AEROELASTIC INVESTIGATION OF PATTERN HINGELESS HELICOPTER ROTOR IN FORWARD FLIGHT

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SUMMARY: An aeroelastic modelling of pattern hingeless helicopter rotor in forward flight is presented in this paper. The coupled aeroelastic problem accounts for the mutual dependence between blade structure and rotor aerodynamics. The aerodynamic model uses Blade Element Momentum Theory (BEMT). BEMT gives good accuracy with respect to time cost. The structure model uses Finite Element Method (FEM). The aerodynamic model is based on the well-known solver MATLAB, and the structure model is based on the well-known solver ANSYS. The obtained results show that the proposed modeling is efficient, rapid and gives reliable results. This modelling is also useful and applicable for airplane propellers, wind turbine rotors and airplane wings.

Keywords: Helicopter, Aeroelasticity, Aerodynamics, Structural dynamics.

1. INTRODUCTION

Aerodynamic and inertia forces act on the helicopter blade in flight. These forces deform the helicopter blade and as a result, the aerodynamic forces distribution changes. The new aerodynamic forces distribution deforms the blade. In addition, that changes the aerodynamic forces distribution again. At a certain instant the aerodynamic and inertia forces, and elasticity forces will be balanced. Therefore the fully coupled aeroelastic problem must account for the mutual dependence between blade structure and aerodynamics.

In the last years the prediction of airloads on the helicopters rotors is based on a numerical approach, where the flow is simulated using Computational Fluid Dynamics (CFD) tools with moving boundary conditions. The computations normally include a comprehensive rotor code, coupled to Euler or Navier-Stockes solvers [4, 13, 15]. The examples for a successful application of CFD are the codes FLUENT, TURNS of NASA, FLOWer of Deutshes Zentrum für Luft und Raumfahrt, elsA and WAVES of ONERA [15]. For aeroelastic calculations the CFD method has to be very time consuming. Thus it can be replaced by Blade Element Momentum Theory (BEMT) or the vortex wake method which show a good accuracy with respect to time cost [11]. In these methods, the helicopter blade is divided into a number of independent elements along the length of the blade. Each section of the blade acts as 2-D airfoil, which produces aerodynamic forces and moments.

The structure of helicopter blade has been modelled in different ways but mostly relies on a modified beam model or one-dimensional finite elements [13].

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The lumped-parameter approach is used to determine the helicopter blade deformations under the effects of aerodynamic and inertia forces. There the continuous blade is presented by a number of discrete segments, so that the partial differential equations of blade deformations are replaced by a set of simultaneous ordinary differential equations. The methods using this approach are the Holzer-Myklestad method [3], collocation method [1] and Finite Element Method (FEM) [1, 5, 14, 17]. The FEM solvers as ANSYS, ABAQUS, NASTRAN and ADAMS are often applied at the investigations of helicopter rotor dynamics.
The advanced helicopter code called UMARC is well validated and extensively used in the helicopter rotor dynamics investigations. The rotor-fuselage equations are formulated using Hamilton's principle and are discretized using finite elements in space and time. The blade airloads can be computed using quasi-steady aerodynamics, linear unsteady aerodynamics or nonlinear unsteady aerodynamics [2, 6].
Other successful helicopter code is CAMRAD. The used model is a combination of structural, inertial, and aerodynamic models. The rotor aerodynamic model is based on free vortex method, which takes in account the unsteady flow effects, including a dynamic stall [8, 6].
The aim of this work is to present an aeroelastic investigation of hingeless helicopter rotor in forward flight. The structural model uses FEM, and aerodynamic model uses BEMT. The structural model relies on ANSYS code, and aerodynamic model relies on MATLAB code.

2. STRUCTURAL MODEL OF A HINGELESS PATTERN HELICOPTER ROTOR

The advantage of hingeless rotor is its mechanical simplicity. It eliminates the flapping and lead/lag hinges by using an elastic element or elastic blade to accommodate blade motion. But the design of the blade in most cases is rather complicated. The sketch of a hingeless rotor is shown in Fig.1.

