OPTIMISATION OF THE STRUCTURE OF A HELICOPTER BLADE IN VIEW OF REDUCING CABIN VIBRATION

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Abstract
The study presented in this paper aims at bringing the blade internal structure into a global multi-physics optimization of the helicopter rotor. The optimization is applied to vibration reduction in forward flight with aeroelastic and multidisciplinary constraints. The objective function consists of the dynamic hub loads, and behaviour constraints are imposed on dynamics, performance and manufacturability criteria. A genetic algorithm is used to conduct a global search of the design space among numerous combinations of blade physical parameters with discrete values (positioning of tuning masses, composite skin layers, counterweight materials…). The novelty brought by this study includes simulations integrated in a tool-chain based on physical parameters with manufacturability constraints.

NOTATIONS

b	Blade number
C_T	Thrust coefficient
C_D	Drag coefficient
C_{M_x}	Moment coefficient
$\boldsymbol{D}$	Vector of design variables
$F_x{}^{5\Omega}$	Force applied by all blades on the fuselage in the longitudinal axis at the harmonic b
$F_y{}^{5\Omega}$	Force applied by all blades on the fuselage in the lateral axis at the harmonic b
$F_z{}^{5\Omega}$	Force applied by all blades on the fuselage in the vertical axis at the harmonic b
$g(\boldsymbol{D})$	Constraints
J	Objective function
N_c	Number of constraints
N_{dv}	Number of design variables
σ	Rotor solidity
Ω	Rotor angular speed

INTRODUCTION AND BACKGROUND

Passive and active anti-vibration devices already exist on helicopters to reduce vibrations generated by the dynamic hub loads [1]. This paper focuses on another existing technique [2-7] which is to design the rotor so as to minimize the hub dynamics loads. For a b-bladed rotor, each of $b-1$, b and $b+1$, shear loads are transmitted to the fixed frame. Nowadays, the vibration problem is approached by designing the blades with adequate frequency separation between its eigen-frequencies and the rotor harmonics. Aeroelastic couplings have proven, theoretically and experimentally [8], to be a lever for reducing the hub loads. Since the 1980s, the optimization of the blade structure has been studied [2-7] and it was shown that typical levels of vibration reduction are in the range of 15−60% relative to the baseline vibration levels. The effects of internal blade structure on dynamic hub loads are relatively well-known even if the prediction of such effects is still not fully satisfactory.

1. METHODS AND TOOLS

This section describes the tool chain, automatizing the exchanges between the different software, which was set-up as a part of the optimization process. Details on the optimizer are also given in this section.

1.1. Optimization loop

The optimization loop gathers two parts (figure 1):

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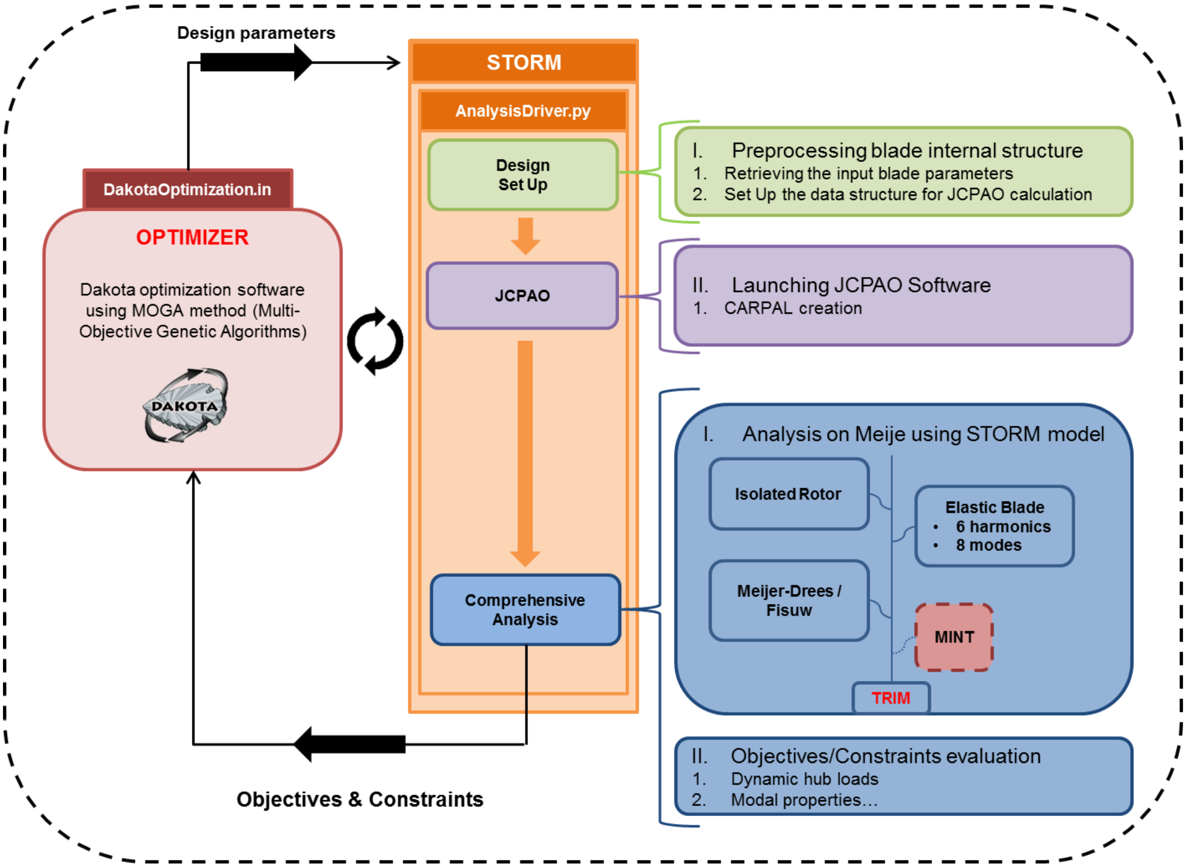

