AERODYNAMIC DESIGN OPTIMIZATION OF HELICOPTER ROTOR BLADES IN HOVER PERFORMANCE USING ADVANCED CONFIGURATION GENERATION METHOD

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Abstract

This study proposed a process to get optimal helicopter rotor blade shape regarding aerodynamic performance discipline by using a new geometry representation algorithm CST which uses both the Class Function/Shape Function Transformation. By this approach, airfoil shape was considered as design variables. This optimization process was constructed by integrating several programs which were developed by Department of Aerospace Information Engineering of Konkuk University. The design variables include twist, taper ratio, point of taper initiation, blade root chord, coefficients of airfoil distribution function. Aerodynamic constraints consist of limits on power available in hover and forward flight. While, the trim condition must be attainable.[1] This paper considers rotor blade configuration for hover flight condition only, so that power required in hover was chosen as objective function of optimization problem. Sensitive analysis of each design variable showed that airfoil shape has an important role in performance of rotor. The optimum rotor blade reduced hover power required 7.4% and increased figure of merit 6.5% are a good improvement for rotor blade design.

1. INTRODUCTION

Regarding to blade aerodynamic performance design, there are two common approaches. First, most of researchers now focus on blade shape design to optimize the aerodynamic performance of rotor blades by selecting the point of taper initiation, root chord, taper ratio, and maximum twist which minimize hover power while not degrading forward flight performance.[1] This approach usually deals with integration of several programs to build an optimization process. Second, some works tried to solve this problem by CFD methods. These CFD methods are reasonable for hover case but long time consuming. Moreover, in forward flight, the flow filed passes the blade is very complex to apply CFD method. Therefore, the CFD method is not suitable for preliminary design phase because of quick estimation requirement. With the target of quick estimation for preliminary design phase, this study follows the first approach with advanced improvements. In this study, a new geometry representation algorithm which uses both the Class Function/Shape Function Transformation (CST) method was applied to take a consideration of airfoil shape. The advanced points of this CST method are high accuracy and few variables of geometry representation.[2] Therefore, this work dealed with the same problem of blade aerodynamic performance design was mentioned above and some additional design variables came from airfoil shape consideration.

The satisfactory of aerodynamic performance design was defined by the following requirements which must be right for any flight conditions: the required power must be less than the power available, and the rotor blade must be trimmed.[1]

The process of the design was represented in figure 7. This process includes sizing module also. After getting a size of helicopter, helicopter rotor blade shape optimization process would be performed as next step of design process. Following this process, a set of initial values for design variables are chosen from sizing module. The airfoil base line which is airfoil NACA0012 was chosen for the first step of design process. Then, blade shape such as chord distribution, twist distribution, and airfoil points coordinate are generated. The power required for hover and forward flight were computed by KHDP program, and trim condition is checked. Airfoil analysis is performed by 2KFoil program to generate airfoil aerodynamic characteristics in C81 format. Some others additional codes to generate airfoil coordinates, chord distribution and twist distribution were implemented in order to build a full framework for optimization process in Model Center software. Model Center is a powerful tool for automating and integrating design codes. Once a model is constructed, trade studies such as parametric studies, optimization studies, and DOE (Design Of Experiment) studies may be performed.[3]

The required power in hover analysis is performed by using blade element method which considers the airfoil characteristics.

2. ANALYSIS PROGRAM

2.1. KHDP (Konkuk Helicopter Design Program)

KHDP is a helicopter sizing, performance analyis and trim analysis program was developed in Konkuk University.

