The Role of Parametric CFD Analysis in Engineering Design

White Paper

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INTRODUCTION

In an earlier white paper,[1] Tecplot, Inc. discussed the market trends driving the adoption of parametric computational fluid dynamics (CFD) analysis and the associated challenges. In this paper, we will discuss in more detail the role parametric CFD analysis plays in the engineering design process.

There are five stages in the application of parametric CFD analysis to engineering design: problem definition, dimensional reduction, experimental design, management of CFD simulations, and metadata analysis. Among other things, the metadata analysis stage may include surrogate modeling, visualization, optimization, sensitivity analysis.

The concepts discussed in this white paper are applicable to the engineering design of a wide range of devices. However, for clarity, we will focus primarily on one aspect of the aerodynamic design process for commercial aircraft — the addition and placement of vortex generators on the wing of an airliner. This example illustrates the significant impact and breadth of analysis that may be required after a seemingly minor change to an aerodynamic configuration.

ENGINEERING DESIGN

According to Ertas and Jones,[2] engineering design is "... the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative) in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing and evaluation."

Fluid dynamics is one of the primary engineering sciences used in the design of a wide variety of vehicles, machines, and other devices. Examples include aircraft, automobiles, marine vehicles (ships, boats, submarines, etc.), structures (buildings, bridges, oil platforms, docks, etc.), pumps and turbines, and the production and cooling of electronic devices. In the past, the fluid dynamic analysis of these devices was often fairly simple, using empirical formulas from engineering handbooks or other highly simplified analysis techniques. As computer power has become cheaper, the fluid dynamic analysis is shifting toward more complex and powerful computational fluid dynamics (CFD) techniques.

Problem Definition

As part of the design process, requirements are defined for the system, component, or process. For machines, these requirements will include the operating envelope of the system. This defines the range of conditions, or input parameters, over which the device is required to operate safely. These ranges may be defined by regulatory requirements, market requirements, or the environment in which the machine must operate. In many cases, seemly simple changes in a device design must be validated over the entire operating envelope.

In the case of commercial airliners, the operating envelope is the range of all parameters that define the flight regime of the airplane. These include the flight parameters: Mach number, altitude, Reynolds number, angle-of-attack, and yaw angle; and the configuration parameters: control surface positions, thrust settings, wing flap position, and landing gear position. For example, consider the range of Mach number (speed as a fraction of the speed-of-sound). The upper limit of Mach number is generally between 0.8 and 0.9 (flying just below the speed of sound). The lower range is much more complicated, being a function of many other flight and configuration parameters, it is generally set by the market need for the airliner to land on existing airport runways.

Among the requirements for an airliner are the market requirement that it be efficient and the regulatory requirement that it be safe. Throughout the operating envelope a safe aircraft will be controllable, stable, have good handling qualities, and have aerodynamic loads within the structural limits. A stable aircraft will tend to continue in the same direction despite a small perturbation (from turbulence, for example) and a controllable aircraft will change direction upon request (suitable control surface movement). The aircraft designer will extensively test, using CFD simulations, wind-tunnel tests and flight test, the aircraft design to ensure that it meets these requirements. An analysis of the aircraft aerodynamic behavior throughout the operating envelope is a parametric analysis.

Figure 1: Vortex generators on a wing

Figure 1 is a photo from the window a commercial aircraft. On the upper surface of the wing, beyond the jet engine is a line of small vertically-mounted fins called vortex generators. These vortex generators are typically added to correct some undesirable flight characteristics — generally low-speed (high angle-of-attack) instability or insufficient controllability. These undesirable flight characteristics are often caused by boundary-layer separation over the wing control surfaces. Due to the wing sweep, boundary-layer separation on the outer portion of the wing is a common problem on commercial jets. As shown in

Figure 2, vortex generators circulate high-energy flow into the boundary layer, suppressing boundary-layer separation and mitigating the stability or controllability problems.

Vortex generators are used in a wide range of engineering applications when there is a need to mitigate the effects of boundary-layer separation. They are commonly used on wind turbines blades to reduce separation on the thick airfoil sections near the hub. Their use on wind turbines has increased the power produced under certain conditions by 4-6%. [3] Likewise, inlets and diffusers in a wide range of industries are susceptible to boundary-layer separation and can benefit from properly placed vortex generators.

