments was of the same importance, except the side force that was not taken into consideration in the trimming procedure. The above concerns the all presented flight conditions except the hover where the trimmed-flight state was defined by:

(5) $$W_{L\text{-}W} = W_D = W_S = W_l = W_m = W_n = 1$$

To find a minimum of function (3) the classic, iterative approach was applied. The helicopter-flight simulation started from certain conditions, defined by initial values of: $\theta_0, \theta_S, \theta_C, \theta_{TR}, \varphi, \phi$. Usually, the flow state obtained for initial flight controls did not fulfilled the equation (2). In such case, the new, corrected values of flight-control vector $\overline{\Theta}_n$ were evaluated according to the formula:

(6) $$\overline{\Theta}_\mathrm{n} = \overline{\Theta}_\mathrm{p} + \left[\frac{\partial\overline{\mathrm{T}}}{\partial\overline{\Theta}}\right]^{-1} \cdot \left(\overline{\mathrm{T}}_\mathrm{r} - \overline{\mathrm{T}}_\mathrm{p}\right)$$

where $\overline{\Theta}_p$ is the current value of control vector $\overline{\Theta}$, $\overline{\mathrm{T}}_p$ is the current value of force-moment vector $\overline{\mathrm{T}}$, $\overline{\mathrm{T}}_r$ is the required value of vector $\overline{\mathrm{T}}$, and $[\partial\overline{\mathrm{T}}/\partial\overline{\Theta}]$ is the gradient matrix. Usually, to obtain relatively good convergence of helicopter trimming, the procedure (6) has to be applied several times, iteratively. However, in helicopter-trimmed-flight simulations presented in this paper, only a one-step trimming procedure was applied. Quality of evaluation of the gradient matrix $[\partial\overline{\mathrm{T}}/\partial\overline{\Theta}]$ strongly influences the success of the helicopter-trimming process. In the presented approach, the gradient matrix was evaluated using the Least Mean Square method, based on results of helicopter-flight simulations conducted several times for different values of flight-control-parameter vector $\overline{\Theta}$. In general, the gradient matrix $[\partial\overline{\mathrm{T}}/\partial\overline{\Theta}]$ should be evaluated/ modified in each iterative step of the trimming process and for each computational case of a helicopter flight. Two gradient matrixes differ especially from each other, when two computational cases of helicopter flight differ significantly from each other with respect to the advance ratio:

(7) $$\mu = \frac{\mathrm{V}_\infty}{\mathrm{R} \cdot \Omega}$$

where:

- V_∞ - flight velocity,
- R - radius of main rotor,
- Ω - angular velocity of main rotor.

To determine the gradient matrix, dependent on the advance ratio, based on a possibly small number of auxiliary simulations of a helicopter flight, the following approach was applied. The gradient matrix was assumed in the form, in general quadratic, with respect to the advance ratio (μ):

(8) $$\left[\frac{\partial\overline{\mathrm{T}}}{\partial\overline{\Theta}}\right](\mu) = A \cdot \mu^2 + B \cdot \mu + C$$

where the matrices A, B, C have been evaluated using the Least Mean Square method, based on results of helicopter-flight simulations, conducted several times for different values of flight-control-parameter vector $\overline{\Theta}$ and different values of advance ratio μ. It was expected (and finally proven based on presented research) that the described approach can lead to a significantly reduced number of auxiliary helicopter-flight simulations, while keeping good evaluation of the gradient matrix for different values of the advance ratio.