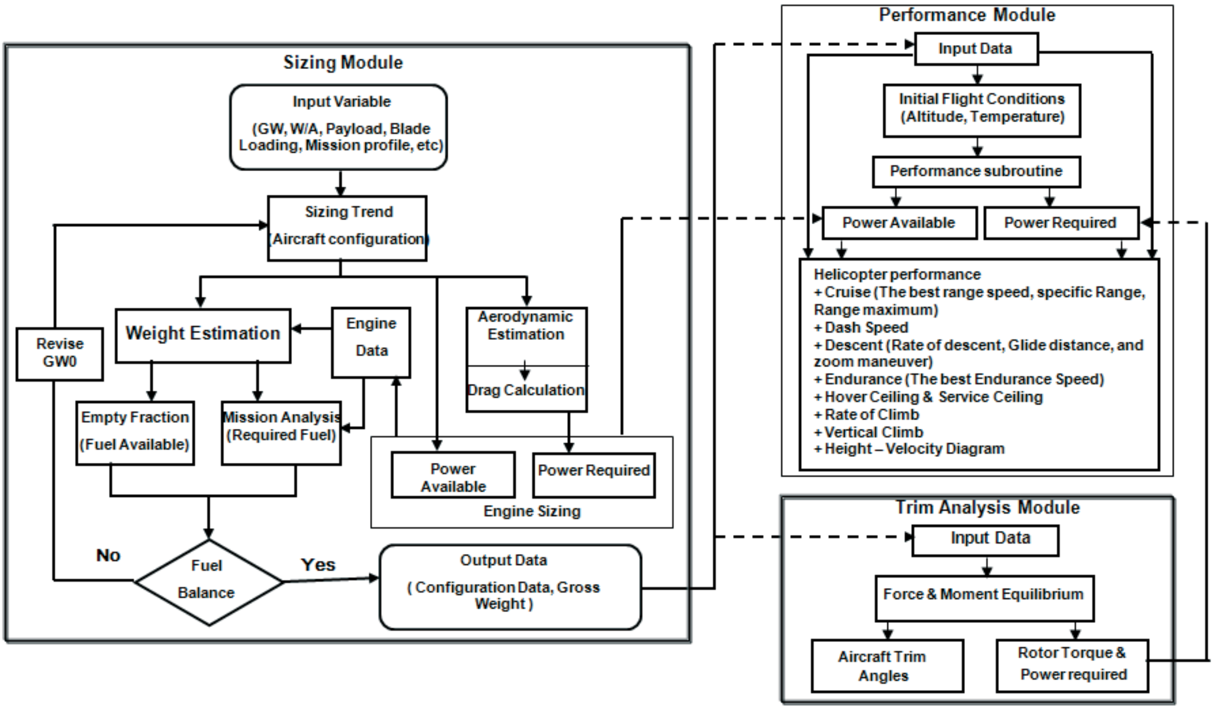


Fig.1. KHDP Program process.

These codes were developed to be used in the conceptual design phase and hence used empirical formulas to reduce computing times.[4]

2.1.1. Sizing module

The sizing process based on graphical design techniques developed during the 1950's and 1960's and were initially utilized with nomographs.

A graphical design method, called the fuel ratio or R_F method is typical of the developed techniques.[5, 6]. This method was used to construct the whole process of sizing as shown in figure 1.

This process starts from mission analysis and performance requirements analysis. The performance requirements are specified in terms of hover capability and cruise speed requirement at a specified altitude and temperature, which reflect the environment where the vehicle is expected to operate. The mission requirements address the critical relationship between payload, range and hover time, which will determine the type of rotary wing aircraft.

Based on empirical formulas, this module is able to generate following sizing results.

+ Geometry data: main rotor, tail rotor, fuselage, tail fin.

+ Weight data: gross weight, empty weight, fuel weight.

+ Mission performance data: Each mission segment fuel requirement.

The sizing module is validated by comparing with the data of existing helicopter UH-60A as shown in table 1 below.

Table 1. Sizing module validation

Parameter	UH-60A	Data from Sizing Module
Gross Weight lb	22000	21409
Empty Weight lb	10901	11241
Disk loading lb/ft^2	9.7	10.0
Main rotor diameter ft	53.66	54.2
Solidity	0.084	0.089
Main rotor tip speed ft/sec	725	722.3
Number of main rotor	4	4
Tail rotor diameter ft	11	11.7
Tail rotor tip speed ft/sec	685	703.6
Fuselage length ft	50.6	48

2.1.2. Performance analysis module

To quickly understand and image the helicopter behavior, the performance analysis module was developed. An analytical method was used to provide the designer with a reliable tool of sufficient fidelity to assist in the design process. The module based on an energy approach, and it has been written to yield results quickly and inexpensively.[7, 8]

This module is able to predict following performance:
+ Vertical Climb (Maximum)
+ Rate of Climb (Maximum Rate of climb)
+ Ceiling (Hover Ceiling, service Ceiling)
+ Dash speed, Maximum cruise speed
+ Cruise Flight (Maximum range, cruise speed for maximum range, Endurance, cruise speed for maximum endurance…)
+ Descent
+ Autorotation
+ Height-Velocity diagram
+ Acceleration and deceleration
+ Turn maneuver

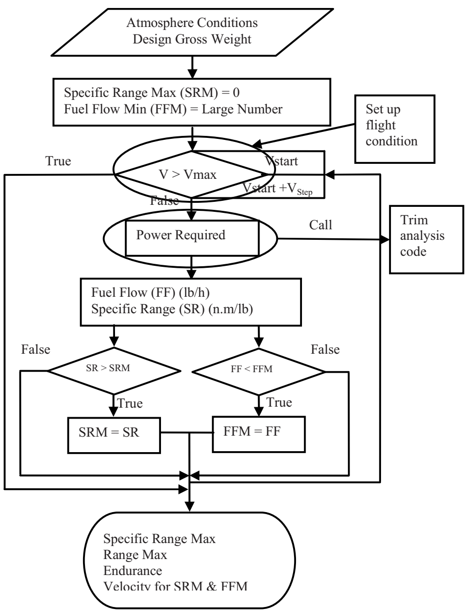


Fig. 2. An algorithm for performance analysis in cruising flight.

