Extension of the Optimization Environment POEM with Respect to Aeroelastic Effects

Benedikt König, Martin Kutzbach, Thorsten Lutz

Universität Stuttgart, Institut für Aerodynamik und Gasdynamik (IAG),
Pfaffenwaldring 21, D–70550 Stuttgart, Germany
email: {koenig}{kutzbach}{lutz}@iag.uni-stuttgart.de

Summary

The present paper describes the implementation of an static aeroelastic analysis module in the optimization environment POEM. One intended application of the extended tool is the optimization of flexible adaptive transonic wings. A loose coupling scheme combines a CFD solver based on the RANS equations with a FEM using a Timoshenko beam structure. Numerical results of the coupled analysis of a rectangular wing in subsonic flow are compared to experimental data.

1 Introduction

Aircrafts in flight are subject to elastic deformations due to the aerodynamic loads. These deformations are particularly significant for the high aspect ratio wings of large transport aircraft with high wing loading. Thereby, the extend of the deformations varies with the flow condition. Within the transonic flight regime varying deformations greatly influence the position and strength of appearing shock waves as well as the pressure distribution and, thus, significantly alter wing performance [1].

Aerodynamic wing design is traditionally done without considering the structural deflections caused by the aerodynamic forces. The deformations are usually determined subsequently and a jig shape is tailored such that the loaded and deformed wing takes the desired optimum shape at a certain design point. Though, due to load changes resulting from fuel consumption as well as to speed and altitude changes dictated by air traffic control transport aircraft operate within a certain range of flight conditions.

One means to increase the aerodynamic efficiency for a range of flight conditions is the application of adaptive elements like variable camber (VC) and/or shock control bumps (SCB). The Design of an SCB in the strongly non–linear transonic flow is a trade off between a broad range of application and high optimization at one design point. Highly optimized devices react very sensitive towards changes in the pressure distribution. This may not only influence the effectiveness of adaptive elements but also even deteriorate the overall aircraft performance. Therefore, an optimization of adaptive aerodynamic elements applicable to wings should account for aero–structural coupling effects to accurately predict the resulting pressure distribution.

Until recently most industrial aeroelastic applications were based on linear aerodynamic methods which are not suitable to analyse non–linear transonic effects [14]. A discussion of current industrial technology needs with respect to aeroelastic design and optimization is given in Hönlinger et al. [7].

Lately, various software tools for numerical optimization of aircraft considering aeroelastic effects have been developed. Gumbert et al. [5] introduced a method called Simultaneous Aerodynamic and Structural Design Optimization (SASDO) and showed results for wing planform optimizations; Martins et al. [11] developed a coupled aero–structural design method for complete vehicles. Both methods apply Euler analysis coupled with finite element methods. Sensitivity analysis of the coupled system provides the necessary derivatives for gradient based optimization algorithms.

At the IAG the POEM tool is being developed, which is an analysis and direct numerical optimization tool. Recent applications of POEM include subsonic aeroacoustic airfoil optimizations [10]. Sommerer et al. [13] showed the potential for drag reduction of the combined application of VC and SCBs on transonic airfoils (see Fig. 1 for representative results). Kutzbach et al. [9] investigated the effect of three–dimensional flow on SCBs using an infinite swept wing. It was shown that an additional cross flow component within the boundary layer increases the relevant displacement and momentum loss thickness but does not significantly influence the SCB effectiveness.

The present work is a step towards the optimization of adaptive devices for elastic finite wings. It describes the extension of the analysis capabilities of POEM to three–dimensional aeroelastic problems. The following sections first introduce the analysis and optimization tool POEM and give some examples on current results concerning adaptive elements. Then static aero–structural coupling in general is briefly reviewed and the aeroelastic module implemented in POEM is described. Finally results applying the aeroelastic analysis module to a subsonic example given in literature and to a generic transonic wing are presented.