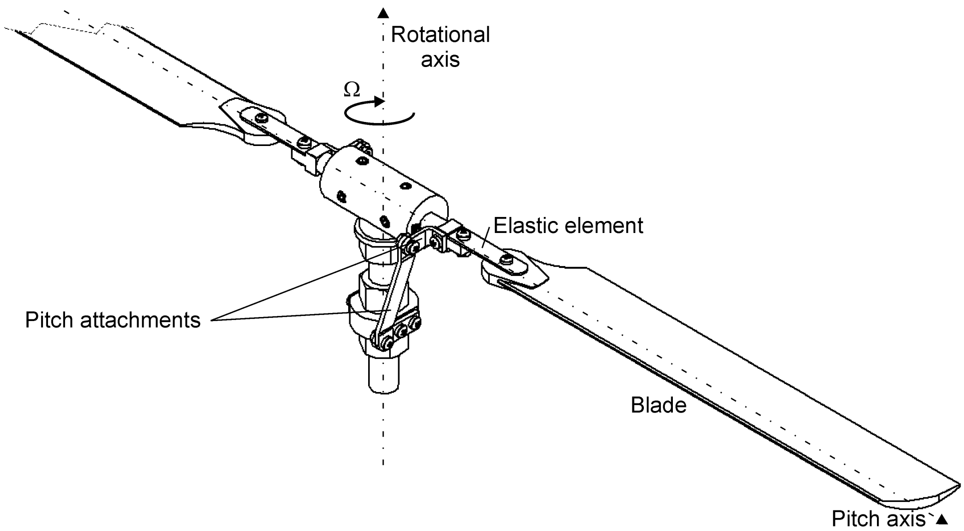
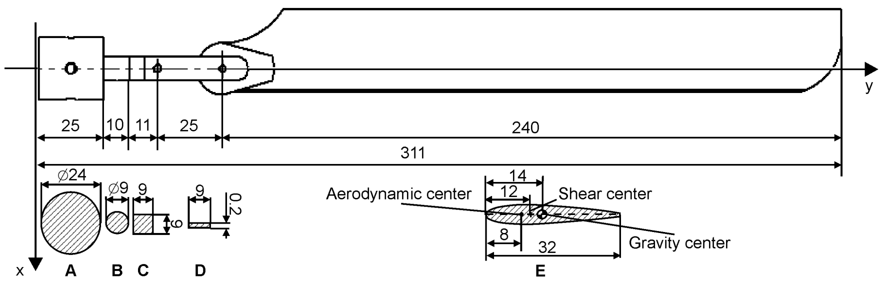
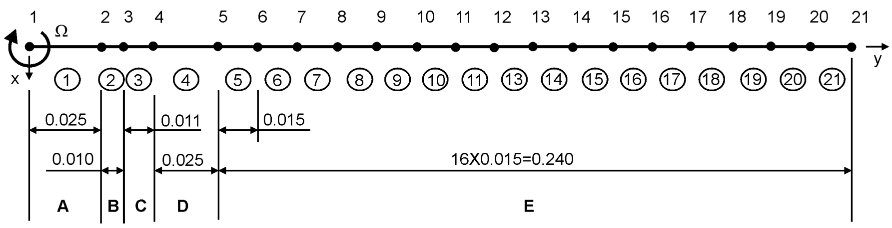


Fig.1: Sketch of a pattern hingeless rotor

An ANSYS code is used for the structural analysis. The equivalent beam model of the helicopter blade uses finite element BEAM44 (Table 1). The element has six degrees of freedom at each node: translations in the nodal *x*, *y*, and *z* directions and rotations about the nodal *x*, *y*, and *z*-axes. This element uses different asymmetrical geometry without coinciding centre of gravity and elastic centre. The blade is divided into 21 finite elements, as shown in Table 1. The material of the blade hub is Aluminum 7079, the elastic element is from stainless steel AISI 304, and the blade is from balsa. All necessary data are shown in Table 1. Gyroscopic or Coriolis effects are included in the calculations.