Figure 1 : Global view of the multidisciplinary optimization.

1. Optimizer: The single or multi-Objective Algorithm is developed by DAKOTA software. DAKOTA generates individuals which are evaluated in an external model (evaluator). For each generation *k*, the evaluation is launched *n* times, with *n* the number of individuals in generation *k*. When all individual evaluations are returned by the evaluator, DAKOTA is responsible for selection, crossing and mutation and then creation of the new generation. This process is repeated several times until it is stopped by the user (set with number of evaluations or number of generations.) For the study, the number of individuals in the population is constant for each generation and set at 200.

2. Evaluator: This is a routine called by DAKOTA for evaluating the individuals. In a general way, the Evaluator is a tool which allows the computation of objectives and constraints defined in DAKOTA from a parametric input file.

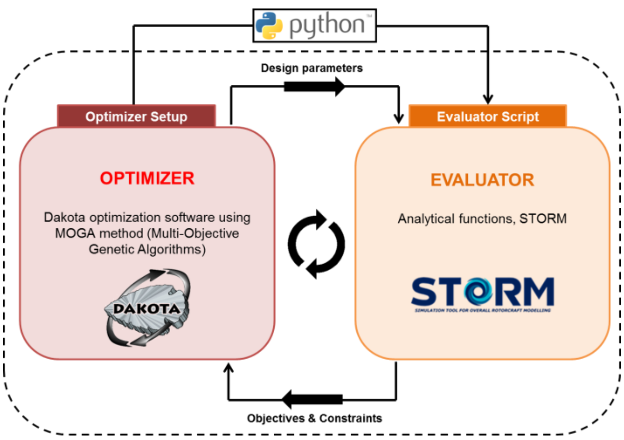

Figure 2 : Optimizer and evaluator.

1.2. Tool chain

The tool chain is composed of several blocks, which are independent and replaceable according to the user (figure 2).
The tool chain blocks are the following:
1. *Preprocessing*.
This block is a routine coded in Python. It analyzes and sets up the data structure from DAKOTA representing the blade physical degrees of freedom

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for the calculation of the blade properties (JCPAO calculation).

2. Blade properties calculation.
The Airbus Helicopters internal software JCPAO (Airbus Helicopter blade design tool) is used to define the complex blade internal architecture, the 2D homogenization of blade section properties and the loads in the different components of the blade. The blade mass, inertia, geometric and stiffness data are all contained in a text file (CARPAL) describing the blade characteristics section by section. The possible/acceptable range of the design parameters are also defined within this tool.

3. Aeromechanic calculation.
The Airbus Helicopters Comprehensive analysis code STORM (Simulation Tool for Overall Rotorcraft Modelling), the successor of HOST (Helicopter Overall Simulation Tool) [9] is used to compute the aeromechanic behavior of the isolated rotor for a 3-degree-of-freedom trim. The values are prescribed for the the lift, the propulsive force and the rolling moment. The shaft angle is then prescribed as equal to the arctangent of the ratio between the drag and the thrust coefficients.
4. *Postprocessing.*
Objective functions, multidisciplinary constraints are calculating and setting up for returning to DAKOTA.