2 Optimization Environment POEM

2.1 Overview

The (Parallel Optimization Environment with Modular structure) (POEM) consists of three main modules, namely the optimizer, the geometry module and the analysis module (see Fig. 2). As optimization module either an evolutionary strategy with covariance matrix adaption (CMA ES) by Hansen and Ostermeier [6] or the commercial optimization software Epogy by Synaps can be utilized. The CMA ES generates a new set of design variables by mutation and recombination of the selected best individuals of a generation with individual de–randomized step size adaption (covariance matrix adaption).

Epogy offers various algorithms of different classes, including genetic algorithms, downhill simplex method, as well as methods of sequential quadratic programming (SQP). Hybrid methods, being cocktails of the available algorithms, can be set up and "trained" for particular tasks.

So far, the geometry module contains various parameterization techniques to generate and modify airfoil contours. Either direct methods using bezier curves or inverse methods based on conformal mapping are available. Parameterizations for shock control bumps and rigid trailing–edge flaps can be applied. The parameters of these geometry descriptions represent the design variables used by the optimization algorithm.

The third module is for aerodynamic analysis. Various well–established flow solvers are implemented and the most suitable for the flow problem under consideration can be chosen. Airfoil sections for subsonic application can be analysed with the coupled panel boundary–layer code XFOIL. For subsonic aeroacoustic optimization XFOIL is coupled to a module for trailing–edge noise calculations. In the transonic speed regime designs are evaluated using either the 2D coupled Euler integral boundary–layer code MSES by M. Drela [4] or the structured finite volume solver FLOWer from DLR [8].

2.2 Numerical Methods

The aerodynamic analysis tool used in this work is the FLOWer code developed within the German MEGAFLOW project [8]. It solves the compressible two– or three–dimensional Reynolds–averaged Navier–Stokes (RANS) equations in integral form on block–structured grids. Spatial discretization is done either by second–order central differences according to Jameson or by upwind schemes. Time integration of the main equations is accomplished by an explicit five–stage Runge–Kutta scheme. For convergence acceleration local time stepping, implicit residual smoothing and a multigrid technique are available. Different eddy–viscosity or Reynolds–stress turbulence models are implemented to close the RANS equations.

The commercial meshing software IGG by Numeca is applied to generate structured computational grids. Rather than using a grid deformation algorithm to adopt the grid to the geometric modifications during the optimization process a new grid is generated automatically for every optimization cycle. For automatic grid generation IGG supports an extended version of the Python script language. Scripts for different classes of configurations were developed at the IAG and are constantly extended and refined. Currently, scripts for two–dimensional airfoil sections, three–dimensional wings and wing–body configurations are available. Since the same script with the same set of parameters is used for one optimization run all the resulting grids are almost identical. This facilitates the efficient initialization of each iteration step with the flow solution of the previous step.

The benefit of the script–based grid generation approach is the independence of a certain flow solver internal grid deformation algorithm. This is consistent with the modular structure of POEM in general where each module or submodule could be replaced individually. One limitation of this approach is the restriction to steady problems where the geometric conservation law (GCL) is not applicable.

3 Aeroelastic Coupling Module

3.1 Aeroelastic Coupling

Smith et al. [12] distinguishes three classes of fluid–structure coupling. The first one is called *fully coupled analysis* where the governing equations for fluid and structure are combined in one system and solved simultaneously. The second class is the *closely* or *strongly coupled* approach. The flow and structure solvers are independent and only interact at the end of each CFD time step or iteration step. This is the most common approach for dynamic coupling and was for example applied by Buchtala [3] to the coupled analysis of helicopter rotors. The third class is the *loose* or *weak coupling.* Again, separate solvers are used for fluid and structure analysis. But instead of exchanging coupling information after each time step the flow solution is only updated by structural deflections after partial or full convergence.

One of the most appealing features of the weak and strong coupling approaches —the so called staggered procedures— is the possibility to use well established and mature solution methods on the individual disciplines. Implementation of new results into either one of the solvers or even their complete replacement is possible. This facilitates the adaptation of the scheme to different problems.

