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Dynamic Flow Control on Rotor Blades Comprehensive Numerical and Experimental Tools at DLR-Göttingen

by

W.Geissler, H.Sobieczky, M.Raffel,
G.Schewe, M.Jacobs
DLR-Göttingen, Germany

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Abstract
Dynamic flow control on rotor blades is a major subject in helicopter flow research and has recently been verified by HHC- (Higher Harmonic Control) and IBC- (Individual Blade Control) concepts.
With these control devices only the complete rotor blade can be influenced leading to some severe limitations. Further improvements can be expected if the blades are controlled locally, i.e. by dynamic airfoil deformations at blade sections of high aerodynamic efficiency. The latter concept has advantages if detailed flow events like dynamic stall on the retreating blade or transonic effects on the advancing blade are to be influenced favorably. The efficiency of such **on-blade control** concepts has recently been demonstrated by a nose-droop device acting under dynamic stall conditions.
Addressing on-blade control concepts DLR-Göttingen has developed a set of necessary comprehensive numerical and experimental tools to investigate the unsteady aerodynamics about moving and deforming rotor airfoils and blades.
These tools include design procedures to define the suitable shapes of rotor airfoils and blades, the time-accurate calculation of unsteady flows by CFD-codes and experimental tools and wind tunnel facilities to measure instantaneous forces, pressure distributions and complete flow fields about oscillating blade models. In the present paper the main tools already available at DLR-Göttingen are described in detail.

1. Introduction.

In recent years the control concepts HHC (Higher Harmonic Control) and IBC (Individual Blade Control) have frequently been tested on model rotors [1],[2],as well as during flight tests [3]. Considerable improvements with respect to BVI noise- and vibration reduction were shown to be feasible. Noise reductions up to 6dB have been achieved, [4].
Present new investigations are focused on so called on-blade devices, i.e. only a small spanwise part of a rotor blade is made active. The advantage of such devices is obvious: The active part of the blade is located close to the blade tip where it has its highest aerodynamic efficiency. Different on-blade devices have been proposed: Beside of earlier concepts which are based on active (or passive) blowing and suction it seems now feasible to realize chordwise active deformations of the airfoil section itself. Sealed flap devices oscillating about their flap hinge lines are the first to be considered on model rotors [5],[6], and will also be the first to be tested under flight conditions. Moving flaps with only small chordwise extension will be used to reduce BVI noise and vibrations (servo flap device, [7]). Flaps with higher depths are envisaged to improve the rotor performance (Direct Lift Concept). It has to be investigated if the DLC concept may also favorably improve dynamic stall characteristics.
With recent improvements of structural devices towards applications of smart structures and smart materials it is now possible to think of more arbitrary airfoil deformations like leading edge deformations or even a combination of both leading- and trailing edge deformation.

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*DLR-Institute of Fluid Mechanics,**DLR-Institute of Aeroelasticity,***DLR-Wind Tunnels Göttingen

It has been shown by both numerical as well as experimental investigations that a dynamic curvature reduction at the airfoil leading edge shows considerable improvements with respect to dynamic stall characteristics [8]. It has also been shown numerically that drooping the leading edge actively may completely avoid or considerably reduce the dynamic stall vortex [9],[10].
Before these sophisticated control devices are accepted to be integrated into a rotor system, fundamental investigations have to be carried out on research basis where the aerodynamic part as well as the structural part of the problem has to be addressed.
The DLR in Göttingen has developed a set of tools for a systematic investigation of advanced rotor airfoil control devices:
Numerical and experimental tools have been developed to:
1. Design the deforming airfoil shape by a special Geometry Generator software,
2. Calculate the time-dependent flow about the dynamically deforming and oscillating airfoil by means of a Navier-Stokes code system.
3. Either measure the pressures instantaneously by in-situ pressure tabs or using the pressure sensitive paint technique (PSP) to gain informations along the complete blade model surface.
4. Determine instantaneous flow fields utilizing the Particle Image Velocimetry (PIV) as well as Interferometry (Mach-Zehnder, VAG).
5. Simulate model oscillations in appropriate test rigs equipped with actuators to drive the complete blade model.
6. Test blade models in wind tunnel facilities over the complete speed range relevant for rotor applications. The model chord can almost be the full size rotor blade chord with sufficient space to install actuators inside for driving leading or trailing edge flaps (TWG).
In the present paper the different tools available at DLR-Göttingen will be described in detail and results already obtained with these tools will be discussed.