The optimization loop can be launched in parallel mode for reducing computation time of each population.

2. MODELIZATION

2.1. Aeroelastic response

Helicopter vibrations are generated by the combination of aerodynamic, inertial, and elastic sources that form the basis of any aeroelastic response calculation. The optimum design of a helicopter for minimum vibrations in forward flight clearly represents a complex aeroelastic optimization problem with multidisciplinary constraints.

The key ingredients of the aeroelastic response analysis are:

- The structural dynamic model
- The aerodynamic model
- A coupled trim/aeroelastic response procedure that is required for the computation of the steady state blade response

The simulation code used in this study is based on a comprehensive aeroelastic analysis code STORM [9]. The code, developed at Airbus Helicopters, is used to obtain the helicopter dynamics, the flight mechanics, and the performance using simplified aerodynamics (based on the lifting-line method) and simplified blade dynamics (based on a 1D beam model).

2.2. Structural dynamic model

The beam is discretized along the pitch axis as an assembly of rigid segments connected by virtual joints. Elastic blade computations can be performed. Accordingly, blade rigid motions and deformations are assumed periodic. The structural dynamic model is based on modal analysis. Normal modes are used to reduce the number of structural degrees of freedom and allowing trims to be found in a matter of seconds. In this study, eight modes are used: the first four flap modes, first two lead-lag modes and two torsional mode (figure 3). Seven harmonics is set to correctly predict loads up to the sixth harmonic.

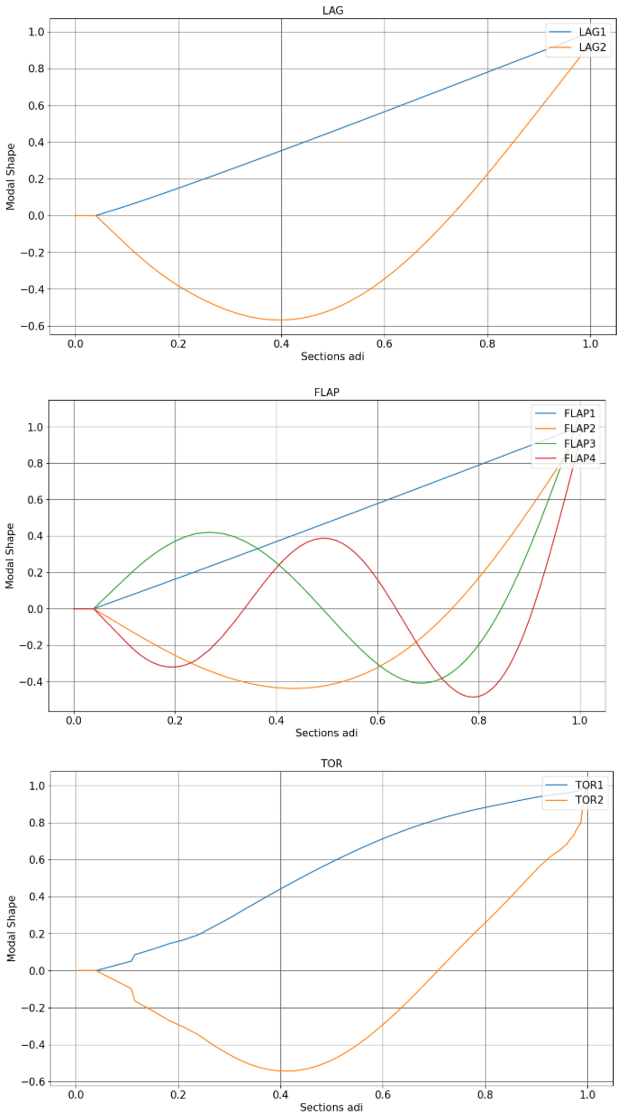

Figure 3 : Modal basis (deformed shape)

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The beam type finite elements used for the discretization have 35 nodal degrees of freedom.

This study is limited to the behavior of isotropic blades with span-wise varying properties.

2.3. Aerodynamic model

For this study, the induced velocity model named FISUW (Finite State Unsteady Wake model) is used to calculate the induced flow distribution on the rotor disk. This finite state model is suited to dynamic load calculation because it can include a rich radial and harmonic representation of the induced flow. A free-wake model may be used in STORM (MINT: Modèle INsTationnaire) to increase the fidelity of calculations. The calculation time however surges to about 30min per trim point.

