Application of Sensitivity Analysis to the Redesign of OGV's.

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Abstract

This paper discusses the application of sensitivity analysis to the redesign of outlet guide vanes (OGV's) in an aircraft high bypass turbofan engine. The redesign is aimed at reducing the interaction of the pylon induced pressure field with the OGV's and fan blades. The redesign is performed using (a) a linear perturbation CFD analysis and (b) a minimisation of the pressure mismatch integral by using a Newton method. In method (a) the sensitivity of the upstream flow field to changes in blade geometry is acquired from the linear perturbation CFD analysis, while in method (b) it is calculated by perturbing the blade geometry and finite differencing the resulting flow fields. The redesigned OGV row reduces the pressure variation at the fan trailing edge by 86%. An OGV row with only 3 different blade shapes is designed using the above method and is found to suppress the pressure perturbation by more than 73%. Results from these calculations are presented and discussed.

Nomenclature

α	Exit Angle from OGV row
ϕ	Interblade phase angle
C_c	Complex constant
k	Circumferential pitch of disturbance
I	The pressure mismatch integral
N	Number of OGV blades in blade row
N_v	Number of design variables
p	Pressure
P	Blade Pitch
$\mathcal{R}$	The real component of a complex quantity
v	The design variable

Superscripts and Subscripts

$\tilde{}$	Perturbation quantities
$_{le}$	Leading Edge of airfoil

Introduction

It has been observed that the fan, in an aircraft jet engine, experiences high level of stresses due to excitation from the flow field (Suddhoo, 1992). Analysis has identified the source of the excitation to be the static pressure field of the pylon located in the bypass duct. It has also been observed that the OGV's suffer a loss of efficiency due to a change in the flow incidence angle, this change can also be attributed to the pressure field of the pylon.

The computational domain is shown in Figure 1. The flow inlet is at the left and it corresponds to the location of the fan trailing edge. Figure 2 shows the circumferential pressure computed at the inlet. It can be observed that the pressure variation is significant.

The pylon, which links the engine to the wing, serves not only as a structural member but also as the conduit for the generator shaft, bleed air duct and hydraulic and control systems. The pylon, therefore, is a large obstacle to the flow in the bypass duct and given its role, cannot be modified easily.

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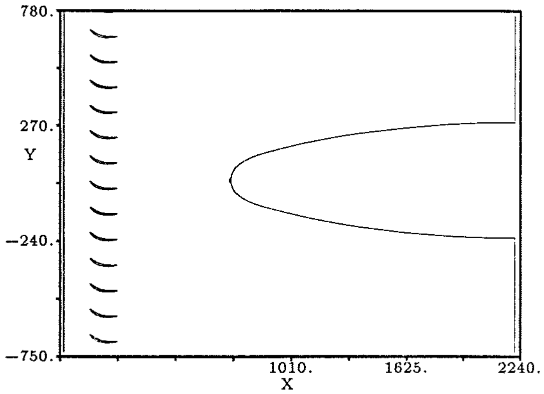

Figure 1: Computational domain for the pylon-OGV computations.

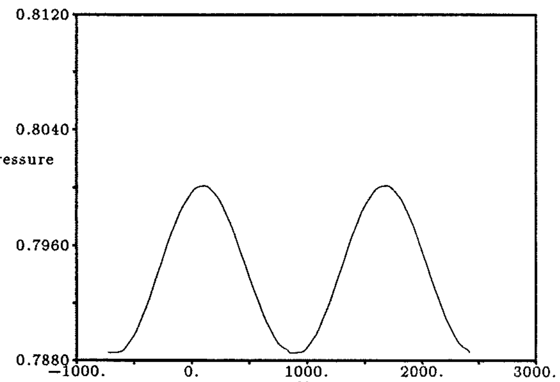

Figure 2: Circumferential line plot of pressure at location of fan.