The module is able to yield not only a specific performance but also series of helicopter performance in different operating environment such as weight of helicopter, altitude, temperature, and forward velocity.

Momentum and blade element theory were applied to calculate the power required in different operations of helicopter which are hover, climb, cruise, descent, autorotation. [8, 9]

Figure 2 showed an example of an algorithm was developed to predict performance behavior of helicopter in cruising flight by momentum theory and blade element theory (BET). BET needs to call trim module analysis to get power required.

A Validated results of this module were shown in table 2. The validated results were got from AS332 L1 helicopter data .

Table 2. Performance analysis module validation

Performance	AS332 L1	Performance Module
Max Speed kts	150	129
Max Rate of Climb ISA, SL, ft/m	1618 at 70kts	1682 at 80kts
Hover ceiling ISA, SL, IGE ft	10663	11000
Hover ceiling ISA, SL, OGE ft	7546	7000
Service Ceiling ft	> 9.500	16800
Service Ceiling, OEI ft	5906	5750
Max Range nm	454 at 136kts	477 at 136kts
Max Endurance hrs	4.24	4.31

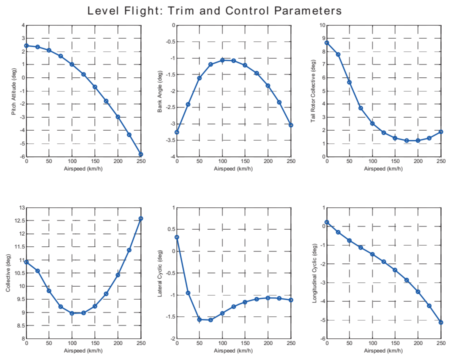
2.1.3. Trim analysis module

Controlling the helicopter is a nonlinear control system design problem. an important part of practical helicopter control is the ability to determine the trim states for the helicopter over all flight conditions. the aircraft is trimmed when the desired balance is achieved or the aircraft enters a desired steady state. The controls to be trimmed are the actuators and the dependent states to be trimmed are the pitch, roll, and yaw, i.e., These states are trimmed for the desired specified steady-state translational velocities and angular rates, variables representing desired steady states.[10]

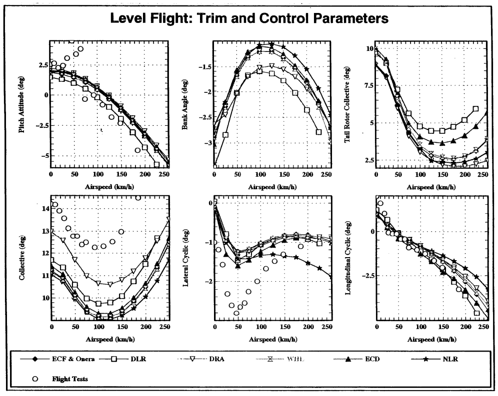
Harmonic balance method was used in this trim code.

The following flight condition was implemented in this code:
+ Straight flight (with or without: climb, sideslip)
+ Vertical flight
+ Turning flight (with or without: climb, coordinated or uncoordinated)

Figure 3 showed some validated results of this trim code.[11]



a. Trim code program results



b. AGARD GATUER experiment data

Fig. 3 Trim and control parameters Results of Bo 105 Helicopter.

2.2. 2KFoil Program

2KFoil is an airfoil analysis program of subsonic isolated airfoils was modified from Xfoil program to be suitable with present study. The main algorithm of this code is a combination of high-order panel methods with a fully-coupled viscous/inviscid interaction method.[12]

The inviscid formulation of 2KFoil is a linear vorticity stream function panel method. A Karman-Tsien compressibility correction is incorporated, allowing good compressible predictions all the way to sonic conditions.[12]

The Viscous formulations come from the boundary layers and wake which are described with a two equation lagged dissipation integral boundary layer and an envelope e^n transition criterion.[12]

The airfoil is going to be analyzed will be inputted to 2KFoil as airfoil coordinate points, and then 2KFoil will generate lift, drag, moment coefficient C_L, C_D, C_M correspond to specific angle of attack, Mach number, and Reynolds number.

2.3. Others Program

Some additional codes to generate airfoil coordinate point, chord distribution and twist distribution were implemented in order to build a full framework for optimization process in Model Center software.

These codes provide various ways to present twist, chord distribution such as: linear, nonlinear distribution…

3. GEOMETRY REPRESENTATION CST METHOD [13]

CST representation method's procedure is shown in Figure 4. This method is based on analytical expressions to represent and modify the various shapes.[2] The components of this function are – *"shape function"* and *"class function"*.

