# Surrogate-Based Design Optimization of Vortex Generators for Transonic Aircraft

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| 学 位 論 文 題 目 | Surrogate-Based Design Optimization of Vortex Generators for Transonic Aircraft<br>（遷音速航空機用ボルテックス・ジェネレータの近似最適設計） |
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# 論文内容要約

As shown in Fig. 1, an array of vortex generators (VGs) is frequently employed to alleviate the shock-induced separation by generating small vertical vortices that supply the momentum into the boundary layer although mounting many VGs on the wings drastically increases the drag under cruise condition. VGs based on engineer's experience can easily make the stall characteristics and the drag of the aircraft be a conventional level though there is no improvement from the other aircraft. In order to efficiently improve the stall characteristics with minimal increase of drag, the VG shape and arrangement should be designed according to proper criteria (design rule) supported by fluid phenomena which are derived from optimization results. However, aerodynamic performance evaluation of VG mounted wings consumes remarkably high computational cost even though computational fluid dynamics (CFD) is employed instead of wind tunnel testing. The efficient global optimization (EGO) is applicable to VG design but must be conducted as efficiently as possible with minimal number of CFD runs. The objective of this dissertation is to efficiently optimize the VG array for transonic aircraft and to extract useful design rules for VGs. VG designs are optimized in three types of configurations: non-swept infinite-wing, swept infinite-wing, and wing-body-tail, using the CFD analysis step by step while optimization methods themselves are modified to deal with the problems revealed in the previous step.

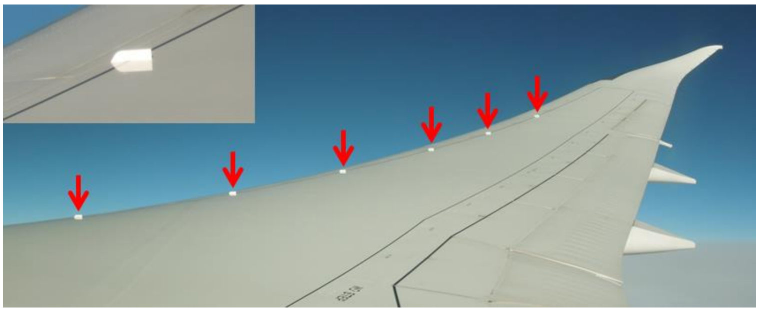


**Figure 1. VGs on Boeing 787's main wing.**

Chapter 1 constitutes the introduction and explains the background and objective of this dissertation.

In chapter 2, multiobjective optimization of VGs on a transonic non-swept infinite-wing is performed using CFD and a multiobjective genetic algorithm (MOGA) coupled with surrogate models. VG arrangements are defined by five design variables: height, length, incidence angle, chord location, and spacing. The objective functions are to maximize lift–drag ratio at low angle of attack, to maximize lift coefficient at high angle of attack, and to shift chord-wise separation location downstream at high angle of attack. To evaluate these objective functions of each individual in MOGA, the ordinary Kriging model (OK) and the radial basis function (RBF)/Kriging-hybrid surrogate model are employed because CFD analysis of the wing with VGs requires a large amount of computational time. Nondominated solutions (NDSs) are classified into five clusters with different aerodynamic characteristics.

First, the solutions with high lift–drag ratio are obtained. A low ratio of the frontal projected VG area to the wing area is preferable to sustain the aerodynamic characteristics under cruise conditions. The VG upstream increases the lift coefficient and shifts the chord-wise separation location downstream by preventing the shock wave from moving upstream of the VG in this case. The solutions that enable the chord-wise separation location to move downstream have broadly spaced VGs with medium height because the VG effect is propagated to a farther chord location by enlarging the vortex scale. It is revealed that the chord location of VG is one of the critical parameters to shift the chord-wise separation location downstream. The solutions where three objective functions are balanced have VGs with medium height and ratio of spacing to height. Appropriate spacing prevents the shock wave from reaching upstream, and high aspect ratio increases the lift coefficient. The solutions with high lift coefficient are divided into two types; one has narrowly spaced small VGs that move the shock wave further downstream and achieve the highest lift coefficient, and the other has narrowly spaced, large VGs that not only move the shock wave downstream but also decrease the pressure coefficient behind the shock wave. These solutions restrict appropriate values of aspect ratio, the ratio of VG spacing to height, and the incidence angle for generating the vortex most effectively. Therefore, it is suggested that five clusters can be classified mainly by VG height, spacing, and their ratio, which control the design trade-offs among three objective functions.

In, chapter 3, the Kriging model with a coordinate transformation of the design space is proposed to improve the approximation accuracy of objective functions with correlated design variables such as VG's height and length, which constitute aspect ratio, and control points of spline curves. The coordinate transformation is conducted to extract significant trends in the objective function and identify the suitable coordinate system based on either one of two criteria: likelihood function or estimated gradients of the objective function to each design variable.

