PROP-BLADE SECTION DESIGN OPTIMIZATION USING WEIGHT/DYNAMIC CHARACTERISTIC SURROGATE MODEL WITH SKIN/SPAR DESIGN VARIABLE

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Abstract

For prop-blade section design optimization, an analysis procedure was established to generate a weight/dynamic characteristic surrogate model based on the general blade section design procedure. The general blade section design procedure consists of requirement analysis, cross-section design, section properties analysis, dynamic characteristics/load analysis and structure analysis to check all requirements are satisfied. Based on this procedure, the database was created by performing section design variable input value generation, section shape and finite element data generation, section properties analysis and dynamic characteristic analysis sequentially. And an artificial neural network algorithm was applied to create a surrogate model of estimated weight and dynamic characteristics with a control prop-blade section design variable. The prop-blade section configuration has consisted of skin, C-spar and form. Section design variable was decided to a thickness of skin(Skin_t), a thickness of spar(Spar_t) and chordwise length of spar(Spar_l) from the leading edge. A database of design variable input values for the creation of a surrogate model was generated using the space-filling method, which is a kind of design of experience and design input variables were generated within a limited range by setting the ranges and constraints of each variable in consideration of the actual prop blade manufacturing characteristics. The weight/dynamic characteristics surrogate model derived through this process was applied to the genetic algorithm and the optimal cross-sectional shape that satisfies the dynamic characteristic requirements and weight minimization was derived.

1. INTRODUCTION

The tilt-based prop-rotor system, driven by an electric motor, operates at two rotational speeds: a forward flight condition and a hover flight condition. The prop-blade used in such a prop-rotor system must satisfy not only the weight requirements and structural safety requirements but also the requirements of the dynamic characteristics so that resonance does not occur in two rotational conditions through section design. In general, the closer the natural frequency of the prop rotor system to an integer multiple of the operating frequency, the greater the vibration load due to resonance. The high-order natural frequency can be neglected because the magnitude of the vibration is small, but the low-order natural frequency has a large vibration, so it should be carefully considered.

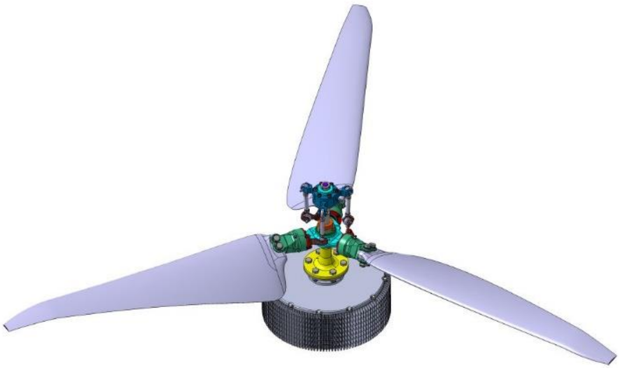

Figure 1 OPPAV Prop-rotor System Configuration

The Korea Aerospace Research Institute is developing an Optional Piloted Personal Air Vehicle (OPPAV) that can take off and land vertically through

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four tilt-prop systems and four lift-prop systems [1]. In this study, in OPPAV's prop-rotor system(Fig. 1), where the hub/control component and the OML(Outer Mold Line) of the prop-blade were determined, a section design optimization method was proposed that satisfies the dynamic characteristics requirements of the prop system and minimizes the weight by adjusting the design parameters that determine the section shape of the prop-blade.

2. Establishment of Prop-blade Section Design Procedure

To perform section design optimization, the basic prop-blade section design procedure should be established first. Therefore, the prop-blade cross-section design procedure was established to satisfy the requirements [2]. First, the section design requirements are analyzed. In this process, the weight allowed for the prop-blade, the structural safety margin, and the frequency separation level in the operating conditions are quantified. And in the next step, predict the load generated from the prop-blade through the weight requirement and operating conditions among the analyzed section design requirements, and determine the section shape considering the manufacturability while satisfying the structural requirements for the predicted load. When the section shape is determined, a specific section design is performed and a section property analysis is performed on the section design result. And predict the weight of the prop-blade by analyzing the sectional properties analysis results. In this process, if the section design result does not satisfy the weight requirement, return to the previous process and revise the cross-sectional design. If the weight requirement is satisfied, dynamic characteristics/load analysis is performed using the section properties analysis results. As a result of the dynamic characteristic analysis, if the possibility of resonance in the prop-blade operating condition is predicted, the prop-blade resonance frequency is adjusted by changing the section design. Also, when an excessive load is expected to be applied to the hub/control component as a result of the load analysis, the section design change is also performed. And finally, by using the load analysis results, structural analysis is performed to check whether the structural requirements are satisfied. If the structural requirements are not satisfied, the section shape/design change is performed, and if the structural requirements are satisfied, the section design shape is confirmed. Figure 2 shows the prop-blade section design process.

