Design Optimization of Composite Rotor Blade of Helicopter

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Abstract: *The composite rotor blades, by design, are intended to meet performance, stiffness, strength and fatigue requirements, taking into consideration the weight and manufacturability. The design process to achieve an optimum blade configuration is highly iterative, considering several design variables. Further, it is of paramount importance to also make a judicial tradeoff between these design variables to achieve acceptable design in the preliminary design phase. The multi-disciplinary and multi-objective nature of the blade design demands suitable optimization techniques to reduce iterations, errors, time and cost. The present study consists two phases. In the first phase, the intermediate design variables are optimized. The intermediate design variables considered for the optimization are sectional properties, stiffness and mass distribution along the span of the composite beam. In the second phase, optimum sectional properties obtained from first phase are used to construct the objective function and the primary design variables are being optimized. The primary design variables are material and geometric parameters such as composite layer orientation, thickness and width of composite beam. Dynamic analysis and stress analysis of rotor blade are carried out using Abaqus. Isight is used for design optimization.*

EI	*Blade bending stiffness (N-mm^2)*
EA	*Blade axial stiffness (N)*
GJ	*Blade torsion stiffness (N-mm^2)*
MI	*Sectional mass property of the blade (ton-mm)*
m_o	*Mass per unit length (ton/mm)*
m	*Non-structural mass (ton)*
ω_{1L}	*Baseline 1st lag rotating natural frequency of the blade (rad/sec)*
ω_{2F}	*Baseline 2nd flap rotating natural frequency of the blade (rad/sec)*

Keywords: *Design Optimization, Design of Rotor Blade, Natural Frequencies, Structural Dynamics, Composite Beam.*

1. Introduction

Design of optimum rotor blade to meet desired dynamic characteristics, performance, strength, and manufacturability requirements is considered as one of the most challenging task in the helicopter design. A systematic optimization procedure to arrive at a proper variation of cross sectional structural and inertial properties will greatly help in the design process, which is normally carried out by trial and error method. Several studies have been carried out for optimum design of rotor blade and a few of them are given here. The main objective of these optimization studies are minimization of hub loads to reduce vibration, minimization of noise, minimization of structural weight, performance enhancement, optimum dynamic characteristics, optimum life and different combinations of the above objectives.

1.1 Previous work

Friedmann P.P, 1983, applied structural optimization techniques to reduce the vibration on a helicopter rotor blade in forward flight, which is the first of kind in the blade design. The objective function in this optimization study was to minimize the oscillatory vertical hub shear loads of a four bladed, hingeless rotor. Peters D.A, 1986, described the optimal design procedure for placement of natural frequencies. CONMIN, a FORTARAN program developed for the structural optimization which is based on the mathematical non-linear programming method of feasible directions, was used for the optimization. Aditi C, 1988, addressed the minimum weight design of helicopter rotor blades with constraints on coupled flap-lag natural frequencies. The other constraints included in this study were autorotational inertia of the blade and stress due to centrifugal loading. The program CAMRAD was used for the modal analysis and CONMIN was used for optimization. The optimum design of rotor blade made up of composite material was discussed by Barwey D, 1994. Murugan M.S, 2003, used response surface method to optimize the sectional properties for low rotor vibration. Lim J. W, 2014, presented a study to improve the performance of rotor blade through optimization. Even though a formal optimization technique was not used in this study, searching for an optimal rotor design was successfully demonstrated by applying parameterization. Subramanian K, 2016, developed a methodology for the design of an optimum helicopter rotor blade having non-uniform properties. The prediction of hinge offset was demonstrated in this study which is critical parameter for placement of natural frequencies in a hingeless rotor blade. A metallic rotor blade was chosen for the demonstration of the optimization process. The computational codes, Structural Dynamic Analysis of Rotor Blades (SDAR) and Cross Sectional Properties Evaluation (COPE) developed at Helicopter Lab of IIT-Kanpur were used in addition to the optimization program developed in the above work.

