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Active Flow Control Based on Transonic Design Concepts

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ACTIVE FLOW CONTROL BASED ON TRANSONIC DESIGN CONCEPTS

(INVITED PAPER)

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Abstract

Computational tools for geometry preprocessing, numerical simulation of steady and unsteady flows and results visualization for studying the calculated phenomena are presented for a few aerodynamic studies aimed at flow control in rotor aerodynamics and wing section design. Experiments with 2D and 3D adaptive devices are discussed.

Introduction

Flow control has become a source for design innovations requiring a refinement of our research and development methods. Learning from nature as well as using our knowledge bases leads a way to making better use of fluid mechanic and aerodynamic structures in various technical applications [1].

Steady and unsteady flow quality in the speed regime of subsonic and transonic Mach numbers is substantially influenced by shock wave formation and their interaction with viscous flow. Systematic design methods have therefore been developed during the past 3 decades to avoid strong shocks and theoretical concepts have been presented to adjust contours to the requirements of favorable flow. More recently hardware realizations of such concepts begin to become reality at least in a few research projects.

This presentation reports about some activities related to flow control at DLR Göttingen, reviews our results of the past 4 years and shows some new developments in this direction. Experimental investigations are still to be done for most of these concepts, especially for active flow control, while steady configurations with a few varied surface modules have been investigated in 2D airfoil and 3D configuration studies. This paper stresses the importance of preprocessing tools for adaptive airfoils, wings and other 3D configurations with their 4D extension to model shapes varying with time. From fast airfoil analysis to unsteady 3D Navier Stokes solvers a variety of operational CFD codes is available today, some have been used in our studies and we have adapted them to be design tools for flows with reduced shock waves. Visualization and animation is crucial for understanding the computed results, when especially the extension of our knowledge base for transonic flow phenomena to explain dynamic effects is still poor; we try to find suitable illustrations also for teaching purposes.

A couple of case studies will be presented, with proposing shape variations in the regions of airfoil leading and trailing edges and for local curvature control by bumps added to the surface geometry.

Numerical modeling tools

The activities to be reported here make use of our flexible geometry preprocessors, fast numerical evaluation by operational CFD codes and finally the modern tools of graphic visualization.

Geometry definition

Since the early days of CFD code development a crucial problem is the definition of boundary conditions beyond being able to describe some simple test cases of 2D and 3D shapes with mathematical accuracy. The goal of offering arbitrarily dense sets of surface data for refined and complex configurations is a prerequisite for using advanced computational flow analysis. We have developed geometry generators [2] with a strong control of shape parameters which most efficiently influence the aerodynamic behavior of an aerospace component, this way giving an intelligent input for commercial CAD methods to carry on with data production.

Airfoils used to be given from data bases for 3D wing or rotor blade design; now we tend to optimize such shapes with a set of parameters. Their number is as low as possible and for many applications has been tested to yield target shapes known from other methods. We presently use 11 basic parameters to obtain airfoils which model many given known shapes to good accuracy. Alternatively, ex-

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ternally given input data are accepted for geometry definition.

Local deformations applied to airfoils are first investigated by numerical simulation. Optimum shapes require availability of analytical models for ramps and bumps, leading and trailing edges are deformed mimicking the boundary condition of sealed slats and flaps. Simple analytic functions for rapid data generation are used, like a bump function based on suitable deformation of a sine function with adjustable parameters for location on the contour, (un)symmetry, ramp smoothness and crest curvature, see Figures 1 and 2:

$$z = z_2 \cdot \sin(f(x))^{g(x)}$$

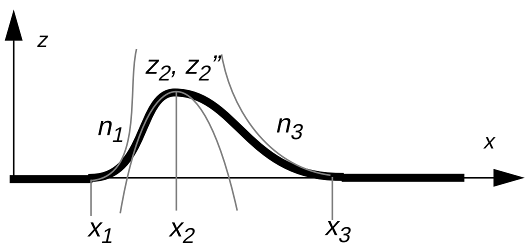

Fig. 1: Parameters for bump shape optimization

Mathematical models with parameters which are found useful for aerodynamic performance of the deformed component still need to be put to reality: First in wind tunnel models for experimental investigation and later in devices controlling the actual flight vehicle shape. Our knowledge still has to be developed about required deformation quantities on selected portions of the vehicle which presently is achieved by various CFD simulations of the flow past series of configuration changes by those model functions.