By using CST method, the curve coordinates are distributed by following equation:

$$y(x/c) = C_{N2}^{N1}(x/c)\cdot S(x/c)$$

Where $C_{N1}^{N2}(x/c) = (x/c)^{N1}(1-x/c)^{N2}$: Class function

N1, *N2*: Exponents

$$S(x/c) = \sum_{i=0}^{N}\left[A_i \cdot (x/c)^i\right]$$: shape function,

x: non-dimensional values from 0 to 1.

c: curve length (if shape is like airfoil upper curve, c is chord length)

For formulation of CST method, Bernstein polynomials are used as a shape function.

$$S_i(x) = K_i x^i (1-x)^{n-i}$$

Where $K \equiv \binom{n}{i} = \dfrac{n!}{i!(n-i)!}$: binomial coefficients

n : order of Bernstein polynomial

i : numbers 0 to *n*

CST method follows the process which shown in Figure 4. First, the given data points converts to non-dimensional values. Second, the class-function exponents and degree of shape function are defined. Then, in fitting process shape function coefficients are calculated. Finally, by multiplying shape function and class function, the distribution function are obtained.

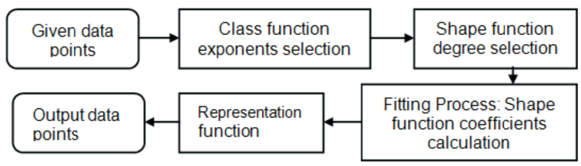


Fig. 4. Representation procedure using CST method.

Figure 5 shows the airfoil geometry is represented by using CST method and NURBS. In this case, control variables are the coordinates of control points (5 variables for upper curve and 5 for lower curve). CST method with 4 control variables has a better fit to existing airfoil than NURBS which uses 10 control variables.[13]

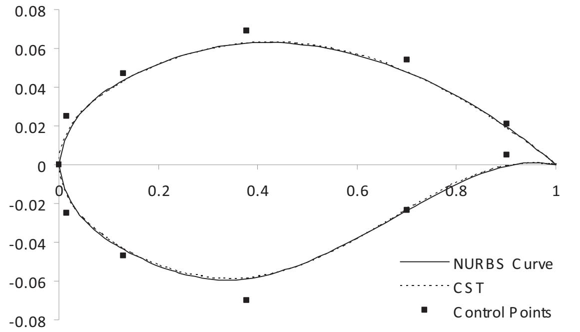


Fig. 5. RAE 2822 Airfoil representation.

Figure 6 shows the absolute errors of an airfoil generation with CST and NURBS (5 control points for each curve, 4th order blending functions). Generation by NURBS at the tail part of airfoil has bigger errors.

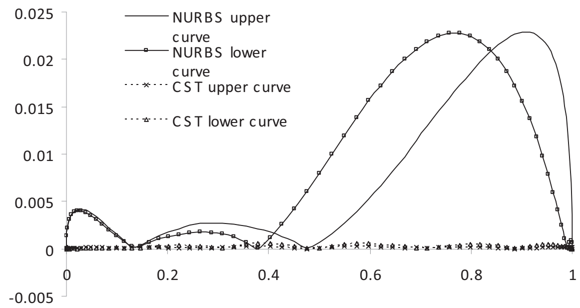


Fig. 6. Absolute errors in airfoil generation.

The advantage of CST method in comparison with others method such as Spline, B-Splines or NURBS is can represent curves and shapes using few scalars control parameters and very accurately.

In this study, airfoil baseline was chosen as NACA 0012. With the given data coordinate points in Cartesian coordinate space, a curve fitting was generated using 4th order Bernstein polynomials.

The Class function for the airfoils was: $C(x) = x^{0.5}(1-x)$

Airfoil distribution function defined as upper curve and lower are presented sequently as below.

$$y_l(x) = C(x)\begin{bmatrix} A_{lo}(1-x)^4 + A_{l1}4x(1-x)^3 + A_{l2}6x^2(1-x)^2 \\ + A_{l3}4x^3(1-x) + A_{l4}x^4 \end{bmatrix}$$

$$y_u(x) = C(x)\begin{bmatrix} A_{uo}(1-x)^4 + A_{u1}4x(1-x)^3 + A_{u2}6x^2(1-x)^2 \\ + A_{u3}4x^3(1-x) + A_{u4}x^4 \end{bmatrix}$$

Where: A_{u0} = 0.1718; A_{u1} = 0.15; A_{u2} = 0.1624; A_{u3} = 0.1211; A_{u4} = 0.1671; A_{l0} = -0.1718; A_{l1} = -0.15; A_{l2} = -0.1624; A_{l3} = -0.1211; A_{l4} = -0.1671