1.2 Current study

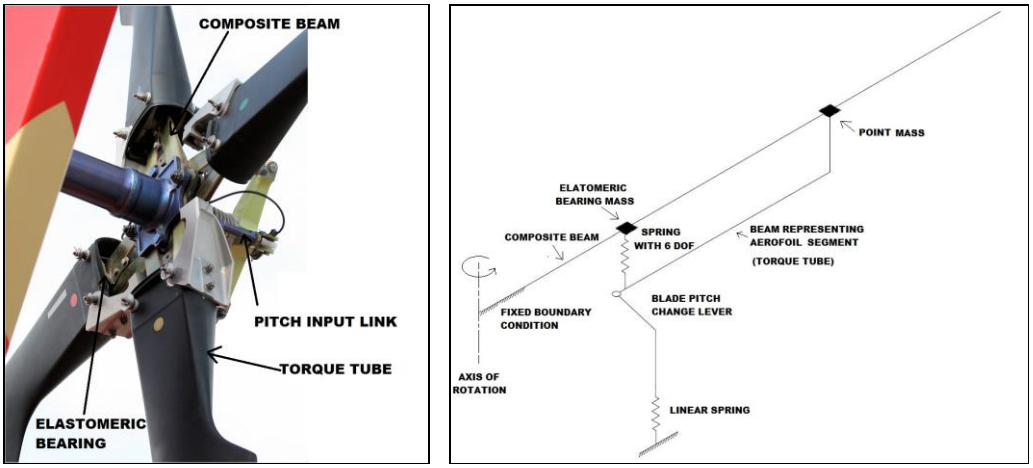
In the current study the optimum design of composite rotor blade is carried out in two phases. In the first phase, the objective function is constructed with the desired dynamic characteristics of the blade, subjected to axial stress constraint. The sectional stiffness and mass properties are optimized in this phase. In the second phase the layup scheme is being arrived for the optimized sectional properties obtained from the Phase-I.

Dynamic characteristics of a rotor blade play an important role in overall design of rotorcraft by influencing vibratory loads and handling qualities. The rotating natural frequencies of rotor blade need to be finalized at the preliminary design stage. Further, these frequencies shall not coincide with the rotor operating frequency or its harmonics. So it becomes paramount important to place the natural frequencies properly in the preliminary design stage of a rotor blade, which can reduce the additional weight and cost involved due to, either design modification or providing vibration control devices in the later stage of helicopter development. Hence the natural frequencies are considered to construct the objective function in the phase-I. Increased blade stiffness under centrifugal field makes it difficult to alter the fundamental rotating natural frequencies. Hence the placement of desired natural frequencies is a challenging task in the practical rotor blade design. The usage of composite material for manufacturing rotor blade helps to overcome this challenging task by altering the material, its layup and orientation to achieve the desired strength, sectional properties such as stiffness and mass distribution along the composite rotor blade.

2. Development of Rotor Model in Abaqus

The 3D rotor blade analysis problem is dimensionally reduced to a 2D cross sectional analysis and 1D beam analysis problem. This method reduces the time required for the optimization process without sacrificing the accuracy in the results. The 2D cross sectional properties of the rotor blade at various sections were obtained by using an in-house code. These cross sectional properties are given as input to the 1D beam model developed in the Abaqus for stress and frequency analysis.

The tail rotor is one of the critical systems in helicopter which balances the main rotor torque and provides the directional stability to the vehicle. Failure of a tail rotor system may leads to the catastrophic failure of the helicopter. Hence it is paramount important to optimize the design of tail rotor system at the preliminary design stage itself. The present study focuses on the optimum design of a tail rotor blade. A typical 4 bladed tail rotor assembly is shown in Figure-1(a). The rotor blade consists of composite beam with a rectangular cross section at the root segment. The aerofoil section is built above this composite beam which is also known as toque tube. The primary structural loads are carried by the composite beam and it is designed to carry flap, lag and pitch articulations. A torque tube is attached to the composite beam through the elastomeric bearings at the one end and merged with the composite beam at the other end. This torque tube helps to transfer the pitch input from the pilot stick to the twisting motion of the composite beam.



