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Configuration Design and Optimization of Ducted Fan Using Parameter Based Design

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Abstract

In this study, ducted fan configuration design and optimization program is developed. With this program, configuration design and optimization of ducted fan which improves hovering performance is performed. First, the configuration parameters that have effects on performance of ducted fan are selected. Based on these parameters, baseline of ducted is constructed by the program. Optimization problem is formulated based on baseline configuration. Ducted Fan Design Code is used to generate design points. With the baseline configuration, optimization is performed. After optimization, optimum configuration is obtained, and 3D modelling of optimized ducted fan is generated automatically by optimum configuration parameters.

1. Introduction

Lift fan aircraft is the one of compound aircraft which is combining conventional and vertical take-off & landing (VTOL). Lift fan aircraft has many advantage than conventional type aircraft. First advantage of lift fan is that lift fan aircraft can vertically take-off and land. Second is that ducted fan is adequate to install into wing or fuselage. Third is that runway is not required. Last is that it is faster than existing rotorcraft when it is in cruise state. [1]

Chao verifies that the influences of ducted fan's inlet and exit on its figure of merit and thrust. [2][3] By optimizing configuration of inlet and exit, ducted fan's performance can be changed. Configuration parameters for optimization are selected with the standard that the parameters have effects on ducted fan's figure of merit.

Existed studies about performance of ducted fan mostly used computational fluid dynamics which takes long time to get result. However, DFDC [4] (Ducted Fan Design Code) has very fast calculating time compared to computational fluid dynamics. Therefore, optimization using DFDC is expected to contribute to ducted fan configuration optimization.

The main purpose of this study is optimization using configuration parameters that have effects on ducted fan's performance, and optimizes both duct inlet and exit which can improve ducted fan's figure of merit. With improving figure of merit through optimization, not only ducted fan itself, but a lift fan aircraft or multicopter drone is improved also with its ducted fan.

2. Optimization Problem Set up

2.1 Ducted Fan Component

Ducted fan (shroud propeller) produces a thrust by accelerating air through a ducted propeller and expelling the air downstream at the exit of the duct. The duct around the propeller produces thrust augmentation. Hence, a smaller ducted fan is available to be used and still achieve the same amount of thrust as a larger free propeller. (free propeller means propeller without duct.) Also, not only protecting rotor blades from obstacles and some acoustic shielding will be observed. Ducted fan usually has three main components, duct, fan, and hub. The sectional view of ducted fan is below.

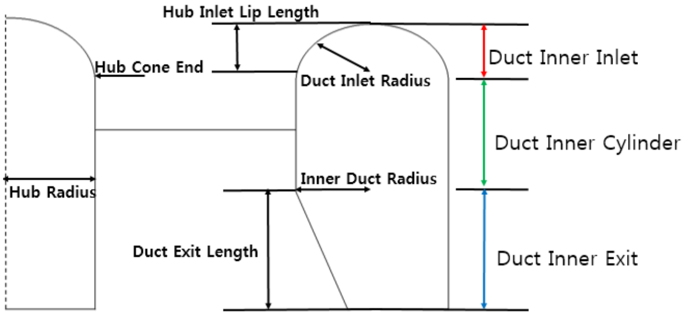

Figure 1 : Sectional view of ducted fan

For optimization, configuration parameters are selected based on the variables which are related to duct inlet and exit. Inlet is important when airflow is coming through ducted fan, so low pressure is made around duct inlet. Exit is significant parameter due to its expanding the wake after rotor. Also, parameters of hub are selected for examining its effect on ducted fan in this study.

2.2 Design Formulation

Optimization problem is formulated to maximize figure of merit of ducted fan. Constraint is build up with available power of engine in a lift fan aircraft. Objective function and constraints are shown as below.

$$\begin{gathered}\boldsymbol{Maximize}: \\ \boldsymbol{f(x) = Figure\ of\ Merit\ (FM)} \\ \boldsymbol{Subject\ to}: \\ \boldsymbol{g(1): Thrust \geq 6000N} \\ \boldsymbol{g(2): Required\ Power \leq 1.5 \times 10^5 W}\end{gathered} \tag{1}$$

Eight design variables are determined which are shown in Table1. Among eight design variables, duct inlet curvature parameter and duct exit curvature parameter are not shown in Table1

Table 1: Design variables

Design Variables	Description	Lower	Baseline	Upper
x_1	Hub Radius	-20 %	0.160	-20 %
x_2	Hub Cone End		0.320	
x_3	Duct Inlet Lip Radius		0.075	
x_4	Duct Inner Inlet Length		0.150	
x_5	Duct Inlet Curvature Parameter		0.320	
x_6	Duct Exit Curve Radius		0.035	
x_7	Duct Exit Length		0.075	
x_8	Duct Exit Curvature Parameter		0.480	

Without exact variables to generate inlet and exit of duct, inlet and exit curves should be generated. Inlet curve is expressed by power series, and exit curve is expressed by parabolic function. Thus, inlet and exit configuration can be drawn with configuration parameters. And, x_5 and x_8 are determined as configuration parameters among eight design variables.

