Aero-Structure Adjoint Formulation for Efficient Multidisciplinary Wing Optimization

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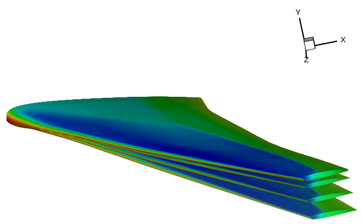
Motivation

Computational Fluid Dynamics is today a reliable tool for the analysis of the flow past wings, and is increasingly used in aircraft design. Since the wing is a coupled fluid-structure system, stationary elastic deflection has to be taken into account during the design. If the design is lead by means of gradient-based optimization techniques,it is thus necessary to include the effects of static elasticity in the gradient computation. On the other hand, the prediction of highly non-linear effects such as shock arise in transonic flow, and shocks interaction in supersonic flow is critical to perform a detailed optimization; this requires the use of high fidelity flow models. Since these models are extremely computationally expensive, an efficient computation of the gradient requires in turn the use of an advanced mathematical tool: the adjoint method. Both these critical requirements can be met by a coupled aero-elastic adjoint formulation, where the coupling is carried out firstly in the physical variables of the two systems, and then in the adjoint variables which are used to calculate the sensitivity.



Convergence to stationary aeroelastic state for transonic flow.

The goal of this work is the development of a aero-elastic coupled adjoint method using industrially relevant software (the DLR flow solver FLOWer and MSC NASTRAN) and its application to test cases relevant for aircraft design, like drag minimization or range optimization.

Coupled aero-structure Adjoint Equations

Let F be the functional of interest and ψ ,$\tilde{\phi}$ flow and structural adjoint fields, while ω and $\tilde{z}$ are respectively the flow and displacement fields. After the solution of the system given by:

- Structural adjoint equation with fluid-coupling term

$$\left(\frac{\partial F}{\partial \tilde{z}} + \psi^T \frac{\partial \mathrm{R}}{\partial \tilde{z}} + \tilde{\phi}^T \frac{\partial \tilde{S}}{\partial \tilde{z}}\right) = 0,$$

- Fluid adjoint equation with structure-coupling term

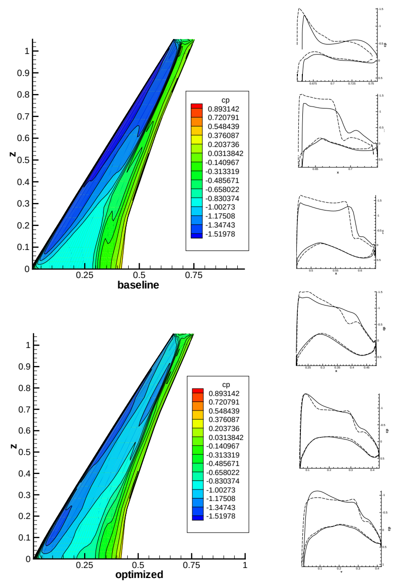
$$\left(\frac{\partial F}{\partial \omega} + \psi^T \frac{\partial \mathrm{R}}{\partial \omega} + \tilde{\phi}^T \frac{\partial \tilde{S}}{\partial \omega}\right) = 0,$$

The sensitivity of F with respect to some design variable a is given by the formula:

$$D_a F = \left(\frac{\partial F}{\partial a} + \psi^T \frac{\partial \mathrm{R}}{\partial a} + \tilde{\phi}^T \frac{\partial \tilde{S}}{\partial a}\right).$$

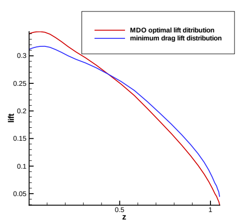
Gradient based Optimization

The sensitivity of relevant quantities like lift, drag and stress obtained from the coupled adjoint formulation are then used to perform and efficient gradient based optimization with an high number of design variables. This makes possible, for a wing in transonic flow, finding a shock-free geometry with 25 % less inviscid drag.



Pressure distribution on the baseline and optimized geometries - drag reduction with constant lift taking into account aero-elastic coupling, 240 shape design variables, coupled adjoint approach.

The multi disciplinary formulation of the coupled adjoint method also allows the evaluation of gradients of cost functions or constraints containing terms coming from the structure side, as in the case of the Breguet formula for aircraft range. A multi disciplinary optimization aimed to range increase finds an optimal design which is different from the single disciplinary optimal design for minimal drag.



Drag minimal and range optimal lift distributions.