(a) Typical tail rotor assembly **(b) 1D Beam model**

Figure 1. Tail rotor System

A rotating blade model with the relevant boundary condition is developed in ABAQUS for the frequency extraction and it is shown in Figure-1(b). The rotor blade model was constructed with 1D beam elements in Abaqus. The cross sectional stiffness properties EI, EA, GA, GJ and mass properties m_0 and MI are defined in the Abaqus bsp file for the composite beam and torque tube. These sectional properties are obtained using an in-house code. The special properties such as springs and inertia, point mass 'm' (non structural mass) are added in the appropriate places in the model as shown in the Figure-1(b). The kinematic couplings are provided in the torque tube and composite beam merging point, through interaction. Blade pitch input arm and torque tube are tied together. The fixed boundary condition is imposed at the root of 1D beam model in Element-1. The boundary conditions are given in Initial step. Centrifugal force is applied to the model through the rotational body force in the analysis step-2. In step-3, frequency analysis was carried out. Non-linear geometry (Nlgeom) option is used for both centrifugal load and frequency step.

1.3 Stress Analysis

The maximum stress occurs at the root segment of the composite beam due to centrifugal load. The section points are defined in the corresponding .bsp file for Element-2 of the beam model, to extract the axial stress due to centrifugal loading. The section points for the corresponding 2D section are obtained from Abaqus through 2D cross sectional analysis. The section point label and 2D element numbers are added to the keywords in the 2D cross sectional analysis. The .bsp output file from this cross sectional analysis is given as input to Element-2 bsp file in the 1D beam model. The cross section of the Element-2 for 2D cross sectional analysis is shown in Figure-2. The maximum axial stress due to centrifugal loading is found to be 28 N/mm^2.

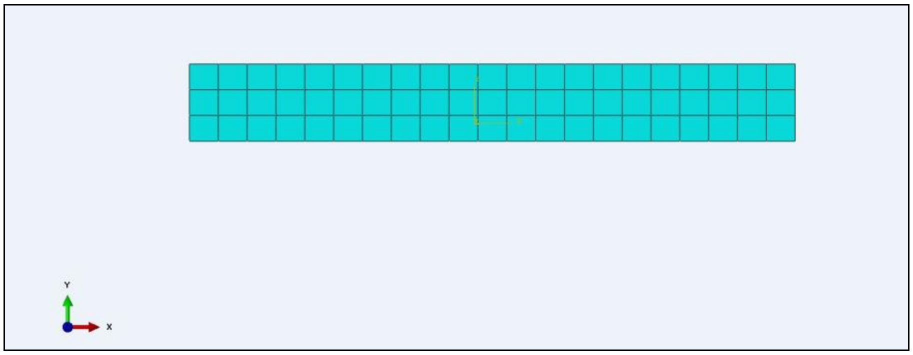


Figure 2. Cross section of Element-2 at the root of 1D beam model

1.4 Natural Frequencies obtained from Abaqus

The natural frequencies and the corresponding modes obtained from the Abaqus are given in Table-1. The mode shapes are identified from the participation factor.

Table-1: Natural Frequencies and Modes

Mode No.	Predominant Participation Factor	Mode	Rotating Natural Frequencies (rad/sec)
1	Z-rotation	1st Flap	254.10
2	X-Rotation	1st Torsion	360.61
3	Y-Rotation	1st Lag	401.48
4	Z-Rotation	2nd Flap	615.95
5	Z-Rotation	3rd Flap	1077.00
6	Y-Rotation	2nd Lag	1837.80
7	Y-Rotation	3rd Lag	2017.60
8	X-Rotation	2nd Torsion	2093.60
9	X-Rotation	3rd Torsion	2795.60
10	Y-Rotation	4th Lag	2979.00

1.5 Mode Shapes

The mode shapes for 1st flap, 2nd flap and 1st lag frequencies are shown in Figure 3 to 5.