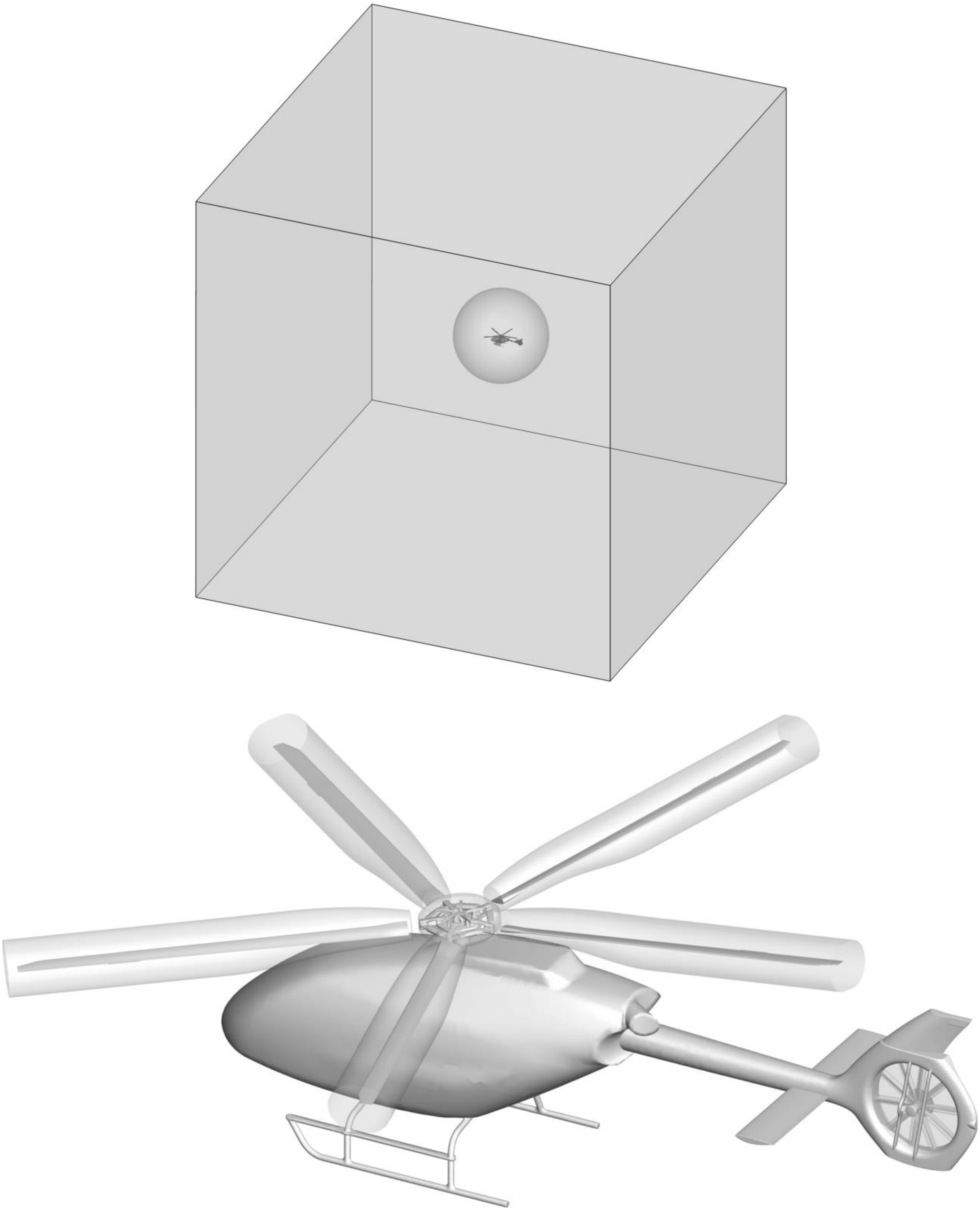

Figure 2. Structure of computational mesh used in trimmed-flight simulations.

3. RESULTS OF SIMULATIONS OF A TRIMMED FLIGHT OF A HELICOPTER

The simulations of trimmed flight have been conducted for the computational model of the helicopter presented in Figure 3.

The simulations have been conducted for the advance ratio (μ) within the range: 0.0 ÷ 0.341. The flight has been simulated at the altitude 400m in standard ISA atmospheric conditions.