Every component in the flow field induces upstream and downstream disturbances. The OGV's induce static pressure perturbations, but these have a very small circumferential wavelength and so decay rapidly in the axial direction and do not affect either the fan or the pylon. However, the pylon has a large circumferential wavelength and so it's pressure pertrubations decay slowly in the axial direction. This disturbance traverses the entire length of the bypass duct and interacts with the OGV's and the fan.

Various mechanisms have been suggested to prevent this interaction (Suddhoo 1992). These include (a) the introduction of additional vanes to divert the flow around the pylon, (b) an increase in the distance between the OGV's and the pylon and (c) tailoring the OGV's to suppress the propagation of the pressure field. Since the pylon induced field has a low axial decay rate, option (b) becomes unacceptable as it will require a considerable increase in engine size. Modifications (a) and (b) are unattractive as they will almost certainly result in increased size and weight of the engine and in the introduction of additional components. Option (c) is appealing because it doesn't involve the introduction of additional components. Kodama and Nogano (1989) have applied actuator disc theory (Kodama 1986) to analyse the problem of stator and downstream strut interaction. Using this theory they have performed stator tailoring to suppress the pressure field of the downstream strut and have also obtained good experimental verification. Cerri and O'Brien (1989) have studied the interaction problems of a stator-strut system at the rotor trailing edge. They have successfully reduced the strut induced pressure field to the same levels of the stator induced field by redesigning the stator blades. Shrinivas and Giles (1995) have used a linear perturbation CFD method to redesign the OGV row and have achieved more than 70% reduction in the pressure variation.

In this paper, the concept of cyclically varying camber is used to redesign the OGV's. The desired OGV blades will induce a pressure variation equal and opposite in magnitude to that induced by the pylon in the upstream flow field.

The camber perturbation (Δy) used in the current redesign is the real part of

$$\Delta y = C_c(x - x_{le})^2 exp(-iky) \qquad (1)$$

where C_c is a complex quantity and $exp(-iky)$ represents the harmonic nature of the perturbation. The changes to camber will be introduced as a modification to the trailing edge so that the leading edge of the blade remains unchanged. This is necessary to maintain a uniform OGV incidence angle. The above equation translates to an exit angle variation of the form

$$\tilde{\alpha} = \mathcal{R}\left(2\ \cos^2(\alpha)\ C_c\ (x - x_{le})\ \exp(-iky)\right) \qquad (2)$$

where α is the mean exit angle from the OGV row.

The crux of the redesign is to determine the appropriate value of C_c. Figure 3 illustrates the extreme perturbations for $C_c = 5 \times 10^{-2}$.

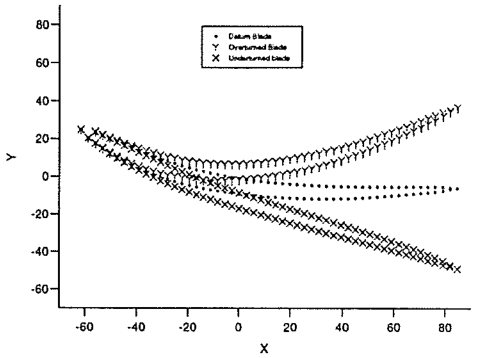

Figure 3: Camber perturbed blades.

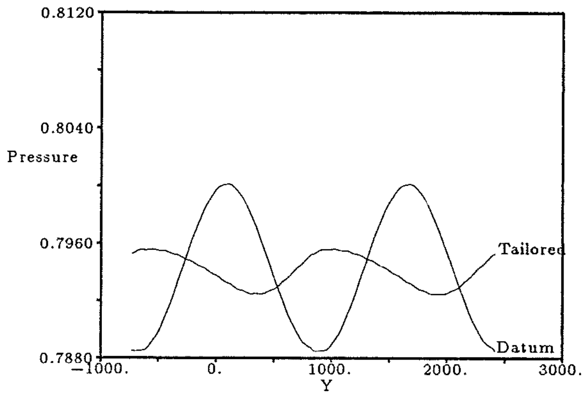

Figure 4: Comparison of pressure variations upstream of the OGV row for a OGV-pylon configuration using uniform and tailored blades.

