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Using Flow Control Devices in Small Wind Tunnels

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Abstract

Complex configurations such as transonic transport aircrafts are well suited for testing modern tools of aircraft design. These tools are computer based systems as well as wind tunnel test devices. This paper reports about combining theoretical, numerical and experimental techniques to analyze and influence specific aerodynamic phenomena such as the flow quality in the wing root area. Large size wind tunnel models are needed to investigate the flow around such specific parts of the model. The aim of controlling transonic flow quality at the wing-body junction in a small wind tunnel has motivated the design for an incomplete and modular configuration. Specific devices are needed to simulate a lift distribution resulting from the complete model: Circulation Control Splitter Blades (CCSB) are replacing the wing tips. The investigated high wing configuration is a generic model for a new military transport aircraft. The model, called the DLR-F9, was tested at the transonic wind tunnel (TWG) at the DLR Göttingen. Results from numerical simulation and a first set of experiments using CCSB's are reported.

1. Introduction

Our knowledge base about supercritical wing technology [1] is used to define shapes which will have a positive influence to the aerodynamic efficiency of an aircraft. With very local shape modifications often leading to a better aerodynamic performance, it is necessary to have strong control of the geometric data. The present investigation is focused on the wing-root area of a high-wing transport aircraft configuration. The wing-body junction is of particular interest.

In this paper investigations on a high wing configuration are described with a model called the DLR-F9. This configuration is laid out for research with adaptive components. Due to the modular construction of the model it is possible to interchange different aerodynamic components.

A relatively large model is needed for wind tunnel tests to investigate the role of local geometry variations, Here, a model scale of 1:30 was found suitable and results in a model span of ~1.2m. To fit the model into the adaptive test section of the 1x1m Göttingen transonic wind tunnel (TWG), the wing tips had to be cut off and replaced by control devices to ensure the local flow quality of this incomplete aircraft model, which is comparable to the complete configuration with wing tips. Due to their sole purpose of influencing the spanwise lift distribution, we call these control devices **C**irculation **C**ontrol **S**plitter **B**lades (CCSB). Allowing for a more or less comfortable adjusting of these devices, the present goal is to control the local flow quality in the wing-body junction area. This should be feasible in a first experiment; later the procedure might be accelerated by automated devices.

In the following, the theoretical concept for CCSB, derived from basic lifting wing aerodynamics is explained. Some numerical results for simple wings, using 2D and 3D flow analysis codes will show that there are various options to define the geometrical shapes of CCSB's. For practical applications in the present case study, we use the results of an Euler code analysis of the flow field around the complete wing-body configuration to estimate the range of adjustable CCSB's mounted on the clipped wing tips in the wind tunnel.

2. Aerodynamics of incomplete wings

The distribution of aerodynamic load on a specific wing of finite span in the simple, classical case of inviscid flow, is determined by lifting wing theory. An ideal elliptic load (circulation Γ) distribution is sketched in Figure 1 as function of the span. A clipping of the wing tips would result in a substantial reduction of both total lift and sectional load, also in the center section.

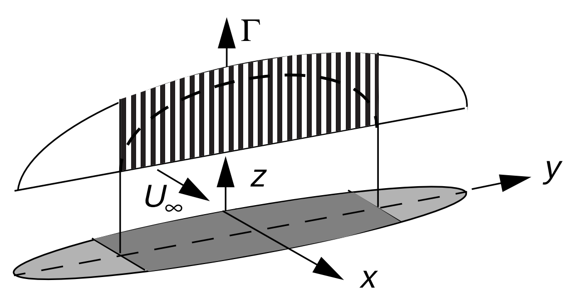

Figure 1: Lift distribution on a finite wing; load reduction on the wing with clipped tips.

Maintaining the elliptic distribution of the original wing along the wing with clipped tips would require means to control the flow around these clipped tips, such as end plates contoured like stream surfaces of the flow past the original wing.

