AEROELASTIC ANALYSIS OF HELICOPTER ROTOR USING VIRTUAL BLADE MODEL AND EQUIVALENT BEAM MODEL OF A BLADE

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Abstract

Modern helicopter rotor blades design requires taking into account complex aeroelastic phenomena. Sophisticated computational fluid dynamics and structural dynamics models, available on the market, coupled together enable such analysis with very high fidelity. However, the computational cost of this type of simulation is usually very high and for this reason, it cannot be used in interactive design process or optimization run. Complex Fluid Structure Interaction models are excellent tools for validation purposes, but the design process requires simpler models with lower computational cost and still relatively high accuracy and capabilities. The paper presents a new efficient methodology for calculating helicopter rotor loads, deformations and performance. It uses the well-known Navier-Stokes equations aerodynamic solver – ANSYS Fluent, and modified Virtual Blade Model (based on Blade Element Theory) for rotor flow calculation. This connection guarantees exceptional capabilities and fidelity in comparison with simulation time. The dedicated structural dynamics solver, based on equivalent beam model of a blade and Finite Difference Method, was developed and coupled with CFD part using User Defined Functions in Fluent software. The accuracy of created module was validated with wind tunnel tests data of IS-2 helicopter rotor model, performed in Institute of Aviation. The results of calculations were compared with experimental data for a hover state and a forward flight with three different flight velocities. The comparisons showed very good agreement of the data in most of the analysed cases and pointed out new research possibilities. The presented aeroelastic helicopter rotor model combines all advantages of using three-dimensional Navier-Stokes solver with relatively low computational costs and high accuracy, confirmed by wind tunnel tests. It could be used successfully in helicopter rotor blades design process.

Keywords: rotorcraft, helicopter, blade, aeroelasticity, rotor, aerodynamics, CFD, VBM

1. Introduction

Flight of a helicopter is a very complex phenomenon. It is inherently unsteady compared to airplanes flight, because rotating rotor generates dynamically changing loads. Due to structural and mass characteristics of blades, the aerodynamic, structural and inertial forces play very important role in blade dynamics. The coupling of these three types of forces leads to the aeroelastic behaviour of the blades. For this reason, during design process of a helicopter rotor, the influence of blade motions and deformations on aerodynamic loads and vice versa should be taken into account. Nowadays, most of commercially available Computational Fluid Dynamics (CFD) and Computational Structural Dynamics (CSD) solvers coupled together allow performing Fluid Structure Interaction (FSI) with very high fidelity. However, the computational cost of this type of analysis is usually very high and for this reason, it cannot be used in interactive design process or optimization run. Complex Fluid Structure Interaction models are excellent tool for validation purposes, but the design process requires simpler models with lower computational cost and still relatively high accuracy and capabilities. The work presented in this paper was done to create such a compromise computational model. In order to maintain high capabilities of the newly developed methodology, the decision was taken to use one of the most widely recognized as an industrial standard CFD solvers – ANSYS Fluent – to obtain aerodynamic forces acting on the blades, with

modified Virtual Blade Model (VBM) module to get a good compromise between accuracy and economy. There are several methods of aerodynamic analysis of helicopter rotors in ANSYS Fluent [1, 9], but VBM has been successfully used for several years for this purpose [5, 6, 10, 11], which proves its usefulness. The CSD part in proposed methodology incorporates dedicated in-house Blade Deformation Solver (BDS), which is based on equivalent beam model of a blade. Similar structural simplification of a blade was used with less sophisticated aerodynamic model in [12, 13], with good results. After describing the computational model in the first part of the paper, the second part focuses on validation process based on Wind Tunnel Test (WTT) data for a model rotor from a light helicopter. Comparison between experimental data and numerical analysis results showed the potential of presented methodology and pointed out new research possibilities.