2.4. Isolated rotor model

The dominant source of vibratory loads is dynamic stall which is characterized by flow separation and excessive vibration levels. In order to avoid this phenomenon the selected forward-flight speed V_h is equal to $150\,kts$ level, and an advance ratio μ of 0.36. To correctly conduct the performance assessment, it is necessary to trim the rotor at a prescribed propulsive force.

A three-variable objective trims the rotor at prescribed values for the lift ($\frac{C_T}{\sigma} = 0.085$), propulsive force ($\frac{C_D}{\sigma} = 0.0022$), and rolling moment ($\frac{C_{M_x}}{\sigma} = 4.4e^{-4}$). The shaft angle is then prescribed from the helicopter's trim. It's the sum of the angles between Tip Path Plane and Hub plane, between Hub plane and Helicopter reference line and finally between Helicopter and Horizontal.

2.5. Loads calculation

The hub loads are then obtained using a force summation approach. For this, motion-induced aerodynamic and inertial loads are integrated along the blade span to obtain blade loads at the root, and then summed over all the blades to obtain fixed frame hub loads.

Out-of-plane loads: F_z et M_z

(1)	$F_z = b\sum_k F_z^{\ kb} e^{ikb\Omega t}$
(2)	$M_z = be\sum_k F_y^{\ kb} e^{ikb\Omega t}$

In-plane loads : $F_x, F_y, M_x et\ M_y$

(3)	$F_x = \frac{b}{2}\sum_k e^{ikb\Omega t}(F_x^{\ kb-1} + e^{i\frac{\pi}{2}}F_y^{\ kb-1} + F_x^{\ kb+1} + e^{-i\frac{\pi}{2}}F_y^{\ kb+1})$
(4)	$F_y = \frac{b}{2}\sum_k e^{ikb\Omega t}(F_y^{\ kb-1} + e^{i\frac{\pi}{2}}F_x^{\ kb-1} + F_y^{\ kb+1} + e^{-i\frac{\pi}{2}}F_x^{\ kb+1})$
(5)	$M_x = e\frac{b}{2}\sum_k e^{ikb\Omega t}(e^{-i\frac{\pi}{2}}F_z^{\ kb-1} + e^{i\frac{\pi}{2}}F_z^{\ kb+1})$
(6)	$M_y = -e\frac{b}{2}\sum_k e^{ikb\Omega t}(F_z^{\ kb-1} + F_z^{\ kb+1})$

Equation [1-6] show that when an isotropic rotor is considered (rotor tracking and balancing), most dynamic loads are canceled. The rotor acts as a filter. Only harmonics corresponding to multiples of the number of blades are transmitted to the fuselage. These dynamic loads, even if limited to $kb\Omega$ harmonics, are responsible for discomfort and for alternate stress on components.

3. OPTIMIZATION

3.1 Formulation of the Blade Optimization Problem

The objective function, design variables, and constraints are the several ingredients which will be used for the optimization chain. A general constrained optimization problem [10] can be written mathematically as follows: Minimize

$$\boldsymbol{J}(\boldsymbol{D})$$

Subject to:

(5)	$\boldsymbol{g}(\boldsymbol{D}) \leq \boldsymbol{0}$ $\boldsymbol{h}(\boldsymbol{D}) = \boldsymbol{0}$ $\boldsymbol{D^l} \leq \boldsymbol{D} \leq \boldsymbol{D^u}$

Where $\boldsymbol{D}$ are design variables, and the superscripts l and u are lower and upper bounds, respectively. The objective function as well as constraint functions can be nonlinear.

A b-bladed rotor transmits forces and moments to the fuselage at the main rotor harmonics times the number of blades ($b\Omega$)as the principal source of vibration. Thus, the objective function consists of a combination of the b/rev oscillatory hub shears and moments. The forces are normalized by the rotor steady thrust, and the moments are normalized by the rotor steady yawing moment. For a five bladed rotor, the objective function is given by:

$$J = K_F\sqrt{(F_x{}^{5\Omega})^2 + \left(F_y{}^{5\Omega}\right)^2 + (F_z{}^{5\Omega})^2} + K_M\sqrt{(M_x{}^{5\Omega})^2 + \left(M_y{}^{5\Omega}\right) + (M_z{}^{5\Omega})} \tag{7}$$

Where K_F and K_M are the weighting factors and selected to be 1.

$$\boldsymbol{D_j^l} \leq \boldsymbol{D} \leq \boldsymbol{D_j^u}, \boldsymbol{j} = \mathbf{1}, \mathbf{2}, \dots, \boldsymbol{N_{dv}}$$

In addition, two types of *behavior constraints*, given by :

$$g_i(\boldsymbol{D}) \leq 0, i = 1,2, \dots, N_c$$

Are placed on the design variables.

