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Rapid and Optimal Design of a Ducted Fan Using a Neural Optimal Algorithm

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ABSTRACT: Considering the optimal performance and new applications of the ducted fans, especially in unmanned aerial vehicle missions, this paper aims to provide an optimal and rapid method for designing aerial vehicles based on new mathematical and analytical tools which improved and accelerated many of the long engineered processes. In this new fast design method, an initial design is carried out based on the momentum theory. Then by connecting the matrix laboratory and a ducted fan design code software, several optimal design schemes for the duct are extracted by the particle swarm optimization and direct algorithm. The parameters search domain in the algorithm is obtained from the initial design with the momentum theory method and the various results of optimization software, in the case. Finally, in order to obtain the final duct design, according to the optimized information, a multilayer perceptron neural network using an error backpropagation algorithm is trained which in order to obtain the optimal training samples and the network output validations, the neural network is trained and test by 28 airfoils sample. In the redesign loops, without a time-consuming optimization, the trained neural model can extract the duct parameters very quickly, based on the constraints of structure, control design, and mission targets.

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1- Introduction

Nowadays, Unmanned Aerial Vehicles (UAV) are developing at a considerable rate of the variety and range of applications. In general, UAVs are divided into fixed-wing, Vertical Takeoff Or Landing (VTOL), and hybrid type. The VTOL has a special place among the drones because of the ability to takeoff and landing vertically. Duct fans are a kind of VTOLs, usually composed of one or two fans in an outer duct, and their control surfaces are symmetrically underneath the fan. In Fig. 1, different parts of a ducted fan sre introduced. The ducted fan uses a combination of rotors and wings, but instead of the usual shape, the wing surrounds the rotor annularly. The duct increases the trust and provides lift during the cruise flight. Flights and wind tunnels tests prove the ducted fan benefits which are mentioned in reference [1].

any papers focus on the optimal design of the ducted fan [2], but in these articles, only empirical or analytic methods such as Blade Element Theory (BET) and Momentum Theory (MT) are used which optimization or acceleration of these methods has not been considered with novel evolutionary algorithms or neural networks.

In the paper, an attempt has been made to provide an optimal and fast way to design a ducted fan. In the new method, first, using the momentum theory, based on the requirements of the mission defined for the UAV, an initial design is performed, then The initial model is optimized with the Ducted Fan Design Code (DFDC) software, which is based on classical vortex/blade-element methods of Drela and Youngren [3], and a general 3Dimensional (3D) vortex-lattice or panel method for aerodynamic analysis of ducted fans.

The used optimization method is the Particle Swarm Optimization (PSO) algorithm, the search domain of the optimization parameters is extracted from the initial

Fig. 1. ducted fan details

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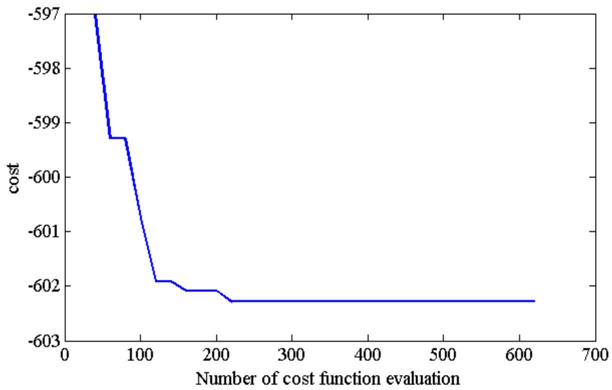

Fig. 2. Airfoil optimization information of NACA23018

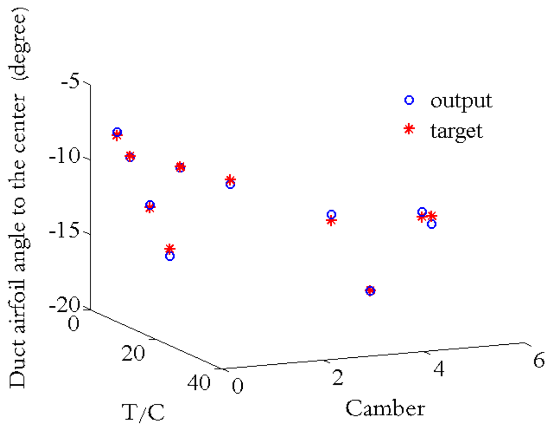

Fig. 3. Estimation of airfoil installation angle using neural network with 10 training samples