2. Methodology of computational modelling of aeroelastic helicopter rotor

The approach to computational modelling of aeroelastic helicopter rotor, presented in this paper, incorporates modified VBM module for aerodynamic calculations and newly created BDS module for structural dynamics. The original VBM is available by request from ANSYS distributor and it was described in [15]. In VBM, every single blade is not explicitly modelled, but the whole rotor disk is replaced by momentum sources in the rotor disk cells (Fig. 1). This indirectly yields a pressure jump across the disk, which changes with the radial and azimuthal position. The momentum sources are calculated using well-known Blade Element Theory (BET) [7, 8, 14], which assumes two-dimensional flow and approximates the blade forces at each point of the rotor disk region by using previously calculated or measured airfoils characteristics. The original VBM does not operate on blade mass data, so it cannot designate blade-flapping angles. User can take into account that effect during simulation, but he needs to know the information about flapping angles *a priori*.
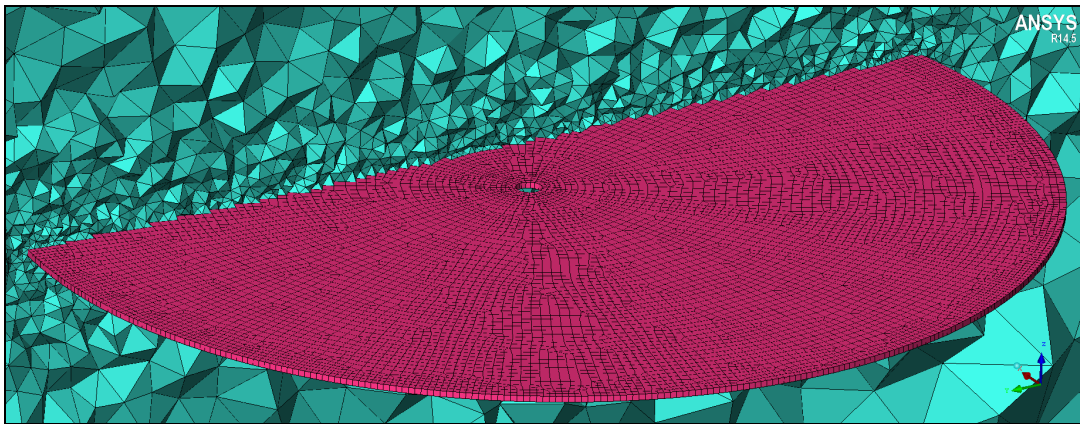

Fig. 1. Typical hexahedral mesh in rotor disk region surrounded by tetrahedral mesh in the domain (cross-section)

The structural part of the simulation is based on equivalent beam model of a blade. The Euler-Bernoulli beam theory was used to formulate partial differential equations (PDE) for blade bending/flapping and blade torsion/pitch steering. Both equations were coupled together. The lead-lag motion of a blade and bending in the plane of the highest stiffness was neglected in presented model. The derived system of equations was similar to that described in [7, section 9-4.3]. The Finite Differences Method was used to solve PDE equations in time domain. Contrary to CFD part, where the flow was calculated as a steady state case, the structural simulation was of the transient type. In this case, the convergence of the solution was monitored and judged basing on the values of deflections of the blade at a few azimuthal angles in the subsequent revolutions of the rotor.

The general scheme of the methodology is shown in Fig. 2. The data exchange between the

CFD part and CSD part was an iterative process. Blade Deformation Solver sends to Virtual Blade Model module information about:

– total blade section pitch angle (which consists of blade pitch control, geometric twist and deflection angle due to elastic torsion),
– angles of blade deflection (the result of blade bending),
– dynamic forces (which come from blade flapping – in BDS these forces act as damping forces).

The total blade section pitch angle and angles of blade deflection modify the angle of attack of a blade in VBM, while the dynamic forces are transferred directly to momentum sources calculation routine and added to static forces. The data exchange is carried out once every tens iterations of FLUENT program and during its iterations sent data does not change. On the other hand, VBM sends to BDS flow velocity fields, which are used to designate new angles of attack and blade loads for the next structural dynamics iteration.

