TRIMMED SIMULATION OF A TRANSPORT AIRCRAFT USING FLUID-STRUCTURE COUPLING

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1 INTRODUCTION

The accurate prediction of the aerodynamic coefficients under cruise conditions is of major importance for assessing the aircraft's fuel consumption. To this end, fluid dynamics, structural mechanics and flight mechanics have to be considered: on the one hand, the structure elastically deforms under the influence of the flow and a state of static aeroelastic equilibrium is reached; on the other hand, the aircraft's loads are balanced by adjusting control surfaces, which influences the flow.

A procedure has been developed to account for this interplay. For the interaction between fluid and structure (FSI), a partitioned approach is followed to make use of highly-specialized solvers for each discipline: for the equations governing the flow, the hybrid RANS DLR-TAU-code is employed, whereas for the structural equations, ANSYS is used. The trimmed states are computed using a Newton method, in which the derivatives are calculated using finite difference approximations or, alternatively, using the discrete adjoint.

The first test case shows the trim results for a 2-dimensional wing-tail configuration, comparing the approach using finite difference approximations with the one using the discrete adjoint. The second test case uses finite differences for finding the trimmed state for the DLR-F12 transport aircraft configuration in viscous flow, comparing the results of a rigid aircraft with the ones where the wing was allowed to deform elastically.

2 TRIM ALGORITHM

For cruise conditions, i.e. steady level flight, and small angle of attack (AoA), the trim problem reduces to finding the value of the trim input parameters AoA α and control surface angle η such that lift balances weight and the aerodynamic moment vanishes (assuming that thrust is set so as to balance drag and not to result in any moments). This entails the conditions $C_L = \hat{C}_L$ and $C_{M_y} = 0$, where C_L is the lift coefficient, $\hat{C}_L$

its goal value and C_{M_y} the moment coefficient, respectively. This problem is solved by a Newton method which reads for this case

$$
\begin{pmatrix}
\frac{\partial C_L}{\partial \alpha}^{(k)} & \frac{\partial C_L}{\partial \eta}^{(k)} \\
\frac{\partial C_{M_y}}{\partial \alpha}^{(k)} & \frac{\partial C_{M_y}}{\partial \eta}^{(k)}
\end{pmatrix}
\begin{pmatrix}
\Delta \alpha^{(k)} \\
\Delta \eta^{(k)}
\end{pmatrix}
=
\begin{pmatrix}
\hat{C}_L - C_L^{(k)} \\
-C_{M_y}^{(k)}
\end{pmatrix},
\tag{1}
$$

where k denotes the trim iteration number and $\Delta \alpha$ and $\Delta \eta$ the step sizes. The matrix on the left side is the Jacobian $\mathbf{J}$, whose entries are, in general, not given explicitly; they are calculated either by finite differences or by means of the discrete adjoint. The Jacobian is factorized using singular value decomposition to account for trim problems resulting in non-square or ill-conditioned Jacobians. The new values for the trim parameters are then calculated as follows:

$$
\vec{z}^{(k+1)} = \vec{z}^{(k)} + \kappa \cdot \Delta \vec{z}^{(k)},
\tag{2}
$$

where the vector $\vec{z}$ is composed of the parameters α and η; κ is a factor used to assure that the trim input parameters stay within prescribed limits.

A successful trim process is characterized by the fact that either the ℓ^2-norm of the current step size vector or the ℓ^2-norm of the vector on the ride side of equation (1), which signifies a quality measure of the solution, reach prescribed tolerances.

3 COUPLING BETWEEN DISCIPLINES

To account for the interaction between fluid and structure, a partitioned approach has been adopted. The finite-volume DLR-TAU-code is used to solve the Navier-Stokes equations on a hybrid mesh consisting of prisms and tetrahedra, or, in case viscosity is neglected, the Euler equations on a tetrahedral mesh. The elasto-static equations governing the structure are solved by ANSYS for a finite-element model of the wing consisting of shell elements with clamping at the root. Following a CFD calculation, the aerodynamic loads on the interface are transferred to the structural grid by means of nearest neighbour mapping; after the calculation of the nodal displacements of the structure, those are transferred to the CFD mesh by volume spline interpolation[1]. Then, the CFD mesh is deformed by a technique based on radial basis functions[1], and a new coupling cycle begins. This continues until maximum displacements of subsequent coupling cycles or aerodynamic coefficients for subsequent flow calculations differ only insignificantly, indicating a state of static aeroelastic equilibrium.

CFD meshes have been generated by Centaur. They may include overlapping mesh blocks around certain components, which may then be rotated by means of the Chimera technique. On structural side, only the influence of the elasticity of the wing is taken into account. It is modeled by skin, spars and ribs based on the aerodynamic surface mesh.

As to the coupling of FSI procedure and trim algorithm, the FSI procedure is taken as inner loop of the trim algorithm, accepting new values for the input parameters, such as AoA α or control surface angle η, from the trim algorithm and providing the aerodynamic coefficients C_L and C_{M_y} in static aeroelastic equilibrium.