The first type of behavior constraints are *blade eigen-frequency placement constraints*, which are prescribed upper and lower bounds on the flap, lag, and torsional frequencies of the blade. The fundamental flapping frequency placement constraint is written as :

$$g_{flap}(\boldsymbol{D}) = \frac{\omega_{F1}}{\omega_U} - 1 \leq 0$$

And

$$g_{flap}(\boldsymbol{D}) = 1 - \frac{\omega_{F1}}{\omega_L} \leq 0$$

Where ω_U and ω_L are the prescribed upper and lower bounds on the fundamental flap frequency. This procedure is the same for lag and torsion frequencies, i.e. g_{lag} and $g_{torsion}$. The eigenfrequencies of the blade do not match any rotor excitation frequency to avoid undesirable resonances. Those eigenfrequencies calculations are predictive and reliable thanks to MODPAL calculations for straight blades.

The second behavior is the *inertial properties constraint*, which ensures that mass redistributions produced during the optimization do not degrade the autorotational properties of the rotor. The mass polar moment of inertia should be at least 90% of its baseline value. This constraint is written as:

$$g(\boldsymbol{D}) = 1 - \frac{J_P}{0.9J_{P0}}$$

In the further publications, more constraints will be added to the study.

3.2 Discrete Genetic Optimization Algorithm

3.2.1 Description

The genetic algorithm is based on darwinistic evolution principles and natural selection (*Darwin 1859*).

- Population of individuals is evolving from generation to generation. Each individual is more or less "powerful" according to its characteristics. Natural evolution enhances the characteristics that make an individual powerful.
- The renewal of a generation is taking place in four phases :
    - Selection of a parents part for breeding
    - Crossing of selected parents to generate offspring
    - Random mutation (variation) of one part of the offspring
    - Selection between children and parents for the next generation
- Evolution allows the appearance of more and more powerful individuals. The rapidity and efficiency of this process is depending on:
    - The size of the population
    - The representation (encoding) of individuals
    - The operator of selection and variation

The figure 4 shows the procedure of a genetic algorithm.

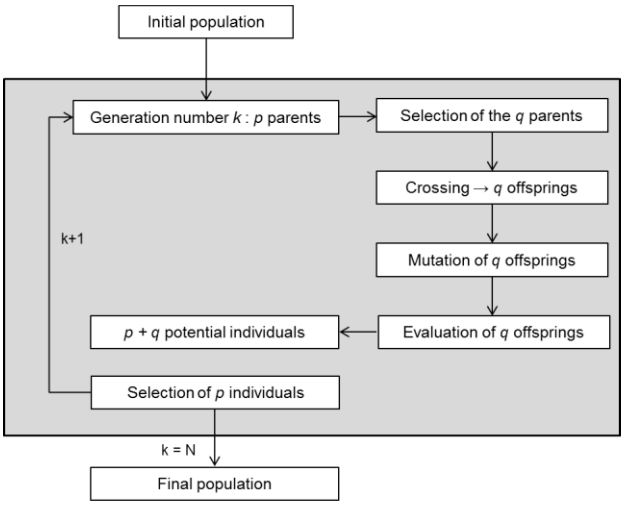

Figure 4 : Genetic Algorithm process.

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3.2.2 Minimisation problem

$$\boldsymbol{min_x\, f(x)}$$
$$\rightarrow \begin{cases} \boldsymbol{variables\ x = "phenotype"\ of\ individual} \\ \boldsymbol{function\ f = "power"\ of\ individual} \end{cases}$$

The population is constituted of *p* individuals. The evolution aims at:

- Keeping the best solutions (selection)
- Exploring new solutions (variation)

Selection operators are based on performance function:

- Deterministic selection
- Selection for breeding, for replacement.

Variation operators brings random solutions

- Modification of one part of the variables
- Variation by crossing, by mutation

The genetic algorithm uses a binary representation of the individuals ("genotype"). The binary genotype is transcribed in "phenotype" (variables of the design space) before evaluation.

Moreover, this type of optimization was chosen because it offers the capability to optimize on a discrete design space, which cannot be realize with other methods like surrogate models for example.