The coupling between VBM and BDS was realized inside one compiled User Defined Function (UDF) library in ANSYS Fluent environment. The complete VBM+BDS module allows taking into consideration also such problems as the flap-torsion kinematic coupling and controlling system torsional stiffness.
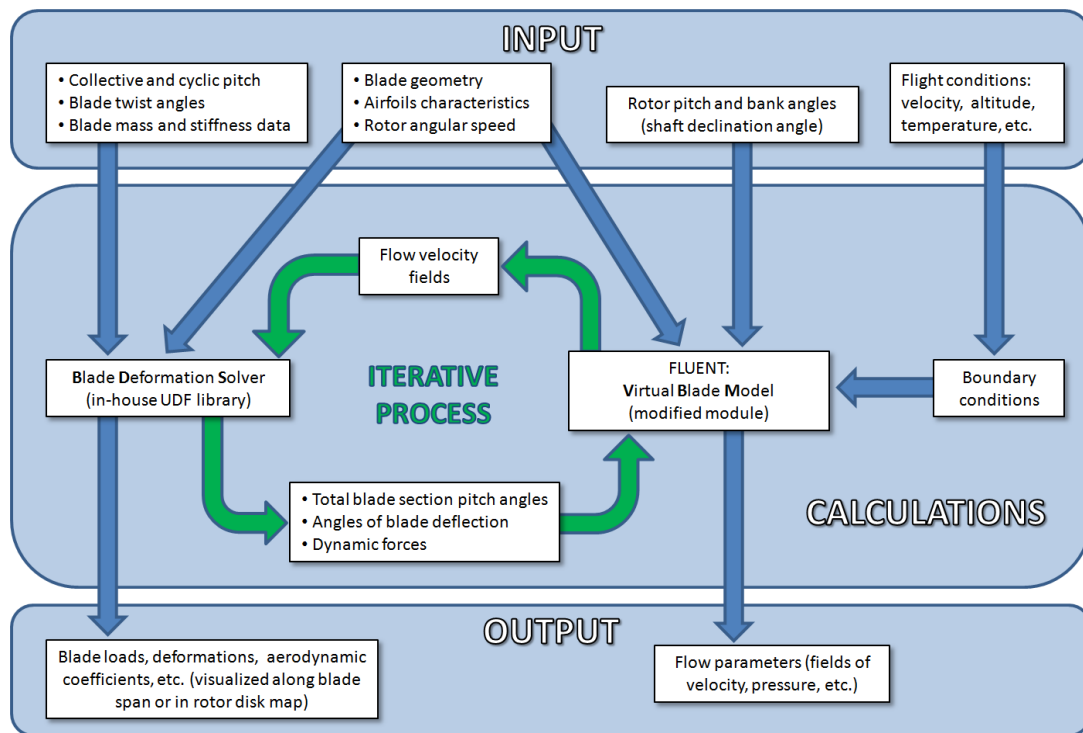
Fig. 2. General scheme of presented computational methodology