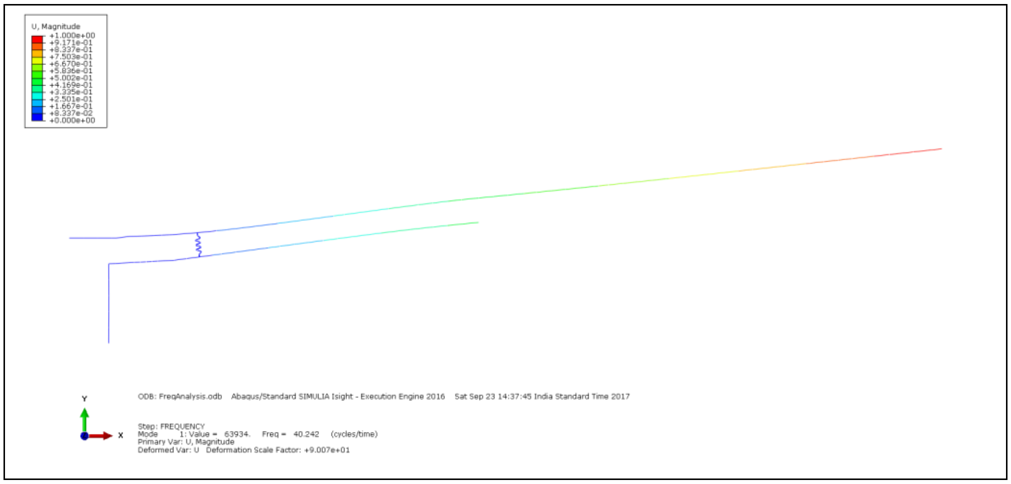


Figure 3. 1st Flap mode.

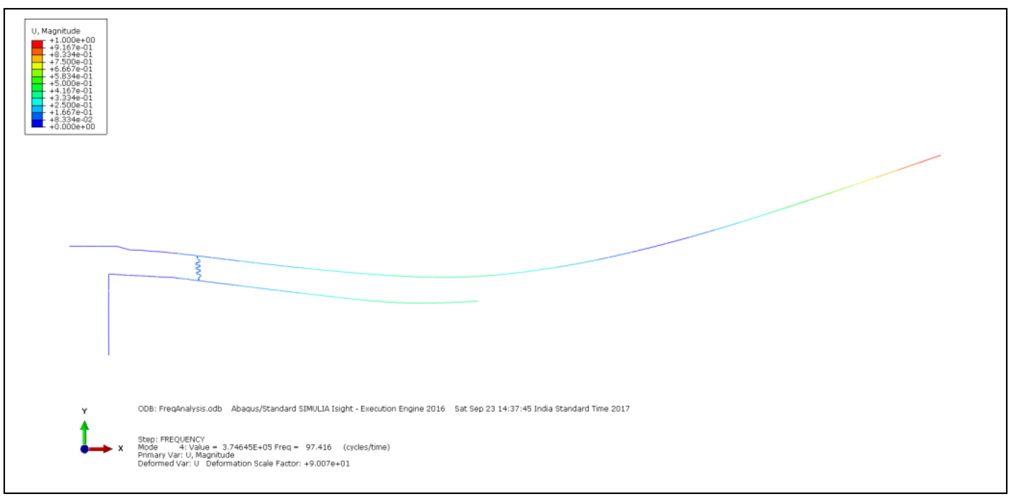


Figure 4. 2nd Flap mode.

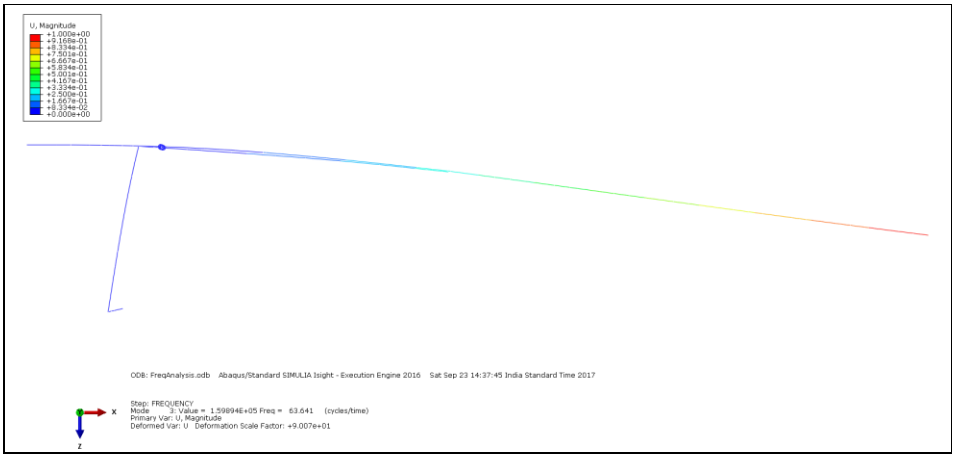


Figure 5. 1st Lag mode

1.6 Model Validation

The fundamental frequencies obtained are validated with Nastran results. It is found that the fundamental modes are matching with Nastran results with sufficient accuracy. The validation of non-dimensional natural frequencies is given in Table-2. The frequencies are non-dimensionalized with respect to rotor speed of 233.94 rad/sec.

