Helicopter main rotor blade structure parametric optimization using graphic programming language

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Abstract

This work presents the method of preliminary structure optimization of main rotor blade using parametric modelling. As a basis for parametric blade structure calculations the analytical model is provided in this paper. The equations of rigid blade loads and bending moment loads are shown.

The parametric modelling is conducted using GRIP (Graphic Integrated Programming) language. The structure of blade is generated automatically. The code inbuilt analysis systems provides a inertia examination of the geometry. The program for calculating the blade loads and natural mode shapes and vibration is presented. The code works in the loop, where at the end the generated geometry is a proposal of structure with optimal dimensions for the possible lowest mass. As an output of the study, the alternatives for main rotor optimization are developed.

1. Introduction

The recent military conflicts revised the possible operations that can be conducted by helicopters on modern battlefield. The necessity of constructions that are able to provide better characteristics for widespread military operations is noted by manufacturers and the national authorities. As a result, a lot of countries are enhancing current configurations and searching for brand new solutions of VTOL vehicles. Therefore also in Military University of Technology a studies focused on finding new approaches and design possibilities for rotorcraft are being conducted. The research were predated with the evaluation of helicopter constructions features and parameters that are responsible for the rotorcraft performance. The analysis took into consideration nearly 70 newest helicopters designs from all over the world. The results of the comparison were published in [1].

The main goal of the research is to develop an multicriteria optimisation procedure to provide a solution, using newest computer aided design methods. The results of researches that are also focused on main rotor optimisation are published in [2]–[6], and typically for the strength problems in [7]. Some research institutes are focused on main rotor optimization problems, the ONERA French Aerospace Lab and DLR German Aerospace Centre. Thei results are showed in [8]–[12]. The proposed solution is to used parametrization in CAD geometry design. The benefits of using this kind of solution were presented in [13], [14]. The parametrization is also used nowadays for airfoil design [15]–[17], structural design [18], [19] and aerodynamic design [20]. Therefore the second step, after comparison analysis, was a preparation of main rotor blade shape as a parametric model using GRIP language. The evaluation of the model, as an application into CFD analysis, were published in [21]. Also in further researches the CFD fluid domains were parametrized and simultaneously generated with full n-bladed rotor for CFD analysis of different flight conditions. The aim of the preparing the CFD environment and parametrisation of rotor model and its enclosures is to obtain a solution for quick preparation of FSI (fluid structure interaction) analysis.

The second part of preparing the FSI analysis is to prepare a MES structural loads simulation. Therefore, to combine it with the optimisation procedure, also the parametric structural model is needed to be prepared. The preparing of a model for further analysis with preliminary strength analytical calculations is presented in this paper. The preparation of CAD parametric model is conducted using GRIP (graphic integrated programming) language, which is implemented in Siemens NX software. The examples of GRIP usage is shown in [22]–[24]. This language is providing a possibilities of generating external body or inner structural parts of airframe which is actually being designed. Within the code the

mathematical calculations, logical conditions and geometry creation are possible. The main advantages of the presented solution, which will be shown in this research, are the mass and inertia analysis which are build within the code. The functions offer the possibilities to obtain numerical features of any geometry shapes, that can be used for preparing an optimisation procedure. The code of program, presented in this paper, which is generating geometry which is preliminary prepared and calculated for given flight conditions is prepared by the authors.

The analytical analysis for the structure generation are prepared using MATLAB software. The originally prepared codes with implemented mathematical formulas for main rotor loads and bending moments calculations is also described in this work.

2. Analytical model

2.1 Calculation of main rotor aerodynamic load

To calculate the main rotor aerodynamic loads for structural analysis the main rotor trim angles is needed to be estimated. The method of trimming were shown in previous work. The trimming can be made for all type of flight conditions. Obtaining pith angles and flap angles are the first step to calculate the main rotor blade load:

$$\theta(\psi) = \theta_0 - \theta_1 \cos(\psi) - \theta_2 \sin(\psi) \tag{1}$$

$$\beta(\psi) = \beta_0 - \beta_1 \cos(\psi) - \beta_2 \sin(\psi) \tag{2}$$

where θ are pith angles, β are flap angles and the ψ is rotor blade azimuth.
The rotor thrust which can be accepted as a rotor lift is given with the equation :

