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Numerical Tools for Unsteady Viscous Flow Control

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Abstract:

This paper reports about progress in the development of numerical tools for adaptive aerodynamic configuration design. We try to illustrate the use of new software components allowing for the parameterized modelling of boundary conditions and the simulation of compressible steady and unsteady viscous flows including a computational flow control model. A coupling of these tools and the use of computer-graphic visualization and animation of flow control through adaptive devices accelerates the development of transonic wing or helicopter rotor sections with high aerodynamic efficiency.

1. Introduction

Aerodynamic design is widely focused on finding geometric shapes for airframe or turbomachinery components which perform efficiently for certain operating conditions, i. e. cruise flight or engine design load. Compromises for a fixed shape are necessary for multipoint design requirements where more than one set of operating conditions are to be met. The ideal shape would be a flexible aircraft to change its shape for optimal efficiency in any practically occurring operating condition. Despite the unlikelyness of manufacturing global or large scale flexibility, certain adaptive components are to become reality sooner or later in new generation aerospace products.

Examples of high practical importance are varying flow conditions of helicopter rotor blades [1]: Velocity differences in the advancing and retreating phases and the need to counteract the resulting differences in lift production through the variation of angle of attack pose several aerodynamic and structural problems which still need further improvements. One of the tasks therefore is the development of adaptive devices on airfoils and other flow control mechanisms to improve aerodynamic and aeroacoustic rotor efficiency. Such improvements will be a challenge for hardware construction but in a time of possibly developing a product with ‘virtual technologies’, software is needed to model the actually occurring as well as the desirable operating conditions with numerical methods.

The purpose of this contribution is to report about a coupling of several software tools enabling the aerodynamic design engineer to define shape modifications in steady and unsteady flow conditions which promise certain improvements; experimental and other tests then need to verify the advantage of such theoretically found geometry variations.

2. Software tools for aerodynamic design.

Geometry data are the link between numerical modelling and product component definition. Computational fluid dynamics offers a variety of algorithms for modelling complex flow processes, with either fast codes meeting some degree of engineering accuracy or computer programs with larger effort for obtaining high accuracy results. Engineering data as well as refined results need visualization tools; a fastly growing market of high performance graphic desktop computers invites to make full use of interactive compute graphics for this purpose. Here we stress a systematic approach to use geometry generation, CFD with possibly accelerated analysis, and visualization methods for solving some design tasks occurring in unsteady aerodynamics like rotor flow.

Geometry generator

Airfoils are basic elements for lift generation of an aerospace vehicle. Analytical functions to generate new airfoil shapes are welcome if they are formed with a number of parameters high enough to effectively control their aerodynamic properties but as low as possible to reduce manual or automated optimization procedures. The first author provided a geometry tool [2] for 3D configurations, which since then has been refined to serve design purposes in the whole Mach number region. Interpretation of a 3D wing geometry with spanwise variation of its sections as a series of variable geometry airfoils is a straightforward application to unsteady 2D airfoil flow boundary conditions.

For applications to generate 3D wings or rotor blades, airfoils are usually given by catalogs published on the base of prior systematic research, like the NACA series of airfoils, or more recently, refined shapes for new projects are developed in a separate design effort and prescribed by a dense set of surface point data, input for the geometry generator. Our tools allow for both options, here we stress a shape variation of airfoils with a practical background:

Sealed flaps and slats are used to control flow quality and lift by a variable camber distribution along chord. The mathematical model allows to rotate a nose or/and tail portion of the airfoil with elastic sealings, defined only by input slat and flap angles and chordwise hinge locations and extent of the sealing, (Fig.1).