Redesign using a linear perturbation CFD method

In this approach described by Shrinivas and Giles (1995), a linear perturbation code (SLiQ, developed by Giles (1992)) is used to model the OGV row as a linear cascade. It is assumed that there is no variation in either the geometry or the flow in the third dimension. When performing a linear perturbation analysis for unsteady motion, the flow solution is of the form

$$\tilde{U}(x,y)\exp(i\omega t).$$

The actual physical perturbation is always the real part of the complex quantity in these equations. It is well-known that in linear unsteady analysis, the general solution can be decomposed into a sum of particular solutions satisfying the periodicity condition

$$\tilde{U}(x,y+P) = e^{i\phi}\tilde{U}(x,y), \quad (3)$$

where ϕ is known as the inter-blade phase angle and P is the blade pitch. The use of this equation as a periodic boundary condition allows the computation to be performed on a single blade passage, and then the solution in other passages can be reconstructed from

$$\tilde{U}(x,y+nP) = e^{in\phi}\tilde{U}(x,y). \quad (4)$$

The inter-blade phase angle is given by

$$\phi = kP = \frac{2\pi P}{L} = \frac{2\pi}{N} \quad (5)$$

where N is the number of OGV's per pylon in the 2D cascade. In the current SLiQ analysis for an annular cascade with one pylon, N is the number of OGV's in the cascade.

In the analysis mode, the perturbation pressure field due to the pylon is specified through the downstream boundary conditions. The discrete linear equations for the interior of the domain come from a natural linearisation of the nonlinear discrete equations coming from a standard finite volume discretisation. This includes the linearisation of the solid wall boundary conditions on the OGV's. The inter-blade phase angle is specified, the complex flow solution is computed for the single passage, and then the real perturbation quantities are reconstructed for all blade passages in a post-processing step.

In the design mode, the perturbation in the camber of the OGV's defines a consistent linear perturbation of the body-fitted computational grid. This introduces a source term into the discrete linear equations throughout the grid. Because the camber perturbation has cyclic periodicity, it is again possible to perform the calculation on a single blade passage by imposing the complex periodic boundary condition with the appropriate inter-blade phase angle. The design mode is executed without the downstream boundary condition imposing the pressure perturbation of the pylon. Instead, the goal is to determine the camber perturbation which generates an upstream flow perturbation equal in magnitude and opposite in sign to that produced by the pylon's interaction with the OGV's. Then, by linearity, the sum of the two solutions will give a combined flow solution corresponding to the presence of the pylon and the cyclically cambered OGV's and giving no flow perturbation upstream of the OGV's, (except for the very local pressure field associated with each OGV).

The pressure variation at the fan trailing edge due to the redesigned OGV row is presented along with the original pressure variation in figure 4. It can be seen that the pylon field has been over corrected, resulting in a pressure variation opposite in phase to the original disturbance.

Investigation into the cause of this overcorrection has attributed it to two possibilities (a) a feedback effect or (b) an inherent nonlinearity in the system. Despite the over-correction the design approach has been successful in greatly reducing the pressure variation upstream of the OGV's.

Further reduction can be achieved by using sensitivities computed from a nonlinear CFD analysis. The following section describes such an attempt and the reduction obtained from such a study.