4. DESIGN PROCESS

4.1. Design Considerations

Helicopter hover performance is expressed in terms of power loading or figure of merit (FM). In this study we assume rotor thrust and weight of helicopter are equal. Therefore, the hover power required should be made as small as possible.The hover power requried to drive the main rotor is formed by two components: induced power, profile power (to overcome viscous losses at the rotor). The induced power and the profile power primarily influence the blade aerodynamics performance design.[7]

The conventional approach of blade aerodynamics performance design is started with the selection of the airfoils which could be applied over various regions of the blade radius. The choice of airfoils is controlled by the need to avoid exceeding the section drag divergence Mach number on the advancing side of the rotor disc, exceeding the maximum section lift coefficients on the retreating side of the rotor disc.[1]

The present work considers the effect of blade airfoil shape on power required. Therefore, a baseline airfoil NACA0012 was chosen as a unique airfoil through blade to simplify the process of optimum design. Moreover, this approach can deal with various helicopters which operate in various velocity ranges. The considerations of selection of base line airfoil are skipped.

A changes of A_0 and A_4 coefficients of CST method are sufficient for airfoil shape modification.[2] These coefficients were also the design variables of examined optimal problem.

With above mentions, this approach leads the induced and profile power are functions of twist, taper ratio, point of taper initiation, blade root chord, A_0 and A_4 coefficients of airfoil distribution function. Satisfactory aerodynamics performance is defined by the following requirements:[1]

+ The power required must be less than the power available.

+ The helicopter must be able to trim at hover flight condition.

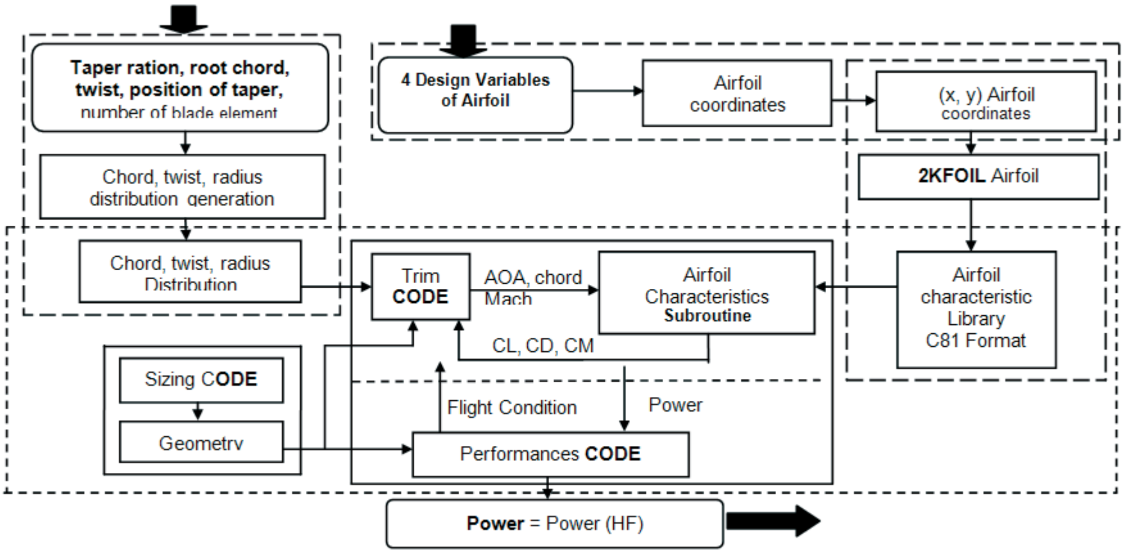


Fig. 7. Design synthesis process

4.2. Design synthesis process

The design synthesis process was showed in figure 7. The rectangular with dash line represented a module which is integrated in model center software. Each module is connected with others module by data input/output flow which are the mutual parts. The arrows pointing into modules present the design variables, while the one pointing out present the objective function.

There are 4 modules were implemented in this optimization framework which are chord, twist, radius distribution generation module; airfoil points coordinate generation module; airfoil characteristic library with C81 format module; sizing, trim, performance analysis module. The chord twist, radius distribution were generated by a code in which the geometry representation can be change, such as linear, non linear function. In this study, chord distribution generated base on root chord, the point of taper initiation, and taper ratio. Twist distribution is assumed varies as linear function along the blade. Radius distribution was divided by equal annulus area of rotor disk. These distributions would be the input data for trim code in trimming process.

Four coefficients of airfoil distribution function were defined as initial input data of design process after getting the fitting curve of airfoil baseline NACA0012. Then, airfoil coordinate points were generated by using CST function. With airfoil coordinate points, 2KFoil will generate airfoil characteristics library with C81 format which are the airfoil lift, drag, moment coefficients with respect to angle of attack for different mach numbers (from 0.1 to 0.9).
KHDP program with performance analysis module provides many options for objective function. The objective function of this study was chosen as power required in hover. Helicopter data are going to be analyzed by performance code come from either sizing module or user inputs.