Table 1 Description of the structural helicopter rotor FEM model

Rotor sketch, shown dimensions are in (mm)					
Section properties:	A	B	C	D	E
Section area: A, m	0.452×10^{-3}	0.636×10^{-4}	0.810×10^{-4}	0.180×10^{-5}	0.106×10^{-3}
Inertia moment about the x axis, I_{xx}, m^4	0.163×10^{-7}	0.321×10^{-9}	0.547×10^{-9}	0.600×10^{-14}	0.127×10^{-9}
Inertia product, I_{xz}, m^4	0.000	0.000	0.000	0.000	0.000
Inertia moment about the y axis, I_{zz}, m^4	0.163×10^{-7}	0.321×10^{-9}	0.547×10^{-9}	0.122×10^{-10}	0.127×10^{-9}
x coordinate of shear center about c.g., x_{sc}, m	0.000	0.000	0.000	0.000	0.002
z coordinate of shear center about c.g., z_{sc}, m	0.000	0.000	0.000	0.000	0.000
Finite element model: Nodes: 1-21 Elements: 1-21					
Elements Type:	BEAM 44				

Material properties:	Elements: 1-3 Aluminum 7079, isotropic material	Element: 4 Stainless steel AISI 304, isotropic material	Elements: 5-21 Wood: Balsa, orthotropic material
Elastic modulus, E_x, GPa	71.7	190	3.400
Elastic modulus, E_y, GPa			0.156
Elastic modulus, E_z, GPa			0.051
Shear modulus, G_{xy}, GPa	26.9	79	0.183
Shear modulus, G_{xz}, GPa			0.126
Shear modulus, G_{yz}, GPa			0.017
Density, ρ, kg/m^3	2800	8000	160

3. LOADS ON THE HELICOPTER BLADE

In forward flight, the asymetry of the onset flow and dynamic pressure over the disk produces aerodynamic forces that are functions of blade azimuth position. The mathematical modeling of this regime is more complicated than hovering regime, but blade element momentum theory (BEMT) also gives a good basis of analyse of rotor aerodynamics in forward flight. When it's used a part of aeroelastic codes, this method is very time efficient and gives good accuracy with respect to time cost.

In this method, the helicopter blade is divided into a number of independent elements along the length of the blade. At each blade element, a force balance is applied involving 2D blade section lift and drag with the thrust and torque produced by the element. At the same time, a balance of axial and angular momentum is applied. The force balances produce a set of non-linear equations which can be solved numerically for each blade section. The description in this paper follows *Leishman* [11].

Figure 2 shows the incident velocities and aerodynamic forces at a blade element on the helicopter rotor.

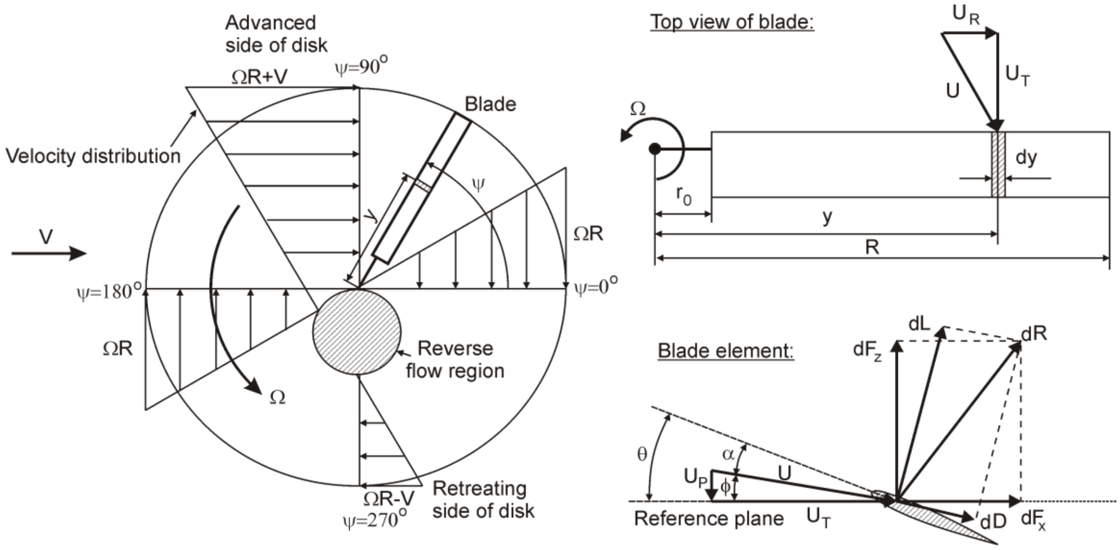


Fig. 2: Incident velocities and aerodynamic forces at a blade element

As is shown in Fig.2, the resultant flow velocity at each blade element at a radial distance *y* is