Redesign using a Newton Method

It is possible to describe the redesign as a minimisation of the pressure mismatch integral I, written as

$$I = \frac{1}{2} \int_Y (p - p_{\ specified})^2 dy. \tag{6}$$

The discrete form of this equation can be written as

$$I = \frac{1}{2} \sum_i \left(p_i - p_{i\ specified}\right)^2 \Delta y_i \tag{7}$$

where the p_i is the pressure evaluated along the line located at the inlet to the computational domain. The design exercise is aimed at minimising I. At a minimum

$$\frac{\partial I}{\partial \vec{v}_j} = 0; \qquad 1 \leq j \leq N_v \tag{8}$$

where $\vec{v}$ is the vector of design variables and N_v is the number of design variables. Linearising about the current position in the design space we get the following N_v Newton equations.

$$\sum_{j=1}^{N_v} \delta\vec{v}_j \cdot \frac{\partial^2 I}{\partial \vec{v}_j \partial \vec{v}_k} = -\frac{\partial I}{\partial \vec{v}_k}; \qquad 1 \leq k \leq N_v \tag{9}$$

Substituting equation (7) in (9) we get

$$\sum_{j=1}^{N_v} \delta\vec{v}_j \cdot \sum_i \left[\frac{\partial p_i}{\partial \vec{v}_j} \frac{\partial p_i}{\partial \vec{v}_k} + (p_i - p_{i\ specified}) \frac{\partial}{\partial \vec{v}_j}\left(\frac{\partial p_i}{\partial \vec{v}_k}\right) \right] \Delta y_i$$

$$= -\sum_i \left(p_i - p_{i\ specified}\right) \Delta y_i \frac{\partial p_i}{\partial \vec{v}_k}; \qquad 1 \leq k \leq N_v \tag{10}$$

The terms within the square brackets represents the Hessian matrix for the pressure mismatch integral I. We neglect the second term in the square brackets because it is harder to compute. It has been observed by Drela (1990) that the neglected term has a minor impact, since when we approach the minima, $(p_i - p_{i\ specified})$ becomes small.

In the current problem, $N_v = 1$. The only design variable in use is C_c so equation (10) can be rewritten as

$$\delta v = -\frac{\sum_i \left(p_i - p_{i\ specified}\right) \frac{\partial p_i}{\partial v} \Delta y_i}{\sum_i \left(\frac{\partial p_i}{\partial v}\right)^2 \Delta y_i} \tag{11}$$

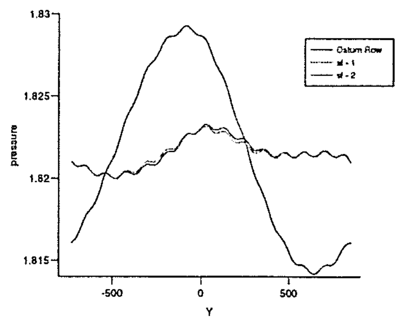

Figure 5: Plot of circumferential pressure variation for continuously varying camber case.

where v represents C_c and δv represents the change in C_c suggested by the Newton system to achieve a minimisation. $(p_{i\ specified})$ is specified as the mean pressure, this objective tries to drive the pressure variation to zero.

The sensitivity of the flow field to perturbations in the design variable, represented by $\frac{\partial p_i}{\partial v}$ in equation (11), is calculated by a finite difference procedure. The flow field around the datum geometry is first computed then the blade geometries are perturbed by a specified amount and the new flow field is obtained. The pressures obtained from these solutions are finite differenced to obtain the sensitivity.

Numerical experiments

A redesign of the OGV row was attempted using the Newton method. The reduction in pressure variation achieved was very impressive. The pressure variations are presented in figure 5. The first step predicted by the Newton scheme achieved a reduction of over 86% (curve sf-1 in figure 5). The second step made a minor correction and resulted in a small increase, decreasing the pressure suppression to 85% (curve sf-2 in figure 5). No further reduction was achieved. The reduction of the pressure variation normalised with respect to the initial variation is shown in figure 6.

Engineering issues regarding number of blades

One problem with this design procedure is that it generates N different blade shapes. This leads to unacceptable additional costs both in the manufacture of the OGV's and in the airlines' costs of maintaining stocks of spare parts. A practical compromise is to use a limited number of different OGV's; for example three, one with the datum exit

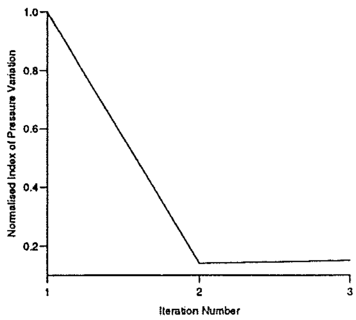

Figure 6: History of pressure variation for the continuously varying camber case.