2. Geometry Generator.

Software tools have been developed to design dynamically deforming airfoil and blade surfaces as a preprocessing of boundary conditions for Computational Fluid Dynamics (CFD-) tools, to calculate the complex flow involved. The definition and adaption of deforming surfaces is guided by the fluid dynamic knowledge base and its application to aerodynamic design [11].
The software employs analytic functions with suitable parameters to create local shape modifications with strong control of geometric properties like slopes and curvatures, with constraints only by the limitations of mechanical verification.

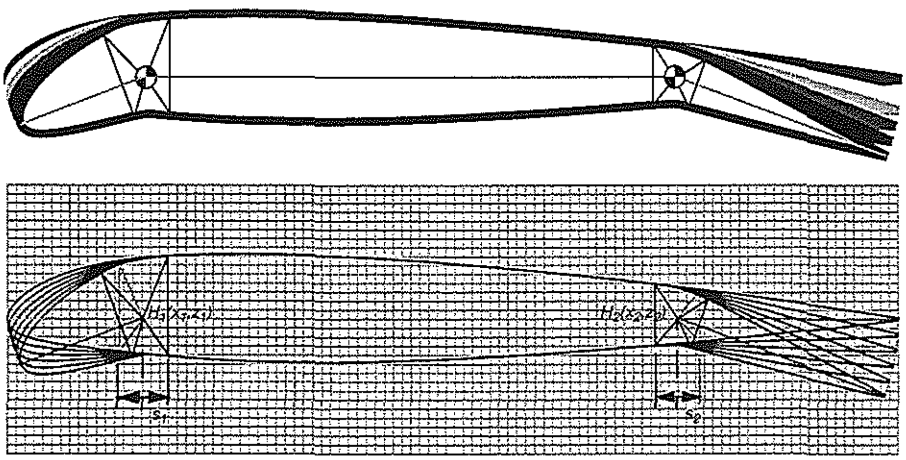


Fig.1:
Adaptive Aerodynamic Components.
Airfoils with Sealed Flaps and Slats.
Stepwise Deformations for Time-dependent Numerical Calculations.

3. CFD Tools.

For the calculation of the unsteady flows about oscillating airfoils including surface deformation CFD tools based on the time-accurate Navier-Stokes equations have been developed, [9]. A grid generation procedure has been applied where the grid outer boundary is attached to the space fixed frame and the inner boundary (airfoil surface) is allowed to deform in correspondence with the airfoil oscillation and deformation. With this grid generation procedure it is possible to treat cases of oscillating and deforming shapes where the time dependent shape variations have been determined by the Geometry Generation tool of section 2. Fig. 2 shows as an example the vorticity contours about a NACA23012 airfoil under deep dynamic stall conditions. The leading edge part of the airfoil is modified by a nose-droop device. The upper figures show a strong dynamic stall vortex developing on the basis airfoil at the maximum incidence of 25° at both M=0.1 (left) and M=0.3 (right). The lower figures show corresponding results for the nose-drooping case: The dynamic stall vortex has been completely suppressed in the low Mach number case. For the higher Mach number a vortex is still present but its strength is strongly reduced. Improvements on force- and moment coefficients are shown to be large [9]. Further local modifications at the position of a supersonic bubble terminated by a small but strong shock wave has further improved the results also for the M=0.3 case, [10].