3.3 Dynamic Design of the Blade

The figure 5 shows the blade degrees of freedom for the internal structure. For this case there are almost thirty parameters and each parameter can take approximatively three values.

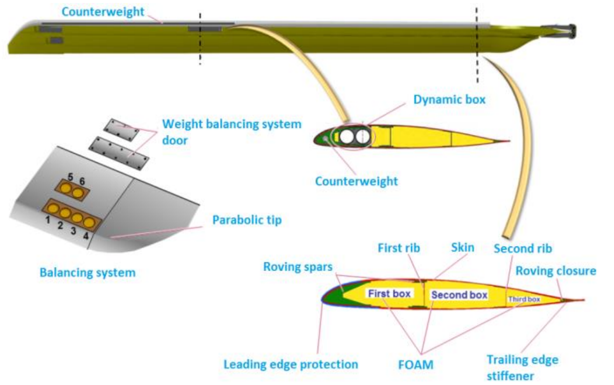

Figure 5: Blade degrees of freedom.

3.4 Sensibility Analysis

The vector of *design variables* $\boldsymbol{D}$ consists of blade physical parameters with discrete values (positioning of tuning masses, composite skin layers, counterweight materials…) resulting in a total of 30 design variables. In order to reduce drastically this number, a sensibility analysis is established. The variability of modal placement and loads due to them is used to choose the parameters which be selected for the global optimization.

4. RESULTS

Results of sensibility analysis are presented in this section for two parameters: added mass and composite skin layer.
Each loop of CARPAL generation (JCPAO) and trim calculation (STORM) took about 6 minutes.
Each parameter is set up to analyze its contribution for loads and frequencies placement.

3.4.1 Frequency

As shown in figure 6, the position of the mass box along spanwise and its value (0kg, 1 kg or 2 kg) can be used to modify eigenfrequencies.

The centrifugal stiffness increases with the distance between the mass and the rotational center of the rotor, hence the mass must be located near the blade tip to increase the eigenfrequencies. For decreasing the eigenfrequency of a mode, the mass must be located on an anti-node (see figure 3) because the generalized mass increases with the amplitude of the motion of the added mass.

The figure 7 shows the influence of the added composite skin layer on the eigenfrequencies. This layer could modify radically the eigenfrequency lead-lag mode without changing other eigenfrequencies. This parameter will be used for respecting modal constraints.

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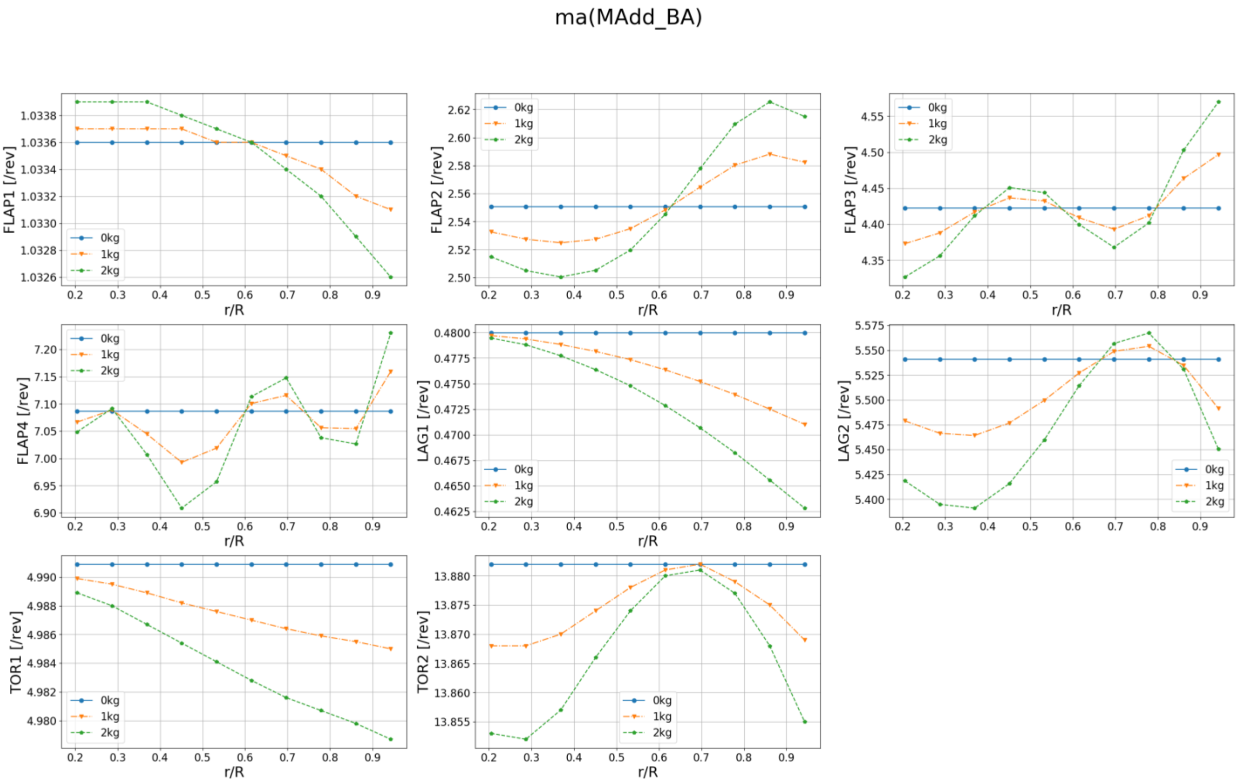