Flow analysis codes and a field evaluation postprocessing are needed for a systematic design of such plates to be mounted onto the clipped wing tips. Simple 3D flows past a swept wing and past an elliptical wing were studied to determine the geometrical details of plates confining the ideal flow to a physically limited portion of the wing.

Swept wing theory allows an efficient use of 2D airfoil analysis CFD codes to determine the flow past an infinite swept wing. Experiments carried out [2] with elements of such wings mounted between wind tunnel walls required a contouring of the walls to compensate for the enforcing of plane flow boundaries. Figure 2 illustrates the application of swept wing theory to create a swept wing element between suitably contoured wall boundaries: 2D airfoil flow with the normal component of the Mach number plus a tangential component allows for integrating the flow field starting from selected upstream positions.

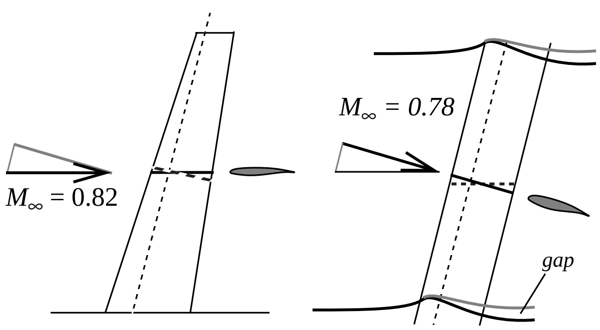

Figure 2: Swept wing and experimental setup for simulating an infinite swept wing with contoured sidewalls.

Differences in upper and lower flow vector distributions result in a gap of a stream surface at the trailing edge, see also Figure 3. This gap is proportional to circulation and therefore poses a major problem for running tests with varying angle of attack and hence varying lift: adaptive contoured walls allowing for gap variations would be needed. For model calculations we used Drela's airfoil analysis code, extended to an expert system [3], and our 3D CFD postprocessing software HIGHEND [4].

The technique of contoured walls is well-known but requires substantial modifications to the wind tunnel. Our goal is to minimize these additions and make them part of the wind tunnel model itself. This seems reasonable for the planned investigations of local flow phenomena but may open other possibilities for future testing of 'partial models in small wind tunnels'.

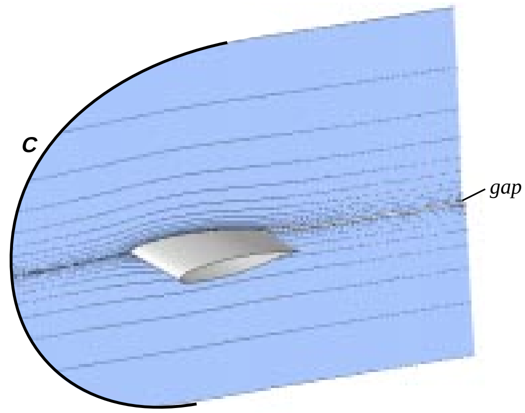

Figure 3: Stream surface integrated from infinite swept wing flow field, starting from given initial curve c. Note the discontinuity downstream of the wing trailing edge.

Another set of results was obtained from applying a new CFD Euler/Navier-Stokes code [5] to a finite 3D wing in transonic flow. Stream surfaces near the wing tips and for varied angle of attack were computed, information is obtained for the proportionalities between lift and gap size, and to test the CFD code for a detailed analysis of the complete wind tunnel configuration with CCSB's. Figure 4 and Figure 5 illustrate results for stream surfaces near the wing tips. Similar to the 2D phenomena governing infinite swept wing contoured walls, we observe that the stream surface has strong twist near the wing surface, resulting in the above mentioned gap, and approaching an undisturbed sidewall plane in larger distance from the wing, corresponding to the far field behavior of the 3D lifting wing horse shoe vortex singularity.