The large number of possible choices of the parameters influencing flow quality are reduced if we learn from fluid mechanic phenomena modelling: local solutions to the equations of motion suggest choice and quantity of parameters like those in the above bump function to control local and sometimes global flow structure. This applies most dramatically to transonic flow which requires a careful tuning of flow boundary surfaces to arrive at efficient performance in this speed regime.

Transonic design techniques

An important part of our knowledge is experience about the quantitative flow changes reached by certain shape modifications. A few systematic techniques to design airfoils and wings for transonic speeds have been developed. We prefer the ´fictitious gas´ concept which helped us to

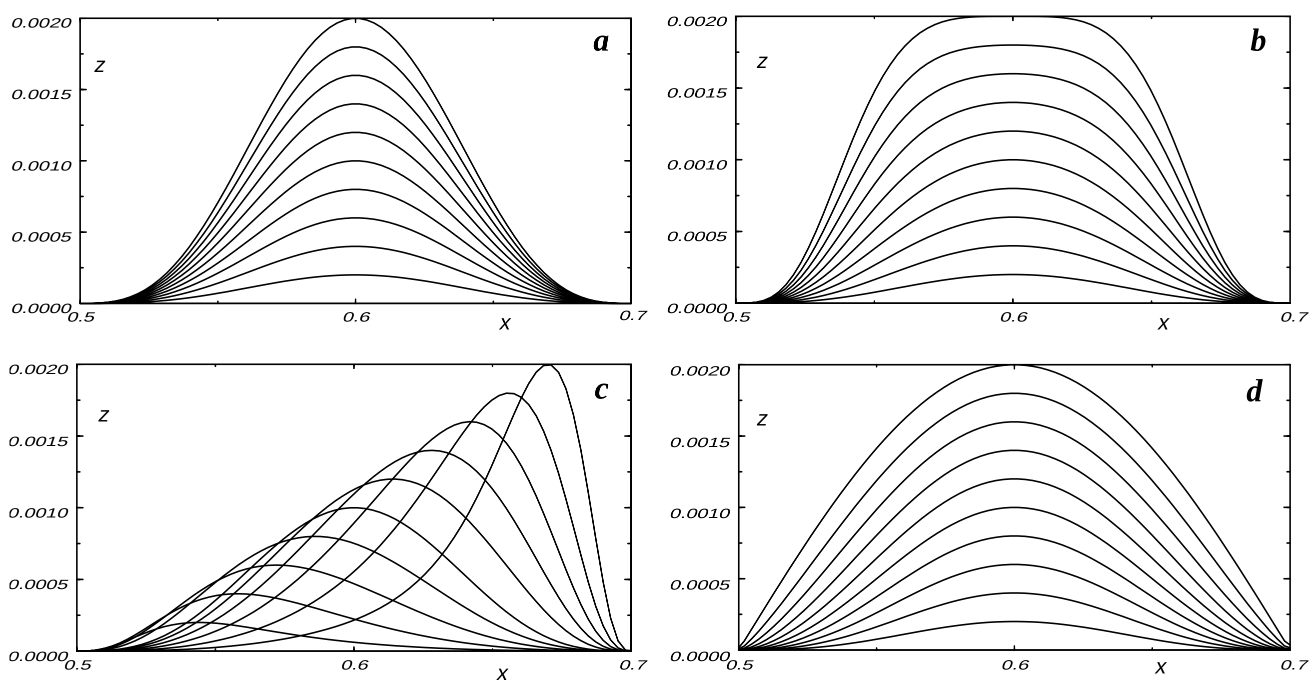

Fig. 2: Bump shape variations by 3 independent parameters besides bump height z_2 only (a): Crest curvature z_2''(b), crest location x_2 (c), end ramps exponent $n = n_1 = n_2$ (d). Constant range $x_1 < x < x_3$.

learn about local geometry changes needed to yield the removal of a recompression shock from an airfoil in transonic Mach number. From the inverse design concept to direct shape definition following practical constraints we may get ideally optimum, or simply ’improved’ airfoils: our experience with such design exercises trains our ability to adapt a configuration to varying operation conditions [3].

Specialized CFD codes

After performing series of steady flow computations with modified boundary conditions we use a time-accurate Navier/Stokes solver for 2D airfoils [4] which has been extended to run in a shock-free design version, with the inverse method of characteristics completing the calculation and yielding part of the airfoil contour.

