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Robust design and analysis of a conformal expansion nozzle with inverse-design idea

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Abstract This paper examines robust optimization design and analysis of a conformal expansion nozzle of flying wing Unmanned Aerial Vehicle (UAV) with the inverse-design idea. In view of flow features and stealth constraints, the inverse-design idea is described and the uncertainty-based robust design model is presented. A robust design system employs this model to combine deterministic optimization and robust optimization and is applied into design of a conformal expansion nozzle. The results indicate that design optimization can conform to the anticipation of the inverse-design idea and significantly improve the aerodynamic performance that meet the requirement of 6σ. The present method is a feasible nozzle design strategy that integrates robust optimization and inverse-design.

1. Introduction

Modern flying wing Unmanned Aerial Vehicles (UAVs) always employ the Conformal Expansion Nozzle (CEN) to improve aerodynamic/stealth integrate performance (such as the RQ-180). The CEN has special design features. On the one hand, the nozzle has good shadowing effect of the airframe to reduce Radar Cross-Storage (RCS). Its expansion surfaces have the certain curvature. The edges of exit generally are parallel to the edges of the airframe as much as possible. On the other hand, to ensure good aerodynamic performance, expansion surfaces of the nozzle need refinement design. These surfaces can improve flow features of the nozzle in complex conditions, such as expansion, compression and interference. Therefore, in view of stealth constraints, aerodynamic design and analysis of the conformal expansion nozzle have been widely concerned.

Gapone et al.[1] studied aerodynamic performance of the Conformal Single-Expansion Nozzle (CSEN) at different speeds. Berrier and Leavit[2] analyzed flow distortion characteristics of CSEN. MacLean[3] applied experiment methods to examine the flow characteristics of CSEN. Carlson[4] investi-

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gated static performance of a Single Expansion Ramp Nozzle (SERN). Capone and Schirmer[5] explored static internal performance of a SERN with multi-axis thrust vectoring capability. Marathe and Thiagarajan[6] conducted effect analysis of geometric parameters on the performance of SERN. Huang et al.[7] used data mining for design exploration of a SERN. Damira et al.[8] carried out parametric optimization of SERN. Gruhn et al.[9,10] has improved the SERN performance by aerodynamic flap design. These researches always focus on high speed nozzle and pay attention to parameter effect and single-point optimization. They take little consideration to multi-point performance and uncertainties for the conformal expansion nozzle of modern flying wing UAV. So, it is necessary to concern multi-point performance and uncertainties to carry out the conformal expansion nozzle design of flying wing.

To improve multi-point performance, design must start from the design idea. For a long time, the inverse-design idea has been extensively used in the design of airfoil and wing. If inflow/outflow interference is taken into account, the inverse-design idea can be applied to the design of conformal nozzle. Facing uncertainties, how to carry out robust optimization is the emphasis of the nozzle design. The robust optimization should concern not only the uncertainty of flight condition but also geometrical uncertainty. Based on these uncertainties, lots of authors studied robust optimization. Lee[11] and Li[12] et al. carried out uncertainty-based optimization design of nature laminar flow airfoils. Huang et al.[13] studied robust optimization design of wing. Li et al.[14] investigated robust optimization of nacelle using 6σ criterion. Most of the studies pay little attention to the inflow/outflow uncertainties of flying wing (especially nozzle). But they provide reference for robust optimization method of the nozzle design. In fact, the robust optimization method needs the numerical simulation method as the basic guarantee in design process. The structured Reynolds-Averaged Navier-Stokes method, which employs the $\gamma - \overline{Re}_{\theta t}$ transition model[15] and solves transport equations of the intermittency γ and the local transition onset momentum thickness Reynolds number $\overline{Re}_{\theta t}$, is a common numerical simulation method. It can be used in design and analysis of flying wing nozzle.

Based on all the above, the inverse-design idea should be described and the uncertainty-based robust design system needs to be built in design of the conformal expansion nozzle of flying wing. The performance of the design nozzle would be particularly analyzed by the $\gamma - \overline{Re}_{\theta t}$ transition model.

2. Design system

2.1. Inverse-design idea

Starting from airframe/intake-exhaust integration configuration, the design of a conformal expansion nozzle is carried out. Fig. 1 shows the shape of airframe/intake-exhaust flying wing[16] that includes a nozzle. Only the parameters of the nozzle are adjusted in nozzle design process.

The inverse-design idea is proposed and involves four elements. Firstly, the edges of the nozzle exit need to parallel the edges of airframe for stealth. The location of the nozzle exit is initially defined. Secondly, the area of the nozzle exit is gained by approximate isentropic expansion. Thirdly, the surfaces of the nozzle have special curvature to fit great expansion. At last, there are slip lines between shear flow of the nozzle exit and outflow to avoid shock wave and reduce inflow/outflow interference. In fact, the center line of the nozzle is close to chord of the fuselage to produce slip lines.

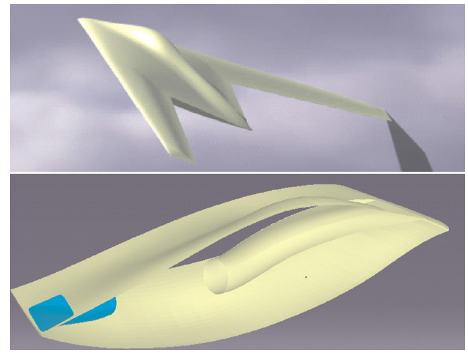

Fig. 1 Shape of flying wing and airframe/intake-exhaust.

The inverse-design idea is used for the parametric approach and determining basic space of design variables. On the one hand, the length, width, central point coordinates and round corner radius of the nozzle exit are 6 basic variables, which can determine the nozzle exit. On the other hand, 9 cubic curves (8 of edges, 1 of center) are selected to guide the streamwise of nozzle, which has 18 variables. Based on these variables, the nozzle is transformed into digital surfaces. The initial full-aircraft mesh is generated by Gridgen. The local mesh of the nozzle is automatically reconstructed by the TransFinite Interpolation (TFI) method.

Fig. 2 shows basic schematic of the nozzle view and guide curves. The nozzle has some special curvature constraints of curvature to meet the inverse-design idea. The guide curves adopt cubic spline (as Eq. (1)) of 5 points, which are divided into equal segments along the chord.

$$S_i(x) = [a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3] \quad i = 0, 1, \ldots, 4 \tag{1}$$

In Eq. (1), $S_i(x)$ stands for y or z coordinate values, x and x_i are the coordinate values of anywhere and the ith point respectively. a_i, b_i, c_i and d_i are parameters which can be determined by coordinate values of five points. Based on the inverse-design idea, the middle and two end points (the first, third and fifth points) can be determined by the inlet and exit of the nozzle. The y or z values of two other points are design variables.

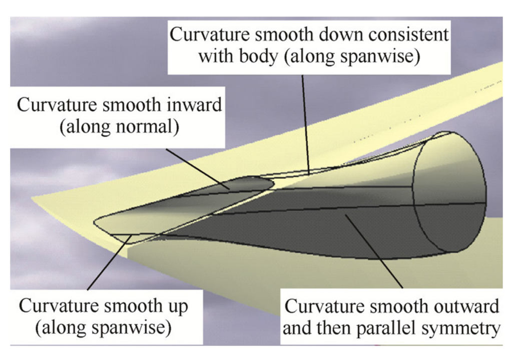

Fig. 2 Schematic of nozzle view and guide curves.

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