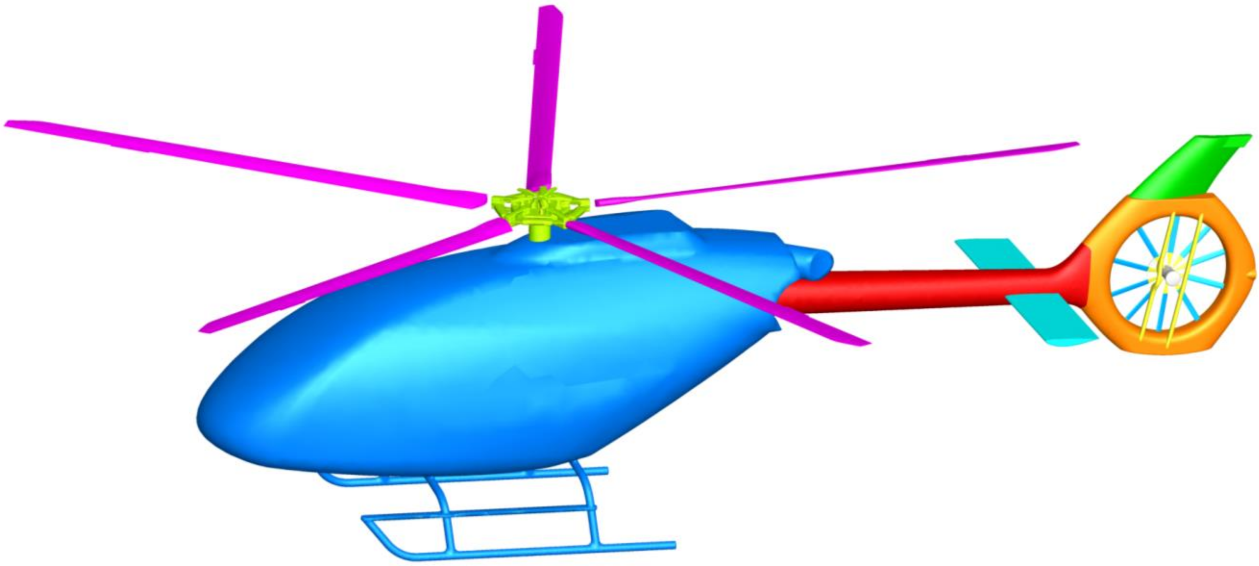

Figure 3. Computational model of the helicopter used in simulations of trimmed flight.

For a determination of trimmed-flight state in hover, the all six flight controls were taken into consideration and the weights used in definition of function (3) were established as shown in equation (5). For all forward-flight cases, only the five flight controls were taken into consideration, i.e.: $\theta_0, \theta_S, \theta_C, \theta_{TR}$, φ. In all these cases, the weights used in definition of function (3) were established as described in equation (4). So, the side-force balance was not required to be fulfilled in these cases.

In initial stage of the computations, several dozens of auxiliary simulations of helicopter flight were conducted to determine the advance-ratio dependent gradient matrix, in the form (8). The multiple simulations aiming at direct determination of trimming-gradient matrix were conducted for the following values of advance ratio μ = 0.000, 0.049, 0.159, 0.243, 0.341. On the other hand, for the advance ratios μ = 0.074, 0.099, 0.131, 0.195, 0.292 the trimming-gradient matrix was determined using the approximation presented in Equation (8). After determination of the advance-ratio dependent gradient matrix (8), the actual simulations of trimmed flight of the helicopter were conducted. Initially, the flight controls have been established based on simplified evaluations (e.g. based on the Blade Element Theory). For these settings, the helicopter-flight simulation was conducted, using the ANSYS FLUENT solver. After reaching satisfactory convergence and periodicity of flow, the current force-and-moment vector $\overline{\mathrm{T}}$ has been evaluated based on forces and moments averaged during one revolution of main rotor. Next, using the formula (6), a new, corrected value of flight-control vector $\overline{\Theta}_n$ has been evaluated. The flight simulation has been continued with the flight controls smoothly changing from the initial to their corrected values. After this process, the new state of the helicopter flight has been obtained. Usually, this state has been much closer to the trimmed flight than the initial one.

Figure 4 presents exemplary results of trimming obtained for helicopter in forward flight. Left side of the Figure 4 presents time-dependent resultant forces and moments acting on the helicopter, captured before conducting of the trimming, during one period of revolution of the main rotor. Right side of the Figure 4 shows the same quantities captured after conducting of the trimming. One may notice that even after first step of the helicopter trimming, the resultant forces and moments are oscillating around zero (which is the goal of the trimming) much more exactly than it was in the case before trimming. In particular, the balancing of aerodynamic lift and helicopter weight is improved through trimming by the factor 5. Figure 5 presents qualitative results of simulation of trimmed forward flight of the helicopter: static-pressure contours visualised on a helicopter surface. Table 1 presents a quantitative analysis of total balance of forces and moments acting on a helicopter, before and after performing the trimming procedure, for sequential values of advance ratio. Sequential columns in the Table 1 correspond to:

- advance ratio (μ),
- flight state (before/after trimming),
- value of function $\Phi(\overline{\Theta})$ defined in Eq. (3),
- efficiency of trimming (η) defined as follows:

$$\eta = \frac{\Phi(\overline{\Theta}_A)}{\Phi(\overline{\Theta}_B)} \tag{9}$$

where $\Phi(\overline{\Theta}_B)$ and $\Phi(\overline{\Theta}_A)$ mean the values of function Φ calculated before and after the trimming, respectively. The results presented in Table 1 show that trimming efficiency (η) reached values even below 0.1. That means more than ten times improvement of the balance of forces and moments acting on a helicopter. It should be emphasized that such a large improvement in trimming accuracy has been achieved only in one step of the iterative trimming procedure. These good results are especially visible for the flight cases, where the trimming-gradient matrix has been determined directly. For the cases, where the trimming-gradient matrix has been determined based on the approximation (8), the trimming accuracy has been usually worse.

Figure 6 shows how the parameters controlling the trimmed flight of a helicopter are changing with the flight velocity. The Figure presents flight controls (θ_0 , θ_S, θ_C, θ_{TR}, φ) corresponding to the trimmed flight as functions of the advance ratio (μ). The highest changes have been noticed for the collective pitch of tail-rotor blades (θ_{TR}) while the lowest changes and mild run have been observed for the longitudinal cyclic pitch (θ_C) of main-rotor blades.

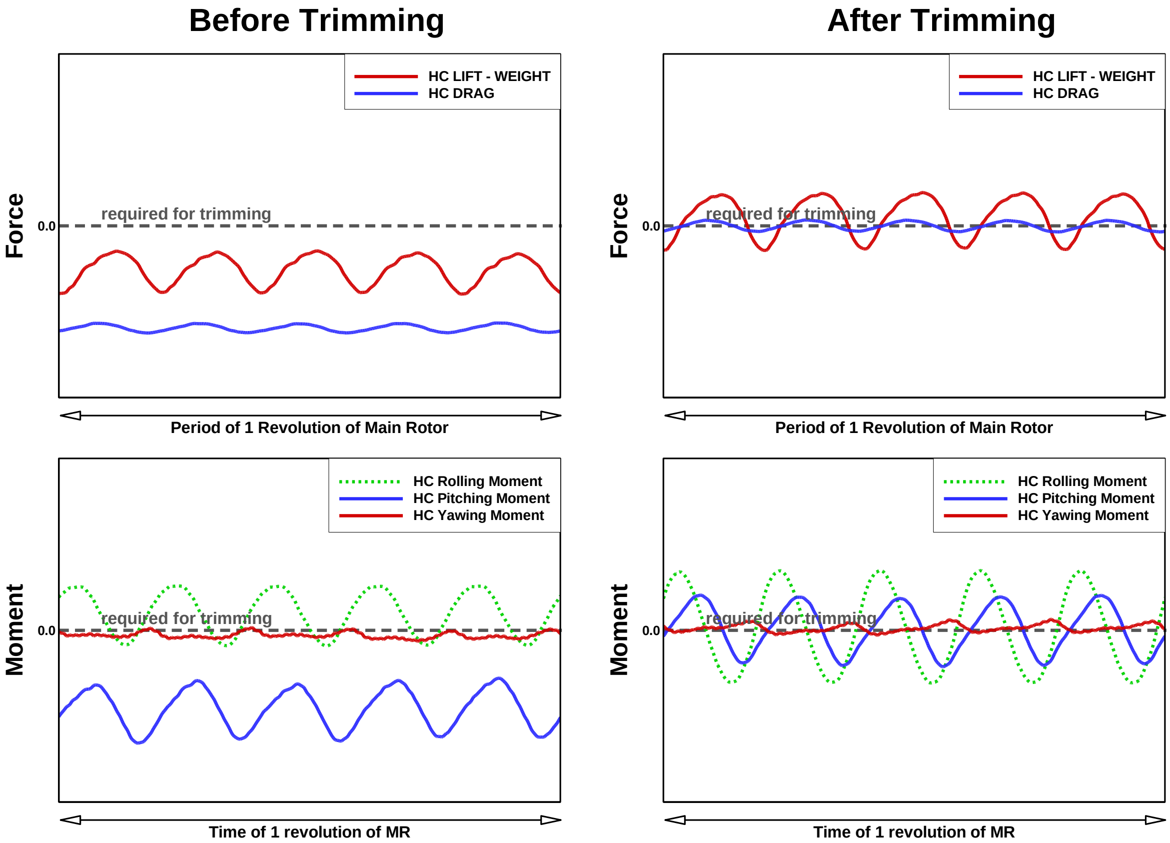

Figure 4. Global forces and moments acting on the helicopter in forward flight before (left) and after (right) trimming procedure.