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For those parameters, mathematical formula is formed to perform parametric design. Following figure shows that duct is divided into three geometrical parts.

2.3 Sensitivity Analysis

Sensitivity analysis is performed with eight design variables, and four design variables are eliminated due to their less than 1% effects on the objective function. Finally, x_4, x_5, x_6, x_8 are selected as a final design variables.

2.3 Optimization Result

There are many optimization method, but Sequential Quadratic Programming method is used in this study due to its fastness of reaching to optimum result. Optimum result and stopping criteria of this study is shown in the tables below.O

Table 2 :Stopping Criteria

Variables	Value
Max Iteration	1000
Max Function Evaluation	1×10^{5}
Tolerance Constraints	1×10^{-4}
Tolerance Function	1×10^{-6}
Tolerance design variables	1×10^{-5}

Table 3 : Optimum Result

Variables	Description	Baseline	Optimum Result	Unit
x_4	Duct Inner Inlet Length	0.1500	0.1800	m
x_5	Duct Inlet Curvature Parameter	0.3200	0.3540	-
x_6	Duct Exit Curve Radius	0.0350	0.036	m
x_8	Duct Exit Curvature Parameter	0.0	0.1312	-
Figure of Merit	-	0.8217	0.8693	-
Thrust	-	5950	6020	N
Required Power	-	144000	139000	W

Compared to baseline, optimum result shows that approximately 6% of figure merit is increased by inlet and exit optimization. And, also larger inlet and exit curvatures parameters are used to make larger figure of merit of ducted fan.

2.4 3D Modelling

After optimization of ducted fan, 3D modeling of optimum ducted fan is generated based on the optimum configuration parameters. Automated configuration design program is constructed based on Python. It generates inlet and exit curves with the equations from optimum result which is stored in Matlab program.

This study is focused on the inlet and exit of ducted fan configuration, so that there is no change in hub and rotor blades in this design process.

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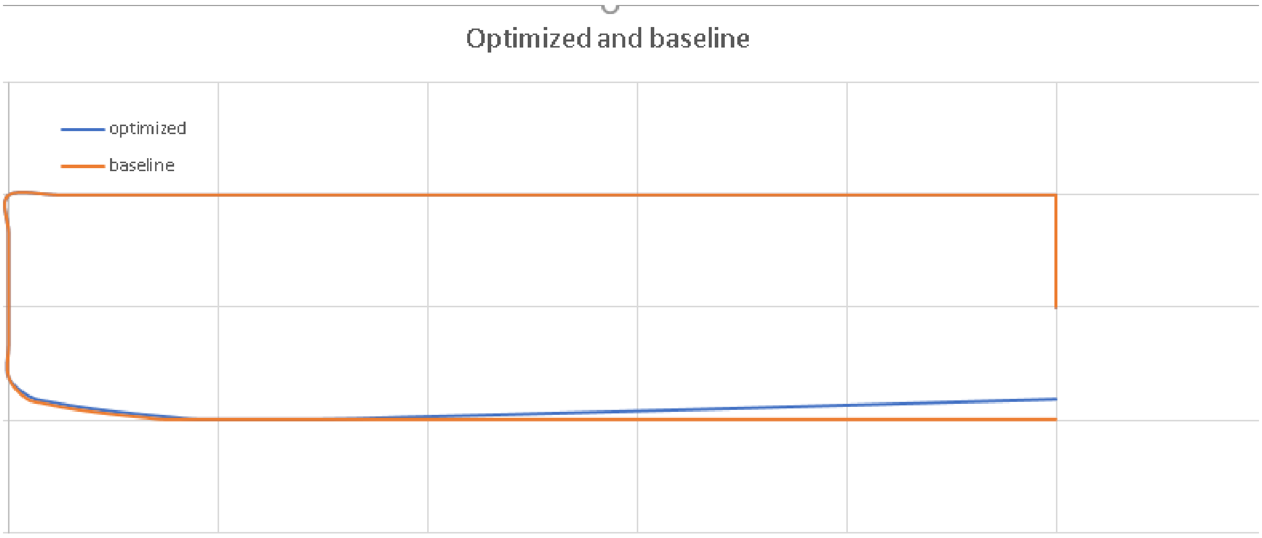

Figure 2 : Optimized Configuration

3. Conclusion

In this study, figure of merit is increased due to configuration optimization of inlet and exit of ducted fan based on the parameters. Configuration parameters are the components of duct inlet and exit parameters and selected by sensitivity analysis. Optimization method is Sequential quadratic programming. After configuration optimization, figure of merit is increased 6% compared to the initial model. And its configuration information is automatically sent to 3D modeling program. This 3D modeling program does not need any input from users but optimum duct configuration information from optimization program. Thus, this study shows that configuration of inlet and exit of ducted fan is critical to performance of itself, also it shows that performance can be improved through optimizing the inlet and the exit and shown with 3D modeling program.

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