Understanding the phenomena

We see characteristics as a part of the geometry, extended into the flow field: the steady 2D patterns as well as the 3D visualization of Mach waves on an airfoil surface in unsteady flow teaches us where shapes are sensitive to small changes. Airfoils in high subsonic Mach numbers exhibit large supersonic domains, with shocks triggering separation and breakdown of aerodynamic performance. The same may occur in very low Mach numbers near the leading edge of an airfoil with high angle of attack: An equally strong shock may destroy flow quality and lead to separation right at the leading edge [5]. Here we may apply re-design techniques generating shape modifications which should be realized by mechanical devices in experimental set-ups.

The following case studies make use of these modeling tools, implemented in geometry preprocessing, used for flow model manipulation and motivating development of new postprocessing (visualization) tools.

Case studies

Airfoil modifications are still our primary work topic using the abovementioned tools and experimental investigations before three-dimensional applications can be studied. A single 3D configuration was defined for experimental investigations, consisting of variable model parts: Geometry of a high wing transport aircraft wing-body combination has been generated and shape variations are applied for two different purposes:

First, variable inserts for the wing root area with different degree of filleting are tested to define a case study for optimization with a 3D highly parameterized shape module. Second, the model with a wing span of 1.30m was investigated in a wind tunnel of 1.00m width with clipped wings because only the flow details near the wing root were to be studied in detail there. To maintain the design wing load locally, circulation control splitter blades (CCSB) were mounted to the clipped wing tip. These devices have adaptive flaps to adjust wing load optimally to the clean wing design (elliptic) load distribution [6].

This example, with the technology of an adaptive wind tunnel is in fact a complex case study of active flow control, but it is interesting mainly for experimental techniques and will be reported in detail elsewhere. Our main interest is focused on airfoils with added devices modifying the flow boundary in a controlled way. So far we see this mainly at the leading and at the trailing edge and on some selected portions of the surface. The following examples will illustrate our approach.

Airfoil leading edge variations

Applications to helicopter rotor blades justify the study of 2D airfoils in steady and unsteady flow. Here we are first interested in modifying the leading edge to influence flow quality in the retreating phase of the rotor blade, where a high angle of attack should make up for lift reduction through reduced flow speed. Dynamic stall is the phenomenon to be controlled and we do this by a drooping of the airfoil nose in flow with high angle of attack [7]. In addition to this shape modification which substantially reduces dynamic stall separation, we try to reduce the shock - and with it the negative effects of shock-viscous interaction - terminating the local supersonic bubble sitting on the leading edge [8]. We do this by a local nose flattening as the shock-free design method tells us, see Fig.3. Further improvements have been gained, a remarkable delay in dynamic stall has been found, see Fig. 4.

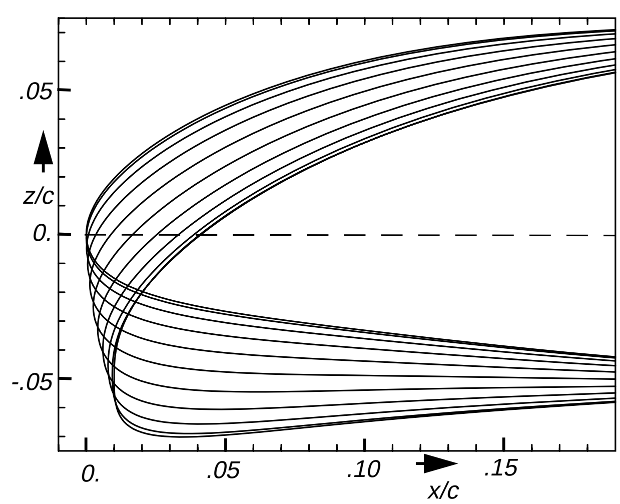

Fig. 3: Basic airfoil NACA 23012 with cyclic nose droop and additional cyclic flattening of the nose tip.

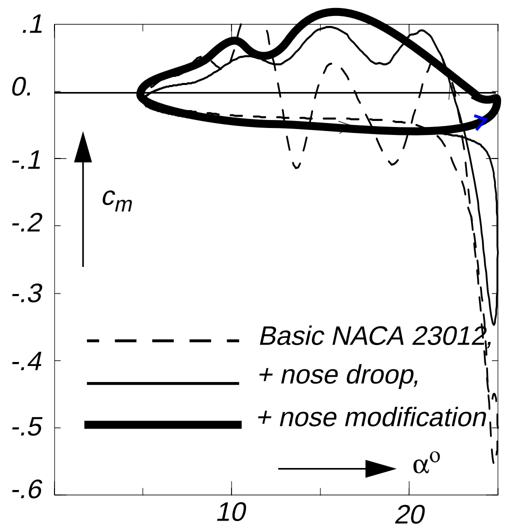

Fig. 4: Moment coefficient, unsteady airfoil flow: Periodic pitch $5^o < \alpha < 25^o$ in $M_\infty = 0.3$, removal of negative damping for delay of dynamic stall.