4 DISCRETE ADJOINT APPROACH

The discrete adjoint approach is employed as an alternative to finite difference approximation to calculate the derivatives of the aerodynamic coefficients w.r.t. input parameters such as AoA α or control surface angle η. It is embedded in the trim algorithm to determine the trimmed state under cruise conditions. This trimmed state, though only involving two input and two output parameters, is used exemplarily to show the potential of using the adjoint for derivatives w.r.t. variables set on the farfield, such as AoA α, and variables defining the position of components, such as the angle η.

The adjoint equations are solved using an iterative scheme such as backward Euler. The derivatives w.r.t. AoA α are then readily available. For the derivative w.r.t. control surface deflection η, only the so-called metric sensitivities remain and are calculated using finite difference approximations based on the information of the complete mesh[2]. To this end, mesh deformation based on rigid-body rotation of the component is required, for which radial basis functions are applied[1].
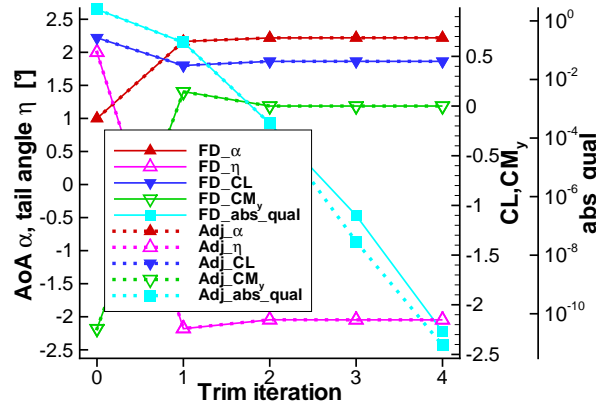
5 RESULTS

Figure 1: Trim convergence for a 2-d wing-tail configuration

The first test case is a 2-dimensional configuration composed of wing and tail with symmetric NACA-profiles. The mesh is composed of triangles on which the Euler equations are solved for a Mach number of $Mach = 0.76$ by the DLR-TAU-code. The AoA α is set on the farfield, whereas for a different tail angle mesh deformation based on radial basis functions has been applied. The goal of the trim process was for the aerodynamic coefficients to reach $C_L = 0.45$ for the lift coefficient and $C_{M_y} = 0$ for the moment coefficient. Figure 1 shows the convergence of the trim input parameters and the coefficients as well as the measure for the quality of the solution, denoted "abs_qual". It can be seen that the trim procedure with the adjoint performs slightly better than that with finite differences in finding the trim state.
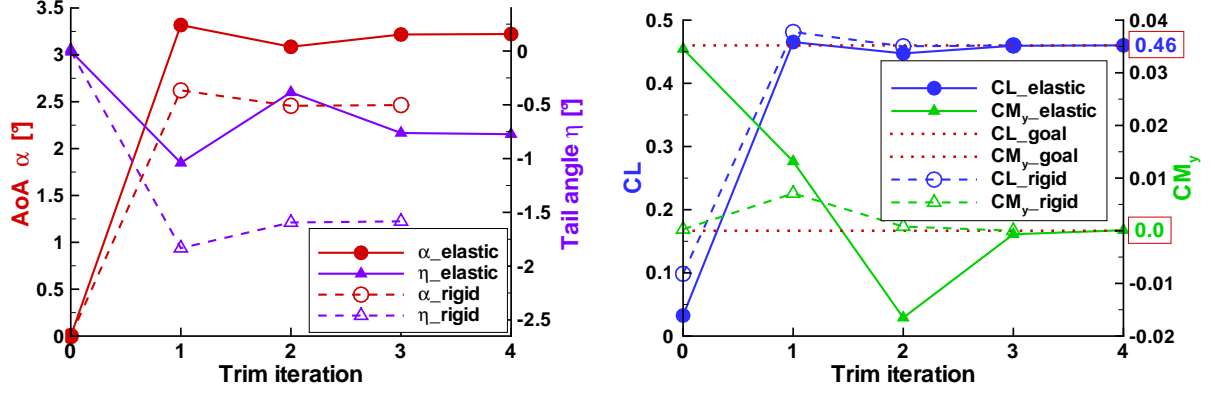
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Figure 2: Trim convergence for the DLR-F12 transport aircraft

As second test case, the DLR-F12 transport aircraft was trimmed for cruise conditions of $\hat{C}_L = 0.45$ and $\hat{C_{M_y}} = 0$ using finite differences. The hybrid CFD mesh consisted of about 4.25 million points and contained overlapping mesh blocks around the horizontal tail, enabling its rotation. The TAU-code was used to solve the Navier-Stokes equations for a Mach number of $Mach = 0.85$. Only the wing was taken to be elastically deformable. Figure 2 shows the convergence of trim input parameters and aerodynamic coefficients for the rigid and the partially elastic aircraft. Both trim processes are successful. It can be seen that the values for the trim input parameters at the trimmed state differ quite significantly. This highlights the importance of considering elasticity effects when computing cruise conditions.

6 CONCLUSIONS

The results show that, firstly, the discrete adjoint approach can be incorporated successfully in a trim procedure, and secondly, that elasticity effects may not be neglected when calculating the flow under cruise conditions. In the future, the discrete adoint approach will be applied to more complicated configurations involving elasticity and to more demanding trim problems involving multiple control surfaces.

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