$$dT = \frac{1}{2} a\rho(\theta U_T^2 + U_p/U_{UT})dr \tag{3}$$

where a is the lift curve slope, ρ is the air density. However to calculate the thrust an velocity components at the blade are needed to be estimated:

$$U_p = \Omega R(\lambda' - \frac{x\dot{\beta}}{\Omega} - \mu\beta \cos\psi \tag{4}$$

$$U_T = \Omega R(x + \mu \sin\psi) \tag{5}$$

where Ω is main rotor rotational velocity, R is the rotor radius, and μ is the advance ratio. The inflow ratio is given with:

$$(\lambda' = (V \sin\alpha_D - v_i)/ \Omega R \tag{6}$$

where V is the rotorcraft velocity α_D is rotor disc angle of attack and v_i is the rotor induced velocity.

2.2 Calculation of rotor blade normal modes and frequencies

In order to calculate the bending shapes of rotor blade the natural frequencies and normal modes are needed to be estimated. There is no simple procedure or one technique to determine the values of vibration parameters. The one which were chosen for this research is the Rayleigh-Rith method, the algorithm which is used in the work is based on [25]. In this method the energy equation of rotating beam is minimized:

$$\epsilon = \int_0^R \left\{ EI \left(\frac{d^2y}{dr^2}\right)^2 + \frac{1}{2}\overline{m}\Omega^2(R^2 - r^2)\left(\frac{dy}{dr}\right)^2 - m\omega^2 y^2 \right\} dr \tag{7}$$

where E is Young Modulus, I moment of inertia, y natural mode shape, ω is natural frequency.
The applied method of solution provides possibilities for usage the method in numerical software. The equation is transformed into matrix form, with transformation of each part into Fourier series. This provides the non constant mass distribution application into the procedure and to take benefits from orthonormality properties of Fourier series. Also to simplify the procedure the spanwise coordinate is given with $x = \pi r/R$. Then the euqations parts are :

$$\frac{EI(x)\pi^2}{R} = \sum_1^\infty p_n \cos nx \tag{8}$$

$$\frac{\bar{m}\Omega^2 R^2 (\pi^2 - x^2)}{2\pi^2} = \sum_1^\infty q_n \cos nx \tag{9}$$

$$y = a_0 x - \sum_1^\infty a_n \sin nx \tag{10}$$

Substituting the parts of energy expression we get:

$$E = \int_0^\pi \{ (\sum_1^\infty p_n \cos nx) (\sum_1^\infty n^2 a_n \sin nx)^2 + (\sum_1^\infty q_n \cos nx) \\ (a_0 - \sum_1^\infty n a_n \sin nx)^2 - r_0 \omega^2 (a_0 x - \sum_1^\infty a_n \sin nx)^2 \} dx \tag{11}$$

These equation can be written in a matrix form and A and B are symmetric matrices with p and q coefficients:

$$(A^{-1}B - \frac{I}{\Gamma^2})\underline{a} = 0 \tag{12}$$

Where $\Gamma^2 = 2\omega^2 r_0$ and a is a matrix of coefficients of normal modes shape. Calculating the latent roots of the matrix $A^{-1}B$ the natural frequencies and shapes are obtained.

2.3 Calculation of rotor flapping blade bending moment values and shapes

After the preparation of preceding results the bending moment can be calculated for different spanwise coordinates and azimuthal position. First step is to determine the outside forces on the blade. The outside forces consist of :

- the elementary lift $dT=dF_a$
- the blade weight $m'gdx$
- centrifugal force of rotation $m'\omega 2\, xdx$
- the force inertia for flapping $mx\ddot{\beta}$

The total forces acting on a blade are $dF_d = dF_a - m'g - m'\omega 2\, x - mx\ddot{\beta}$. The applied procedure of calculation was to estimate the distribution of bending moment to the third harmonic of natural shape.

To calculate the bending moment the equation of the equation of deflection with damping is used:

$$\frac{d^2}{dx^2}\left(EI\frac{d^2 y}{dx^2}\right) - \omega^2 \frac{d}{dx}\left(s\frac{dy}{dx}\right) + m'\ddot{y} + K\dot{y} = F'_d(x,t) \tag{13}$$

where s is static moment with respect to axis of rotation and K is the damping coefficient. The method of solution that were applied in the research is proposed in [26]. This methodology was chosen because it consist of solving the equation methods that can be easily applied into program that were prepared.