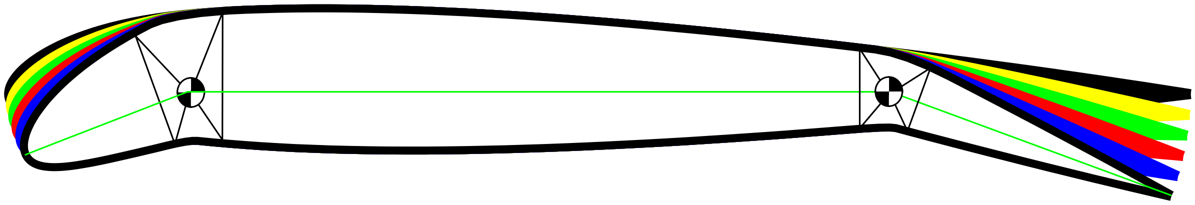


Figure 1: Sealed slats and flaps geometry variation to a rigid airfoil

Airfoils used in helicopter rotor design include the NACA 23012 section, which among other airfoil families can be generated analytically and was used in our applications as a baseline for some examples of shape variation. Simple but efficient shape variation tools are bump functions to add or subtract local thickness to a contour, our geometry software has options to calibrate location, height, (un)symmetry and crest curvature of smooth bumps to be added, with these parameters function of wing span for 3D models or interpreted as controllable airfoil shape modifications for 2D unsteady models.

CFD tools development: Navier Stokes code with an option for gasdynamic flow control

Numerical modelling of unsteady compressible flow is done here presently using a time - accurate 2D Reynolds-averaged Navier Stokes solver [3] written by the second author primarily for the use in unsteady helicopter rotor and transonic airfoil aerodynamics.

A new option in this code is the implementation of the fictitious gas (F. G.) design concept for the design of supercritical airfoils: Originally developed for potential flow numerical models [4], the concept recently was extended for an implementation in Euler solvers [5]. With potential flow still a mere mathematical model to manipulate boundary value problems in order to solve the design problem of generating shock-free airfoils and wings, the introduction of the concept to the more general Euler equations allows a physical interpretation of this manipulation: The equation of state is changed by a local energy transfer controlled by local velocity if it exceeds a certain threshold value. For applications to supercritical transonic flow this models a flow control process applied only in limited areas of the flow if the threshold velocity is the critical sound speed a* which is a constant defined by upstream flow parameters only. This mathematical manipulation or modelled flow control results in a local flow Mach number not exceeding unity anywhere: the controlled flow is subsonic within the whole flow field. Implementation of this concept to numerical Euler solvers is depending on the code, either a fictitious pressure-density, density-velocity or pressure-velocity relation need to replace the algebraic formulation for the equation of state.

An extension of this concept to Navier Stokes equations is straightforward but needs some correcture within the viscous domain of the boundary layer to ensure smooth crossover from ideal gas to fictitious relations at the threshold. The second author has introduced this concept to his Navier Stokes code which required a modification of the fictitious equation of state within viscous regions, where pressure and density are no longer constant along the fixed critical threshold velocity $q_s = a^*$:

Equation of state for both the inviscid Euler and the Reynolds-averaged Navier Stokes version of the code for ideal gas flow is

$$p/\rho = (\gamma - 1) \cdot \left(e - \frac{q^2}{2}\right), \tag{1}$$

with p the pressure, ρ the density, e the internal energy and q = a*Q the velocity, γ the ratio of specific heats.

A fictitious relation

$$p/\rho = Fct(Q, \lambda, \mu_t), \tag{2}$$

replaces the equation of state (1), once Q > 1, following [5] but extending this work into the viscous domain with eddy viscosity μ_t in turbulent flow and with a free parameter λ, characterizing fictitious gas properties. Modified from the Euler fictitious gas we have

$$p = p_s(\mu_t) \cdot \left\{1 + \frac{2\lambda\gamma}{2-\lambda} - \frac{\lambda\gamma}{2-\lambda}(Q+1)\left[1 + \frac{1}{\lambda}(Q-1)\right]^{1-\lambda}\right\}, \tag{3}$$

$$\rho = \rho_s(\mu_t) \cdot \left[1 + \frac{1}{\lambda}(Q-1)\right]^{-\lambda}, \tag{4}$$

where the values p_S and ρ_S for inviscid flows are equal to the critical values p* and ρ* but for viscous flow are functions of eddy viscosity μ_t and therefore depend on the turbulence model (here: the Baldwin lomax model). An analytical relation for $p_S(\mu_t)$ and $\rho_S(\mu_t)$ consistent with this flow control is not known yet but in the numerical code a functional dependence is found from the previous time steps and used as a correction within the modified domain, the boundary of which in contrary to inviscid flow excludes the airfoil contour: See the details in Fig. 2, illustrating the sonic isotach bending into the boundary layer but the critical pressure isobar reaching the surface. This isobar is used as an initial condition for an inviscid method of characteristics in the same way as for previous potential flow and Euler calculations.