3. Test cases based on experimental data

The presented computational model of aeroelastic helicopter rotor was validated on the base of wind tunnel measurements conducted in the Institute of Aviation. The model of a 3-bladed main rotor of IS-2 light helicopter was built in 1:3.23 scale [4] and mounted on a test stand in the 5-meter diameter wind tunnel. It was tested in hover conditions and three different forward flight velocities (19.95, 25.08, 34.96 m/s). In every case thrust and torque was measured (among others quantities) in a function of collective pitch angle. The speed of the rotor blade tip was set to $V_{tip} = 190$ m/s, which corresponds to angular velocity $\Omega = 163.65$ rad/s. The decline angle of rotor shaft axis was fixed to $\alpha_{shaft} = -5°$ for forward flight cases. The detailed description of performed Wind Tunnel Tests (WTT) can be found in publication [3] or internal report of the Institute of Aviation [2].
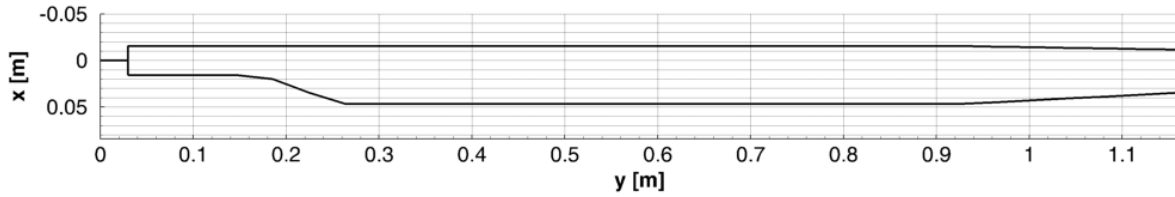
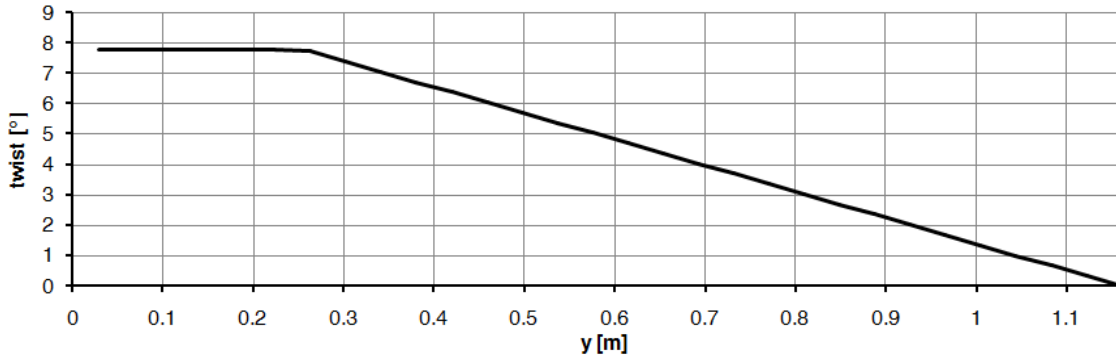*Fig. 3. Blade geometry of the IS-2 helicopter rotor model*

Fig. 4. Blade geometric twist angle

Tab. 1. IS-2 helicopter rotor model data and wind tunnel test parameters

Number of blades	3	V_{tip} [m/s]	190
Rotor diameter [m]	1.161	Ω [rad/s]	163.65
Flap hinge position [m]	0.0294	V_{flight} [m/s]	$\mu = V_{flight}/V_{tip}$
Flap-torsion coupling coefficient [-]	0.4019	19.95	0.105
Construction cone angle [°]	0	25.08	0.132
Control system torsional stiffness [Nm/rad]	300	34.96	0.184

All mentioned parameters were treated as inputs for created calculation model. The mass and stiffness data, also needed to simulate dynamic response of the blades, was prepared basing on measurements of selected parameters along blade span. The blade was designed with use of two airfoils – ILHX4a1-12M1 from root to about 80% span and ILHX4a1-9M1 at blade tip (linear change of the airfoil from 80% span to the tip). Two-dimensional airfoils aerodynamic characteristics, needed to calculate rotor loads in VBM+BDS module, were previously obtained in ANSYS Fluent with use of compressible flow model and k-ω SST Transitional turbulence model, for Mach numbers from 0.3 to 0.74 and Reynolds numbers corresponding to selected blade chords. Hinge sections of the blade (y < 0.22 m) were aerodynamically approximated by cylinder drag characteristics (CL = 0, CD = 1).