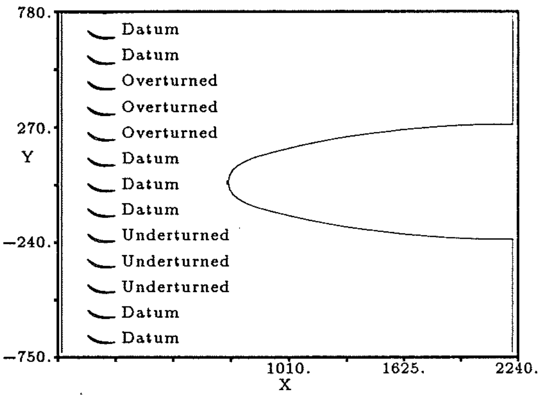

Figure 7: Grouping of blades for 3 blade case.

flow angle, one with overturning and one with underturning. These can then be grouped and collectively designed to completely cancel the first circumferential harmonic of the pressure field generated by the pylon.

Such a design was attempted and the results are presented here. Figure 7 shows the grouping of the blades used. The magnitude of change in flow exit angle was the same for the overturning and underturning blades. The first step of the Newton scheme achieves a 72% reduction in the pressure variation. Subsequent iterations make minor corrections with the final figure at 73.8%. The pressure plot is presented in figure 8 and a plot of the pressure variation index is presented in figure 9. These results are extremely encouraging since the current design is "practical" and can easily be used in a industrial environment.

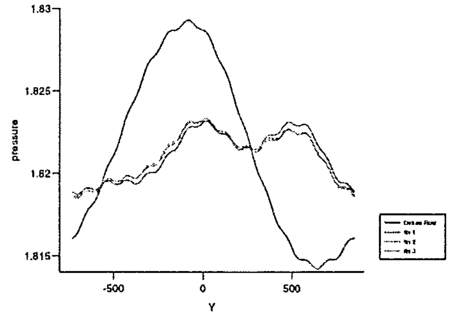

Figure 8: Plot of circumferential pressure variation for 3 blade case.

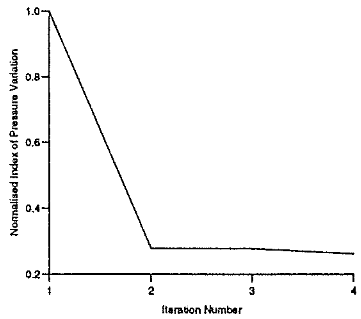

Figure 9: History of pressure variation for the 3 blade case.

Computational issues

The computations were performed using a 2D Euler code on an unstructured grid. The grids were generated using an advancing front grid generator (Lindquist 1990). The grid generator reads the blade and pylon geometries as input, the perturbed grids were generated by suitably altering the blade definitions used by the grid generator. In the current study the grids had about 50,000 cells (26,000 nodes).

The Euler code has been implemented using the OPlus library (Burgess 1994) and therefore can run in parallel. Further acceleration is achieved by using a multigrid method. This considerably reduces the turn around time of each iteration. Each Euler solution took about 37 minutes of wall clock time on 4 nodes of an IBM SP1. During the current exercise, the two calculations (of the unperturbed and perturbed geometries) were run concurrently, each using 4 nodes of a 8 node IBM SP1. The time required by the finite difference procedure is negligible in comparison to the CFD compute time (under 5 seconds on 1 node of the SP1).

Conclusions

Redesign of an OGV row has been performed using two different methods. Both achieved impressive results. The Newton method was further used to perform a practical redesign using a limited number of different blades. Significant pressure reduction was achieved in this case, indicating an acceptability in the industrial design process.

Acknowledgments

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