In an international collaboration our numerical modeling tools are tested with an experiment using an NACA0012 airfoil with deformable nose [9]. Curvature control at the leading edge is the main purpose here, the challenge is a satisfactory numerical modelling of the flow near this deformed leading edge. Problems arise from trying to find the experimental unsteady boundary conditions in order to model them with a suitable selection of varying geometry parameters for CFD simulation.

Airfoil trailing edge variations

Some recent experiments using an airfoil with an oscillating flap provide data to validate our numerical tools for simulation of flaps (Fig. 5) of variable size or other similar devices near the trailing edge for unsteady flow control [10], [11].

The experimental setup is depicted in Fig 6: Pressure sensors along the blade midsection and unsteady force- and moment measurement by a piezoelectric balance are carried out. PIV Laser allows for instantaneous flow field measurement.

Applications to rotor aerodynamics are of interest, but also steady flow past wing sections may be influenced favorably by control devices near the trailing edge.

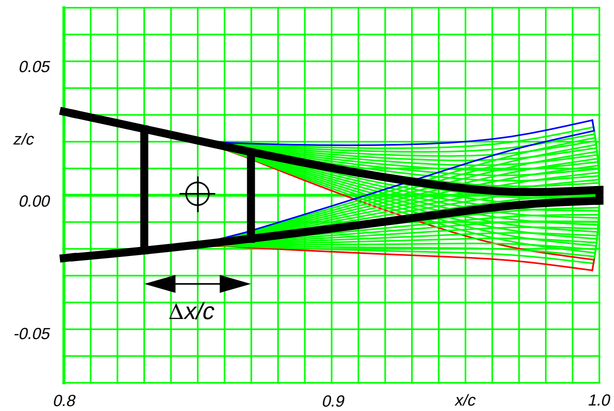

Fig. 5: Sealed flap modeled by locally elastic domain connecting rigid parts of original airfoil