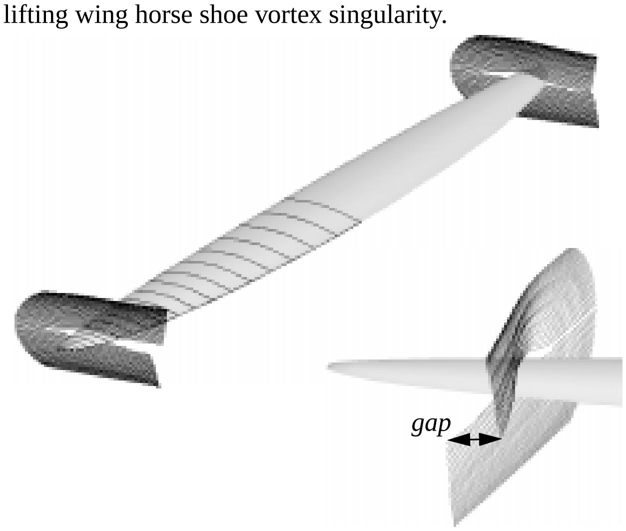

Figure 4: Stream surfaces past elliptic wing at 90% of halfspan, larger gap resulting from higher lift.

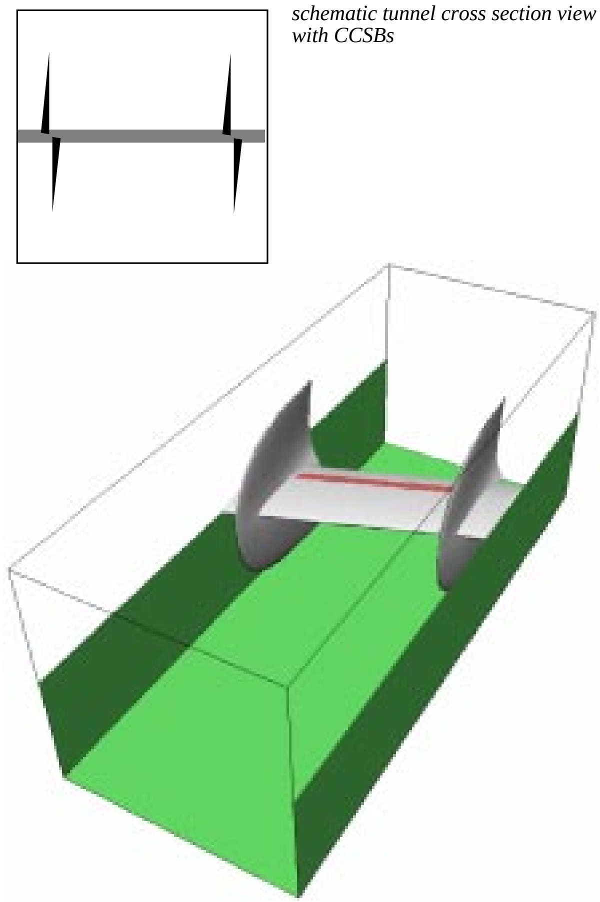

Figure 5: Swept wing in wind tunnel: Finite size choice of contoured CCSB's with smoothened gap. (Proposal for an experiment to study swept wing shock-boundary layer interaction control).