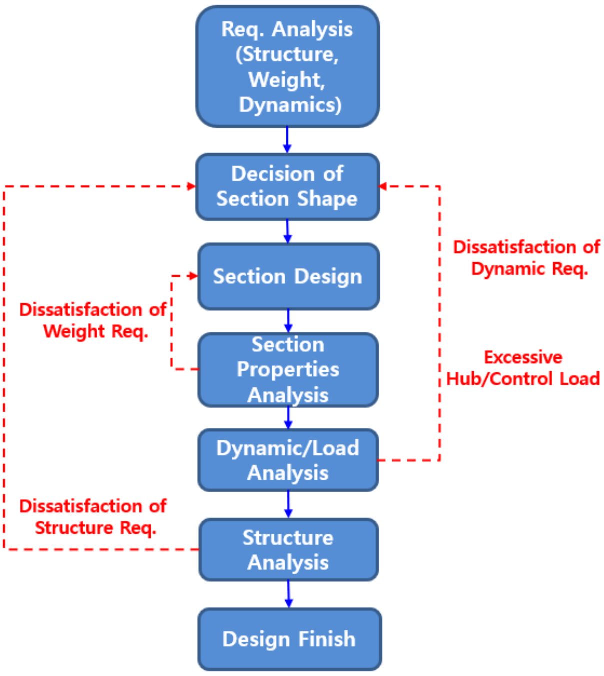

Figure 2 Prop-blade Section Design Process

3. Establishment of Analysis Procedure for Generating a Surrogate Model of Prop-blade Section Design

Based on the prop-blade section design procedure described above, an analysis procedure for generating a surrogate model of weight/dynamic characteristics according to the prop-blade section design variables was established. First, the blade OML information (airfoil data, planform data), material information, and hub characteristic information, which are already determined information before the prop-blade section design is performed, are input. And by applying the DOE (Design of Experiment) method, a data set of design variables that can control the shape of the internal components of the prop-blade is generated. And based on the blade OML and the set of internal component design parameters for each section, the section model for the prop-blade span direction cross-section is generated. After that, this section model is converted into finite element information and section property information is obtained through section property analysis using the finite element information. And based on the analyzed section property information, load and dynamic characteristic information are acquired through the helicopter comprehensive analysis program. In this process, the load information is applied to the structural analysis, and the calculated safety margin information is stored in the database together with the weight and dynamic characteristics information obtained in the previous process. And when the analysis procedure for all design variable sets is completed, a surrogate model is derived based on the database. In this process, JMP [3] was used to create a set of design variables using the DOE method and to construct a surrogate model using the database. Umbrella [4] was used for blade section model generation and finite element discretization, KSec2D [5] was used for section property analysis and section structure analysis, and CAMRAD II [6] was used for prop-rotor system load/dynamic characteristics analysis. And the Octave [7]/DAKOTA [8] package was used as a driver to sequentially perform these procedures and obtain the target value. Figure 3 shows the analysis procedure for generating a surrogate model of the blade section design, and the functions and outputs of the software used in each step.

