Transition model based design method investigation on laminar flow nacelle

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Abstract. Aerodynamic shape optimization of natural-laminar-flow (NLF) nacelle for long-range wide-body transport aircraft was investigated. Perturbed class function/shape function transformation (CST) method was used to parameterize the three typical generatrix of the nacelle combined with the perturbation based transfinite interpolation method to achieve surface and space grid update. The k-ω SST (shear stress transport) turbulence model and γ - Reθ transition models were used to predict the transition location. The gradient based optimization method called Sequential Quadratic Programming was selected for the high efficiency. Natural laminar flow design was performed on three dimensional nacelles and about 45%~55% laminar flow region was achieved by the optimization design.

1. Introduction
Large transport aircraft is the most competitive field in the international aviation industry. The challenge for its development is how to meet the increasingly demanding requirements of economy, safety, comfort, and environmental protection [1]. For example, NASA plans to reduce the fuel consumption rate of the next three generations of civilian transport aircraft by 33%, 40%, and 70% compared to the current B737. In response to these harsh requirements, it is necessary to strengthen the design and research on improving the aerodynamic efficiency of aircraft.

Natural laminar flow control, also known as passive laminar flow control, has put forward high requirements for pneumatic surface design. Many newly developed large aircraft in Europe and the United States have adopted laminar nacelle or are currently developing natural laminar nacelle [2]. Pneumatic performance has improved significantly. For example, the engine compartment of the Boeing 787. European Airbus companies are about to conduct a laminar nacelle flight test on the A340 aircraft under the Clean Sky Project. The two-channel wide-body passenger aircraft currently being developed in China has high requirements for economic and environmental protection, and will use engine pods with large culvert ratio. Therefore, the research on the design method of laminar nacelle is of great significance to the design of large aircraft in China. The optimization results show that the surface laminar flow range can be expanded through laminar design [3]. It can be seen from the domestic literature [4] that carried out the research on the optimal design of the axisymmetric nacelle, and the results showed that the laminar flow range was about 50% chord. In this study we carried out a research on the design method of natural laminar flow for the non-axial symmetry nacelle with angle of attack.
2. Methodology

2.1. $\gamma - Re_\theta$ transition model

The accurate prediction of turning positions is one of the key technologies for the design of laminar short nacelles. At present, the two most used methods in engineering design are the $e^N$ method and the transition model method. The $e^N$ method is mainly based on linear stability theory and test data. It is a semi-empirical method in which the value of $N$ is greatly affected by the environment. In use, the relationship between turbulence and $N$ is mainly determined by experiments, and it is difficult to generalize to three-dimensional flow. This turning point calculation uses the transition model [5][6]. This model does not pursue the simulation of the specific complex physical processes of the transition, but controls the generation of intermittent factors in the boundary layer through empirical correlation functions and turning momentum Reynolds numbers. Then determine the position of the turning point. The transport equation of the intermittent factor $\gamma$ is defined as:

$$\frac{\partial (\rho \gamma)}{\partial t} + \frac{\partial (\rho \gamma u_i)}{\partial x_i} = P_{\gamma 1} - E_{\gamma 1} + P_{\gamma 2} - E_{\gamma 2} - \frac{\partial}{\partial x_i} \left[ (\mu + \frac{\mu_s}{\gamma}) \frac{\partial \gamma}{\partial x_i} \right]$$

(1)

$$P_{\gamma 1} = C_{\alpha 1} F_{\text{length}} \rho S [\gamma F_{\text{onset}}] \gamma^3$$

(2)

$$E_{\gamma 1} = C_{\alpha 1} P_{\gamma 1} \gamma$$

(3)

2.2. Design status and optimized mathematical model

The design state is Mach number $Ma = 0.76$, angle of attack $\alpha = 2.0$, Reynolds number $Re = 1.0 \times 10^7$ (consistent with the 2.4m wind tunnel atmospheric pressure test), the calculation of turbulent $Tu$ is 0.1%, and the nacelle Reynolds reference length is 3.25m. The reference area is about 288 m$^2$. The objective function and constraint are expressed as follows:

$$\min\ C_D$$

$$s.t.\ \bar{t} \geq 1.1 \ast \bar{t}_{\text{initial}}$$

(4)

(5)

Since the grid density has a great influence on the turning position, the grid independence test is carried out before the optimization design. Using the GCI method [7], Drag is the main basis for comparison. The results are shown in Table 1. In order to save computing resources and time, a medium-density grid is used. The scale is 3.7 million grid points and the surface grid is less than 1. The far field is greater than 20 times the length of the nacelle.