Table 2. Validation of natural frequencies

Mode	Non- Dimensional Rotating Natural Frequencies	
	Abaqus	Nastran
1st Flap	1.087	1.116
2nd Flap	2.633	2.697
1st Lag	1.717	1.538

3. Selection of design variables for optimization

The design variables can be classified into primary design variables and intermediate design variables (Subramanian K and Venkatesan C, 2016). The primary design variables are the geometric parameters of the composite beam such as thickness and breadth of the composite beam at the root segment, layup orientation and type of material. The intermediate design variables are the sectional properties stiffness and mass distribution along the span of the composite beam. The intermediate design variables are function of the primary design variables.

4. Design optimization

4.1 Phase-I: Optimization of intermediate design variables

The objective function for the phase-I optimization is constructed with the desired natural frequencies and it is given in equation (1). The value for weighting factors are taken as 1 for both the objectives. Intermediate design variables are optimized in the Phase-I.

Minimize

$$J_1=\sqrt{(\omega_{1L}-380)^2+(\omega_{2F}-580)^2} \quad \text{---- (1)}$$

ω_{1L} and ω_{2F} are the baseline 1st Lag and 2nd Flap natural frequencies which are 400 and 615 rad/sec respectively. The objective of the Phase-I study is to obtain the optimum sectional properties to achieve desired 1st Lag and 2nd Flap natural frequencies which are 380 rad/sec and 580 rad/sec respectively. The corresponding sectional properties of the rotor blade are taken as baseline values for the design variables.

The design optimization of rotor blade is carried out using Isight. In the first phase, the optimization is done in three stages. In the first stage a DOE technique is used to study the sensitivity of the design variables on objective function and the natural frequencies. In the second stage, an approximation model is created for the sensitive design variables by using the DOE data. In final stage the optimization is carried out using the approximation model.

4.1.1 Design of Experiments (DOE)

The workflow for the DOE is given in Figure-6. The workflow consists of Data Exchanger component, which is used to write sectional properties data to the .bsp files. The Simcode component writes point mass data in to the Abaqus input file. This component reads natural frequencies and stress data from Abaqus data file. The Abaqus job is executed from command line in the Simcode component. The objective function which given in Equation-1, is evaluated using calculator component. The output files (.bsp files) in the Data Exchanger are linked to the Simcode in the Data Link tab. Optimal Latin Hypercube technique is used to construct DOE model.