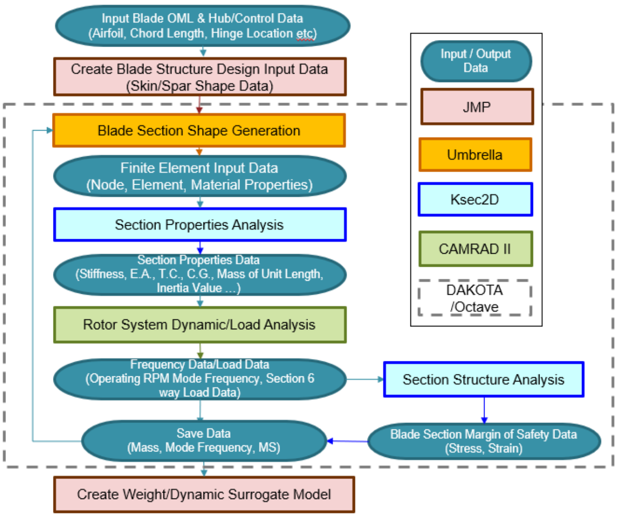

Figure 3 Analysis Procedure for Generating a Surrogate Model of Prop-blade Section Design

4. Optimal Design Environment Configuration using Prop-blade Weight/Dynamic Characteristic Section Design Surrogate Model

The environment was constructed so that the weight/dynamic characteristics optimal design shape could be derived by applying the prop-blade weight/dynamic characteristic section design surrogate model to the genetic algorithm. Design variables determined by the section shape of the prop-blade are identified and configured as input variables for genetic algorithms. In this process, it is judged whether the genetic algorithm input variable randomly generated satisfies the design variable constraint. If the constraint is not satisfied, the input variable is not used and a new input variable is created. When an input variable that satisfies the constraint conditions is generated, it is applied to the weight/dynamic property surrogate model to derive weight and dynamic property predicted values for the design value. Then, the fit value is derived by applying the predicted values of the weight and dynamic characteristics to the objective function reflecting the results of the requirement analysis performed previously. The objective function for deriving the fit value was configured to apply a penalty value if the predicted weight and dynamic characteristics did not satisfy the requirements. MATLAB was used as the computational environment to derive the optimal section design shape by applying the surrogate model to the genetic algorithm [9]. Figure 4 shows the optimal section design environment for the prop-blade to satisfy weight/dynamic characteristics requirements.

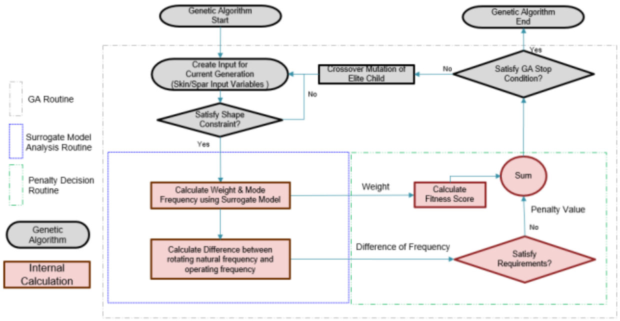

Figure 4 Optimal Design Environment for Satisfaction of Weight/Dynamic Requirements

5. Prop-blade Weight/Dynamic Characteristic Section Design Optimization

5.1. Analysis of Weight/Dynamic Characteristic Requirements

Resonance avoidance requirement is applied so that resonance does not occur in operating conditions for the dynamic characteristics requirement of a general rotor system. The OPPAV vehicle to which the prop blade designed in this study is applied has two prop-rotor operating conditions: a helicopter mode for vertical take-off and landing and an airplane mode for forward flight. Therefore, the dynamic characteristic requirements of the prop-blades were selected so that the /rev frequency of the 1st to 4th modes for forward flight conditions and hover flight conditions were separated by 0.15 or more from the prop rotor operating frequency integer multiple of each flight condition. And the weight condition was selected as the minimum weight that satisfies the dynamic characteristics requirement.

5.2. Decision of Prop-blade Section Shape and Analysis of Section Design Variables

The cross-sectional shape of the prop-blade was selected as a C-spar shape which material of carbon fabric ±45° is applied to the skin and material of carbon UD 0° is applied to the spar by considering the level of load applied to the prop-blade compared to the material strength and manufacturability. In this simple shape prop-blade, the skin supports most of the shear load including torsional load, and the spar supports most of the tensile load including centrifugal force. The section design variables of the C-spar prop-blade were selected as factors that can implement the skin and C-spar. First, for the skin, $Skin\_t_i$, which indicates the number of layers of composite material of the skin, was selected as a design variable. And for the spar, $Spar\_t_i$, indicating the number of laminated layers of the spar, and $Spar\_l_i$, indicating the length of the spar from the leading edge, were selected as design variables.

