Aerodynamic shape and planform optimization of wings using a viscous reduced adjoint gradient formula

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The focus of CFD applications has shifted to aerodynamic design. This shift has been mainly motivated by the availability of high performance computing platforms and by the development of new and efficient analysis and design algorithms. In particular automatic design procedures, which use CFD combined with gradient-based optimization techniques, have had a significant impact on the design process by removing difficulties in the decision making process faced by the aerodynamicist.

Typically, in gradient-based optimization techniques, a control function to be optimized (an airfoil shape, for example) is parameterized with a set of design variables. Then, a suitable cost function to be minimized or maximized is defined (drag coefficient, lift/drag ratio, difference from a specified pressure distribution, etc). The governing equations, for example the Navier-Stokes equations in the present study, can be introduced as a constraint in order to express the dependence between the cost function and the control function. The sensitivity derivatives of the cost function with respect to the design variables are calculated in order to get a direction of improvement. Finally, a step is taken in this direction and the procedure is repeated until the optimum solution is achieved.

Because the gradient calculation can be the most time consuming portion of the design algorithm, a fast way of calculating the accurate gradient information is essential. The computational cost of gradient calculation can be dramatically reduced by the control theory approach since the computational expense incurred in the calculation of the complete gradient is effectively *independent* of the number of design variables. In the control theory approach the necessary gradients are obtained via the solution of the adjoint equations of the governing equations of interest. The only cost involved is the calculation of *one* flow solution and *one* adjoint solution whose complexity is similar to that of the flow solution.

The present work builds on the foundation of control theory for systems governed by partial differential equations originally laid out by J.L. Lions[1] and first used in transonic flow by Jameson.[2] In fact, the method has even been successfully used for the aerodynamic design of complete aircraft configurations.[3] Recently the authors have also included wing planform as design variables and have successfully designed a wing of the aircraft configuration which produces a specified lift with minimum drag, while meeting other criteria such as low structure weight, sufficient fuel volume, and stability and control.[4]

Based on the promising results from our wing planform optimization strategy applied to inviscid flow and from our viscous aerodynamic design techniques,[5,6] in the present work the wing shape and planform optimization methods are applied to viscous flow in order to take into account the viscous effects such as shock/boundary layer interaction, flow separation, and skin friction and eventually produce more realistic designs. The design method, which is greatly accelerated by the use of control theory, is further enhanced by the use of a new continuous adjoint method, which reduces the volume integral part of the adjoint gradient formula to a surface integral.[7] The computational savings in gradient calculation are particularly significant for three-dimensional aerodynamic shape optimization problems on general unstructured and overset meshes by eliminating the dependence of the gradient formulas on the mesh perturbation. The methods in this work are the culmination of ongoing studies over the past 14 years, since the adjoint method was first formulated for shape optimization in transonic flow.[2]

References

[1]J.L. Lions. *Optimal Control of Systems Governed by Partial Differential Equations*. Springer-Verlag, New York, 1971. Translated by S.K. Mitter.

[2]A. Jameson. Aerodynamic design via control theory. *Journal of Scientific Computing*, 3:233–260, 1988.

[3]J. Reuther, A. Jameson, J. Farmer, L. Martinelli, and D. Saunders. Aerodynamic shape optimization of complex aircraft configurations via an adjoint formulation. *AIAA paper 96-0094*, 34th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 1996.

[4]K. Leoviriyakit and A. Jameson. Aerodynamic shape optimization of wings including planform variables. *AIAA paper 2003-0210*, 41st Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 2003.

[5]A. Jameson. A perspective on computational algorithms for aerodynamic analysis and design. *Progress in Aerospace Sciences*, 37:197–243, 2001.

[6]S. Kim, J. J. Alonso, and A. Jameson. Design optimization of high-lift configurations using a viscous continuous adjoint method. *AIAA paper 2002-0844*, AIAA 40th Aerospace Sciences Meeting & Exhibit, Reno, NV, January 2002.

[7]A. Jameson and S. Kim. Reduction of the adjoint gradient formula in the continuous limit. *AIAA paper 2003-0040*, 41st Aerospace Sciences Meeting & Exhibit, Reno, Nevada, January 2003.