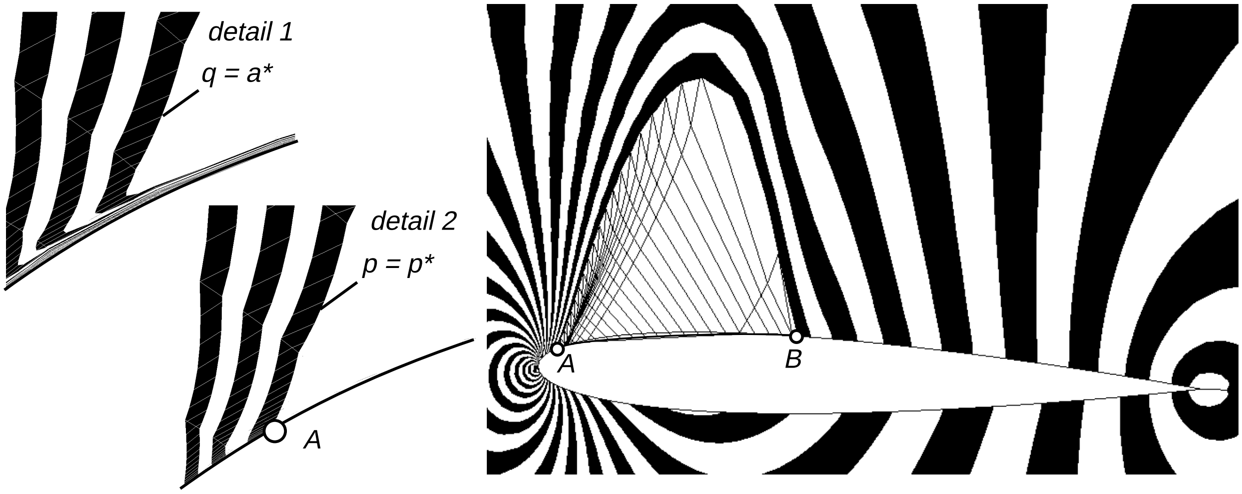
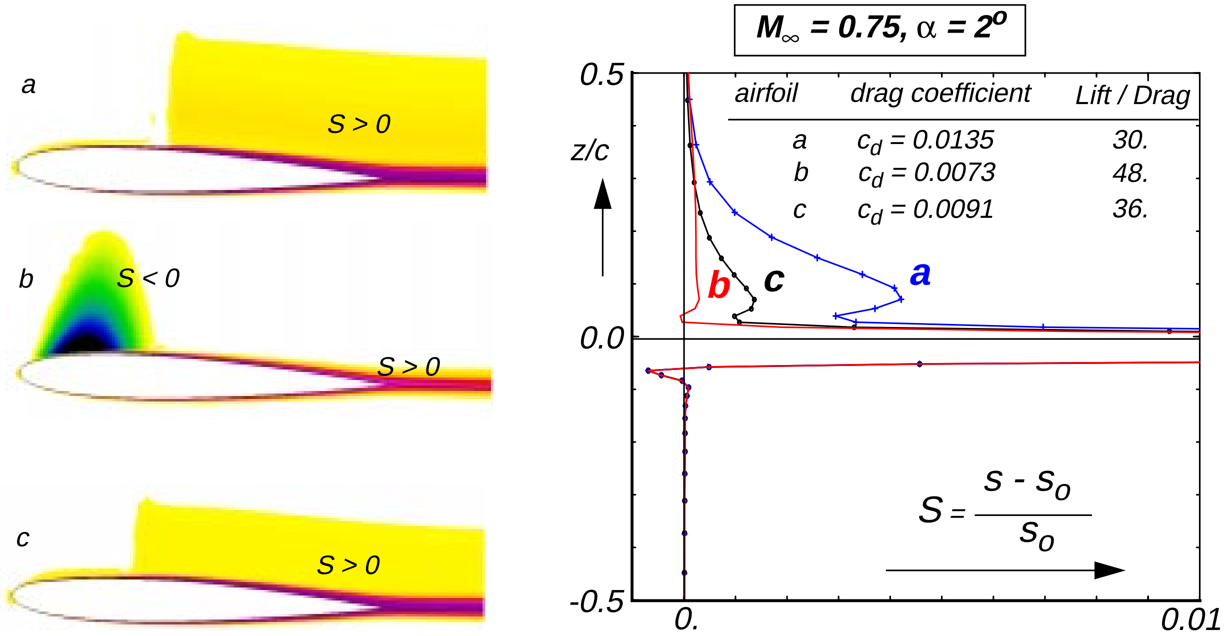