After getting the trim condition, namely, trim condition was attainable and performance as well, the power required will be evaluated to proceed the next loop of optimization process. So, a new set of initial data (root chord, the point of taper initiation, taper ratio, pretwist, A_0 and A_4 coefficients of airfoil distribution function) will be generated depending on optimization algorithm. This loop will be stop until convergence condition is satisfied.

5. OPTIMIZATION FORMULATION AND METHOD

5.1. Design variables

The design variables are maximum pretwist, taper ratio, point of taper initiation, blade root chord, A_0 and A_4 coefficients of airfoil distribution function. The blade is rectangular to station of the point of taper initiation and then tapered linearly to the tip.[14] The twist varies linearly from the root to the tip. NACA0012 was chosen as baseline airfoil, and two coefficients A_0, A_4 are design variables of airfoil shape.

5.2. Constraints

The power required in hover must be less than power available.
The trim constraint in hover is implemented by expressing the constraint in terms of the number of trim iterations iter, the maximum number of trim iterations allowed $iter_{max}$.

$$iter \leq iter_{max}$$

Another constraint used to ensure that the blade tip chord does not become too small.
Where c_t is the tip chord and c_{tmin} is the minimum tip chord allowed. $c_t \le c_{t_{\min}}$

This constraint can be decribed in term of taper ratio range shown in table 4.
The magnitude of A_0 and A_4 coefficients of airfoil distribution function are less than 1.

$$g_i = |A_0, A_4| - 1 \le 0$$

5.3. Objective function and optimization tool

The performance module provides the objective function of optimization problem can be very various. In this study, power required in hover was chosen as objective function.

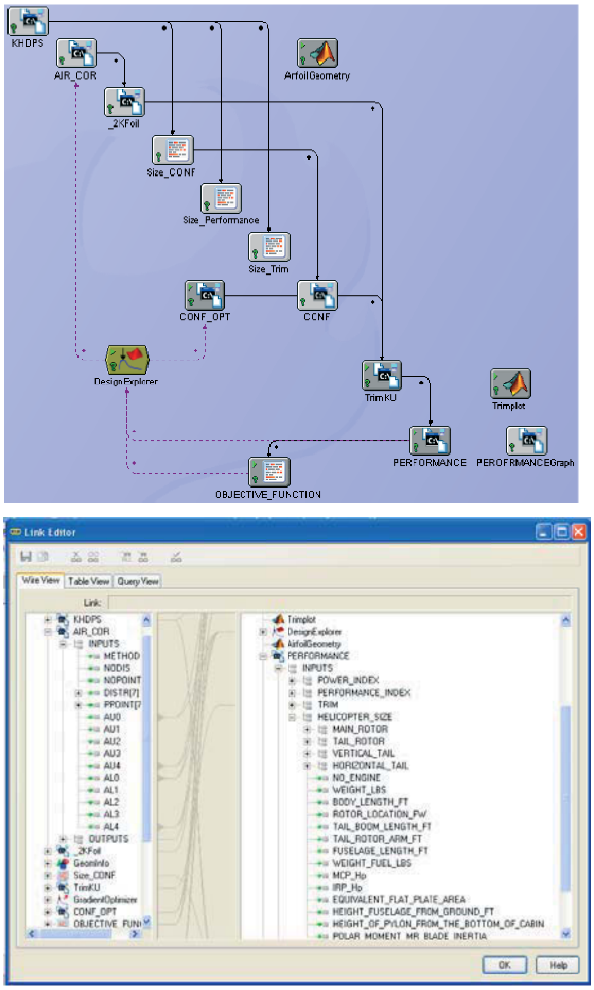


Fig. 8. Design framework and link data in Model Center.

All modules was wrapped in Model Center program which is a powerful tool for automating and integrating design codes. A snapshot of this framework and link data among each module were shown in figure 8. Design Explorer tool was used to perform the optimization search using Model Center. Design Explorer's key technologies are the systematic and efficient sampling of the design space using design of experiments (DOE) methods and the intelligent use of "surrogate" models for problem analysis and optimization. the smooth surrogate models serve as substitutes for potentially expensive and "noisy" computer simulations and make global analysis and optimization of complex systems practical.

The surrogate The surrogate models used by Design Explorer are interpolating Kriging models.[15] To create a surrogate model, Design Explorer executes analysis code (Model Center model) multiple times, and stores the results of each run in a table. The input variable values for this series of runs are chosen to efficiently canvas the design space (using an Orthogonal Array).