And 10 sections (r_b/R_b = 0.18, 0.23, 0.3, 0.4, 0.5, 0.8, 0.7, 0.83, 0.9, 1) were selected in the span direction from the prop-blade for section properties analysis. Therefore, 30 design variables were generated by applying 3 design variables to each of 10 cross sections. Figure 5 shows the prop-blade section shape and design parameters.

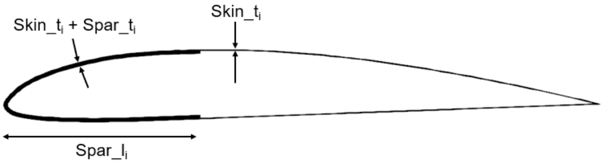

Figure 5 Blade Section Shape and Design Variables

5.3. Creation of Prop-blade Section Design Variables

The DOE method was applied to generate the prop-blade cross-section design parameters. First, the maximum and minimum values were set for the design variables for each section. And, considering the design characteristics of the prop-blade section, the constraint conditions were set so that the value of the design variable becomes the same or smaller as the design cross section goes toward the end of the prop blade span direction. That is, the sequence number of the section of the blade root area was set to 1, the sequence number was set to increase toward the blade tip area, and the value of the design variable of the ith section was set to be equal to or smaller than the value of the design variable of the i-1th section. Table 1 shows the ranges for the design variables, and Equations (1) to (3) show the constraint conditions for the design input variables.

Table 1 Range of Design Variable

Design Variable	Section No.	Section Location (r_b/R_b)	Min. Value	Max. Value
$Skin\_t_i$	1~5	0.18, 0.23, 0.3, 0.4, 0.5	1	5
	6	0.6	1	4
	7~10	0.7, 0.83, 0.9, 1.0	1	3
$Spar\_l_i$	1~10	0.18, 0.23, 0.3, 0.4, 0.5, 0.6, 0.7, 0.83, 0.9, 1.0	10	50
$Spar\_t_i$	1~3	0.18, 0.23, 0.3	1	15
	4~5	0.4, 0.5	1	10
	6~10	0.6, 0.7, 0.83, 0.9, 1.0	1	7

$$Skin\_t_i \geq Skin\_t_{i+1} \tag{1}$$

$$Spar\_t_i \geq Spar\_t_{i+1} \tag{2}$$

$$Spar\_l_i \geq Spar\_l_{i+1} \tag{3}$$

Where i = 1 ~ 9

1,000 sets of section design variable input samples satisfying the design variable ranges and constraints described above were generated. A space-filling method was used for the design variable input sample generation method [10]. Figures 6-8 show the results of generating input samples for each design variable. This result shows that the values generated for each design variable are included within the design variable range defined in Table 1. At the same time, it satisfies the constraints (1) to (3), showing that the design variable value of the i-1th section is equal to or smaller than the design variable value of the ith section.