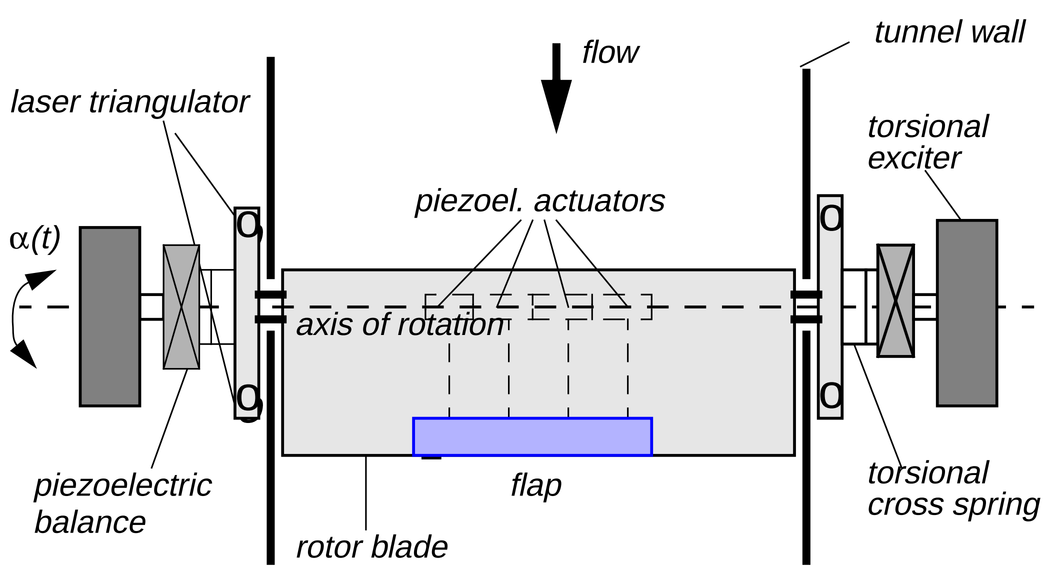

Fig. 6: Test Setup in DLR Transonic Windtunnel Göttingen

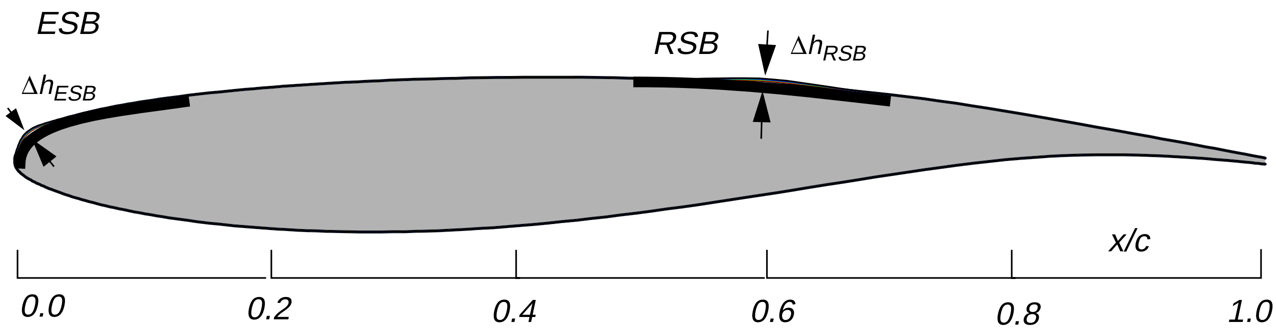

Fig. 7: Airfoil with Expansion Shoulder Bump (ESB) and Recompression Shoulder Bump (RSB)

Flow control by ESB and RSB

This paragraph is dedicated to results derived from the shock-free design method, adapted to practically interesting shape changes like local bumps on the surface. Such bumps are creating curvature distributions similar to those resulting from shock-free redesign [3], but usually their extent over the surface is too large for a practical device added to the wing or blade structure. In [12] a tradeoff between the advantage of bumps of reduced extent and necessarily reduced aerodynamic improvements is studied. We realize that the well-known idea of a bump to be added near the recompression shock for shock-boundary layer interaction control (SBLIC) is just a small rest of a transonic recompression shoulder, which together with a sonic expansion shoulder allows for the isolated solution of shock-free flow. European activities in SBLIC are reviewed in [13]. In [12] we try to go the alternative way of applying an Expansion Shoulder Bump (ESB) which influences the whole local supersonic flow domain so that it also weakens the recompression shock.

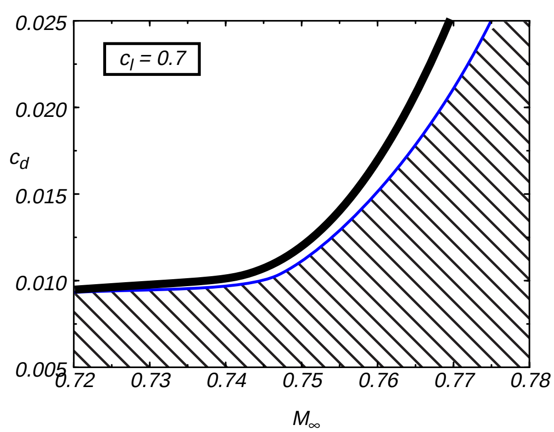

Fig. 8: Drag rise curve of baseline airfoil and envelope of possible improvements by combined variation of ESB and RSB.

Results from numerical simulation of an added ESB show improvements in aerodynamic efficiency (Lift/Drag) up to 8. - 15% depending on the CFD code used.

In a continuation of this study both an Expansion and Recompression Shoulder Bump (ESB & RSB) was used: Fig. 7 shows the ranges of these surface modification: 0 - 15 % chord for the ESB and 50 - 70 % chord for the RSB, with continuous curvatures at the ramps. Both bump maximum heights Δh added to the airfoil surface do not exceed $\Delta h/c \sim 0.003$. For given lift and a range of Mach numbers $0.72 < M_\infty < 0.77$ with different combinations of bump heights an envelope was found showing certain improvents to the drag rise curve (Fig. 8). Again, we observe drag reductions in the order of 10%. These results of a manual optimization, guided by our knowledge base of transonic airfoils, are just a first probe into a parameter space where practical improvements to cruise and off-design conditions are likely to be found and automated optimization routines will find dual ESB/RSB heights to guarantee airfoil operation along the envelope of minimum drag.

An additional dimension to such concepts is added if Mach and/or angle-of-attack changes happen periodically with a frequency to spark strong unsteady effects. This occurs with helicopter rotor blades where Mach number and angle of attack are tuned to ensure constant lift. Also, a tuning of the bumps into observed buffet frequencies may be used to counteract occurrence of this dangerous phenomenon. The flattening at the airfoil nose example Fig. 3 accomodates a nearly shock-free supersonic domain, illustrating that transonic design methodology successfully can be applied to this low speed, unsteady flow.