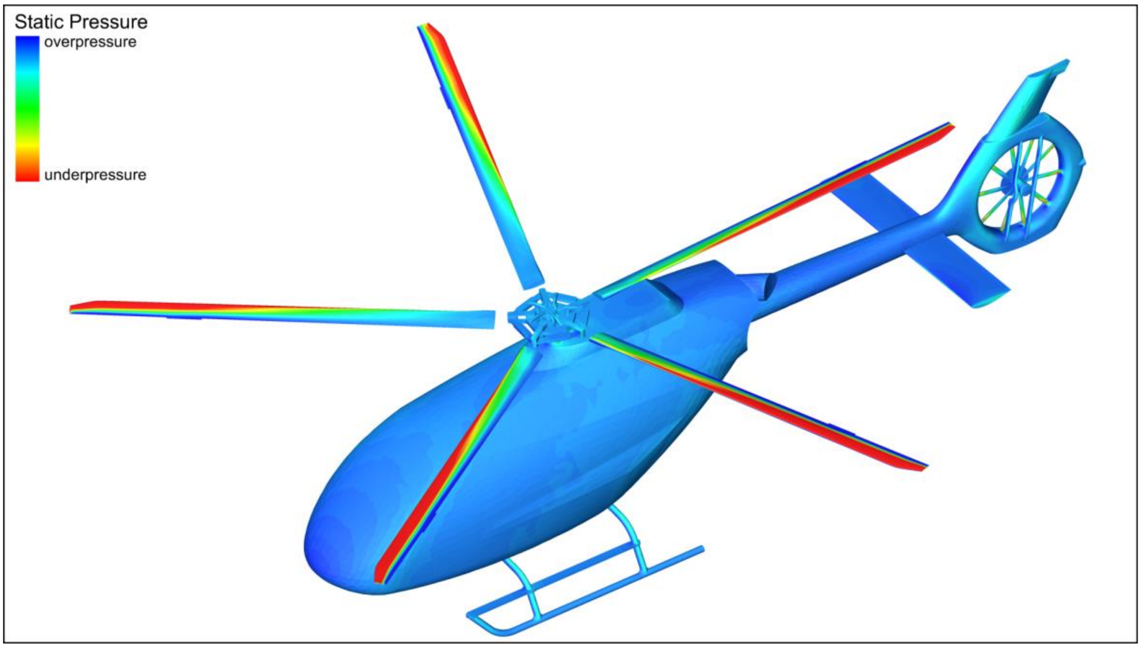

Figure 5. Results of simulation of trimmed forward flight of the helicopter. Static-pressure contours visualised on a helicopter surface.

Table 1. Quantitative analysis of total balance of forces and moments acting on a helicopter, before and after performing the trimming procedure for sequential values of advance ratio.

μ	Flight State	$\Phi(\overline{\Theta})$	η
0.000	*before trimming*	**5.652E-04**	**0.186**
	after trimming	**1.053E-04**	
0.049	*before trimming*	**9.922E-04**	**0.089**
	after trimming	**8.832E-05**	
0.074	*before trimming*	**9.254E-04**	**0.095**
	after trimming	**8.832E-05**	
0.099	*before trimming*	**9.871E-04**	**0.320**
	after trimming	**3.157E-04**	
0.131	*before trimming*	**7.426E-04**	**0.381**
	after trimming	**2.827E-04**	
0.159	*before trimming*	**1.082E-03**	**0.081**
	after trimming	**8.788E-05**	
0.195	*before trimming*	**4.736E-04**	**0.128**
	after trimming	**6.063E-05**	
0.243	*before trimming*	**9.129E-04**	**0.080**
	after trimming	**7.336E-05**	
0.292	*before trimming*	**9.101E-04**	**0.110**
	after trimming	**9.995E-05**	
0.341	*before trimming*	**2.916E-03**	**0.030**
	after trimming	**8.799E-05**	