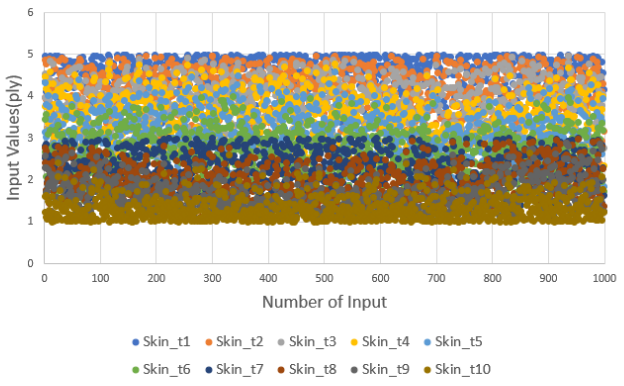

Figure 6 Design Variable Input Set – Skin_t$_i$

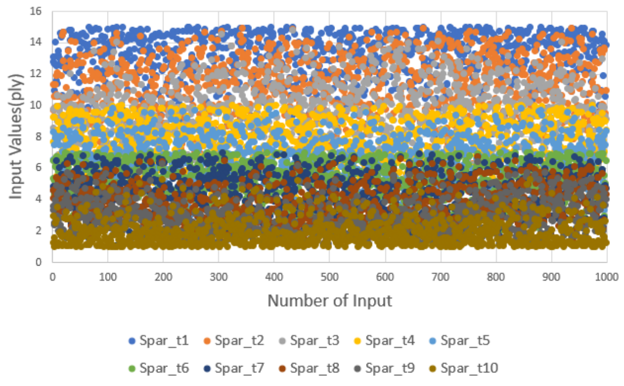

Figure 7 Design Variable Input Set – Spar_t$_i$

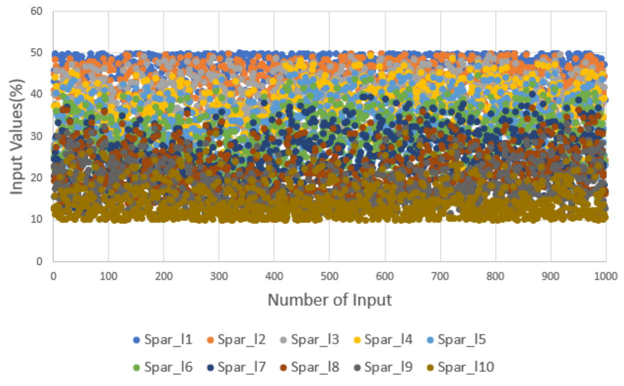

Figure 8 Design Variable Input Set – Spar_l$_i$

5.4. Creation of Prop-blade Weight/Dynamic Characteristic Surrogate Model

Prop-blade weight/dynamic characteristics data for each design variable were obtained by performing the analysis procedure in Figure 3 for 1000 sets of design variable input samples, and based on this, a surrogate model of prop-blade weight/dynamic characteristics was generated. An Artificial Neural Networks (ANN) algorithm, which predicts the target value by adjusting the weight and bias values of each neuron in the process of propagating from the input layer through the hidden layer to the output layer, based on the operation principle of human neurons, was used to generate the surrogate model [11]. To select the number of neurons to be used for generating a surrogate model, 3 to 10 combinations were repeatedly trained. As a result, it was confirmed that when the number of neurons exceeds 6, the mean squared error (MSE) value, which is a loss function used for training, does not significantly decrease anymore. Therefore, 6 neurons were applied to generate a surrogate model. Figure 9 shows the diagram of the artificial neural network model, and Equation (4) shows the sigmoid function applied to the artificial neuron.

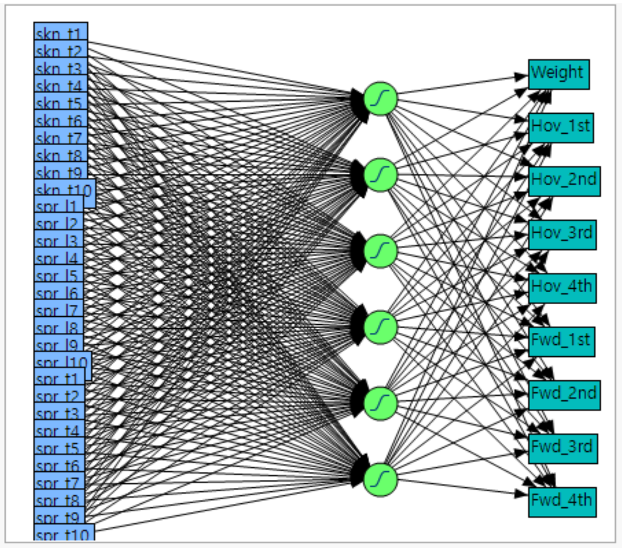

Figure 9 ANN Diagram for Weight/Frequency Prediction

$$f_{sigmoid} = A + \left[B \times TanH\left(0.5 \times \left(\mathrm{C} + (\mathrm{D} \times \mathrm{E})\right)\right)\right] \tag{4}$$

Where $\mathrm{A} = 9 \times 1$ Constant Matrix

$\mathrm{B} = 9 \times 6$ Constant Matrix

$\mathrm{C} = 6 \times 1$ Constant Matrix

$\mathrm{D} = 6 \times 30$ Constant Matrix

$\mathrm{E} = 30 \times 1$ Input Vector

To generate a surrogate model through the artificial neural network algorithm, 666 samples were used for training, and the remaining 334 samples were used for validation of the trained model. Figures 10 to 18 show the accuracy of the weight/dynamic characteristics surrogate model through the R^2 value (Square of the Correlation Coefficient) and the analysis value/prediction value comparison graph.