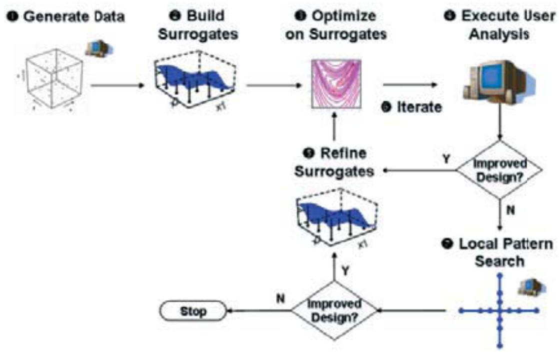


Fig. 9. The process of using surrogate model in Design Explorer.

The process of using surrogate model in Design Explorer tool was shown in figure 9. The surrogate models are selectively updated and refined as the optimization process progresses. Global search mechanisms are implemented to avoid local minimum. A final pattern search guarantees that the best design found is at least a local minimum.

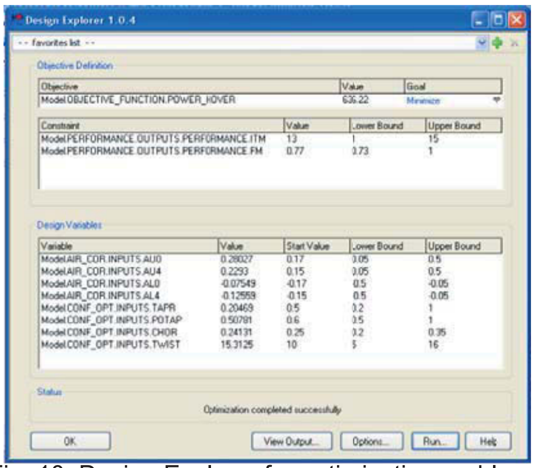


Fig. 10. Design Explorer for optimization problem.

A gradient based optimization algorithm (sequential quadratic programming) is in conjunction with the surrogate models to predict the optimum design for design problem.[3]

The Design Explorer tool was used for this problem was shown in figure 10. And boundary of each design variable was summarized in table 4.

6. RESULTS AND CONCLUSION

Figure 11 shows sensitive analysis of each design variable on objective function. These analysis tell us that those coefficients coming from airfoil distribution function had an important role on performance of rotor. Therefore, this study has told us that airfoil shape should be considered as design variables. This optimizaion problem was applied on rotor blade of Bo 105 LS helicopter.

Table 3 shows optimum results in which the objective function reduced 7.4% and FM increased 6.5%.

Table 3. Optimum results.

	Baseline	Optimization	Improvement
AU0	0.1718	0.28027	
AU4	0.1671	0.2293	
AL0	-0.1718	-0.0755	
AL4	-0.1671	-0.1256	
TAPR	1	0.2	
POTAP	1	0.5	
CHOR	0.27	0.24	
TWIST	-8	-15.3	
FM	0.72	0.77	6.5%
ITM	6	12	
Power HP	687.44	636.22	7.4%

Where:
TAPR: Taper ratio; POTAP: Position of taper initiation; CHOR: Chord length; FM: Figure of merit; ITM: Number of trim iteration; A_{U0}, A_{U4}, A_{L0}, A_{L4}: Coefficients of airfoil shape distribution function.

This study was performed for hover case only. Therefore, we can see that the optimum taper ratio and position of taper are on boudary of these design variables.
The optimum blade shape may have smaller solidity in comparison with baseline. In this case, twist was decrease from -8deg to -15.3deg.

In any case of airfoil baseline, airfoil shape represented by 2 coefficients for upper curve A_{U0}, A_{U4}, and 2 coefficients for lower curve A_{L0}, A_{L4}, are always show an important role in effective performance of rotor. By using CST method, we can represent airfoil curve with few coefficients that is resonable to perform an optimization problem.

A further study on rotor blade design in forward flight and maneuver flight also need to take a consideration of airfoil shape. The requirements that the airfoil section not stall in forward flight and that the drag divergence mach number be avoided.

