IMPROVEMENT OF VORTEX GENERATOR SOURCE MODEL FOR ADJOINT-BASED DESIGN OPTIMIZATION

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ABSTRACT

The present paper deals with a vortex generator source model for the adjoint-based design optimization. To efficiently design the vortex generator inside an S-shaped subsonic inlet, the vortex generator source model is employed instead of the fully gridded vortex generator. The previously developed original source model, however, does not reflect a small change in position and thus has difficulties in differentiation for sensitivity analysis. For this reason, the original source model is modified into a differentiable source model. Through the differentiable source model, a large number of design variables including vortex generator position can be treated with an adjoint variable method. After the optimization with the design variables of the chord length, height, angle of incidence, axial and circumferential positions of each vortex generator, the performance of the target inlet is remarkably improved, showing that the distortion coefficient well over 70% while maintaining the total pressure recovery ratio.

INTRODUCTION

For decades, researchers have shown interests in controlling the flow inside an S-shaped subsonic inlet (S-duct) to improve the engine performance of aircraft that is measured by the engine face distortion coefficient and the total pressure recovery ratio. There is several ways to enhance the flow quality inside an S-duct. The one way is to employ additional flow control devices, such as a vortex generator (VG), jet actuator, Gaussian bump, and so on. Among the available flow control devices, the VG has been adopted in many computational and experimental studies [1]. Especially, a thin-plate type VG is popularly employed among the several types of VG because the lift force by the VG can be mathematically modeled. Bender, Anderson, and Yagle [2] developed the BAY model to describe this lift force, which can be expressed by a suitable mathematical source model. This modeling reduces the computational cost by allowing the flow analysis around the VG without the additional grid generations.

Until recently, the design of experiments (DOE) method has been popularly adopted for the designing VG. However, one of the drawbacks of the DOE-based design optimization is the limitation in the number of design variables, thus the same design condition has to be imposed on all VGs. To overcome this shortcoming, present paper adapts an adjoint-based design optimization, which has flexibility on the number of design variables. Thus, each VG can be independently treated by fully reflecting local flow patterns near the each VG.

To reduce the computational costs of the flow analysis and the sensitivity analysis based on the adjoint variable method, the BAY model is employed as a source model. However the original BAY model cannot reflect a small change in position, original model's applicability for sensitivity analysis has intrinsic limitation. For this reason, a differentiable BAY model is developed by considering sub-cell volume change caused by a small movement of each VG.

The target geometry of design is the thin-plate type VGs installed in the RAE M2129 S-shaped subsonic offset inlet. As a baseline configuration of the VG, a VG170, presented by Anderson [1], is selected. All of the 11 VGs included in the VG170 are designed independently with the design variables of the chord length, height, angle of incidence, axial position, and circumferential position of each VG.

VORTEX GENERATOR

A thin-plate type VG is widely used for controlling flow direction toward inlet or flow separation on wing upper side. A large number of computational grids, however, are necessary for a fully gridded analysis of the VG. To reduce computational cost while maintaining solution accuracy, Wendt, Bender *et al.*, and Jirásek modeled a thin-plate VG as a mathematical source model.

BAY Model

The BAY model is developed by Bender, Anderson, and Yagle for describing lift force by source model [2]. This model is easily employed to Navier-Stokes equations as follows:

$$\Delta V_i \frac{\Delta \rho u_i}{\Delta t} = \sum_j F_M \Delta S + L_i \text{ (Momentum Equation)} \tag{1}$$

$$\Delta V_i \frac{\Delta \rho E}{\Delta t} = \sum_j F_E \Delta S + u_i \cdot L_i \text{ (Energy Equation)} \tag{2}$$

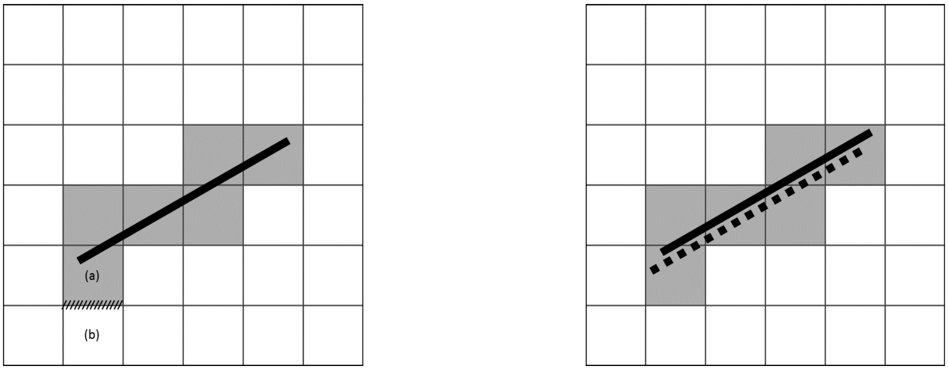
where *j* is the flux summation along the boundary of the cell *i*. Since the local flow direction becomes parallel to the VG, the energy source term of ($u_i \cdot L_i$) disappears. The source term (L_i) representing the lift force can be expressed as a correction term for the loss caused by the deviated flow from the VG surface as follows:

$$L_i = C_{VG} S_{VG} \left(\frac{\Delta V_i}{\sum_j \Delta V_j} \right) \rho \left| \vec{u} \right|^2 \left(\hat{u} \times \hat{b} \right) \left(\hat{u} \cdot \hat{n} \right) \left(\hat{u} \cdot \hat{t} \right) \tag{3}$$

where C_{VG} is a relaxation parameter controlling the strength of the side force, and S_{VG} is the VG planform area. $\Delta V_i / \sum_j \Delta V_j$ is the percentage of the lift force of the ΔV_i (the volume of the cell i), and $\sum_j \Delta V_j$ is the volume of all cells to which the VG is applied. α is the angle of incidence with respect to the flow direction, ρ is the local density, and $\vec{u}$ is the local velocity. And $\hat{b}$ is the unit vector in the spanwise direction of the VG, $\hat{t}$ is the unit vector tangent to the VG, and $\hat{n}$ is the unit vector normal to the VG.