$$U = \sqrt{U_T^2 + U_P^2} \tag{1}$$

The tangential (in-plane) velocity component, U_T, perpendicular to the leading edge of the blade is

$$U_T(y,\psi) = \Omega y + V\sin\psi = \Omega y + \mu\Omega R\sin\psi \tag{2}$$

where $\mu = V\cos\alpha / \Omega R$ is the rotor advance ratio.

The perpendicular (out-of-plane) velocity component, U_P, is

$$U_P = \left(\lambda + \frac{y\dot{\beta}}{\Omega R} + \mu\beta\cos\psi\right)\Omega R \tag{3}$$

where λ is the inflow ratio, β is the coning angle, and $\dot{\beta}$ is the perturbation in velocity as a result of the blade flapping velocity about the equivalent flapping hinge.

The induced angle of attack (inflow angle) at the blade element is

$$\phi = \tan^{-1}\left(\frac{U_P}{U_T}\right) \tag{4}$$

The effective angle of attack is

$$\alpha = \theta - \phi \tag{5}$$

where θ is the pitch angle at the blade element.

When there is torsional elastic deformations of the blade, θ_e, the effective angle of attack is

$$\alpha = \theta - \phi + \theta_e \tag{6}$$

The resultant lift *dL* and drag *dD* per unit span on the blade element are

$$dL = \frac{1}{2}\rho U^2 c C_l dy \tag{7}$$

$$dD = \frac{1}{2}\rho U^2 c C_d dy \tag{8}$$

where ρ is the density of air, c is the local blade chord, C_l and C_d are the lift and drag coefficients.

Finally the forces perpendicular and parallel to the rotor disk are

$$dF_z = dL\cos\phi - dD\sin\phi \tag{9}$$

$$dF_x = dL\sin\phi + dD\cos\phi \tag{10}$$

Because inflow ratio is not known a priori, for its determination is used the linear inflow model of *Drees*. This model is easy to implement in rotor analyse and gives a reasonably good description of the rotor inflow [9,11]. The inflow ratio can be approximately represented by

$$\lambda = \lambda_0\left(1 + k_x r\cos\psi + k_y r\sin\psi\right) \tag{11}$$

where in most cases λ_0 is the mean induced velocity at the center of the rotor. The inflow coefficients are given by

$$k_x = \frac{4}{3}\left(\frac{1-\cos\chi - 1.8\mu^2}{\sin\chi}\right) \text{ and } k_y = -2\mu$$

where χ is the wake skew angle [11].

The equilibrium of the blade depends by the balance of aerodynamic and centrifugal forces. In accordance with Fig. 3, a small element of the blade of length *dy* is considered. The mass of this element is *mdy*. The centrifugal force acting in a parallel direction to the plane of rotation is

$$d(F_{CF}) = m\Omega^2 y dy \tag{12}$$

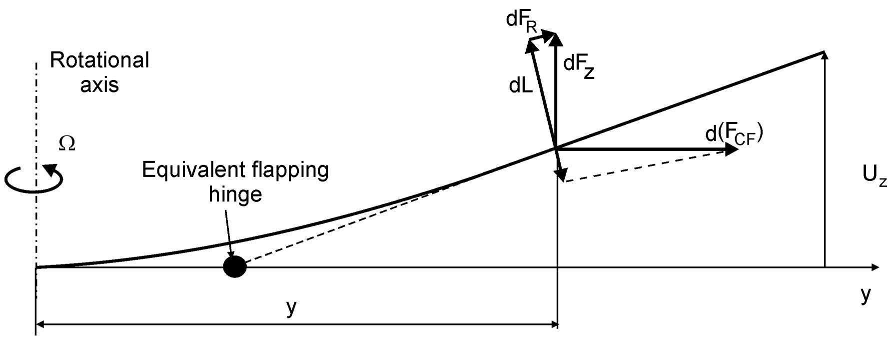


Fig. 3: Equilibrium of blade element aerodynamic and centrifugal forces

Because the aerodynamic center and shear center not coincident, reference to classical airfoil theory gives the section moment dM_x, as taken about shear center, defined in Fig.4