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APPENDIX

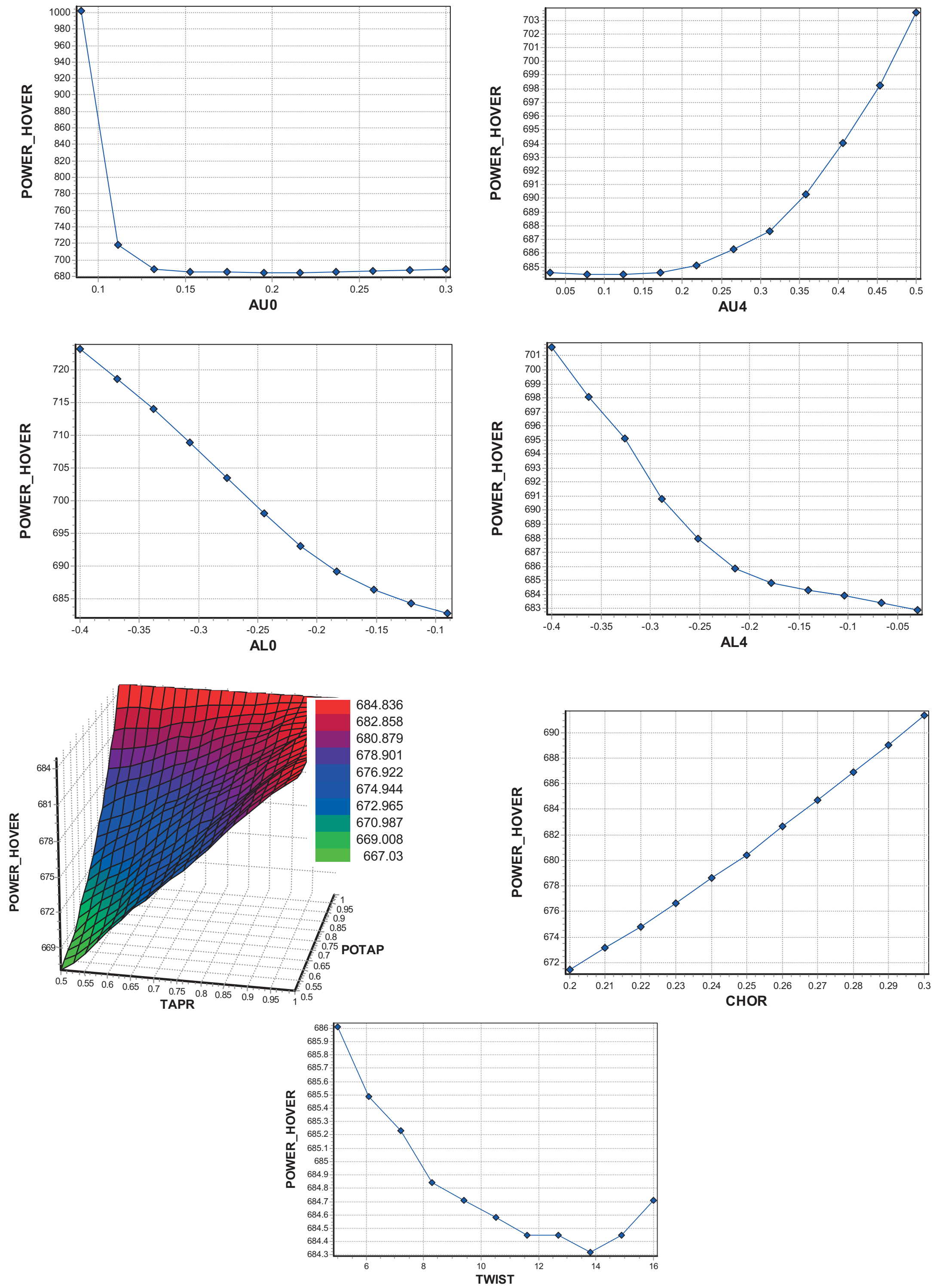

Fig. 11. Sensitive analysis of design variables

Table 4. Design variables range.

	minimum	maximum	Baseline
AU0	0.05	0.5	0.1718
AU4	0.05	0.5	0.1671
AL0	-0.5	0.05	-0.1718
AL4	-0.5	0.05	-0.1671
TAPR	0.2	1	1
POTAP	0.5	1	1
CHOR	0.2	0.35	0.27
TWIST	-16	-5	-8
FM	0.69	1	0.69
ITM	1	15	6

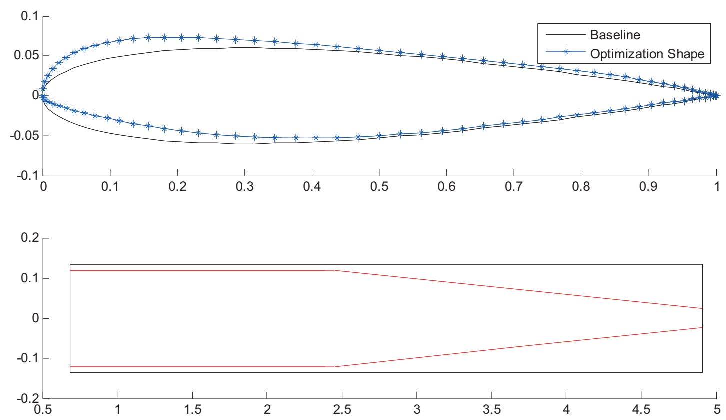

Fig. 13. Optimum results