Table 1. Drag force coefficients for the three grids used in the convergence study.

| Grid    | $10^6$ | $C_D$  | $GCI_{CD}$ |
|---------|--------|--------|-------------|
| Coarse  | 1.8    | 0.000165 | -           |
| Medium  | 3.7    | 0.000182 | 0.664591    |
| Fine    | 6.0    | 0.000183 | 0.00929     |
2.3. Parameterization of nacelle
The minimum design variables and the maximum design space are an important pursuit index of the parameterization method. Boeing Kulfan et al.’s functions/class functions are based on the type function. The parameterization method of transformation (CST) has high accuracy in many parameterization methods [8], and its geometric meaning is clear, and there are few control parameters at the same time. The typical section of the short nacelle is selected in this paper for parameterization by CST method showed in equation 3. The engine lip section and the inner surface of the air intake surface have a significant impact on the engine intake conditions. The design should be mainly determined by the engine parameters. The optimization is mainly aimed at the outer surface of the nacelle, and the half-mode calculation is selected. The shape of the short nacelle is parameterized. The six-order CST (N = 6) method is used to parameterize the top, bottom, and bottom sections, respectively. A total of 21 design variables are used to obtain the modified short nacelle through incremental interpolation. The shape, Capable of accurately describing the shape of the short nacelle with fewer parameters. The parameterization diagram of the short nacelle is shown in Figure 1. The space grid update uses the perturbation based over-finite interpolation TFI method to generate a deformed grid.

\[ f_k(u) = c(u) s(u) \]  \hspace{1cm} (6)

2.4. The optimization method
The gradient based method called Sequential Quadratic Programming (SQP) was adapted in this study. SQP is currently recognized as one of the best algorithms in dealing with small and medium-scale nonlinear programming problems and the modified algorithm transforms the original problem into a series of quadratic programming sub-problems to obtain the optimal solution of the original problem. Taking quadratic approximation of Lagrange function to improve the approximation degree of quadratic programming sub-problems is a very robust nonlinear programming algorithm known at present.
3. Results and discussion

Figure 2 shows the contrast between the upper and lower sections of the short nacelle. From the section shape contrast diagram, it can be seen that after the optimization, the radius of the front edge of each section is reduced, and the relative position of the maximum thickness is greatly reduced. Due to the limitation of the constraint, the maximum relative thickness increases slightly.

Figure 3 shows the distribution of pressure coefficients / friction drag coefficients at the top, bottom, and side sections. From the pressure distribution, the positive pressure gradient range of each feature section of the initial nacelle exists only within 10% of the front edge of the nacelle. The transition point is about 20% of the chord length at the position slightly behind the negative pressure peak.
Figure 3. Comparison of friction coefficient and pressure coefficient between base and optimized NLF nacelle and the abscissa is the dimensionless local chord length.

Figure 4. Comparison of friction coefficient contour between base and optimized NLF nacelle. (side view)

At the same time, due to the presence difference such as negative pressure peak and caused by angle of attack, the upper section turned forward, the lower section turned backward. In the middle of the two nacelles, the optimized shape pressure coefficient shows a positive pressure distribution in a large range from the leading edge, in which the positive pressure gradient increased form a length of 10% to 40%, avoiding the excessive acceleration of the air flow and increasing the shock wave drag. From the results of the optimization of the friction drag coefficient distribution, it can be seen that the transition positions of the three sections have been significantly moved backward to the vicinity of 45% to 55% of the chord length, and the effect of the angle of attack on the different sections is consistent with the origin nacelle.

Figure 4 gives a comparison of the friction drag coefficient cloud diagram on the surface of the original nacelle and the optimized nacelle. The original nacelle has a forward position due to the maximum relative thickness and the large head radius. The transition position is around 20%, and the maximum thickness position is optimized to the central part of the model, so the transition position of
optimized nacelle is greatly moved backward to about 50%, the effect of weakening friction drag is obvious.

4. Conclusion
In this paper, using the CST parameterization method, transition model and programming quadratic sequence optimization method, a cross-acoustic velocity natural laminar module optimization method is established, and a three-dimensional natural laminar module optimization design is carried out. The conclusion is obtained through research

1. Using the CST method to parameterize the outer surface of the short nacelle for typical feature bus, it can use fewer free parameters to achieve better results.

2. Turbulence has a significant impact on the profile transition position dominated by the TS wave. For the designed NLF nacelle, the turbulence ratio exceeds 0.3% and the transition position is significantly advanced.

3. The transition model is accurate in predicting the turning position, and combined with the gradient based sequence quadratic programming optimization algorithm with small computational requirements, it can effectively carry out the natural laminar nacelle design, and the outer surface laminar flow range can be maintained about 45%–55%. In the case of deviation from the design point Mach number, the NLF short nacelle has a good robustness.

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