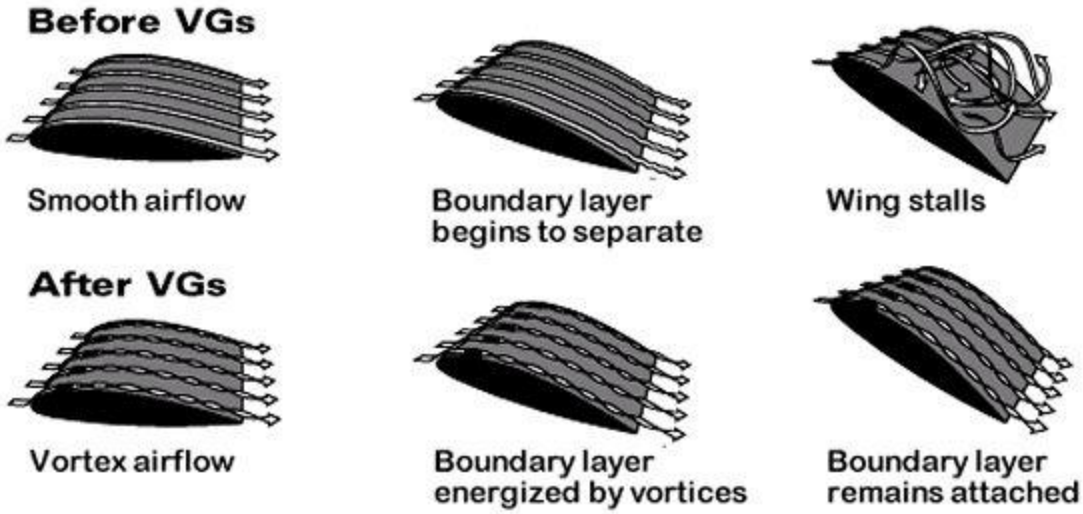

Figure 2: Effect of Vortex Generators on Boundary Layer Separation

While commonly used, vortex generators are an aerodynamic compromise. They delay the onset of boundary-layer separation but they also increase the parasite drag of the wing. Increasing the drag will generally reduce the fuel efficiency of the aircraft. For this reason, aerodynamicists are very careful about when and where they use them.

In Figure 1 there are two sets of vortex generators (VGs): an outboard set of five VGs that are evenly spaced along a straight line and an inboard set of sixteen that are arranged in a shallow V. This arrangement was not random, but designed to ensure adequate stability and controllability while minimizing the impact on fuel efficiency.

How does an aerodynamicist decide where to place these vortex generators? Obviously, they need to test a wide variety of locations. The tests will probably focus on the landing configurations and high angle-of-attack region where the boundary-layer separation occurs, but other flight conditions and configurations cannot be ignored. For example, certain VG distributions may work especially well at eliminating boundary-layer separation at landing configurations but cause unacceptable increased in drag and fuel consumption at cruise configuration. Because it alters the flight characteristics and performance of the aircraft, they need to evaluate the impact of the vortex generators throughout the flight envelope. This is a constrained optimization problem, where one of the constraints is acceptable behavior throughout the flight envelope. Because it involves the entire flight envelope, it is best solved with a parametric analysis.

The placement of each vortex generator (VG) is defined by three parameters: spanwise (wing root to wing tip) location, chordwise (leading edge to trailing edge) location, and angle relative to the aircraft plane of symmetry. In Figure 1 there are 21 VGs, so including all of these degrees-of-freedom would add 63 parameters to the parametric analysis. When added to the five flight parameters and six (minimum) configuration parameters, the design space would have 74 dimensions — very large!

Dimensional Reduction

Like most engineering design problems, the full problem definition results in too many dimensions for a reasonable parametric analysis. Fortunately, it is generally possible to reduce the number of dimensions by taking advantage of previous studies on similar devices. For example, vortex generators have been used since the 1940s and guidelines for their use are available in the literature. [4,5] These include suggested size, spacing, and angle of the vortex generators. The chordwise position of the VGs is more problem dependent, and would be allowed to vary in this parametric study. This brings the number of dimensions down to 21 for the VGs, and 32 overall, still a large design space.