momentum theory design. In the different optimal designs based on various airfoils for the ducted fan body, the design parameters such as airfoil installation angle, airfoil length, and airfoil tip relative to the fan core are obtained different, which greatly affects the design efficiency. Therefore, it is necessary to make several optimizations to choose a proper airfoil for the production of maximum thrust, having an appropriate interior space for proper structure, fuel tank place, and other control and electrical elements, as well as having the minimum weight of the instrument, which is time-consuming. In this regard, in the final design phase, a MultiLayer Perceptron (MLP) neural network was trained based on a number of optimized designs which its input are airfoil properties and its output are optimal values for the airfoil installation parameters. The neural model, can achieve the best possible design of the final duct with all the practical design constraints in the shortest time possible.

2- Methodology

For initial approximations and related calculations, rotor computation methods, such as the BET and MT methods should be used. In this section, the MT method will be used to avoid the difficulties of selecting airfoil blade parameters. This method has two important tools. The first tool is the continuum equation. This tool can be expressed as Eq. (1).

$$\rho AV = \text{cte}, \qquad \rho\text{=cte} \Rightarrow AV = \text{cte} \tag{1}$$

The second tool for applying momentum theory is the Bernoulli equation.

$$\frac{1}{2}\rho V^2 + p = \text{cte} \tag{2}$$

The initial design steps of a ducted fan based on MT are presented in reference [4].

2- 1- Optimization

The PSO algorithm is used to optimize the initial design of the ducted fan. Designing variables include selecting the appropriate airfoil, the size of the inlet, and outlet of duct, which are variables of the airfoil installation angle and airfoil chord length, the airfoil attack edge distance to the fan rotor core, and the distance between the fan edge and the inner body of the duct. The cost function used for the PSO algorithm or direct optimization method is $J = -(T + 10^6 / P)$ or $J = (1/T + 2*10^{-8} P)$, which is the effect of the power and thrust on the cost function. Fig. 2 is an example of an analysis performed on DFDC software used for airfoils in which the cost function value is presented in terms of the number of the cost function evaluations.

The optimal values of the design variables for the 28 airfoil samples are achieved. The direct optimization method is used to validate the values obtained by the PSO optimization method. The direct method always provides a global answer if there are enough examples in the problem-solving domain.

3- Results and Discussion

In this section, in order to obtain optimal values of design parameters, a neural network is trained using the outputs of the PSO algorithm. The results of training a two-layer perceptron neural network with a backpropagation error algorithm with the Levenberg-Marquardt method for the angle of mounting of the airfoil to duct core are shown in Fig. 3. In this model, the input vector to the neural network has the geometric properties of NACA airfoils, including the Camber curvature, the maximum curvature distance from the airfoil attack edge, and the cord to thickness ratio.

As the neural network training information increases, this network will provide a more accurate model of the duct design.

Five five-digit airfoils and five six-digit NACA Airfoils were assigned to the test, which showed that the outputs of the neural network and the output of the PSO algorithm were less than 10% different. Based on the simulations, a sufficient number of samples can be extracted to the neural network based on the required accuracy. For example, for an error of less than 3%, a sample of 15 airfoils is sufficient.

4- Conclusion

According to the momentum theory method, a ducted fan was first designed which only expressed the dimensions of the inlet, output, thrust force and power output in this case. In this method of design, a simple nozzle is considered between the inlet and outlet, where the fan is located in the nozzle throat. But in this paper, a combination of DFDC analytical software for ducted fan analysis, PSO optimization algorithm, and a neural network for the rapid and optimal design of this perpendicular UAV was used. In the first step, using the combination of MATLAB and DFDC software and with the PSO optimization algorithm, the optimal design for each airfoil was performed then a multilayer perceptron neural network was trained to increase the design speed and accuracy based on the optimizations. Optimal sample numbers were obtained for neural network training. Finally, it was found that this neural network is capable of predicting 95% accuracy of design and installation specifications of 4-digit NACA airfoils and with more than 90% accuracy in predicting other NACA airfoils. As a result, this method greatly increases the accuracy and speed of the design.

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