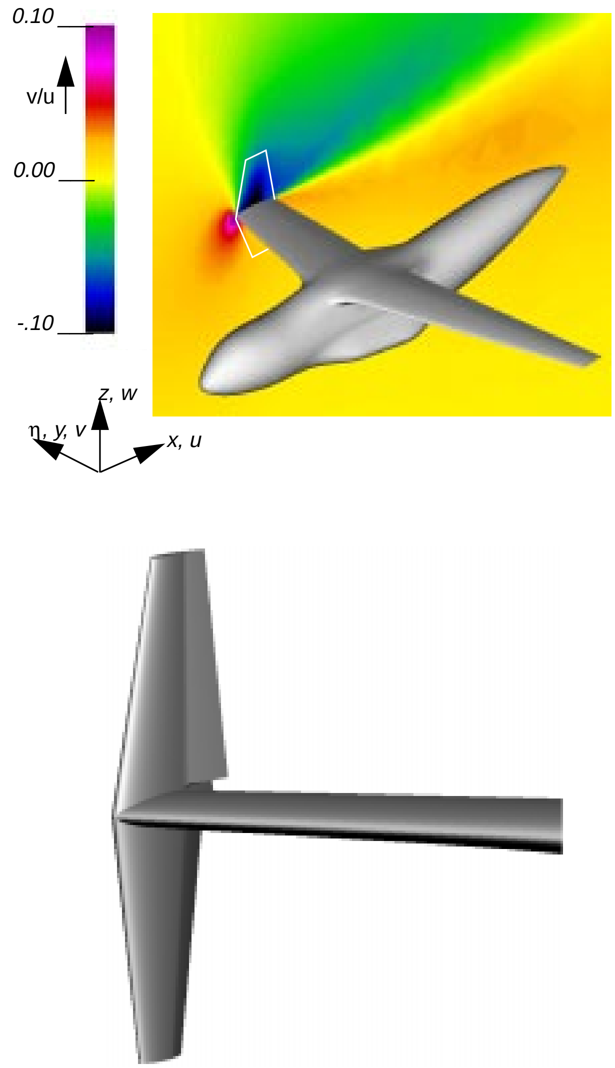

Figure 6: Flow deflection in plane η = 0.6 (M_∞=0.74, α($C_{L,wing}$=0.6)) (above); actually built CCSB with flaps (below).

3. Design of Circulation Control Splitter Blades (CCSB's)

Practical devices simulating a bounding stream surface should be finite and adjustable to various circulations. Relative to model size and to the wind tunnel cross section a choice has to be made for the size and shape of end plates serving as special winglets (CCSB's) for circulation control across span between the devices. Compromises have to be made and parametric investigations seem necessary. Figure 5 shows an idealized geometry for the CCSB's, based on the integration results with a smoothened gap and at most only suitable for one angle of attack.

For a 3D wing-body configuration, the complete model is necessary if aerodynamic performance is to be measured. For detailed studies not requiring the integral data, a partial model to increase the model scale may suffice if changes in the boundary conditions are under control. Focusing investigations on the fuselage and wing root area, we may cut off the wing tips if we compensate for the losses in circulation near the wing center plane (Figure 1). For the configuration to be further explained below, our efforts to control this compensation are illustrated in Figure 6: An inviscid (Euler) CFD flow simulation sheds light in the flow quality in the plane of constant span where a CCSB is planned to replace the wing tip. A practical, finite size CCSB to be chosen suitably is designed as a T-type double winglet with antisymmetrical adjustable flaps. Figure 6 (below) shows a finite size CCSB with a symmetrical section and flaps, it is the device chosen for application to the clipped wings DLR-F9 experiment.

4. DLR-F9: test case for CFD and CAD

The goal of providing precisely defined case studies for the development of computational aerodynamics is achieved in a satisfactory way if surface geometry data for aircraft and its components are created for arbitrary preprocessing of CFD and experiment. This requires geometry definition for both CFD grid generation and for CAD experimental model data production. At the DLR in Göttingen a first case study DLR-F5 [6] was created, experimentally tested and both the surface geometry and experimental results made available to the CFD community. This configuration consists of a clean wing half model in a closed wind tunnel, with a large splitter blade and suction device removing the tunnel boundary layer from the wall where the wing is mounted. Providing experimentally measured inlet, exit and wall flow conditions, boundary conditions for a transonic flow problem are completely defined and have been used by various researchers for development of their Navier-Stokes codes.