Differentiable BAY Model

From the view point of flow sensitivity, the original BAY model needs to be modified because it is formulated with the whole volume of each computational cell that is crossed by the VG, and thus it cannot reflect a small amount of positional change within computational cell. Figure 1-a) shows the volume consideration of the BAY model for the percentage of the lift force. The solid-lined VG and the dash-lined VG shown in Figure 1-b) are treated as the same VG in computational analysis although their actual positions are different. Moreover, it is difficult, with the BAY model, to obtain the gradient information at an interface (for example, the slashed cell-interface in Figure 1-a)) between the cell where the VG is crossed and the one not crossed (cells (a) and (b) in Figure 1-a)), which is caused by the discontinuous source term value.



a) Volume calculation of BAY model b) Limitation of BAY model

Figure 1. Original BAY model

A new differentiable BAY model is thus developed by taking into account a small positional change, which is going to provide more accurate sensitivity information for gradient evaluation. The differentiable BAY model is realized by replacing the whole volume of each cell crossed by the VG with the overlaid VG volume as shown in Figure 2. By projecting the VG into each cell interface, the length of the intersected lines ($\Delta\xi$, $\Delta\eta$) is calculated, which is used to obtain the overlaid VG area or volume. The expression for the lift force is the same as that in the original BAY model.

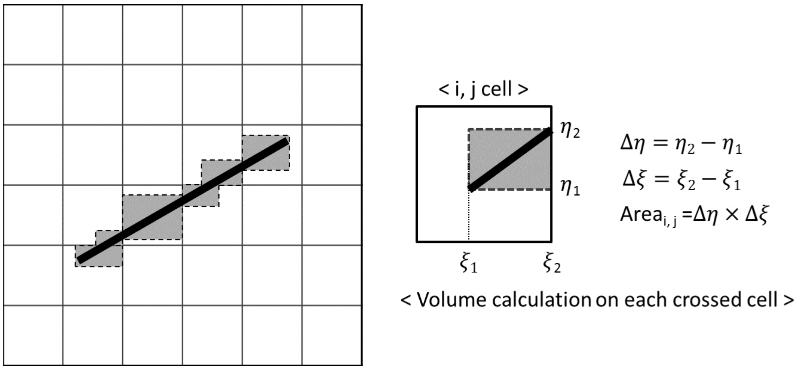


Figure 2. Volume calculation of differentiable BAY model

The analysis results of the differentiable BAY model agree very well with that of the original BAY model and the experimental data.

DESIGN APPROACH AND RESULTS

The gradient-based optimization method (GBOM) was used for the present VG design. An adjoint variable method was employed to obtain the sensitivity information, and the search direction was determined by the Broyden-Fletcher-Goldfarb-Shanno (BFGS) method. As an objective of optimization, a minimization of the DC60, the distortion coefficient for the circumferential angle of 60 degree, was selected for decreasing a non-uniformity of the flow at the engine face. The baseline total pressure recovery ratio (PR) was then imposed as a constraint to maintain the inlet efficiency. The constraint was added to the objective function as a penalty function because both the constraint and the objective function simultaneously affect the sensitivity analysis. The design variables included the chord length, the height, the angle of incidence, the axial position, and the circumferential position of each VG, thus a total of 55 design variables were treated for 11 VGs.

As a result, the DC60 decreased from 0.402269 (without VG) and 0.044150 (with the VG170) to 0.009208 (the designed result) while maintaining the baseline PR. The inlet performance measured by distortion coefficient is remarkably enhanced over 79%. The off-design performance was examined by changing the throat Mach number, which shows that the optimized VG make better performance than the performance of the VG170 even in off-design conditions. Figure 3 shows the optimized VGs shapes and positions installed in the RAE M2129 S-duct, and Figure 4 shows the result of the off-design condition test.

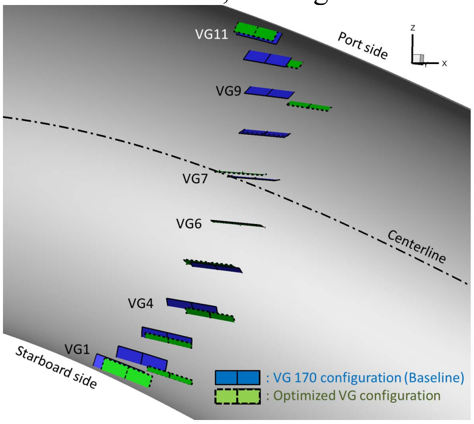


Figure 3. Optimized VG

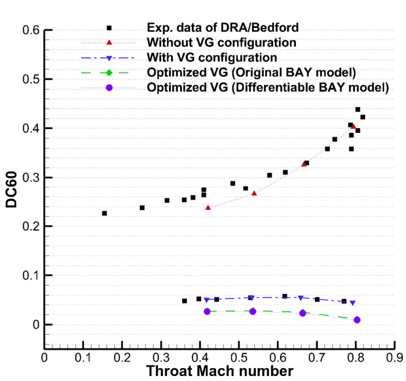


Figure 4. Off-design condition test

CONCLUSION

The differentiable BAY model was developed to improve the original BAY model in terms of a sensitivity analysis. Through this model, the axial and circumferential position of VG can be treated as a design variable for the design of VGs installed in the target S-duct. As a result of design optimization, the inlet performance improved over 70%.

ACKNOWLEDGMENT

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