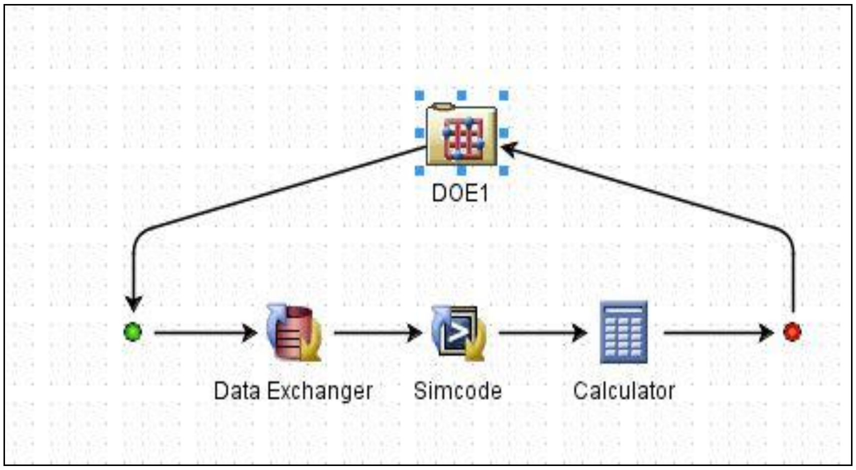
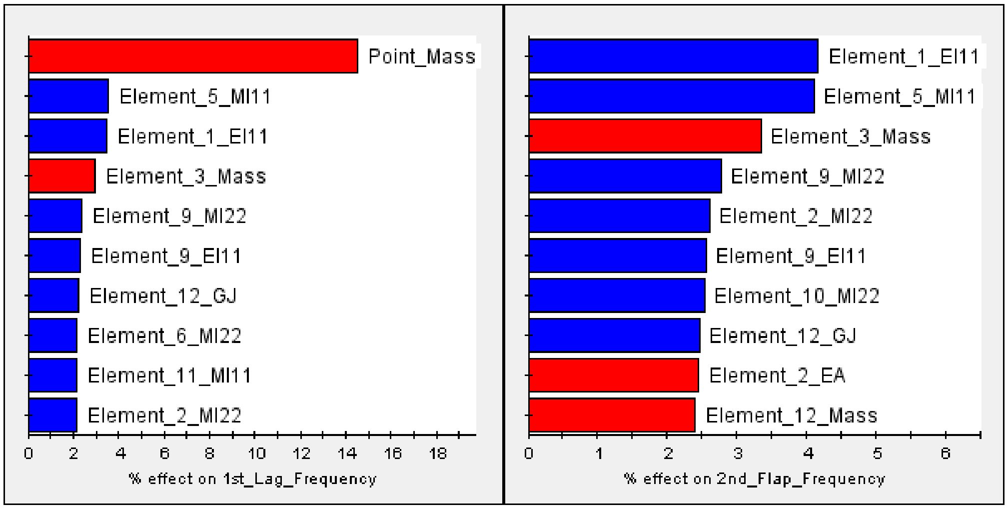


Figure 6. DOE workflow.

In the first phase, optimization of the composite beam is carried out with intermediate design variables i.e. stiffness and inertial properties. The stiffness properties EA, EI, GJ and inertial properties m_0 and MI along the root segment are considered for the optimization. Concentrated mass in the span of the blade is also included for design optimization. Totally 85 design variables are initially considered for the DOE study. The lower limit and the upper limit for the sectional properties are set as +/-10%. The lower and the upper limits for the point masses are set as 200 g and 800 g respectively.

4.1.2 Sensitivity Analysis

The Pareto plots obtained from the sensitivity analysis are given in Figure-7(a), 7(b) and Figure-8. Figure 7(a) and 7(b) show the sensitivity of design variables to the 1st lag and 2nd flap natural frequencies respectively. It shows that 1st lag frequency is more sensitive to point mass (non-structural mass) and 2nd flap frequency is more sensitive to inertial properties than stiffness properties. Figure-8 shows the sensitivity of design variables to the objective function. In general, the Pareto plots show that increase in mass properties results in decrease in frequencies and vice-versa. Also it shows that the frequency changes proportional to stiffness properties. The design variables which are sensitive to the objective function and natural frequencies are identified from this sensitivity analysis. From the sensitivity analysis, it is emerged that 13 out of the initial 85 design variables are considered to be more sensitive in the present study. The design variables identified from the Pareto analysis are given in Table-3 and these design variables are used for construction of an approximation model.



(a): 1st Lag **(b): 2nd Flap**

Figure 7. Sensitivity of design variables on frequency

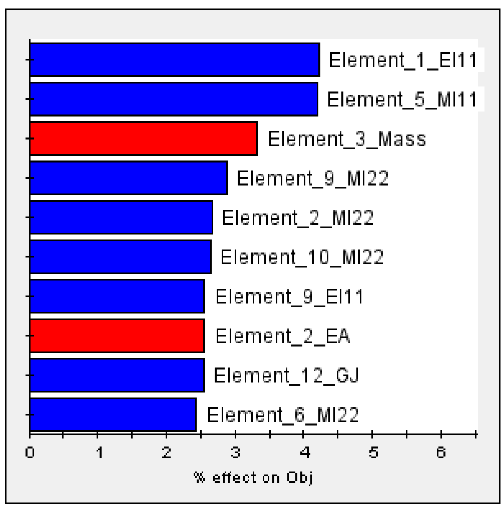


Figure 8: Sensitivity of design variables to objective function

Table-3: Design variables Identified from the Sensitivity Analysis

SI. No	Design Variable identified from the sensitivity analysis
1	Point_Mass
2	Element_1_EI11
3	Element_2_EA
4	Element_2_MI22
5	Element_3_Mass
6	Element_5_MI11
7	Element_6_MI22
8	Element_9_MI22
9	Element_9_EI11
10	Element_10_MI22
11	Element_11_MI11
12	Element_12_GJ
13	Element_12_Mass