The outlined concepts to modify airfoil leading and trailing edges, as well as portions of the contour which control a shock terminating a local supersonic domain, have to be built for experiment and real flight components. Elastic and pneumatic devices are to be developed to this end, some results may have strong potential to be used successfully.

Flow field manipulations

Our knowledge base of fluid mechanics in the transonic domain has been educated by application of the equations of motion and thermodynamics to simulate practical case studies. Complexity of the occurring mixed (elliptic/hyperbolic) type of gasdynamic equations has led us to the 'Fictitious Gas' design method [3], which was implemented in various CFD codes, including our time-accurate Navier-Stokes solver [14]. Originally a purely mathematical process to alter these equations artificially and temporarily to replace them later in the design process by the correct equations, the question arose about a physical interpretation to such manipulations. Initially termed to be 'fictitious' physics, there is still the physical interpretation of a flow-velocity-controlled removal and subsequent re-injection of energy along a streamline within the domain where the velocity exceeds the critical (sonic) value [15].

This is illustrated by depicting the entropy production within the flow field. We compare the transonic flow of a given airfoil in ideal gas flow with a shock, Fig. 9, to a flow past the same airfoil which was computed for a changed equation of state. Besides of the shock now being removed, we observe an area within the sonic line which seems to be cooled in a controlled way but with the inviscid flow constant entropy level restored for each streamline outside the boundary layer once the critical velocity is reached again. Aerodynamic parameters like lift and drag are compared and we observe that there is a strong gain of aerodynamic efficiency.

Regardless of however difficult a practical implementation would be, this example shows that a concept of controlled energy manipulation ***within the flow*** past a constant airfoil shape might allow for similar changes as we have seen them already through simulation of contour variations.

Conclusions

Results for steady and unsteady airfoil flow with variable flow boundary conditions have been shown to have potential in optimizing aerodynamic performance through controlled adaptation to variable flow conditions. With the help of the knowledge bases of low speed as well as of transonic design and using flexible geometry preprocessor tools we apply shape changes to airfoils, wings and rotor blades, which result in drooped noses, variable camber trailing edges and locally added surface bumps.

Bumps in the nose area (ESB) and within the spoiler area of a wing (RSB) optimize transonic flow within practical constraints. Suitable tuning of bump geometries with unsteady flow conditions or with observed buffet frequencies lead to the delay of buffet boundaries or suppression of dynamic stall.

Still a purely theoretical concept, transonic design methodology suggests energy manipulations within localized areas of the flow off the contour, to arrive at substantial improvements of aerodynamic efficiency.

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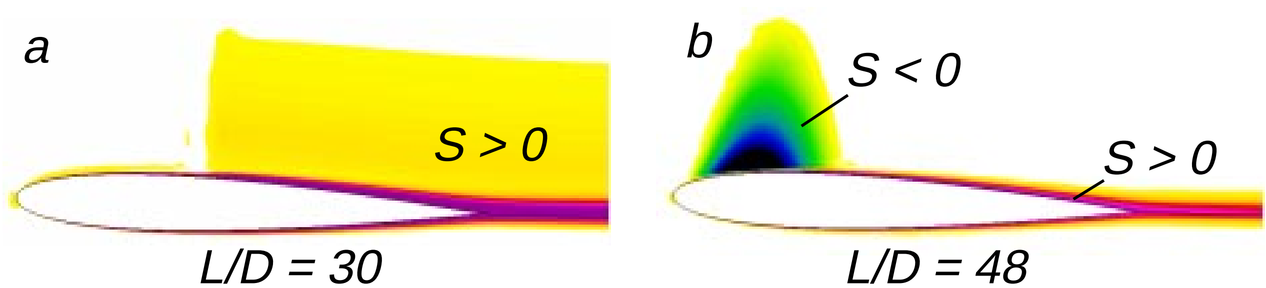

Fig. 9: Airfoil NACA0012 in transonic flow $M_\infty = 0.75$, $\alpha = 2^o$, Re = 2 Mill . Entropy isofringes for ideal gas flow showing entropy production within boundary layer and shock wave (a); For flow with 'fictitious gas' domain (b) a locally decreased entropy suggests interpretation of controlled heat removal and addition. Aerodynamic efficiency (lift/drag ratio) is increased by 60%.

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