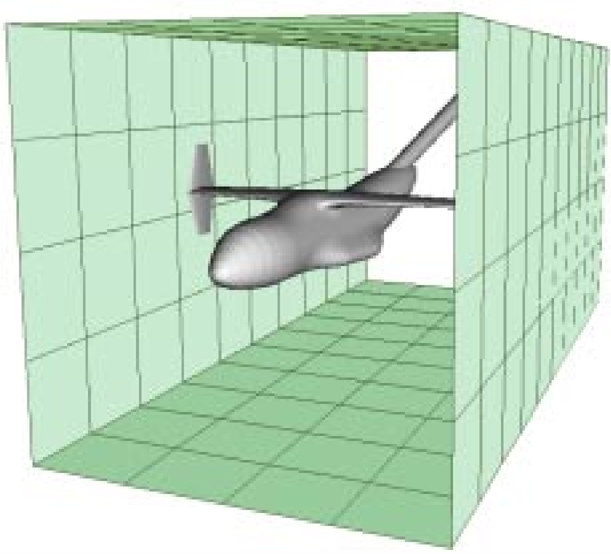

Figure 7: DLR-F9: general arrangement in TWG wind tunnel.

With the new case study DLR-F9 (Figure 7), this tradition of providing a precisely defined shape is continued. This time it is a wing-body configuration derived from a complete aircraft generated with our geometry tool ([7],[8]), plus geometry defined for model support (sting, sword) in the adaptive section of the transonic wind tunnel and - our topic in this paper - CCSB's mounted to clipped wing tips (Figure 6). This configuration has modular structure; parametric variation of the wing body juncture is the primary target of comparing experiment with results from computational optimization strategies. Furthermore, the aerodynamically critical components of the afterbody and the wheel gear box may be interchanged, following the advice to be given by computational optimization. These phenomena are to be observed experimentally in the area of the fuselage, with a wing given and (for this series of investigations) not to be varied.

For this incomplete wing with clipped tips, the reduced aspect ratio has to be compensated by CCSB's. The first experiment with this configuration is aimed at testing this auxiliary device itself, besides collecting data with a first set of modular parts.

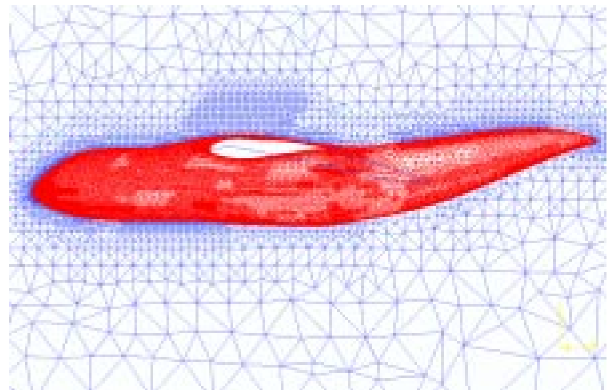

Figure 8: Unstructured grid for Euler flow simulation.

Numerical simulation of the complete configuration within the wind tunnel TWG is carried out to select optimum flaps deflection for a few flow conditions (M_∞, α). Euler analysis must suffice for this first approach, with a flow angle α correction expected to become necessary in the experiment. The code [5] requires an unstructured grid (Figure 8), which was generated with a commercial CAD system [9] after the geometry preprocessor software provided dense surface grids for each component.

Adjustment of the flaps deflection was first estimated from the previous computation of the flow parameters in the CCSB span plane for the unclipped wing (Figure 6, above). This idealized result and basic aerodynamic considerations for airfoils with flap suggested a choice of flap deflections of 10^o outwards for the lower half and of 15^o inwards for the upper half of the CCSB (Figure 6, below). This configuration was computed and pressure distributions were compared with the unclipped wing data. The wing was designed for $M_\infty = 0.72$ using geometry preprocessor functions with parameters which are based on an earlier research project collaboration with the aircraft industry [10]. Pressure distributions show isobars parallel to the lines of constant section chord and also the stronger shock in off-design conditions (M_∞ = 0.74, C_L = 0.6) which sits at nearly constant chord from the root to the tip. A measure of obtaining the circulation of the complete wing in the inner portion of the clipped wing with a suitably adjusted CCSB is therefore the pressure distribution and the shock location. Another sensitive measure is the size of the visualized sonic bubble, compared to the bubble on the unclipped wing.