3. Optimization procedure

3.1 Analytical solving

As a first step of the propose procedure is to resolve the mathematical model which was described in chapter 2. It was implemented into MATLAB environment to solve equations and calculate the values for initial rotor parameters. The results will be a basis for a prepared GRIP program to evaluate best structural shape.

The problem were divided into two separate codes first one was prepared for the main rotor trim with calculation of blade loads and second for blade mode shapes, natural frequencies and finally the bending moment values and distribution.

The first program is started with the rotor geometric and aerodynamic parameters, also the basic helicopter features such as mass are included. The initial blade mass is also estimated. Furthermore in this stage the flight conditions such as flight and climb speed are also given. Next step is to parametrize the rotor chord and twist so they can change their value along the span, the calculated coefficients also will be used in the geometry generating program. Nest step of the program is the trimming of the main rotor pitch and flap angles. The code were partially prepared in the previous stages of research. The trim angles are calculated resolving acting forces horizontally and vertically with reference to the rotor-disc plane. Ater obtaining the trim angles the blade aerodynamic loading can be determined. Solving the equations of velocity component the lift distribution is computed. The force distribution is generated also by a polar chart – Figure 1.
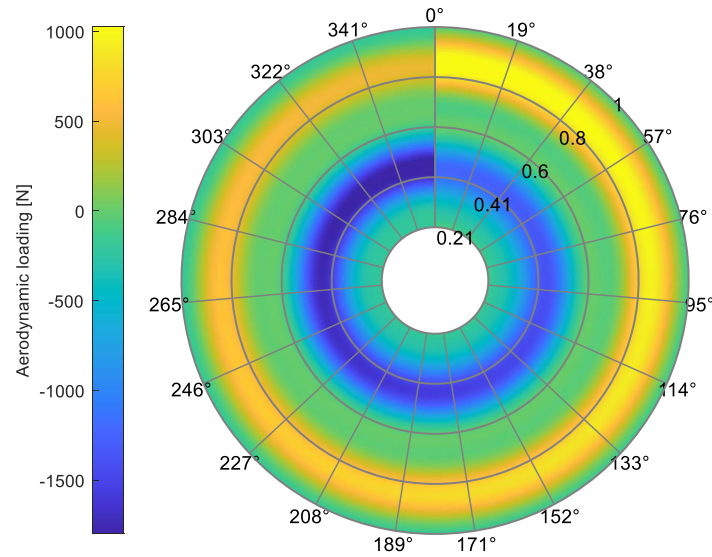