The staggered procedures solve the structural and fluid equations on separate grids which in general do not coincide at the respective boundaries. Thus, to exchange information like aerodynamic forces and structural deformations between both grids interpolation methods must be applied. A thorough evaluation of transfer algorithms suitable for fluid–structure interactions is given in Smith et al. [12].

The coupling scheme applied in this work is a loosely coupled staggered method. The projected task of optimizing adaptive elements does not require time–accurate flow calculations. Hence, a loose coupling scheme which is sufficient for static aeroelastic analysis and is relatively easy to implement was chosen. Experiences during the course of this work showed, that the coupled iteration converges within only a few steps. Taking into account that only partial convergence of the flow solution is needed before a structural deformation update, the increase in computation time was found to be moderate compared to the flow solution of the rigid body.

The numerical methods used within the present investigations are the before mentioned FLOWer code together with the grid generator IGG and the in–house finite element method (FEM) Dynrot. The work flow of one iteration is as follows (also depicted in Fig. 3): Dynrot calculates the deformations of the structure for the given aerodynamic forces. A geometry module applies the deformations to the geometry representation provided either by the user or by POEM and writes the deformed geometric data which is the input to the grid generation script. IGG is started in batch–mode and execution of the script generates a new computational grid. A new flow solution is calculated by FLOWer using the previous one for initialization. The resulting pressure distribution is transformed into nodal loads on the structural grid and the subsequent FEM analysis is initiated.

While aerodynamic analysis of wing–body configurations is possible the aero–elastic coupling is only implemented for wings, so far. The fuselage is currently assumed to be rigid.

3.2 Submodules and Numerical Methods

FEM code Dynrot Dynrot was developed at the IAG for aeroelastic analysis of helicopter rotor blades [3]. It is based on a quasi one–dimensional Timoshenko beam with six degrees of freedom (DOF) per node. The representation as quasi one–dimensional system is a common approach for rotor blades [3] and applicable to high aspect ratio wings of transport aircraft as well. The centerlines of mass, bending and torsion are generally non–coinciding which may lead to coupling effects between the various degrees of freedom. Compared to the four DOF Euler beam, the Timoshenko beam has two additional DOF representing shear deformations. This is of particular interest for high frequency wave propagation problems appearing in unsteady aeroelasticity as it prevents the so called anomalous dispersion [2]. However, as this work only deals with static aeroelasticity this property is not used. The original code as described by Buchtala [3] was modified to allow for swept wings wings with kink. This was done by applying a transformation matrix based on the angles of the wings local quarterchord axis to every beam element.

Geometry preprocessor The geometry representation used is based on rigid cross sections and airfoil sections for fuselage and wing, respectively. The spanwise discretization of the wing uses as many wing sections as the structural model uses nodes. Thus, each wing section is attached to one node of the FEM model. Position and attitude of the sections are adjusted according to the translational and rotational displacements of the respective nodes due to the aerodynamic forces. The deflected and rotated airfoil sections form geometrical input data for grid generation.

3.3 Verification Example

Aeroelastic analysis results used for validation of the process chain are shown. Experimental results for subsonic flow were taken from the Collaborative Research Centre SFB401 [2]. The model considered herein is a rectangular wing with 1 m semispan and a chord length of 222 mm. The flow condition is $v_\infty = 65\frac{\mathrm{m}}{\mathrm{s}}$, $\rho_\infty = 1.24\frac{\mathrm{kg}}{\mathrm{m}^3}$ with a root angle of attack of 6.93°. Fig. 4 shows the wing in its aeroelastic equilibrium configuration. Comparison of numerical results for bending deformation (Fig. 5) and pressure distribution (Fig. 6) to experimental data taken from Britten and Ballmann [2] yield good agreement. Convergence of the coupling process was reached within only a few iteration cycles as is shown in Fig. 7.