To further reduce the degrees of freedom, we could use analytical distributions for the chordwise position of the VGs. The outer five VGs are in a straight line at a constant chordwise position — one degree of freedom instead of five. The chordwise positions of the inner 16 VGs could be approximated by a quadratic equation — three degrees of freedom instead of 16. The result is a total of four degrees of freedom which, when added to the 11 flight and configuration parameters, results in a total of 15 dimensions.

Experimental Design.

In this context, “experimental design” refers to the set of cases (unique combination of independent parameters) that will be run by the CFD code. The cases to run (experimental design) would be selected to efficiently span the design space. High resolution CFD solutions of full aircraft configurations, especially landing configurations, are expensive so the number of cases will be limited. A space-filling design like a Latin Hypercube, or one of its optimal variants, would probably be used. [6] These experimental designs ensure coverage of the full range of each parameter, even with a small number of cases.

For 15 dimensions, even a small parametric study would likely include hundreds of runs. Each run will generate a large amount of 3D field data in addition to the metadata results (forces and moment coefficients, etc.). Ideally, the 3D data will be retained to verify solution quality and investigate the underlying cause of anomalies in the metadata.

Management of CFD Simulations

The full range of issues involved in running a CFD code is beyond the scope of this white paper. Of particular concern is the verification and validation of the solution. For details, the reader should consult one of the guides on the subject.[7] We will touch on a couple of the primary issues.

A key requirement for high-quality CFD solutions is that the grid-spacing be fine enough to resolve the dominant flow features. These include boundary layers, shear layers, vortices, and shock waves. Ideally a sufficiently fine grid would be used to resolve all of these flow features to a high degree, but there is seldom enough compute resources to do this — especially when running a large number of cases. Also, certain sub-grid quantities, such as turbulence, are modeled — and no model is ideal for all flows. For this reason, it is still necessary for CFD experts to evaluate the results to see if any assumptions have been violated.

The analysis of vortex generator placement is a good example of a case that will strain the current capabilities of CFD simulations. If the vortical flows are to be computed by the simulation, a very fine grid is required in the spanwise direction. Normally, the boundary layer is resolved using a very fine wall-normal grid and the grid spacing in the spanwise and streamwise directions is left fairly coarse to reduce the total number of grid points. Furthermore, near the vortex generator the grid must also be refined in the streamwise direction — refinement in all three directions. When the velocity field in 21 streamwise vortices must also be resolved, the number of grid points can get quite large and the CFD simulations very time consuming. It would be necessary for a CFD expert to verify that the fine grid is properly placed to compute the vortices. Alternatively, solution adaptive gridding could be employed to automatically refine the grid in the vortices, but that creates its own set of challenges and the number of grid points would still be very large. Finally, there have been efforts to reduce the number of grid points by modeling the vortex generator geometry as a step-function in secondary velocities [8] — a sub-grid effect. This would allow a comparatively coarse grid in the streamwise direction and reduce the computer resources required for the CFD simulations.

Ideally, the tools used to manage the parametric data will make it easy to verify the quality the CFD solutions. The metadata (data about the CFD runs and derived data like forces and moments) and links to 3D field data files will be stored in a database. A graphical front-end to this database will simplify the access to the data, perhaps through clicking on scatter symbols representing individual cases or data in tables. This will allow rapid evaluation of flow field and grid to look for potential solution quality issues.

METADATA ANALYSIS

The term "metadata" refers to all data about a CFD simulation and all data derived from the CFD simulation. The data about the CFD simulation would include the independent parameters of the analysis (in this case the flight parameters and configuration parameters) and other generally useful information such as the date the simulation run was performed. The data derived from the results of the CFD simulation are the dependent variables, and include integrated quantities such as forces and moments, coefficients of lift, drag, pitching moment, etc., that define the flight behavior of the aircraft.

The effectiveness of the vortex generators is evaluated through metadata analysis. For example, if the rolling moment doesn't change significantly when the controls responsible for rolling the airplane (aileron and/or spoiler) are displaced, the aircraft is not controllable. Both the control positions and rolling moment are metadata.