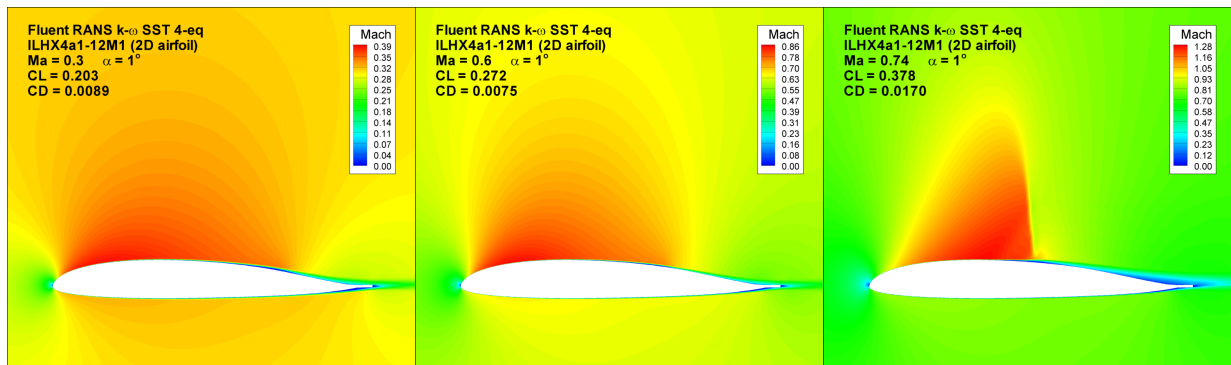*Fig. 5. Contour maps of Mach number for ILHX4a1-12M1 airfoil and three different flow velocities*