Figure 6: Influence of the added mass on eigenfrequencies.

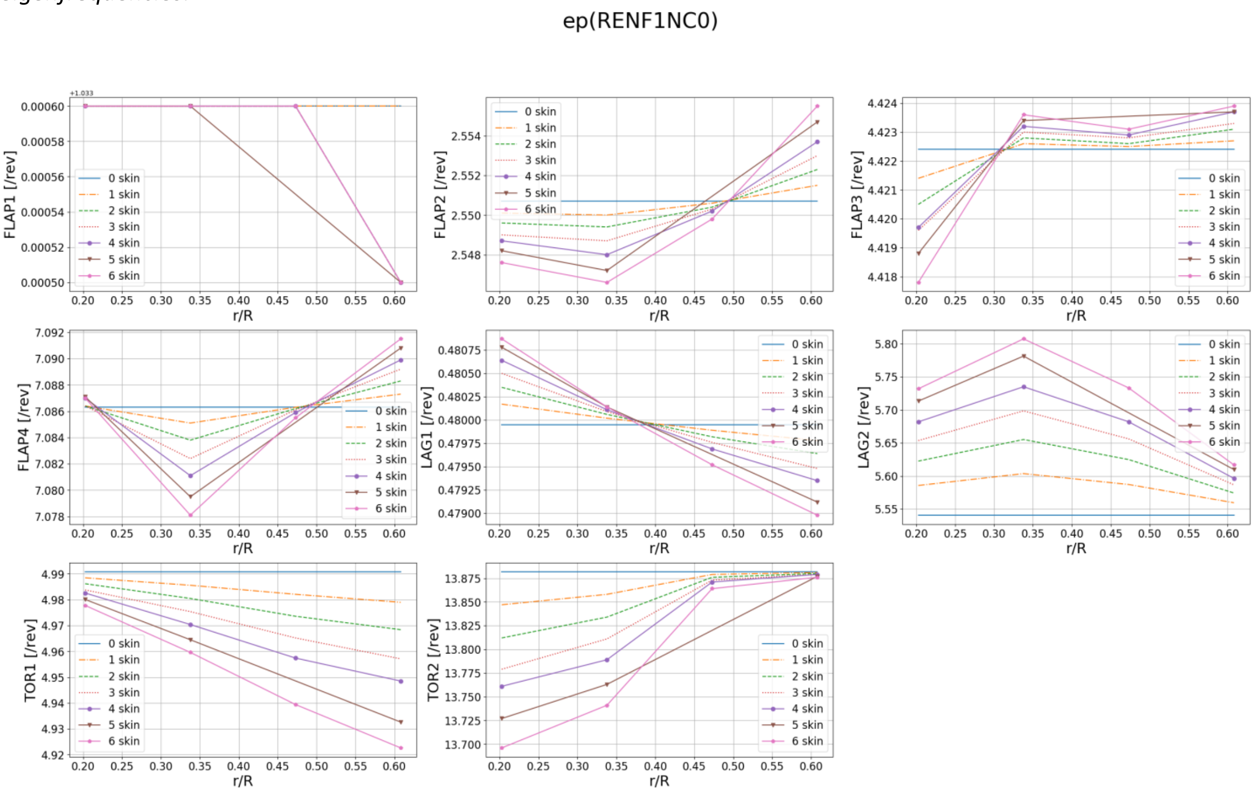

Figure 7: Influence of the composite skin layer on eigenfrequencies.