$$dM_x = \frac{1}{2}\rho U^2 c C_l x_{SC} dy \tag{13}$$

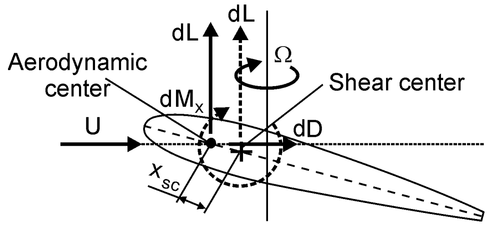


Fig.4: Section moment relevant geometry of a blade element

The helicopter airfoil is NACA 0012. The airfoil data for NACA 0012 are presented in [16]. The rotor angular velocity, Ω, is 261.7 rad/s (2500 rpm), and the helicopter velocity, *V*, is 10 m/s. The blade chord is 0.032 m. The blade has not linear twist. The blade pitch angle is 8^o. The aerodynamic loads are calculated by MATLAB code.

4. NUMERICAL RESULTS

The algorithm of the coupling between the structural model and aerodynamic model is:

1. The aerodynamic forces are computed for an ideal rigid blade by MATLAB code;
2. The aerodynamic and inertia forces are applied on the blade FEM-model by code ANSYS;
3. The linear and angular blade deformations are computed by ANSYS code;
4. The new angle of attack for each element of the blade is computed and new distribution of the aerodynamic forces is received by MATLAB code for next iteration;
5. The new aerodynamic and inertia forces are applied on the FEM-model by ANSYS code;
6. The new linear and angular blade deformation are calculated by ANSYS code;
7. The new distributions of the aerodynamic forces and deformations are compared;
8. If they are changed more than a certain tolerance: go to step 4;
9. The iteration is repeated while a convergence is achieved.

The results are shown in Figs.5-8. Figures 5a, 6a, 7a and 8a show the vertical bending deformations and Figs. 5b, 6b, 7b and 8b show the torsional deformation of the helicopter blade in the tip. The results are obtained by ANSYS code. Figures 5c, 6c, 7c and 8c shows the lift distribution as the results are obtained by MATLAB code.

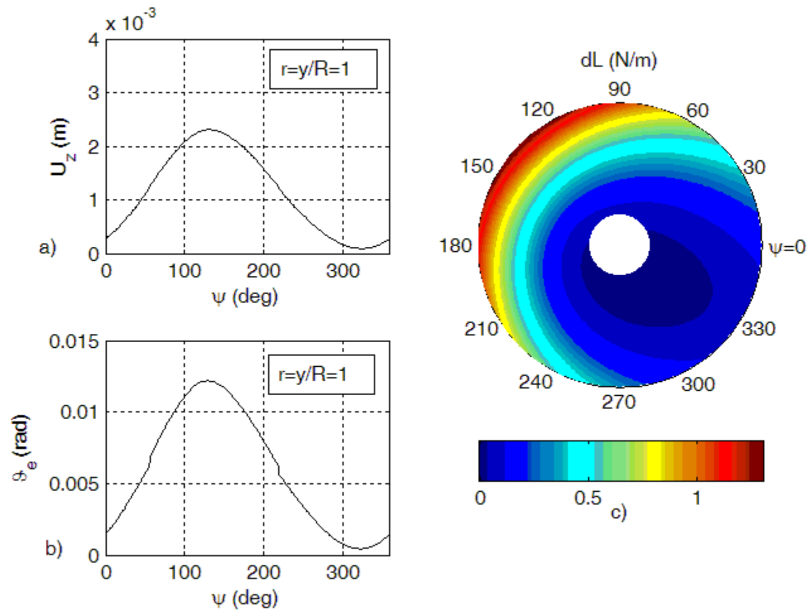


Fig. 5: First iteration. a) Vertical bending deformation, U_z, in the blade tip; b) Torsional deformation, θ_e, in the blade tip; c) Lift distribution, dL