4. CFD simulations of aeroelastic helicopter rotor

The numerical analysis was performed with standard VBM module and presented VBM+BDS module. The original VBM does not consider a flapping motion of the blade, blade deformation, flap-torsion kinematic coupling, and control system torsional stiffness. By comparing its results with VBM+BDS, which calculate all of these quantities, it was possible to check how significant impact they have on the final rotor characteristics. Two different meshes were created in ANSYS ICEM software for numerical simulation – the first for hover case and the second for forward flight cases. They differed in domain shape and size. For forward flight cases domain had rectangular shape (25R x 20R x 25R), while for hover state cases it was a cylinder (diameter 30R x height 25R). The meshes were identical in topology – the rotor disk consisted of one layer of hexahedral elements, where source terms were defined, and the rest of the domain was filled with tetrahedral mesh (Fig. 1). The connection between hexahedral and tetrahedral part of the mesh was realized with use of pyramid elements. The hover case used Pressure Outlet boundary condition on all external walls of the domain, while the forward flight cases used Velocity Inlet for inlet surfaces and Pressure Outlet for outlet surfaces.
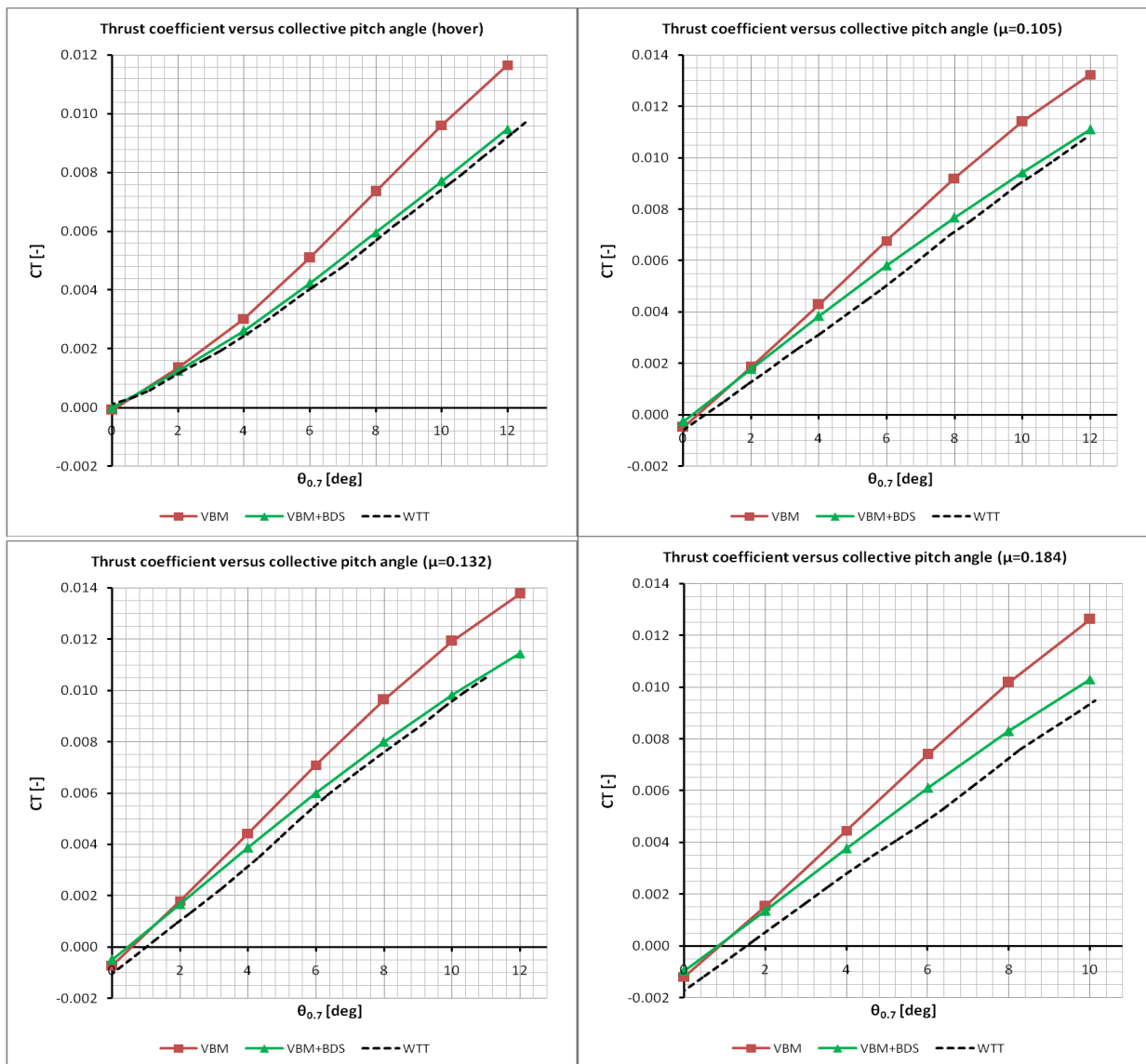

Fig. 6. Thrust coefficient (CT) versus collective pitch angle at 0.7R ($\theta_{0.7}$) for the hover state case and all forward flight cases; wind Tunnel Tests data (WTT) compared with numerical results of original VBM and VBM+BDS models

The results of numerical simulations were compared with Wind Tunnel Tests (WTT) data in terms of rotor thrust coefficient CT (Fig. 6) and torque coefficient CMZ (Fig. 7), defined by the following equations:

$$CT = \frac{T}{0.5 \cdot \rho \cdot (\Omega \cdot R)^2 \cdot \pi \cdot R^2} \tag{1}$$

$$CMZ = \frac{Mz}{0.5 \cdot \rho \cdot (\Omega \cdot R)^2 \cdot \pi \cdot R^2 \cdot R} \tag{2}$$

where:

T – rotor thrust,
ρ – air density,
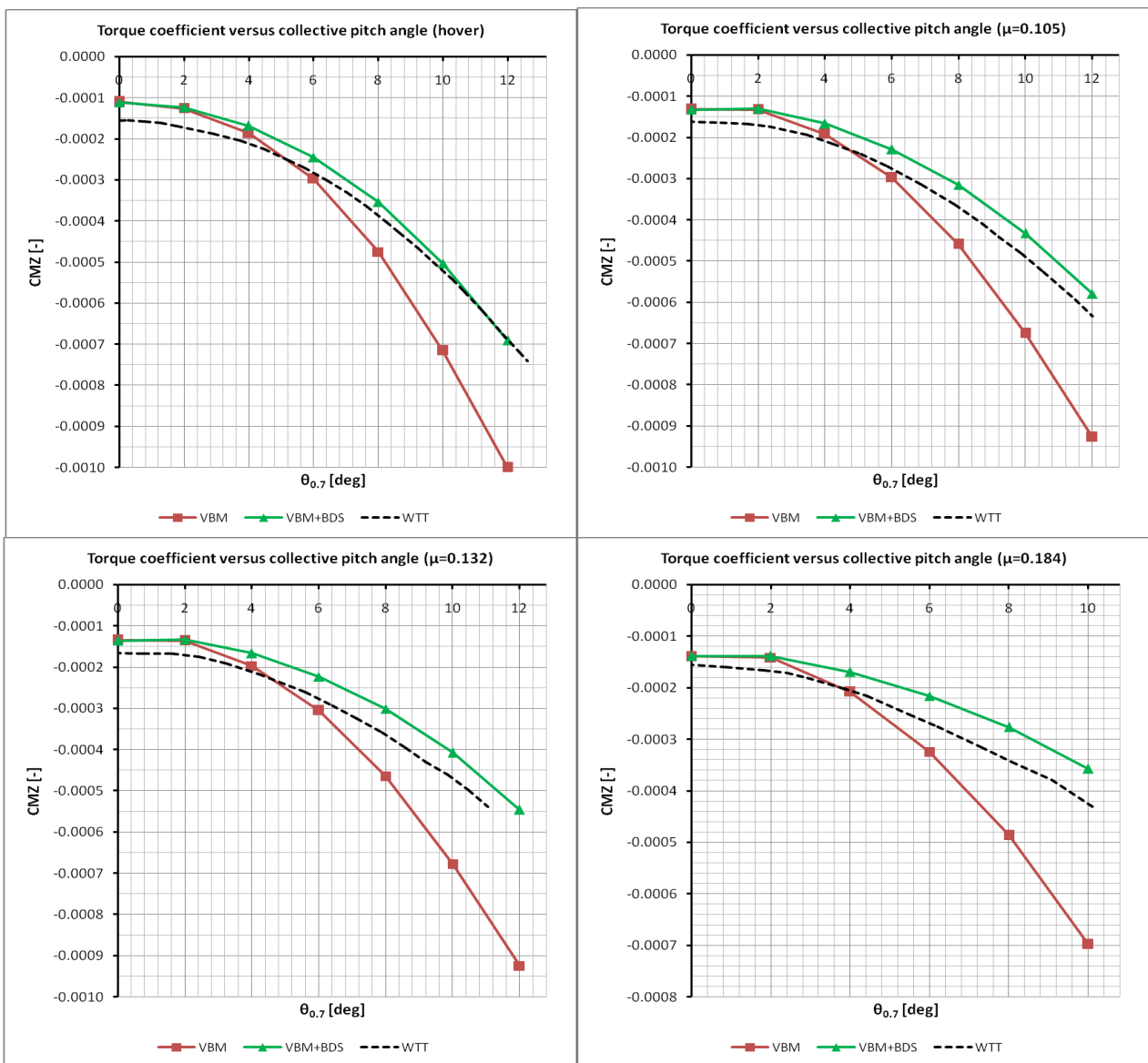Ω – angular rotor velocity,
R – rotor radius,
Mz – rotor torque.