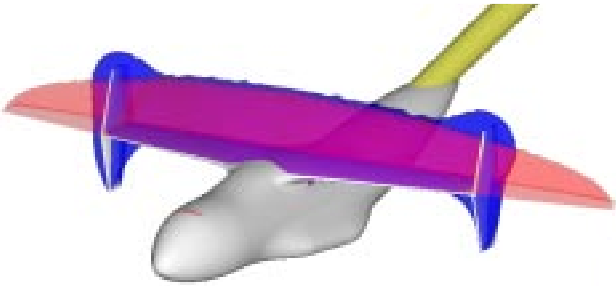

Figure 9: Visualization of sonic surfaces on original wing and on clipped wing with CCSB's.

Figure 9 shows an overlay of the graphics for both CFD simulations: the configuration with full wing in free flight and the clipped wing with CCSBs and model support within the wind tunnel. Displayed are the sonic bubbles for both cases, showing the area of relatively undisturbed wing flow on the clipped wing up to a span close to the CCSBs. Wall interference, displacement and circulation generation show that the CCSBs themselves are deeply immersed in the local supersonic flow bubble. A detailed analysis will suggest how this device in the future may be refined.

5. First experiment with the DLR-F9

The confirmation through numerical simulation that the concept of CCSB with flaps may work in practice, data of all components for a CAD system were provided by the geometry generator and the model was manufactured. We stress here the use of the same software to serve as preprocessor for both CFD and CAD input data production. The present case study serves the purpose of aligning these two routes in applied aerodynamics as a benchmark example. Figure 10 shows a photograph of the model in the Göttingen wind tunnel test section.

The first experiment, in addition to running a whole series of Mach numbers and angles of attack, was aimed at selecting a 'best fit' to the numerically found adjustment of CCSBs. For this purpose, a run-time data analysis was used during the experiment to decide whether the concept worked and where the design criteria were met. A rapid and effective detailed analysis of the flow field was necessary. The analysis involved the evaluation of pressure distribution and local lift at various cross sections of the wing (see Figure 11) as well as an automatic detection of the shock position along the wing span. This was carried out with a special advanced data processing tool [11].

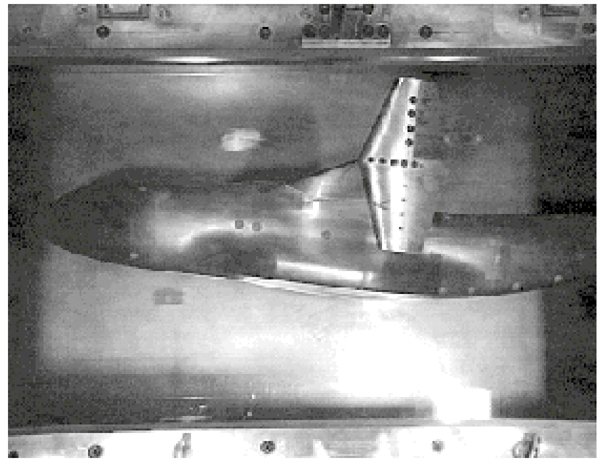

Figure 10: DLR-F9 wind tunnel model in Göttingen tunnel TWG.

As mentioned above, one of the selection criteria for defining a set of flow parameters that allows for valid aerodynamic testing with corrected scale and wing clip influence was the position of the shock on the upper surface of the wing, for the selected flap deflections of the CCSBs the shock should be parallel to the trailing edge of the wing.