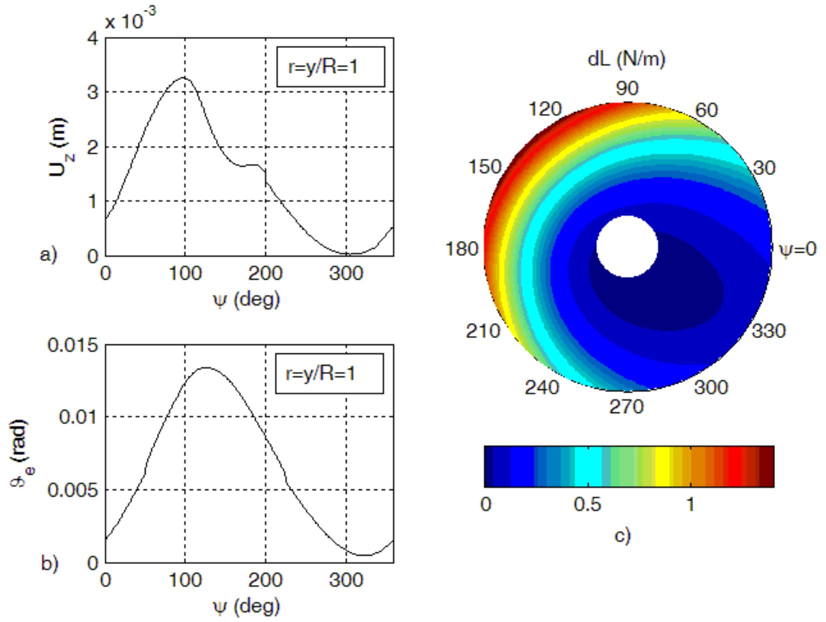


Fig. 6: Second iteration. a) Vertical bending deformation, U_z, in the blade tip; b) Torsional deformation, θ_e, in the blade tip; c) Lift distribution, dL

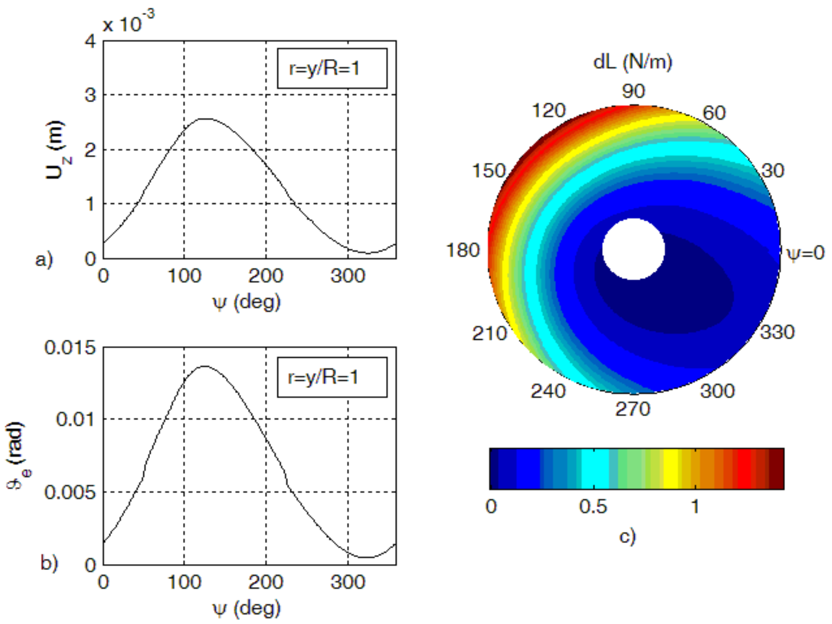


Fig. 7: Thirt iteration. a) Vertical bending deformation, U_z, in the blade tip; b) Torsional deformation, θ_e, in the blade tip; c) Lift distribution, dL

Four iterations of helicopter rotor are made while a convergence has achieved. The drag influences depends weakly from elastic properties of the blade in forward flight, as in hover [14]. Consequently, it is necessary to render an account of the blade elasticity at the calculations of the helicopter rotor thrust, torque and power in forward flight. In addition the aeroelastic effects will influence on the strength calculations of rotor sturcture.