Surrogate Modeling

The first step in analyzing the metadata is generally to create a surrogate model. Like the CFD code itself, the surrogate model takes as inputs the point in parametric space (independent variables) and returns a set of dependent variables: output metadata values like coefficients of lift, drag, pitching moment, yawing moment, rolling moment, etc.

$$(dependent\ variables) = f(independent\ variables)$$

The surrogate model is an approximation of the values that would be obtained by running the CFD code at that point in parametric space, but is much faster. Since many metadata analyses require tens or hundreds of thousands of evaluations of this function, it would be too expensive to run the CFD code every time results are needed at a new set of independent variables.

Surrogate models take a wide variety of forms. Simple models include polynomial response-surface models. These models are a least-square function fit of a polynomial (including cross-terms) in the independent variables. In our example this is a polynomial in 15 dimensions. If it were a quadratic response surface, a second-order polynomial with cross terms, it would have 136 terms. To use this model the experimental design would need to contain at least 136 cases. Higher-order response-surface models, line fourth-order models, are also common but have far more terms, and require more cases, than the quadratic response-surface.

Response-surface models generally don't return the original dependent variables when evaluated at the cases to which it is fit. The total least-square error at these points is minimized, but not zero. If it is required that the surrogate model pass through the exact values of the dependent variable at each case, a more complex interpolative surrogate model like Kriging is required. Kriging is more complicated and expensive than response-surface models, but is still much less expensive per evaluation than running the CFD code. Also, unlike response-surface models, Kriging doesn't have a simple analytical form, so its use in some analyses is more complicated.

Details of the response-surface and Kriging surrogate models, and many others, may be found in books on "design of experiments." [6]

Visualization

A primary use of surrogate models is to allow the visualization of metadata even when the experimental design has cases that are widely dispersed throughout the highly dimensional space. The surrogate model effectively fills the empty space between cases with an approximation of the true data. Using the surrogate model, one can create XY plots of the relationship between metadata variables along any line through parametric space. Likewise, one can create contour plots of any variable along any plane in the parametric space, or create an iso-surface plot of any variable in any 3D sub-space of the parametric space. Using these visualizations, one can intuitively recognize relationships between variables and identify local minima and maxima in the sub-spaces.

The biggest difficulty when visualizing highly-dimensional data, like the 15-dimensional vortex placement problem, is that no small set of low-dimensional (3D or less) subspaces can give a realistic representation of the relationships between variables throughout the full parametric space. To truly understand the data requires more complicated filters and analysis techniques. Filters might include projection to the 3D sub-space of mean, standard deviation, minimum, and maximum values over the other dimensions. This data could then be used in a box plot symbol or error bars to the user an idea of how closely this line-plot represents the data as a whole. Other analysis techniques are discussed in the following sections.

Optimization

Parametric analysis is an effective approach to optimization when the constraints are broadly based. For example, the vortex generator placement problem could be expressed as a constrained optimization. The goal is to minimize drag at cruise while retaining stability and controllability throughout the operating envelope. This would be difficult to do using a gradient-based optimization technique, because the constraint is so expensive to compute. It is far less expensive to compute these constraints using a surrogate model.

Sensitivity Analysis

A common concern in engineering design is the sensitivity of the device behavior to changes in the independent parameters. More specifically, one would like to know the leverage of each independent variable on the changes in each dependent variable. Using a surrogate model, it is relatively straightforward to estimate the sensitivity or perform an analysis of variance (ANOVA). See Fang[6] for details.

In the vortex generator placement problem there are a range of sensitivity-related concerns. For example, how sensitive is the result to the placement and angle of the vortex generators? If it is extremely sensitive, it might be difficult to manufacture the wing. If it is not sensitive at all, there may not be enough degrees of freedom in the placement pattern to actually solve the problem. On the other hand, airlines would prefer it to be relatively insensitive to the loss of one or two vortex generators so the plane could continue to fly despite the loss.

CONCLUSION

Parametric CFD analysis has been shown to play a crucial role in the engineering design of fluid dynamic devices. Engineers who understand the five stages of parametric CFD analysis will have a better understand the behavior of their device over its entire operating envelope and will produce better designs.

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