Figure 2: Airfoil NACA 0012 in transonic flow $M_\infty = 0.75$, $\alpha = 2^o$, Re = 2 Mill., fict. gas ($\lambda = 0.8$) applied within domain q > a (see detail 1) , method of characteristics applied within domain p < p* (see detail 2) . Airfoil contour redefinition (flattening) within interval AB.*



airfoil	drag coefficient	Lift / Drag
a	$c_d = 0.0135$	30.
b	$c_d = 0.0073$	48.
c	$c_d = 0.0091$	36.

Figure 3: Comparison of entropy profiles at the trailing edge: Original NACA 0012 (a) producing wave drag and viscous drag, the same airfoil (b) with F. G. flow control has no wave drag, new airfoil (c) with reduced wave drag.

For a given airfoil with only local modifications allowed, shock-free flow is possible only up to certain limits in Mach number and lift but aerodynamic performance improvements are usually obtained while weak shocks are present. In a coupling of this F. G. flow control computation and the previously mentioned geometry generator, a relaxed surface deformation function is provided and calibrated by the characteristics result. This leads to improved steady flow airfoils with only a quite weak shock wave appearing. This can be illustrated by comparison of the entropy production for the three airfoil flows (Fig. 3): Following Oswatitsch [6], we know that drag is proportional to the entropy produced by the airfoil, indeed the entropy profiles in the wake show a strong reduction of c_d between airfoils a and c (44 counts).
So far, only steady flow results for the Navier Stokes code F. G. extension have been attempted. Rapid steady 2D flow analysis using an Euler code plus boundary layer computation is a welcome ‘fastprocessor’ [7] obtaining drag polars for the newly obtained airfoils with design modifications. Unsteady flow optimization using the geometry tools as well as CFD with gasdynamic flow control as outlined above will be a next step. The surface shape modification results gained from steady flow modelling already prove as a valuable knowledge base for cyclic deformations of adaptive airfoils in unsteady flow as illustrated below.

Postprocessing of unsteady flow analysis and design

An important part of gaining experience from numerically modelling and improving steady and unsteady flows is an efficient visualization postprocessor. Our collection of computational tools to become a complete aerodynamic design expert system makes use of the HIGHEND visualization software [8]. The third author has created video animation of steady and unsteady flow numerical simulation case studies [9] on workstations. Such options made possible by progress in information technology greatly enhance the understanding of 3D and 4D problems as occurring in unsteady processes, optimization cycles and mechanical adaptation systems.

3. Practical results for rotor airfoil adaptation

Unsteady viscous flow simulation in combination with the outlined surface modifications has been used to propose a reduction of dynamic stall effects on helicopter rotor blades in the low speed and high angle of attack portion of the blade retreating phase [10]. A nose droop geometry modification to an NACA 23012 section resulting from an application of the above mentioned leading edge sealed slat model plus surface bumps and harmonic variation of the angle of attack to define periodic boundary conditions is applied and results for cyclic lift, drag and moment loops are obtained. Fig. 4 shows results for the original rigid airfoil, a sealed flap nose droop and an additional leading edge flattening motivated by our knowledge about how to improve local supercritical flow quality by computational flow control. The latter is advisable realizing the fact, that even low speed flow with high lift may exhibit transonic domains with shock-boundary layer interaction right at the leading edge, with consequences for flow separation further downstream.

Remarkable improvements to delay dynamic stall are found. For better understanding of the flow details, 3D visualization shows results with pressure contours on the airfoil surface varying with time and sonic bubbles at the leading edge. Video animation shows the formation and downstream convection of separation vortices, leading to a breakdown of lift on the original airfoil and to nearly no separation on the flattened nose droop section.