Figure 9 shows the coning (flapping up) angle of the helicopter rotor at the final iteration.

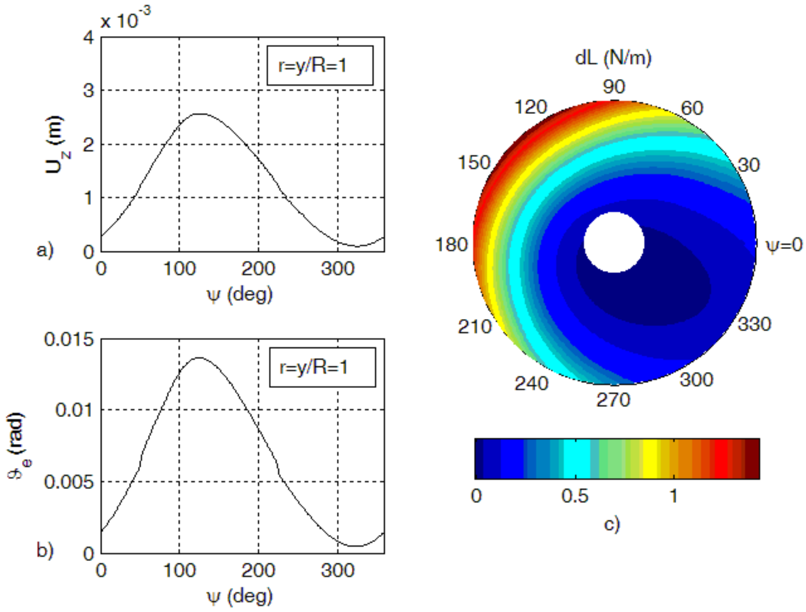


Fig. 8: Forth iteration. a) Vertical bending deformation, U_z, in the blade tip; b) Torsional deformation, θ_e, in the blade tip; c) Lift distribution, *dL*

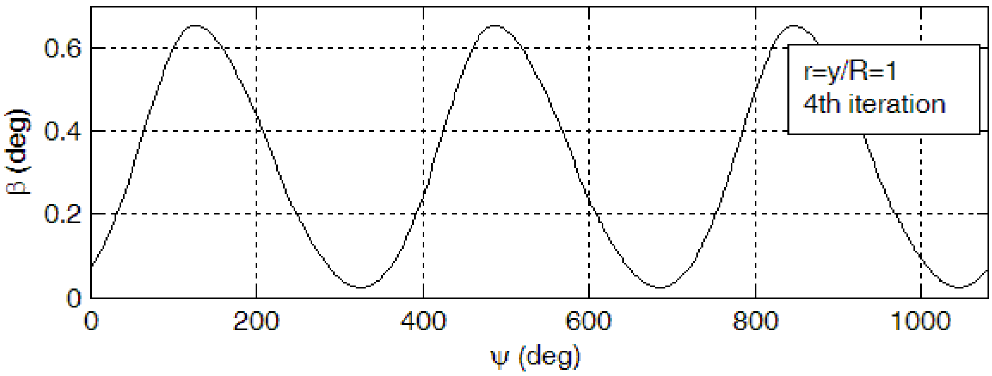


Fig. 9: Azimutal variation of the coning angle β

5. CONCLUSION AND FUTURE WORKS

A simple aeroelastic modelling of pattern helicopter hingeless rotor in forward flightw as presented. The modelling couples aerodynamic code which uses well-known solver MATLAB, and structural dynamic code which uses ANSYS. The effective and fast BEMT method and the linear inflow model of Drees were combined in order to create an aerodynamic model. To analyse the elastic and inertial behaviour of helicopter rotor, the ANSYS uses the Newmark time integration method, as the blade was presented with equivalent beam model. In this modelling the centrifugal and the gyroscopic forces are represented as external forces. The calculations,which are carried out for advance ratio of 0.1, show the robustness of the proposed method. The analysis of results confirms that the centrifugal forces are dominant and the coning angle of the helicopter rotor remains small.
The future study provides experiments in the wind tunnel with a model rotor. The results of this study will permit to create a database, which is needed for a reference with numerical simulations.

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