4 Conclusion

In this paper the implementation of an aeroelastic analysis module into the analysis and optimization tool POEM was presented. The coupled fluid–structure problem is solved using the RANS equations to model the flow and a quasi one–dimensional Timoshenko beam to model the wing structure. Exemplary results were compared to experimental data from the Collaborative Research Centre SFB401.

The next step is to complete the implementation into POEM in order to enable three–dimensional optimization using the aeroelastic module becomes possible. That requires in particular the extension of the geometry module to modify wing planforms. Furthermore, substitution of Dynrot with MSC/Nastran is planned.

References

[1] D. O. Allison and P. A. Cavallo: *Static Aeroelastic Predictions for a Transonic Transport Model Using an Unstructured–Grid Flow Solver Coupled With a Structural Plate Technique.* Tech. Rep., NASA, Langley Research Center, Hampton, Virginia, USA, March 2003.

[2] G. Britten and J. Ballmann: *Navier–Stokes–Based Direct Numerical Aeroelastic Simulation.* In: Proc. of the 22nd International Congress of the Aeronautical Sciences, Harrogate, UK, 27 August – 1 September 2000.

[3] B. Buchtala: *Gekoppelte Brechnung der Dynamik und Aerodynamik von Drehflüglern.* PhD thesis, Universität Stuttgart, Institut fü Aerodynamik und Gasdynamik, Pfaffenwaldring 21, 70550 Stuttgart, Germany, 2001.

[4] M. Drela and M. B. Giles: *ISES: A Two-Dimensional Viscous Aerodynamic Design and Analysis Code.* In: AIAA 25th Aerospace Sciences Meeting, Reno, NV, USA, 1987.

[5] C. R. Gumbert, P. A. Newman and G. J.-W. Hou: *Simultaneous Aerodynamic And Structural Design Optimization (SASDO) for a 3-D wing.* In: AIAA 15th Computational Fluid Dynamics Conference, Anaheim, CA, USA, June 11–14 2001.

[6] N. Hansen and A. Ostermeier: *Adapting Arbitrary Normal Mutation Distributions in Evolution Strategies.* In: Proceedings of the 1996 IEEE International Conference on Evolutionary Computation (ICEC '96), Nagya, Japan, May 20–22 1996, pp. 312–317.

[7] H. G. Hönlinger, J. Krammer and M. Stettner: *MDO Technology Needs in Aeroelastic Structural Design.* In: 7th AIAA/USAF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, St. Louis, MO, September 1998. AIAA 98-4731.

[8] N. Kroll, C. C. Rossow, D. Schwamborn, K. Becker and G. Heller: *MEGAFLOW — a Numerical Flow Simulation Tools for Transport Aircraft Design.* In: Proceedings of the 23rd International Congress of Aeronautical Sciences, ICAS, Toronto, September 2002.

[9] M. Kutzbach, T. Lutz and S. Wagner: *Investigations on Shock control Bumps for Infinite Swept Wings.* In: 2nd AIAA Flow Control Conference, Portland, OR, USA, June 2004. AIAA 2004-2702.

[10] T. Lutz, W. Würz, A. Herring, K. Braun and S. Wagner: *Numerical Optimization of Silent Airfoil Sections.* In: DEWEK 2004, Wilhelmshaven, Germany, October 20–21 2004.

[11] J. R. R. A. Martins, J. J. Alonso and J. Reuther: *Complete Configuration Aero–Structural Optimization Using a Coupled Sensitivity Analysis Method.* In: 9th AIAA/ISSMO Symposium on Multidisciplinary Analysis and Optimization, Atlanta, GA, USA, September 4–6 2002. AIAA 2002–5402.

[12] M. J. Smith, D. H. Hodges and C. E. S. Cesnik: *Evaluation of Computational Algorithms for Fluid–Structure Interactions.* Journal of Aircraft, Vol. 37, No. 2, pp. 282–294, March–April 2000.

[13] A. Sommerer, T. Lutz and S. Wagner: *Numerical Optimization of Adaptive Transonic Airfoils with Variable Camber.* In: Proc. of the 22nd International Congress of the Aeronautical Sciences, Harrogate, UK, 27 August – 1 September 2000.