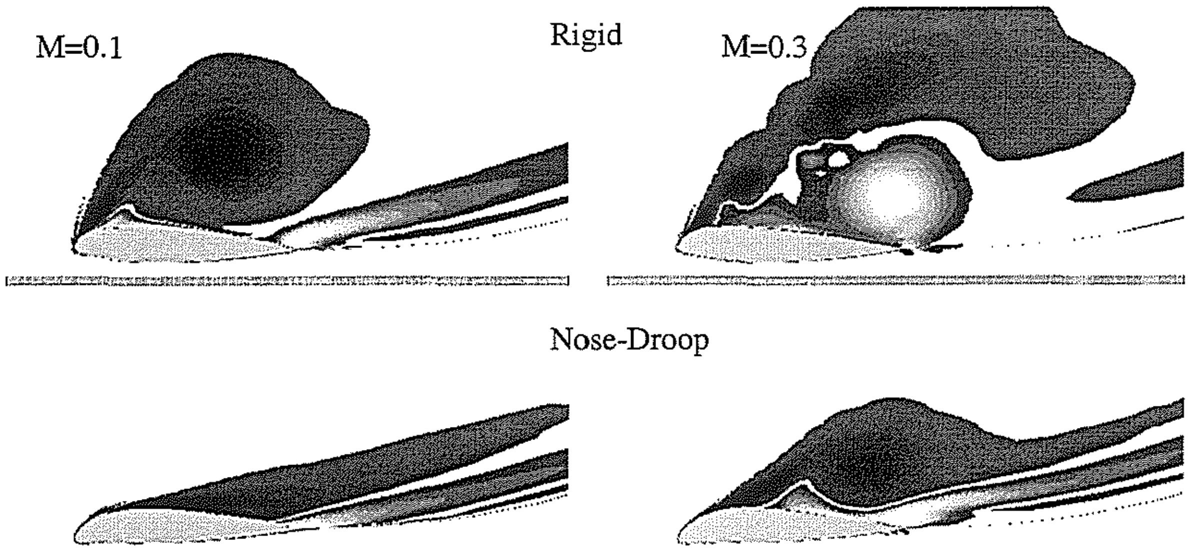


Fig. 2 : Dynamic Stall Control on NACA23012 Airfoil by a Nose-Droop Device
Upper Figures: Basis Airfoil, Lower Figures: Nose-drooping

4. Measuring Techniques:

In addition to numerical investigations experimental tools have been developed which are appropriate for rotor flow applications. Of importance are modern nonintrusive measurement techniques, i.e. the Particle Image Velocimetry (PIV) as well as surface pressure measurements by Pressure Sensitive Paint (PSP). These techniques have the advantage to measure the flow fields instantaneously. In particular PIV has proven to be a measuring technique which gives insight into unsteady separated flows on oscillating airfoils [12], as well as the flow details and development stages of complex tip vortices in the wake of model rotors (HART-projects). Fig. 3 shows the set up of the PIV measuring technique in a wind tunnel. In addition to PIV and PSP several additional measuring techniques like interferometry, hot film sensor technique etc. are available at DLR-Göttingen.

The PIV measuring technique has now been further developed to a 3D stereoskopic device including a system of two cameras for both in plane and out of plane velocity components. Fig.4 shows the test set up of the PIV 3D-device in the DNW open test section for comprehensive measurements of the wake velocity fields during the HART II project.