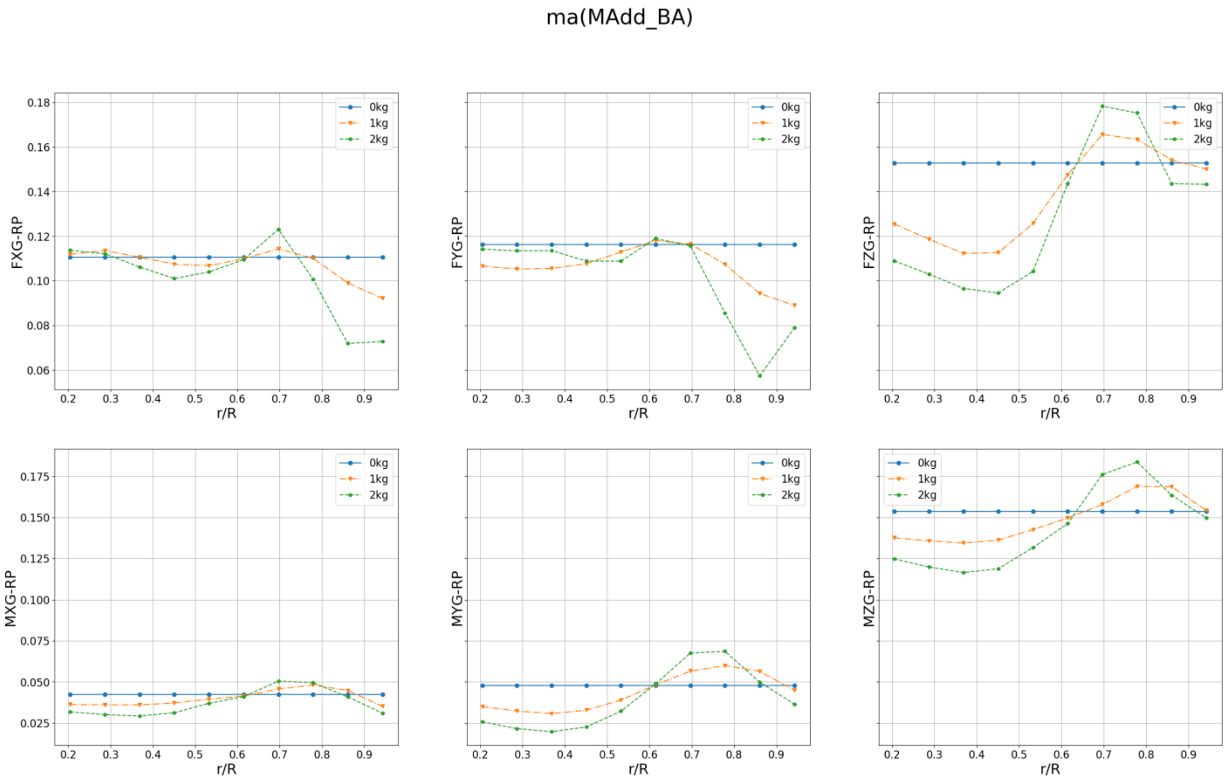

Figure 8 : Influence of the adding mass on dynamic hub loads.

3.4.2 Loads

The dynamic hub loads in forward flight change due to the modification of the internal blade structure by these parameters.

The figure 8 shows the variation of the loads with the location of the spanwisely added mass.

First of all, the figure shows that adding a mass at appropriate location could reduce the dynamic hub loads (points under blue line).

The key information shown on the figures 6 and 8 is the no correlation between frequency placement and loads. At 40% of radius, the eigenfrequencies of the 4^{th} flapping mode is crossing the 7^{th} harmonic (see figure 6), the dynamic hub loads do not seem affected.

CONCLUSION

This study presents the new optimization tool chain performed at Airbus Helicopters. The main topic concerns the vibration reduction of the helicopter when performing blade internal structure optimization. These include design variables such as positioning of tuning masses, composite skin layers, counterweight materials…

The generation of the structural properties was achieved by Airbus Helicopter internal software (JCPAO) which computes the 2D blade section properties.

This capability was integrated in a fully automated multi-objective optimization workflow managed by STORM in order to explore potential candidates with trim analysis.

The design objectives included the minimization of the dynamic hub loads and the pitch link loads under inertial and frequencies constraints.

In this paper, only the results of sensibility analysis were shown. The no correlation between frequency placement and dynamic hub loads is surprising but further numerical investigation will complete this study.

Moreover the optimum candidates from the optimization will be analyzed.

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