Figure 1 Aerodynamic loading for μ = 0.25

Second step for finding the solution is the program that calculates the natural modes and frequencies and then with the aerodynamic load from previous code it solve the bending moment equation. Program calculates vibration properties for the chosen material and the shape of the blade. The moment of inertia in each section is given from the GRIP program which will be described later. The function of Young's modulus and moment of inertia is given with polynomial to fit the values across the span. In the next step each function is transformed into Fourier series using the Fourier Series integral definition. Then the matrices of coefficients are built. Using MATLAB inbuilt functions the eigenvalues of the matrices equation is determined. This are the natural frequencies and mode shapes. In the research the calculations were made to the 7th harmonic, however for the bending moment only the first three were used. To show results the natural shapes are presented on the charts – Figure 2
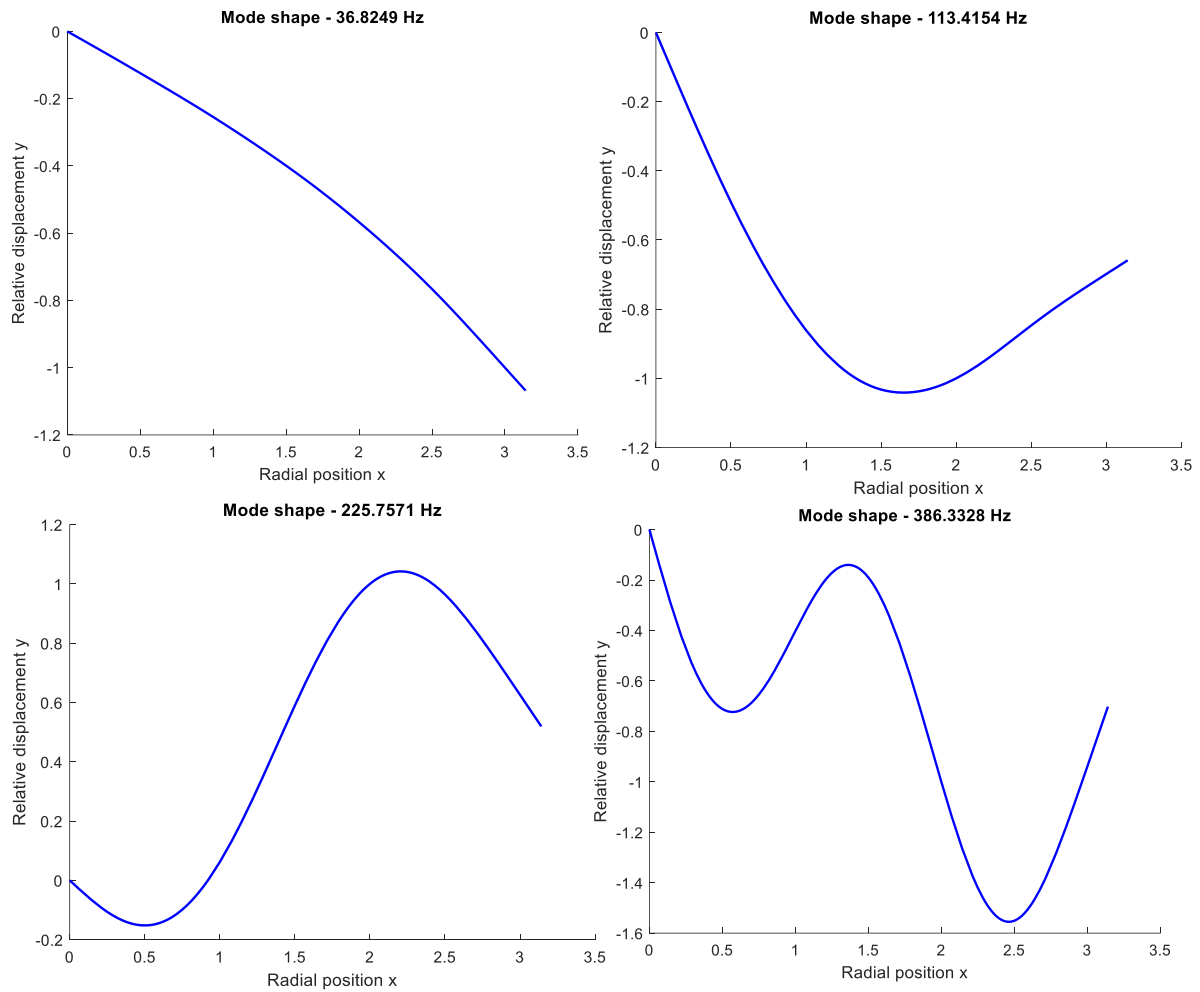
Figure 2 Natural mode shapes

Next the program is solving the bending moment for the first three harmonics. The outside forces with aerodynamic loading are taken into consideration. The values of non rotating blade natural frequencies are computed. The damping coefficient is estimated and next the outside force and mass distribution is correlated with the natural shape. From the results the coefficients for bending moment for each harmonic calculation is given. At the end the bending moments are added to each other. The bending moment is defined as a function of radius and azimuth.

3.2 Geometry programming

The main objective of this study is to obtain a new method for main rotor blade modelling, which will be applied into main rotor optimization loop. The goal is reached using Open GRIP code, which is an integral part of Siemens NX. The program was partially used from the first stage of the studies, because the external geometry is needed to be the same for the further FSI simulation.