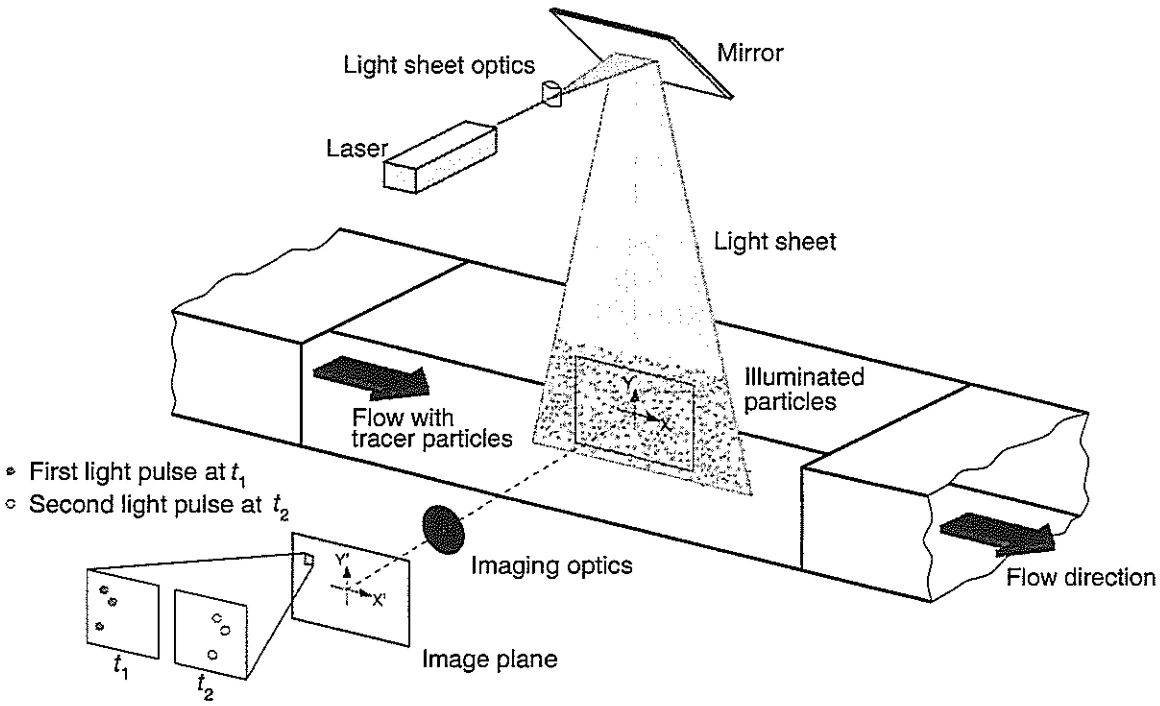


Fig.3: Particle Image Velocimetry for Instantaneous Velocity Field Measurements.