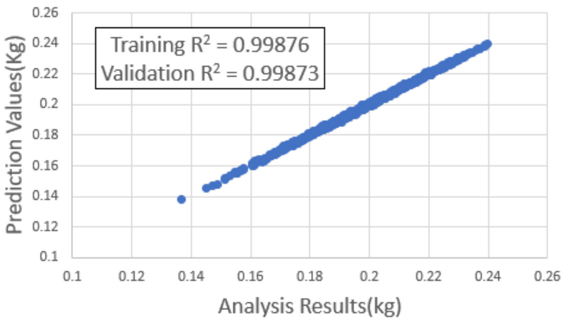

Figure 10 Analysis Results vs Prediction Values – Weight

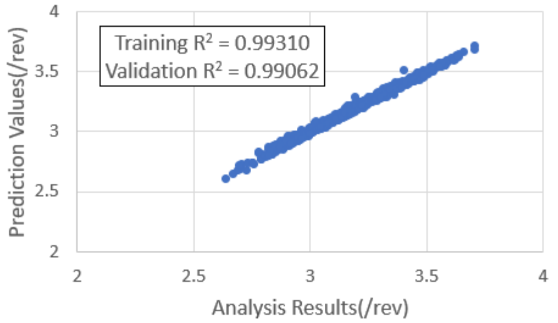

Figure 11 Analysis Results vs Prediction Values – Hover 1st Mode

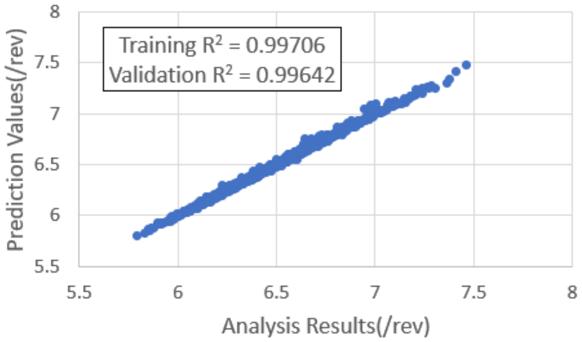

Figure 12 Analysis Results vs Prediction Values – Hover 2nd Mode

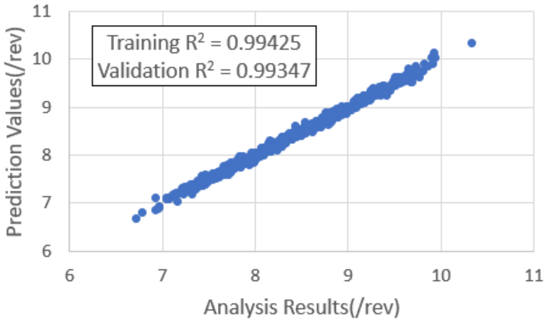

Figure 13 Analysis Results vs Prediction Values – Hover 3rd Mode

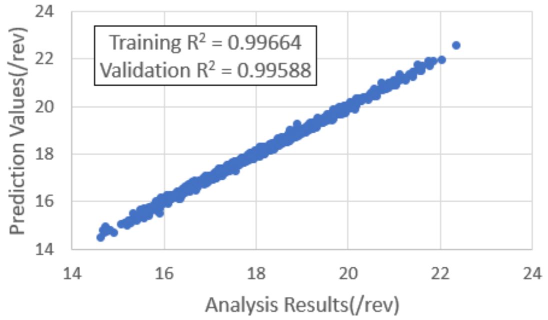

Figure 14 Analysis Results vs Prediction Values – Hover 4th Mode

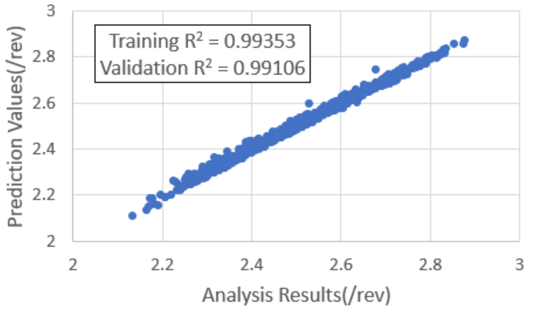

Figure 15 Analysis Results vs Prediction Values – Forward Flight 1st Mode

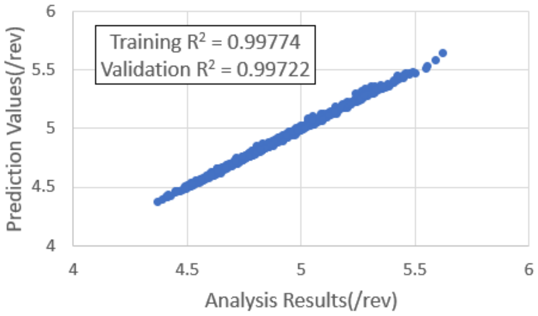

Figure 16 Analysis Results vs Prediction Values – Forward Flight 2nd Mode

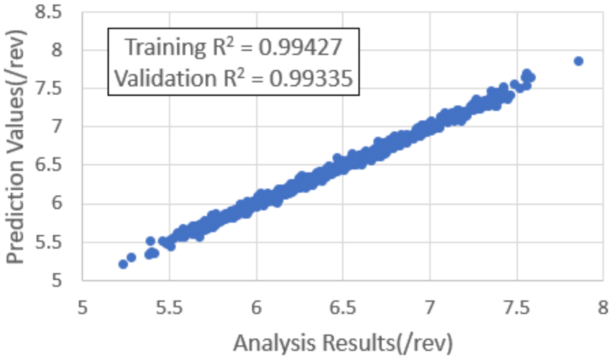

Figure 17 Analysis Results vs Prediction Values – Forward Flight 3rd Mode

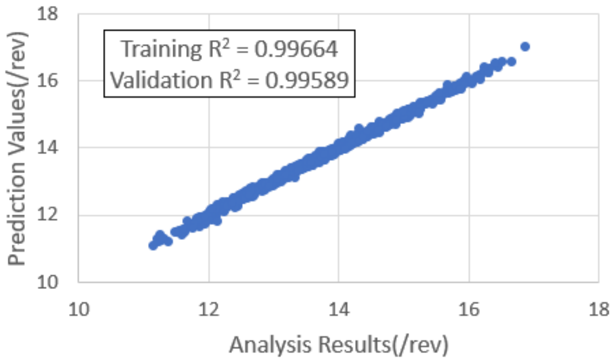

Figure 18 Analysis Results vs Prediction Values – Forward Flight 4th Mode

5.5. Optimal Section Design of Prop-blade Weight/Dynamic Characteristic

Weight/dynamic characteristics surrogate model derived by applying artificial neural network algorithm was applied to the genetic algorithm to perform weight/dynamic characteristics optimal design. To design a prop-blade with the minimum weight in which the 1st to 4th mode /rev frequency of the prop-rotor operating frequency by 0.15 or more in forward flight and hover flight conditions, an objective function was created by reflecting the prop-blade weight to the fitted value. And, when the 1st to 4th mode /rev frequency of the prop blade does not satisfy the requirement, it is configured to reflect the penalty value. Equation (5) shows the objective function for optimal section design of prop-blade weight/dynamic characteristics.

$$\text{(5)} \qquad y = W_b + P$$

$$\text{where } f_{diff} > 0.15, P = 0 \; else \; P \gg 0$$

The weight/dynamic characteristics optimal section design was performed by setting the number of individuals per generation to 200 and the target generation to 100. As a result of performing the optimal section design, the prop-blade section design result was derived with a weight of 0.1607 kg and the 1st to 4th mode /rev frequency differing from an integer multiple of the prop-rotor operating frequency by 0.15 or more. The initial generation showed a level of 0.1842 kg, but as the generations were repeated, the weight decreased and finally decreased to 0.1607 kg. Figure 19 shows the change in the minimum prop-blade weight per generation as the generation progresses, and Table 2 shows the section design results finally derived as a result of performing the weight/dynamic characteristics optimal section design.