The blade model is parametrized in the program with all of main rotor geometric aspects. The designer is able to insert the basic factors into popup input window. The first parameter is the blade chord and rotor radius. The airfoil is created from the txt file with the coordinates, so the operator can prepare the geometry for any chosen airfoil. Next part of parametrization is the polynomial coefficients for twist and chord of the blade, so they can change along the span. The outer shape is filled with the structure. The inner structure of the blade is based on the existing solutions with the main spar and filing in the leading edge part and the honeycomb structure in the trailing edge part. The example of geometry is shown on Figure 3.
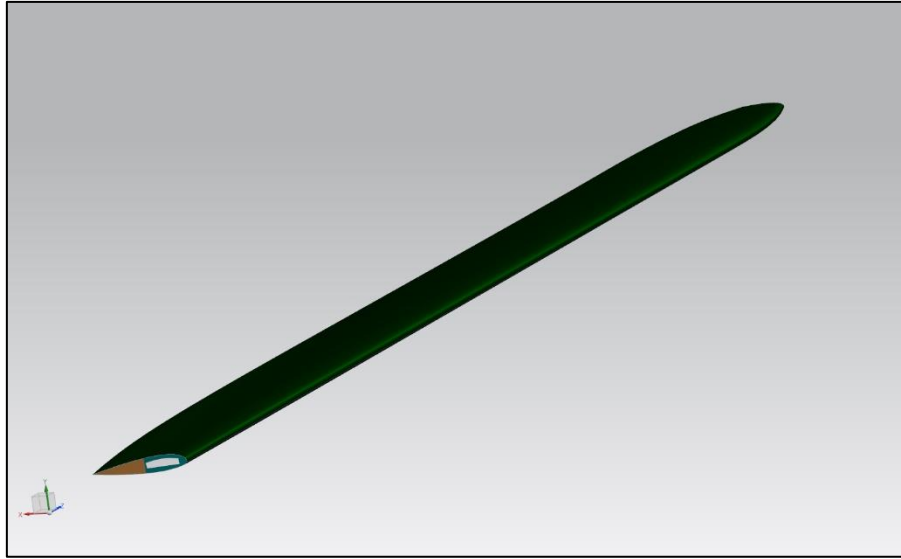
Figure 3 The parametrized geometry

With the prepared solution the blade shape can be freely change with accordance to the analytically calculated values. The shape building is based on inbuilt GRIP commands for the line and splines which prepares the requested shape.

The next part of the program is the analysis and the strength calculation. Using the inbuilt commands the program is conducting analysis of the cross sections and the whole 3D geometry. After analysis the moment of inertia of each cross section is given. The density of the models are programmed by the user, so the 3D analysis gives the mass of the blade. The moment acting on a blade in each section is loaded from the file that were generated with the previously described MATLAB code. With the prepared strength equations it is checking if the required stiffness is enough for the loads. Then the program makes the correction of the spar dimensions to fulfil the stiffness requirement and reduce/increase the spar mass. The example of the code with analysis options is shown on Figure 4.

```
250    SPAR(4)=BSURF/MESH,LNS5(3..4),WITH,LNS3(1..K),TYPE,3,TOLER,.01,.01
251    SPAR(5)=BSURF/MESH,LNS5(4),LNS5(1),WITH,LNS4(1..K),TYPE,3,TOLER,.01,.01
252    SPAR(6)=AUTOSF/LNS1(1),LNS2(1),LNS3(1),LNS4(1)
253    SPAR(7)=AUTOSF/LNS1(K),LNS2(K),LNS3(K),LNS4(K)
254    SPAR(8)=SEW/SPAR(2..7)
255
256    BLD(7)=SEW/SSRF(6..9)
257    MAT=MATRIX/TRANSL,0,0,0
258    BLD(5)=TRANSF/MAT,BLD(7)
259    SPAR(1)=TRANSF/MAT,SPAR(8)
260    |
261    BLD(6)= SUBTRA/BLD(8),WITH,BLD(7),CNT,c $$ enclosure
262
263
264    DELETE/LN,PT2,PT3,PT4,PT5,PT6,SPLC
265
266
267
268    PLN(1)=PLANE/YZPLAN,C0/3+wall
269    BLD(1..2)= SPLIT/BLD(5),WITH,PLN(1)
270
271    PLN(2)=PLANE/XYPLAN,A(3)+1
272    SEC(1..3)= SECT/BLD(1),WITH,PLN(2)
273    BND(1)=BOUND/SEC(1..3)
274    BND(2)=BOUND/LNS1(1),LNS2(1),LNS3(1),LNS4(1)
275    ANLSIS/TWOD,BND(1),MMETER,wyn2
276    ANLSIS/TWOD,BND(2),MMETER,wyn3
277
278
279
280
281
282
283    PRINT/'--------Spar Cross section analysis----------'
284    PRINT/USING,'Cross section area Fdz=#@@@@@@.@@ [mm^2]',wyn2(2)-wyn3(2)
285    PRINT/USING,'Moment of Intertia Idz=#@@@@@@@.@@ [mm^4]',wyn2(9)-wyn3(9)
286    PRINT/USING,' center of mass:  X=#@@@@@@@@@@@.@@@ mm',wyn2(3)
287    PRINT/USING,'                  Y=#@@@@@@@@@@@.@@@ mm',wyn2(4)
288    PRINT/USING,' center of mass:  X=#@@@@@@@@@@@.@@@ mm',wyn3(3)
289    PRINT/USING,'                  Y=#@@@@@@@@@@@.@@@ mm',wyn3(4)
```