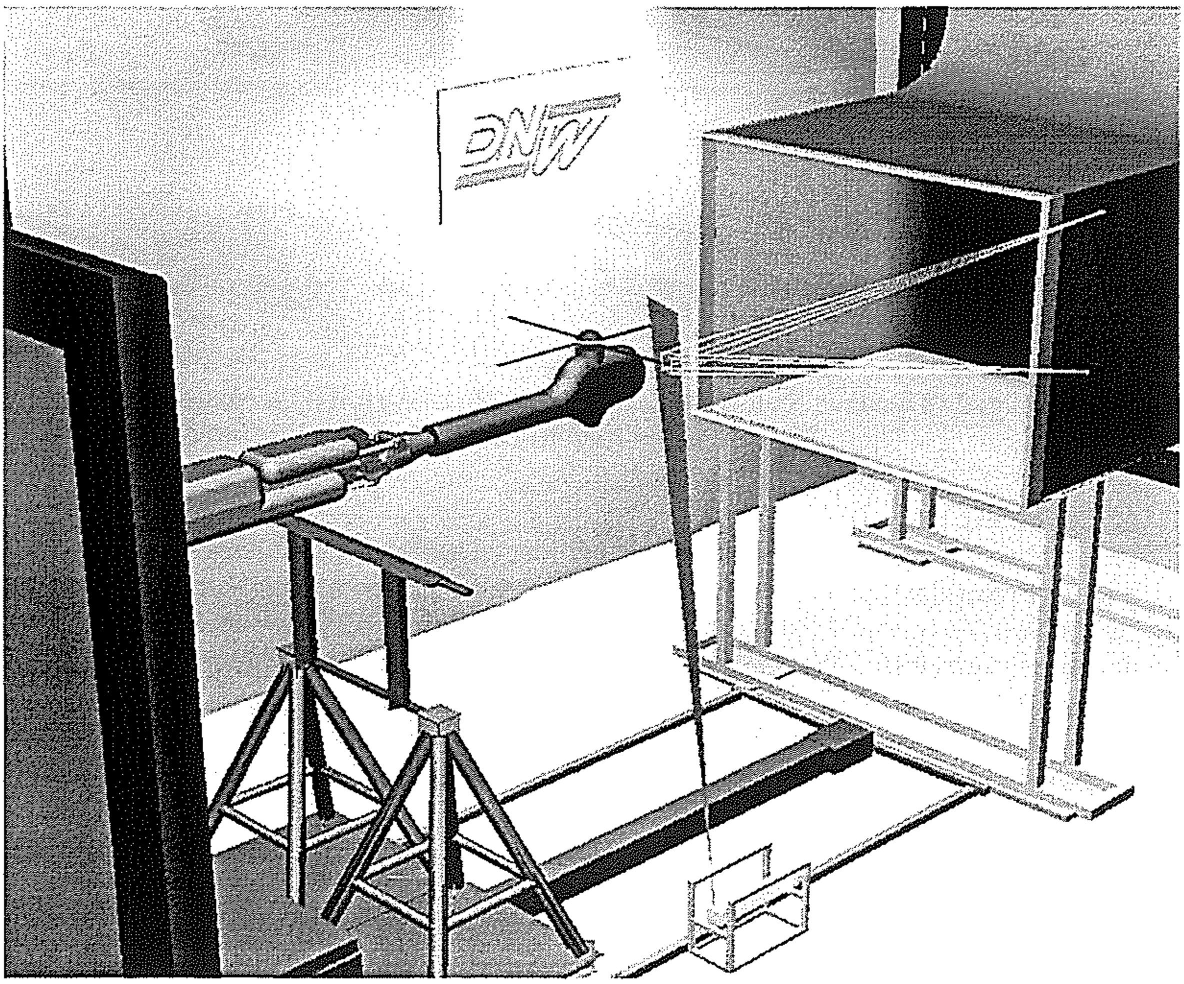


Fig. 4: HART II Test Set-up in the DNW Open Test Section

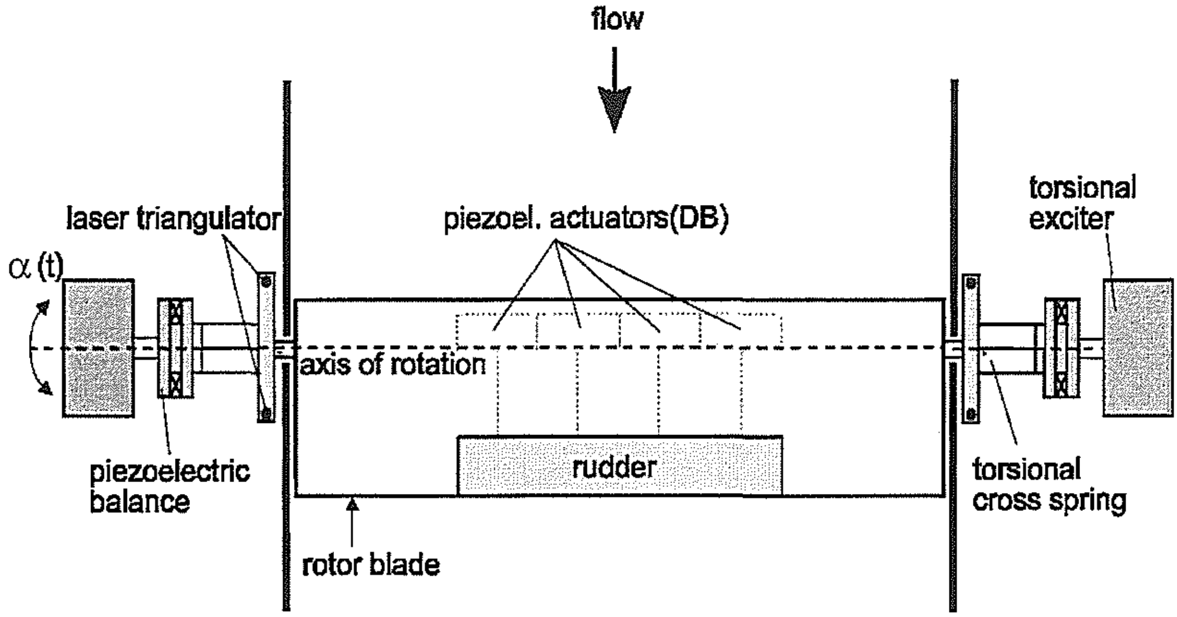


Fig. 5: Test Set-up in the DLR-TWG Wind Tunnel

5. Test set-ups for oscillating models.

For the measurement of steady/unsteady loads, pressures and time dependent flow fields two test set-ups have been developed to operate oscillating 2-D models in the Transonic Wind Tunnel, Göttingen.

The first one [13], (Fig 5), comprises the 2D-wing with both-sided torsional actuation for performing harmonic pitching motion. Optionally a torsional spring (1DOF) can be installed.

The second test set-up has a two-sided elastic suspension for heaving- & torsional motion (2 DOF) in order to perform flutter investigations. Each DOF can be blocked. For forced plunging motion heaving actuators can be installed. In addition the possibility of forced or free lead-lag motion is prepared. Both test rigs contain a rigid Piezo-balance and optical devices for nonintrusive measurement of the wing position.