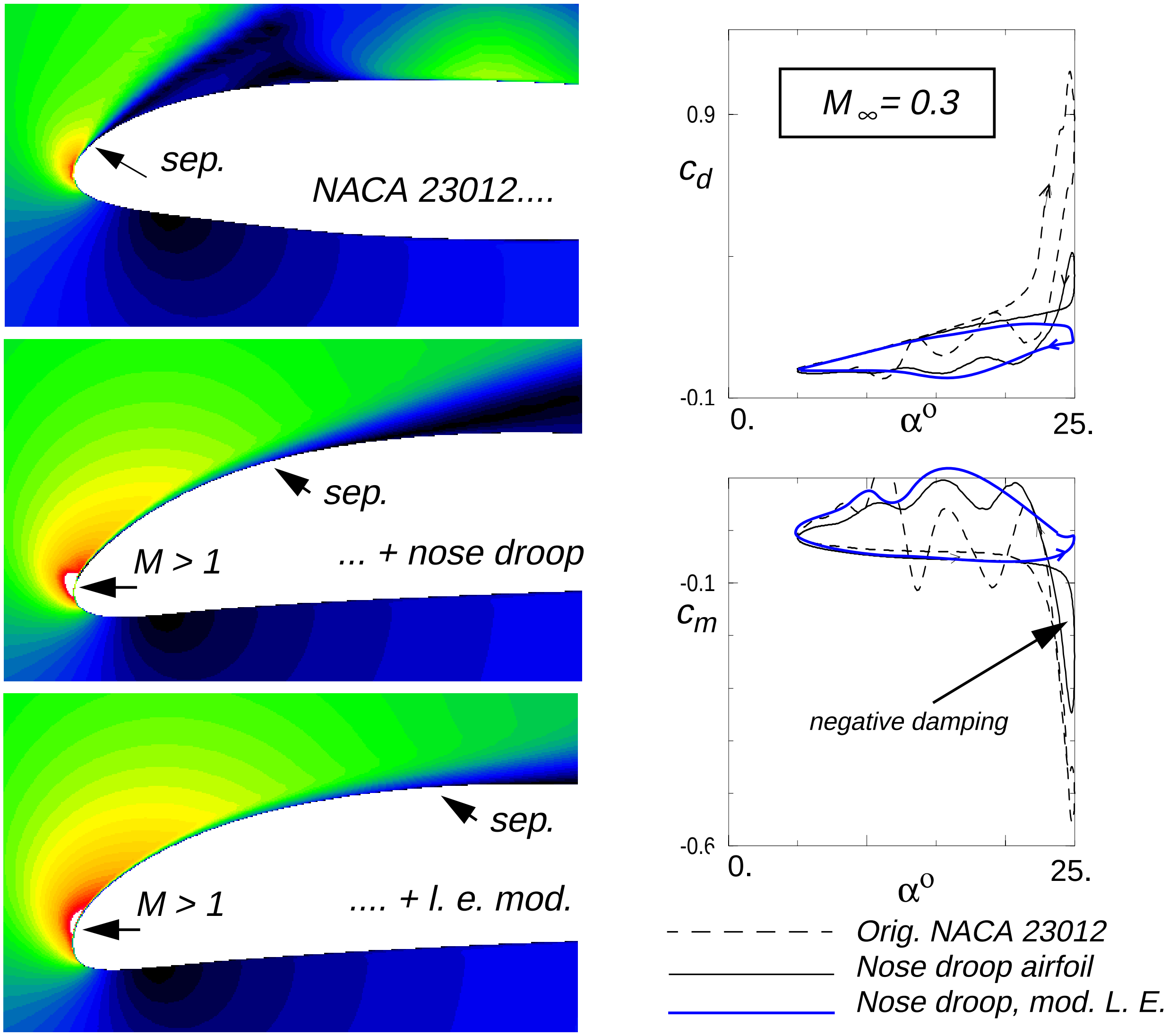


Figure 3: Unsteady airfoil flow M_∞ = 0.3 past original NACA 23012 (above), periodic nose droop with pitch cycle (center), and periodic nose droop plus leading edge modification based on steady flow transonic design knowledge base (below)
Drag and moment coefficients as function of periodic pitch angle $\alpha(t) = 15^o + 10^o \sin(\omega t)$.
Flow field local Mach number visualization at $\alpha_{max} = 25^o$

4. Conclusions

A practical design tool for unsteady flow control has been developed by a combination of a flexible geometry generator and a time-accurate Navier Stokes code with an option to simulate gasdynamic flow control. First results modelling both input geometries and gas properties encourage the use of the concept to design variable airfoil geometries with improved steady as well as unsteady flow aerodynamics. Software development is aimed toward accelerated analysis and design tools, resulting in expert systems for aerodynamics and aeroelastics.

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