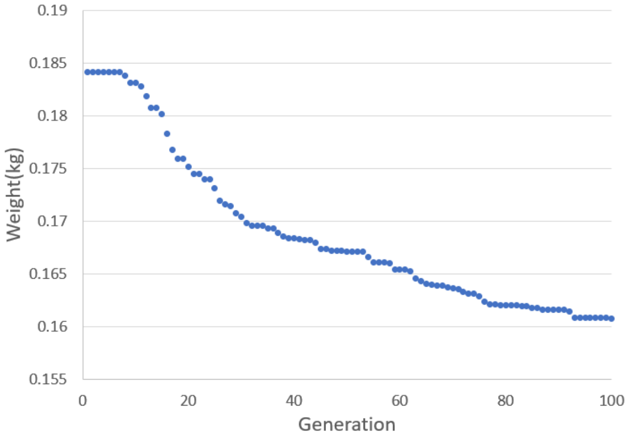

Figure 19 Mass Variation along with Generation

Table 2 Prop-blade Optimal Section Design Results by Genetic Algorithm using Surrogate Model

Section (r/R)	Skin_t (ply)	Spar_l (%)	Spar_t (ply)
0.18	3.05	46.3	8.7
0.23	2.80	40.9	8.2
0.3	2.79	32.9	4.5
0.4	2.77	29.4	4.1
0.5	2.69	24.6	3.3
0.6	2.67	22.5	3.2
0.7	2.48	18.3	2.9
0.83	2.48	15.0	2.7
0.9	2.10	11.9	2.6
1	1.91	10.5	1.4

Table 3 shows the predicted values, analyzed values and the error of the predicted value compared to the analyzed values of the weight and 1st to 4th mode /rev frequency for each operation mode for the optimal section design shape. This table shows that the maximum error of the predicted value is 1.39%, and the dynamic characteristics requirement is satisfied under all conditions. Figure 20 shows the fan plot of the OPPAV prop-rotor system to which the optimal section design shape is applied.

Table 3 Comparison of Prediction Results and Analysis Results

Results		Prediction Results	Analysis Results	Error (%)
Weight(kg)		0.1607	0.1605	-0.15
Forward Flight Mode Frequency (/rev)	1st	2.668	2.703	1.29
	2nd	6.328	6.300	0.46
	3rd	7.288	7.360	0.97
	4th	15.384	15.519	0.87
Hover Mode Frequency (/rev)	1st	2.152	2.183	1.39
	2nd	4.770	4.744	0.56
	3rd	5.652	5.715	1.09
	4th	11.720	11.837	0.99

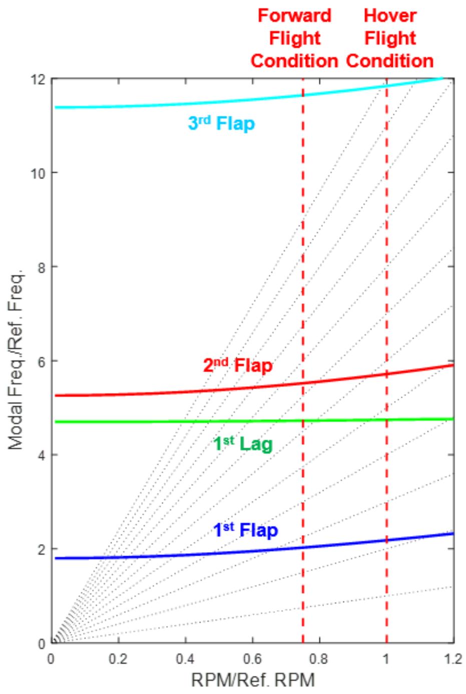

Figure 20 OPPAV Tiltprop Rotor System Fan-plot

6. Conclusions

In this paper, an optimal section design method for prop-blades with the minimum weight that satisfies the dynamic characteristics requirements for a prop-rotor system which hub/control design and blade OML are determined is proposed. For the optimal section design, an analysis procedure was established to generate a surrogate weight/dynamic section design model based on the prop-blade section design procedure, and an optimal design environment was constructed using the weight/dynamic section design surrogate model. An artificial neural network algorithm was used for the weight/dynamic section design surrogate model, and a genetic algorithm was applied for the optimal design. The weight/dynamic characteristics optimal design for the prop-blade of the OPPAV prop-rotor system operated in two modes was performed, and the section shape of the prop-blade with the minimum weight that satisfies the dynamic characteristics requirement was designed. In a future work, it is planned to design an optimal section considering the structural safety margin by reflecting the load analysis and structural analysis results.

ACKNOWLEDGEMENTS

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