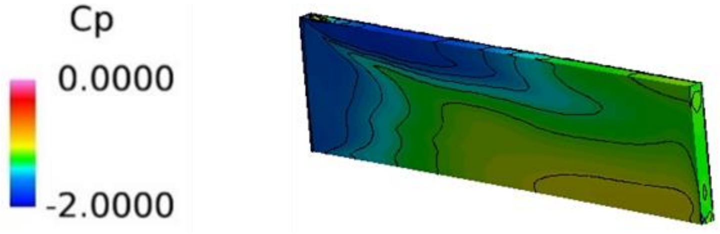
In the application to test functions, the proposed methods approximate the entire function shape more accurately than the conventional method if design variables are correlated with each other and a sufficient number of sample points are employed. The proposed methods also show greater comparative accuracy to the conventional method even if the correlation between design variables is not strong. However, the capability to explore the optimal solution is almost the same among the proposed methods and the conventional method because the proposed methods need a sufficient number of initial sample points to fully exert their capability by improving their approximation accuracy. Additionally, maximizing the likelihood function in the Kriging model is preferable in finding a suitable coordinate system for functions with correlated design variables although this method does not function well when the number of design variables is greater than five. The coordinate transformation based on estimated gradients is available for functions with more than five design variables. This method is more suited to real-world optimization problems with correlated design variables than the former because real-world problems usually include 10–1000 design variables.

Control points of the non-uniform rational basis spline curves defining an airfoil's thickness distribution and camber line are employed as the correlated design variables in the airfoil design optimization. The latter proposed method approximates the objective function (lift–drag ratio) more accurately and finds better solutions than the conventional method although the constraint function (pitching moment coefficient) is difficult to approximate by the proposed method. Therefore, the proposed method reveals usefulness in real-world optimization problem with correlated design variables. These two methods are applied to the following VG shape and arrangement optimizations.

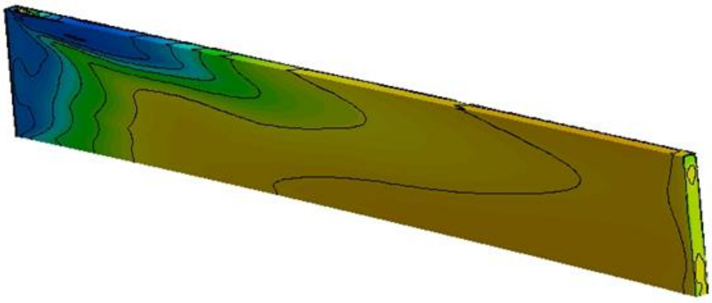
In chapter 4, parametric study and multipoint design optimization of the VG shape on a swept infinite-wing are performed by using CFD to explore a desirable VG design under both cruise and critical condition. We examine the effects of VG height, length, incidence angle, and spacing on lift-drag ratio at a low angle of attack, which determines aerodynamic performance under cruise condition, and stall characteristics shown as lift curves representing critical condition. The present simulation model considers a single VG equipped on a super-critical rectangular wing and the periodic boundary condition is adopted in the span direction to reduce the cost of CFD analysis.

Under critical condition at a high angle of attack, the spacing between VGs has no effect on values of lift coefficients if VG heights are the same and the ratio of spacing to height is more than 20 while the spacing determines the angle of attack at which numerical oscillation caused by buffet occurs. On the other hand, VG height affects maximum lift coefficients because taller VG can generate stronger circulation and provide more momentum for the boundary layer although VG whose height is twice as tall as the boundary layer thickness is inefficient. Considering cruise condition at a low angle of attack, drag coefficients are sensitive to the drag acting on VG itself while lift coefficients are determined by the shock wave location affected by VGs. These different principles yield the extreme values or convergence of lift-drag ratio at a certain value of VG spacing. Additionally, VG with a high aspect ratio can improve the stall characteristics without drawback under cruise condition, while the height and incidence angle controls the balance of aerodynamic performances under cruise and critical condition.

Multiobjective optimization is conducted by nondominated sorting genetic algorithm assisted by the modified Kriging model. VG height, aspect ratio, and incidence angle are optimized to maximize lift coefficient at a high angle of attack, to minimize drag coefficient at a low angle of attack, and to maximize lift-drag ratio at a low angle of attack. Optimization results show that the VG height should be lower than 1.65 times the boundary layer thickness to efficiently improve aerodynamic performances. The NDSs are divided into three parts where the VG height and incidence angle adjust design trade-offs while the high aspect ratio is found to be preferable in most cases. Figure 2 shows the conventional VG and shape-optimized VG that achieves almost the same lift coefficient as the conventional VG with low drag coefficient and high lift-drag ratio.