[14] M. Stettner, A. Eberle, J. Grashof, W. Haase and M. Schneider: *Processes for Aeroelastic Simulation and Optimisation.* In: Proc. of ECCOMAS 2000, European Congress on Computational Methods in Allpied Sciences and Engineering, Barcelona, Spain, 11–14 September 2000.

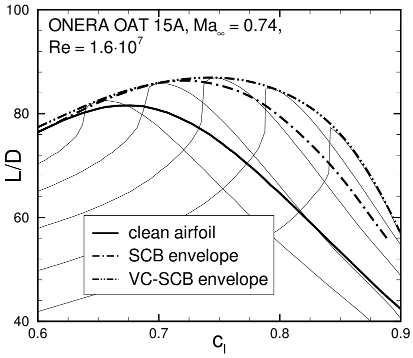

Figure 1 Increase of the aerodynamic efficiency by adaptive devices on a transonic airfoil [13].

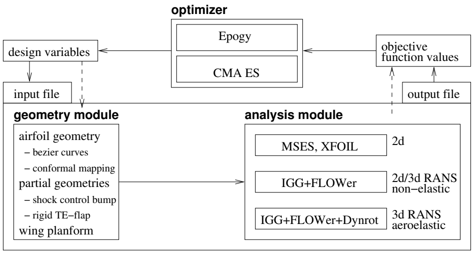

Figure 2 Optimization and analysis environment POEM.

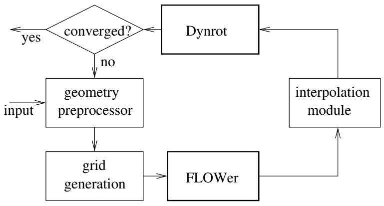

Figure 3 The aeroelastic coupling module.

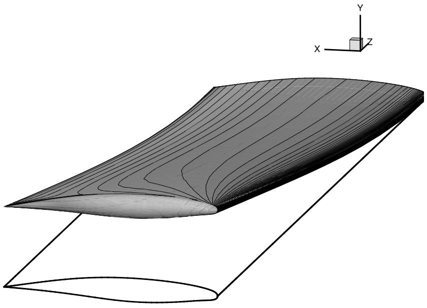

Figure 4 Rectangular wing in aeroelastic equilibrium configuration

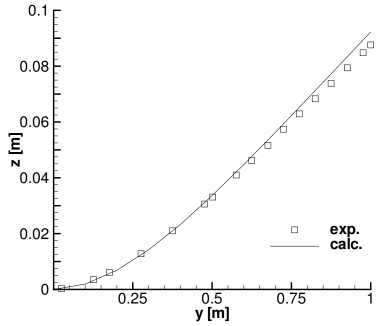

Figure 5 Comparison of measured and calculated spanwise bending deformation (exp. data taken from Ref. [2]).

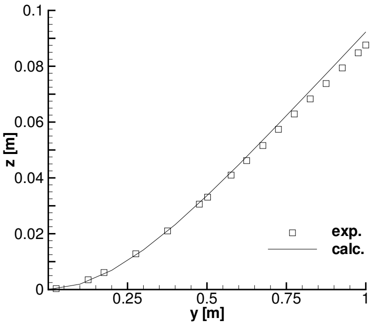

Figure 6 Comparison of measured and calculated c_p in a cross section at 50 % semi–span (exp. data taken from Ref. [2]).

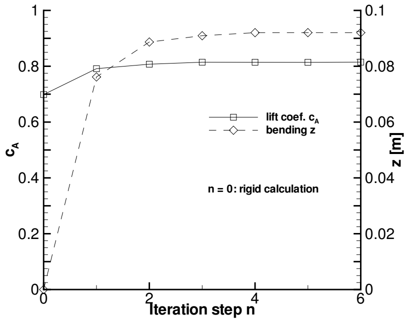

Figure 7 Convergence history of global c_A and bending deformation at the wing tip.