4.1.3 Approximation Model

An approximation model was created in Isight by using the DOE data. Kriging model was used for approximation technique. The model error analysis was done through cross-validation method and about 5% error was found in the approximation model, which is within the acceptable range. The error analysis carried out for the approximation model is shown in Figure-9. The response fits for different design variables and objective function are obtained from the approximation model. Sample response surface is given in Figure-10.

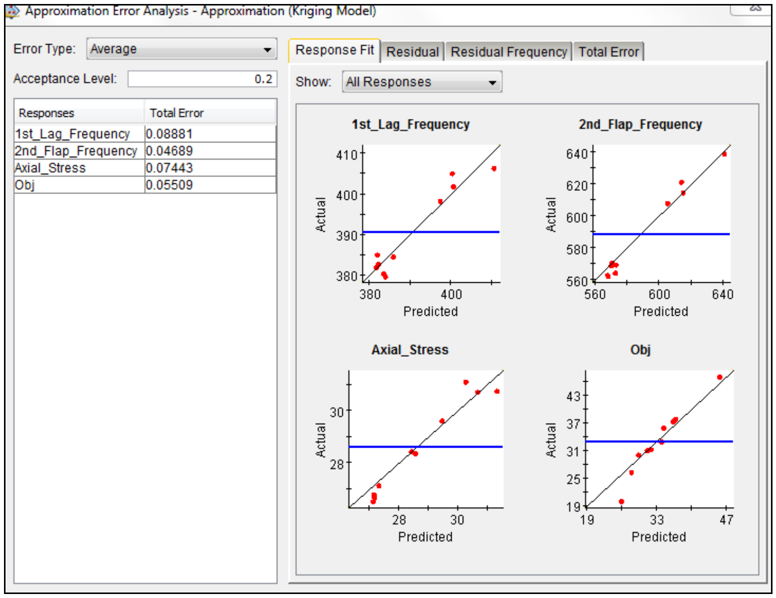


Figure 9. Error Analysis of approximation model

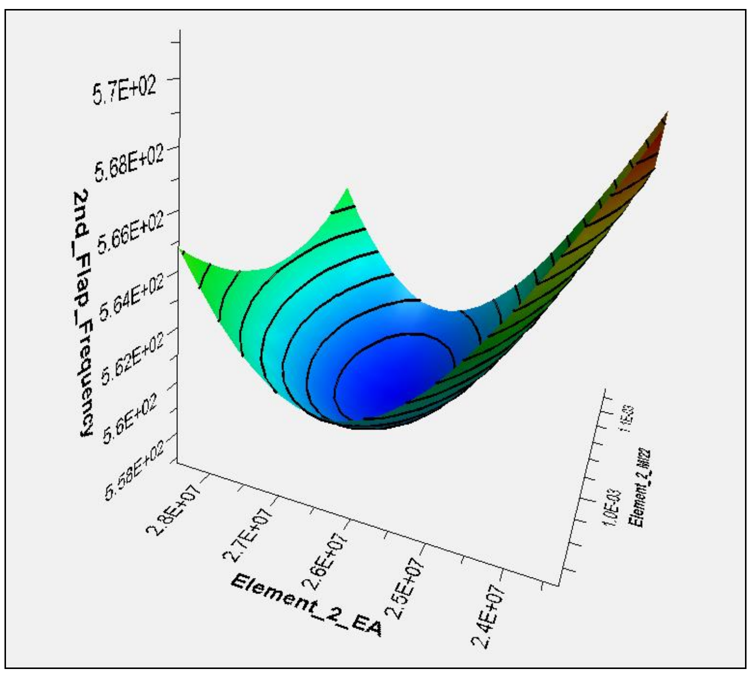


Figure 10. Sample response surface

4.1.4 Isight work flow for Design Optimization

The approximation model developed in this study is used for the optimization. The gradient based algorithm, Hooke-Jeeves method is used for design optimization. The work flow for the optimum blade design is given in Figure-11. The baseline frequencies and the optimized frequencies obtained from the optimization study are given in Table-4. From the optimization results it is found that the desired frequencies are minimized while other frequencies are not varying significantly.