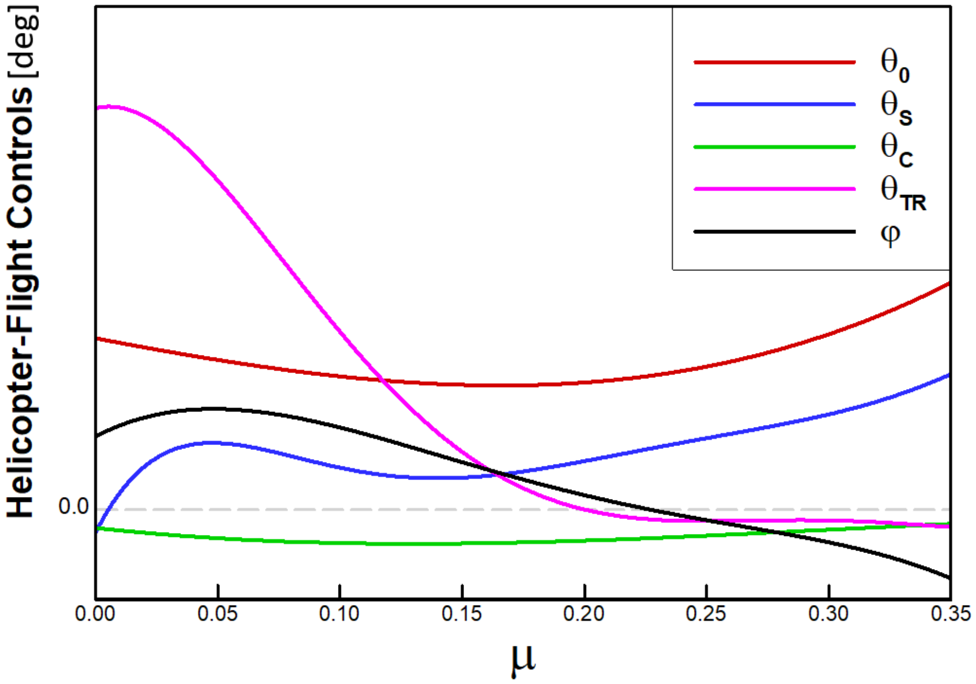

Figure 6. Flight controls (θ_0 , θ_S, θ_C, θ_{TR}, φ) in trimmed flight of a helicopter vs. advance ratio (μ).

4. CONCLUSIONS

The advanced methodology of computational simulation of a helicopter in trimmed flight has been developed and implemented. The methodology is based on the solution of URANS equations in a domain surrounding the flying helicopter. In contrast to the classical approach used to date, the trimming procedure was carried out directly in the URANS solver. The flight-state samples, necessary to determine an advance-ratio dependent trimming-gradient matrix, were obtained using the URANS solver ANSYS FLUENT. Using the same solver, the final, trimmed state of helicopter flight was determined. Preliminary tests of the presented methodology confirmed its high potential and suitability in rotorcraft research and development. The developed methodology has been applied in performance investigations of various flight states of a newly designed small helicopter.

5. REFERENCES

[1] ANSYS, Inc., ANSYS FLUENT User's Guide. Release 18.2. Available from: http://www.ansys.com.

[2] David Peters D., Barwey D., A general theory of rotorcraft trim, Mathematical Problems in Engineering (1996), Volume: 2, Issue: 1, page 1-34.

[3] Peters D.A., Chouchane M., Fulton M., Helicopter trim with flap-lag-torsion and stall by an optimized controller, Journal of Guidance, Control, and Dynamics, Vol. 13, No. 5 (1990), pp. 824-834.

[4] Hassan H.S., Bayoumy A.M., El-Bayoumi G.M., Abdelrahman M.M., Modelling, Trimming and Simulation of a Full-Scale Helicopter, 7th International Conference on Aerospace Sciences & Aviation Technology, ASAT-17 April 11-13 2017, Cairo, Egypt.

Copyright Statement

The authors confirm that they, and/or their company or organization, hold copyright on all of the original material included in this paper. The authors also confirm that they have obtained permission, from the copyright holder of any third party material included in this paper, to publish it as part of their paper. The authors confirm that they give permission, or have obtained permission from the copyright holder of this paper, for the publication and distribution of this paper as part of the ERF proceedings or as individual offprints from the proceedings and for inclusion in a freely accessible web based repository.