Fig. 7. *Torque coefficient (CMZ) versus collective pitch angle at 0.7R ($\theta_{0.7}$) for the hover state case and all forward flight cases. Wind Tunnel Tests data (WTT) compared with numerical results of original VBM and VBM+BDS models*

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5. Discussion of results

The comparison between experimental global rotor data and numerical results shows relatively good agreement. It could be seen that the results of modified VBM+BDS module are much closer to WTT data than obtained with standard VBM module. In terms of qualitative representation of WTT curves presented methodology fared very well for both CT and CMZ characteristics. However, when we take into consideration CT and CMZ exact values there are differences between numerical results and experiment, especially at forward flight case with highest flight speed. The smallest error occurred at hover state conditions, at which CT values are almost identical as WTT data. The CMZ values are less coincident with experiment for hover state, especially at low collective pitch (low thrust) conditions. This difference is also visible for other analysed cases, but in the other cases some error appears also for higher collective pitch values, (high rotor thrust conditions).

The differences between experimental data and numerical results could have many sources. The discrepancies of CMZ values for low collective pitch conditions could be caused by underestimated CD values of airfoils used in presented calculations. Accurate drag estimation by CFD methods is a tough problem and there can be a potential error. Using experimentally obtained airfoils characteristics could be a solution of this problem, provided that WTT will be done for exactly the same Reynolds and Mach numbers as for real helicopter blade. However, the disagreement, which is visible for high collective pitch angles and rise with flight velocity, has a potentially different origin. At forward flight cases, there is a region on the rotor disk where a dynamic stall of the blade could occur. This phenomenon is directly connected with blade flapping, concerns only the retreating blade and becomes more intense when the flight speed increases. During dynamic stall the airfoil lift, drag and moment coefficients could be much different from the static data used for presented numerical simulation. This is the most probably reason of the increasing errors of numerical analysis with increasing flight velocity. To minimize this source of errors one of the experimental dynamic stall models could be incorporated into presented module. This should allow approximating the dynamic stall airfoil characteristics with its static data and improving the complete calculation module accuracy. It should be also noted that when stall occurs the assumption of two-dimensional flow around blade, imposed by Blade Element Theory, is violated. Due to this fact, the stall effects in VBM will always be modelled in a simplified way, even with use of any dynamic stall model.

6. Summary and conclusions

The newly developed methodology of computational modelling of aeroelastic helicopter rotor has been presented. The methodology allows calculating helicopter rotor loads, deformations and performance. It is based on ANSYS Fluent CFD software and is modified Virtual Blade Model to simulate the flow through a helicopter rotor disk with relatively high efficiency and accuracy. The aerodynamic module has been coupled with originally developed structural solver basing on Euler-Bernoulli beam theory. The whole module was written in C programming language and linked with ANSYS Fluent environment through User Defined Functions.

Exemplary CFD simulations, presented in the paper, has been conducted to reproduce the performed in Institute of Aviation wind tunnel tests conditions of IS-2 helicopter rotor model, and validate developed methodology. As it turned out, the relatively good agreement has been noted between WTT data and results of numerical analysis. Newly created calculation module (VBM+BDS) allowed for achieving the results which were much closer to the experimental data than these obtained with original VBM, with almost the same computational cost. Unfortunately, the available WTT data of IS-2 helicopter rotor model contain only global rotor quantities (such as thrust, torque, etc.). It could be extremely useful and interesting to compare also the calculated local blade quantities (such as blade loads, deflections, twist deflection angles, etc.) with another

experimental data set or more complex FSI models.

Because of the promising results, the presented module will be further developed to improve its accuracy and versatility. Performed calculations indicated some discrepancies of numerical results and WTT data, especially at high flight velocities. This could be the reason of relying only on a static airfoil data during calculations. Forward flight of a helicopter is a very complex state with dynamically changing quantities at relatively high rates. To improve the fidelity of presented methodology these dynamic phenomena should be taken into account in numerical simulation process. Using static airfoil aerodynamic coefficients is in fact only an approximation due to dynamic stall effect that occurs on retreating blade of a helicopter. Incorporating one of the experimentally developed dynamic stall models could be the first step to improve presented methodology.

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