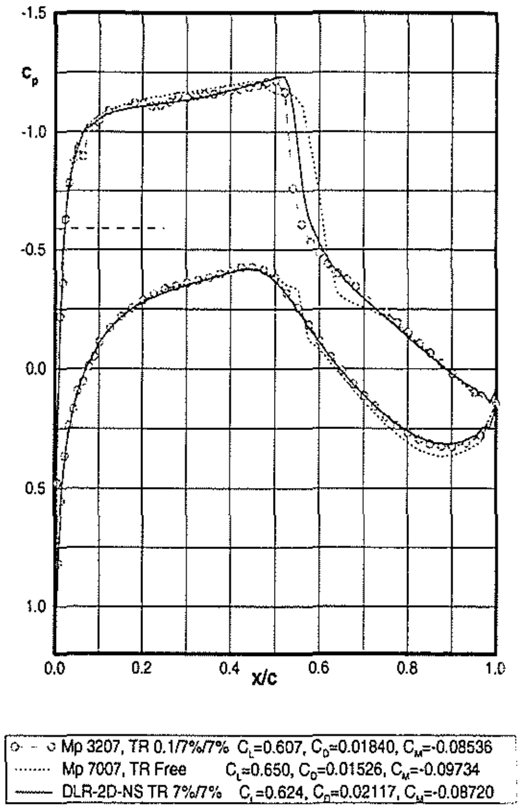
Special software has been developed for data acquisition and reduction purposes of large sets of instantaneous signals (RACT-project, HART-projects).

6. Transonic Wind Tunnel Göttingen (TWG).

For experimental work on rotor airfoils and blades the Transonic Wind Tunnel Göttingen [14] is a suitable tool. The Mach number range of this tunnel has recently been extended into the low speed regime ($0.3 \leq Ma \leq 0.9$), now covering the complete range of rotor relevant flow speeds.

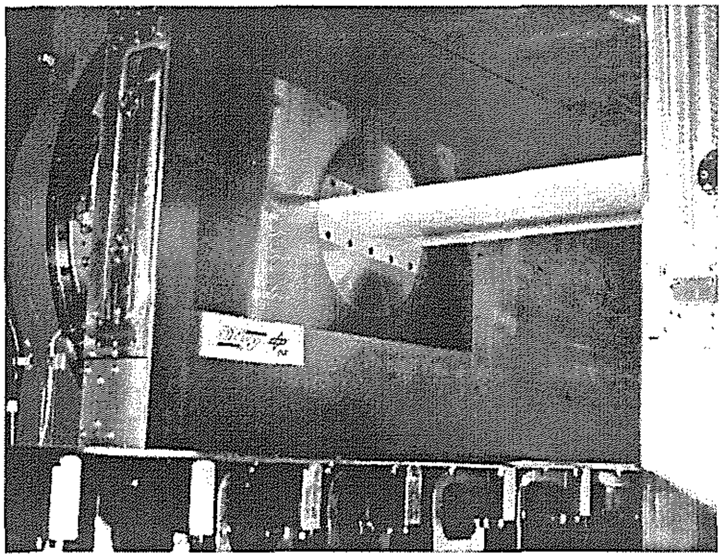
The test section of the wind tunnel has a cross section of 1mx1m and can therefore be used for 2D as well as 3D blade models of almost full size chord dimensions (0.3-0.4m). The tunnel is equipped with an adaptive wall test section with flexible top and bottom walls which is very successfully in use for 2D- and 3D-testing, (Fig.6).