Figure 5 The example of GRIP code

4. Results

As a result the design procedure is proposed. As an example the optimisation procedure were conducted for the W-3 blade. The inner structure were proposed a standard for a rotor blades. The procedure which is proposed in the research is focused on spar optimization, because it is responsible for the bending strength. The spar is checked in the programmed number of sections if it is able to fulfil the strength requirements with accordance to calculated bending moment. The dimensions of the spar filling is increasing while the spar is getting lower dimensions. The carbon fiber composite is proposed as a material for the spar.

The iterative procedure changes the dimensions in each step and evaluate the new shape. The safety factor 1.2 is proposed, but it can be change by the user. If the strength condition is fulfil, the difference between the load and the strength with safety factor is enough small GRIP program generate the ready to use 3D geometry and mass and inertia analysis of the shape. With the mass reduction the centrifugal and weight forces are diminishing, so the procedure is needed to be run once again. As a result the new CAD geometry is given. For the example showed in this work the mass was reduced by 9 kg from the originally used blade on this helicopter.
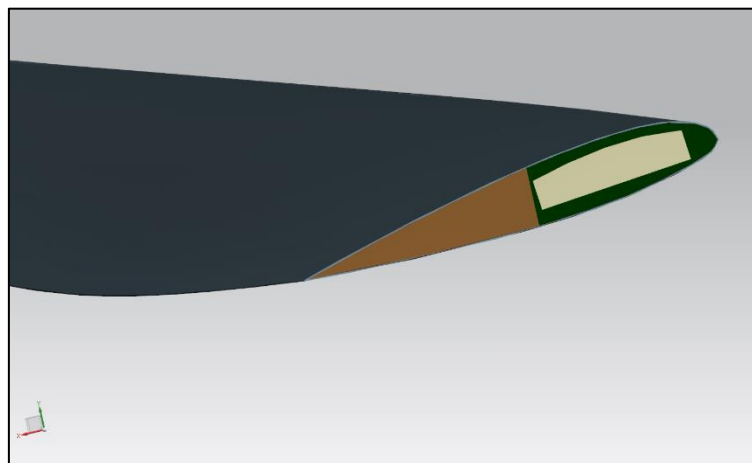

Figure 4 The optimized geometry

5. Conclusion

This work shows a new approach for preparing geometry for further MES and FSI analysis. The first part presents the analytical assumptions for the proposed solution. The loads and vibrations calculation is described. The second part gives the method of solving the analytical problems with a application of modern environment. The method of optimization of the structure is described. At the end the example of the resultant geometry with the mass effect is shown.

The prepared CAD model is fully capable to be an input for any MES software. The proposed solutions provides a few applications for the helicopters design. Firstly the methods for resolving the program of the natural mode shapes and vibrations of the rotating blade, second the blade trim with providing the aerodynamic loading of the blade in function of radius and azimuth, and finally generating and preparing the preliminary optimize main rotor blade structural model. All of that solutions can be used separately or combined for any different blade shapes and flight conditions can be checked. Results of the research gives opportunity the reduce the time of making the final model and evaluating in a different blade configurations. The vibration analysis and trim calculation will be also used for preparing and evaluating further simulations using FSI solution.

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