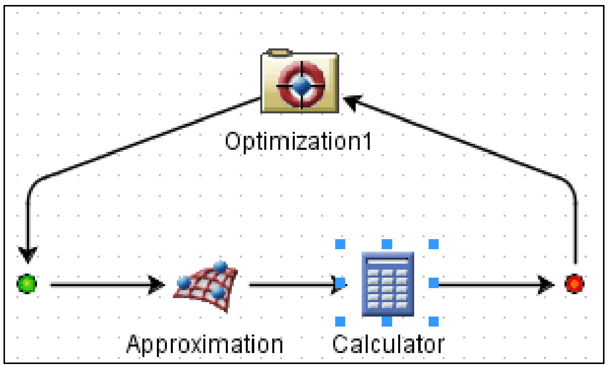


Figure 11. Workflow for design optimization.

Table-4: Results obtained from the optimization study

Sl. No	Mode	Rotating Natural Frequencies (rad/sec)		
		Baseline	Target	Optimum
1	1^{st} Lag	400	380	394.01
2	2^{nd} Flap	615	580	594.89

4.2 Phase-II: Optimization of primary design variables (Work under progress)

In phase-II, the primary design variables are being optimized. The primary design variables are geometric parameters such as composite layer orientation, thickness, width of composite beam at the root and type of composite material (Glass/Carbon). The objective function for the phase-II optimization is given in equation-2.

Minimize

$$J_2 = \left(\frac{EI_y - EI_y^b}{EI_y}\right)^2 + \left(\frac{EI_z - EI_z^b}{EI_z}\right)^2 \quad \text{---- (2)}$$

Since the desired flap and lag natural frequencies are required to be placed in the rotor blade, the objective function is constructed with the corresponding optimum bending stiffness values EI_y and EI_z which are obtained from the Phase-I study. EI^b_y and EI^b_z are corresponding sectional properties of baseline blade configuration. The primary design variables are being optimized using Excel and Script components in the Isight. The excel component is being used to calculate the sectional properties EI during optimization.

5. Conclusion

In this paper the optimum design of a rotor blade carried out in two phases. In the first phase, the sectional properties are optimized to get the desired natural frequencies considering the stress due to centrifugal loading. In the second phase, the geometric parameters are being optimized to achieve the desire sectional properties obtained from the first phase. Abaqus is used to extract the natural frequencies and to carryout stress analysis. Design optimization is carried out using Isight. This optimization procedure will help in reduce the time involved in arriving a feasible rotor blade configuration which is normally carried out by trial and error method.

6. References

[1] Friedmann P.P and Shanthakumaran P, "Optimum Design of Rotor Blades for Vibration Reduction in Forward Flight", Proceedings of 39th Annual Forum of the American Helicopter Society, St. Louies., Mo., May 9-11, 1983.

[2] Peters D.A, Rossow M.P, Korn and Ko T, "Design of Helicopter Rotor Blades for Optimum Dynamic Characteristics", Computers and Mathematics with Applications, January 1986.

[3] Aditi C and Walsh J. L, "Minimum Weight Design of Rotorcraft Blades with Multiple Frequency and stress Constraints", NASA Technical Memorandum, NASA-TM-100569, NASA, Langley Research Center, Hampton, Virginia, March 1988.

[4] Barwey D and Peters D.A, "Optimization of Composite Rotor Blades with Advanced Structural and Aerodynamic Modelling", Journal of Mathematical and Computer Modelling, 1994.

[5] Murugan M.S and Ganguli R, "Design of Experiments Approach to Helicopter Rotor Optimization", 29th European Rotorcraft Forum, Friedrichshafen, Germany, September 2003.

[6] Lim J. W, "Consideration of Structural Constraints in Passive Rotor Blade Design for Improved Performance", 40th European Rotorcraft Forum, Southampton, U.K., September 2014.

[7] Subramanian K and Venkatesan C, "Optimum Design of Realistic Helicopter Rotor Blade with Variable Properties", 5th Asian-Australian Rotorcraft Forum, Singapore, November 2016.

7. Acknowledgement

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