(a) Conventional VG



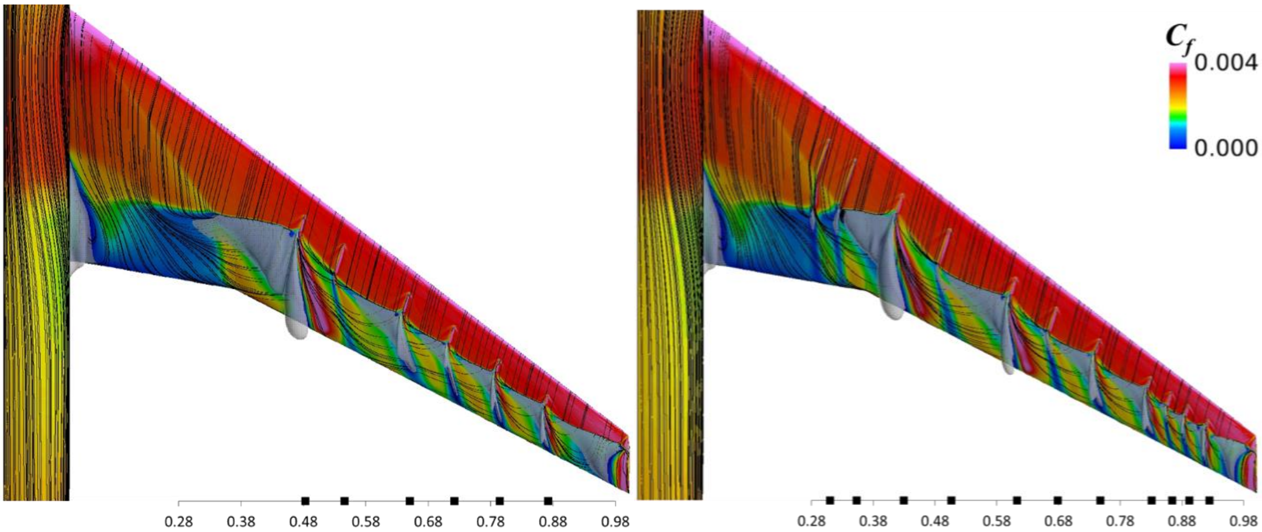
(b) Shape-optimized VG

**Figure 2. Pressure coefficient ($C_p$) distributions of conventional and shape-optimized VGs.**

In chapter 5, indicators to select next additional sample points are proposed and one of them is utilized in multiobjective optimization of the VG arrangement in the wing-body-tail configuration using CFD. These indicators named EPBII and EIPBII corresponded to the expected improvement of the penalty-based boundary intersection (PBI) and the inverted PBI, respectively. These indicators are increasingly applied to EAs because of their capability to explore suitably diverse NDSs. We investigate these indicators in various test problems and compare them with conventional indicators.

Both EPBII and EIPBII can find NDSs with better diversity and convergence than conventional indicators. EPBII more robustly obtains desirable NDSs than EIPBII, and the exploration capability of EIPBII depends heavily on the reference point definition. If a suitable reference point is identified, EIPBII also obtains well-distributed NDSs, even for the problem with a discontinuous Pareto front (PF). We find that weak POSs in the test problems hinder the ability of EIPBII to identify the suitable reference point. Therefore, EIPBII, which essentially fits the convex PF, should be employed for problems with such PF unless they include weak POSs.

After the exploration capability of EPBII and EIPBII are confirmed, the VG arrangement is optimized to ensure the static stability of pitching moment with minimal increase of drag under cruise condition. EGO with EIPBII successfully finds out well-distributed NDSs and three of them dominate the baseline model where 13 VGs are uniformly mounted. Optimization results indicate that widely-spaced only 4 – 6 VGs around the center of the semi-span wing are even effective because VGs prevent the separated flow from propagating to the wing tip as firewalls (Fig. 3 (a)). More improvement is achieved by adding VGs around the wing tip, which efficiently decrease the pitching moment (Fig. 3 (b)). One of these solutions accomplishes to reduce the drag penalty to install VGs to half of the conventional VGs.



(a) Widely-spaced VGs

(b) Ununiformly-spaced VGs

**Figure 3. Distributions of skin friction coefficient ($C_f$), surface flow, and separated regions of optimized VG arrangements in the wing-body-tail configuration.**

Chapter 6 concludes this dissertation. Many helpful design rules for VGs are extracted from the above three cases of multiobjective optimizations assisted by the proposed surrogate models and indicators. These design rules will contribute to achieving the desirable VG design with better aerodynamic performances than that based on engineer’s experiences.