The software provides extraction of the shock position by analysis of the steepest gradient in the pressure distribution after interpolating the pressure profile. This is performed for all measured cross sections of the wing.

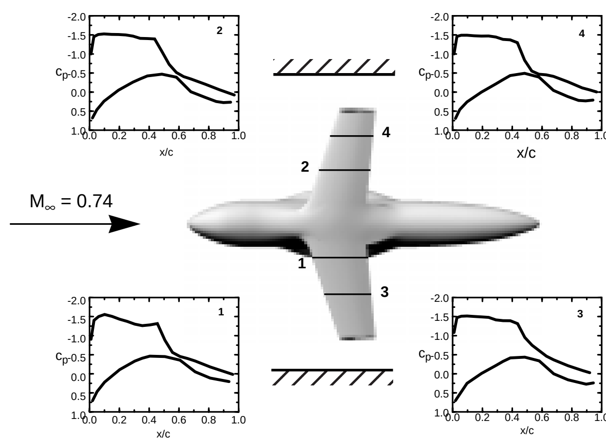

Figure 11: Model geometry relative to wind tunnel sidewalls. Pressure measurements along 4 wing sections, $M_\infty = 0.74$, $Re = 1.7$ Mill, $\alpha = 4.5^o$

Figure 12 shows a comparative visualization of the shock position x_s versus chord length c of the four wing sections plotted against angle of attack α. The CCSBs fit optimally to the flow conditions if the shock positions coincide to a reasonable accuracy which indicates a shock location at constant chord or in general, a flow on the upper wing surface equivalent to that on an unclipped wing.

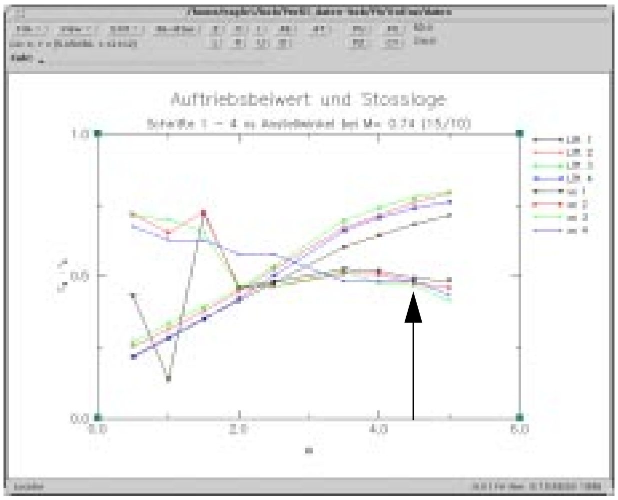

Figure 12: Lift coefficient and shock location vs. angle of attack, four wing sections. (Flow parameters equivalent to Figure 11)

Extracting the shock position for a series of flows with varying angle of attack, as shown here, allows to detect trends in the motion of the shock wave. This may be used for an optimized procedure to adjust the design angle of attack for a given set of CCSBs. The diagram shows that the desired condition seems to be fulfilled optimally at an angle of attack of $\alpha = 4.5^o$

For additional information the lift curves are plotted in the same window. This is important to check for flow separation and the appearance of buffet conditions. Besides the four wing sections of interest here, pressure measurements on selected body sections, as well as routine lift, drag and moment measurements were carried out [12] and represent the first part of data for this study with a series of modular model components.

6. Conclusion and future prospects

An experimental transonic wing-body configuration with an incomplete wing has been developed to allow for special investigations in the wing-root area. The technique of using a new device for circulation control at the clipped wing tips has been described, numerically simulated and verified in a first experiment. The device is a special winglet and is termed here Circulation Control Splitter Blade (CCSB).

Its use is planned for parametric variations of the DLR-F9 modular transport aircraft model to study the role of variable and optimized components in the wing-body junction area. Adaptive components should also prove useful for other concepts influencing local phenomena such as shock-boundary layer interaction control.

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