Fig.7 shows calculated and measured polars for two different airfoil sections. The left figure includes experimental data from the perforated test section. The data are corrected by simple linear correction formulas (see [7]). Figure 6 (right) shows results obtained with the adaptive wall test section. The correspondence with the calculated polar is obvious. No additional corrections are necessary in this case. In case of instationary testing at least wall interferences resulting from the steady part of the flow are eliminated.



Transonic Laminar Airfoil in TWG with Adaptive Walls Test Section

Fig. 6: Blade Model in the TWG with Adaptive Wall Test Section (down), Measured and Calculated Pressure Distributions for the Airfoil Design Point (left)



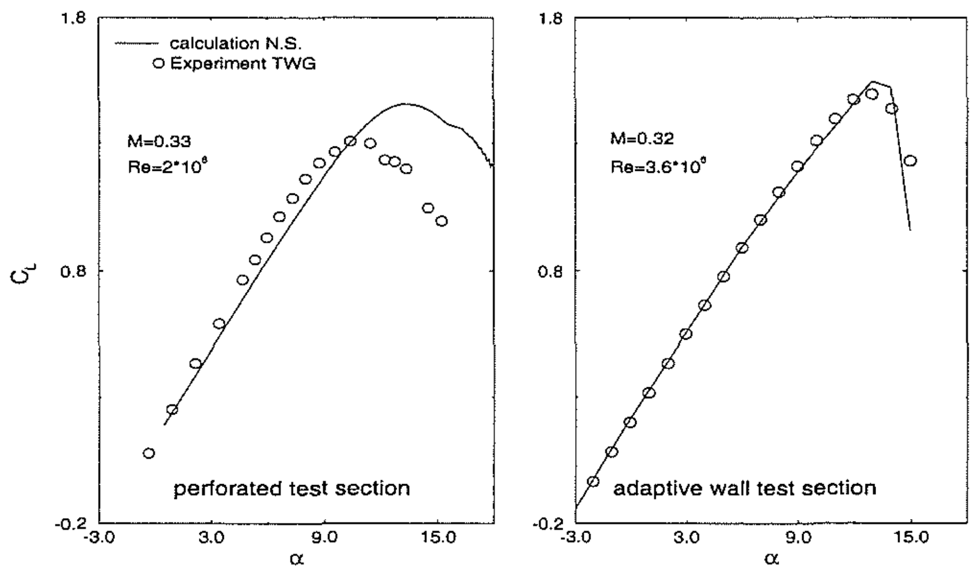


Fig. 7:
Polar measured in perforated test section including wall correction (left). Polar measured in adaptive wall test section (right, different airfoil), no additional corrections necessary.

7. Research Wind Tunnel Göttingen (VAG).

In addition to the large size transonic wind tunnel (TWG) a small size wind tunnel facility (VAG) is operational at DLR-Göttingen, Fig.8. This blow down tunnel allows only measurement of small size models of about 0.1m chord as maximum. The test section has the dimensions 0.1x0.35m and is only suitable for 2D-measurements. The whole Mach number regime necessary for helicopter applications is also available at this tunnel which is equipped with PIV and interferometry measurement techniques. The tunnel has been used intensively for blade vortex interaction investigations (BVI) and will be equipped with a test set-up to do forced model oscillations for dynamic stall investigations.

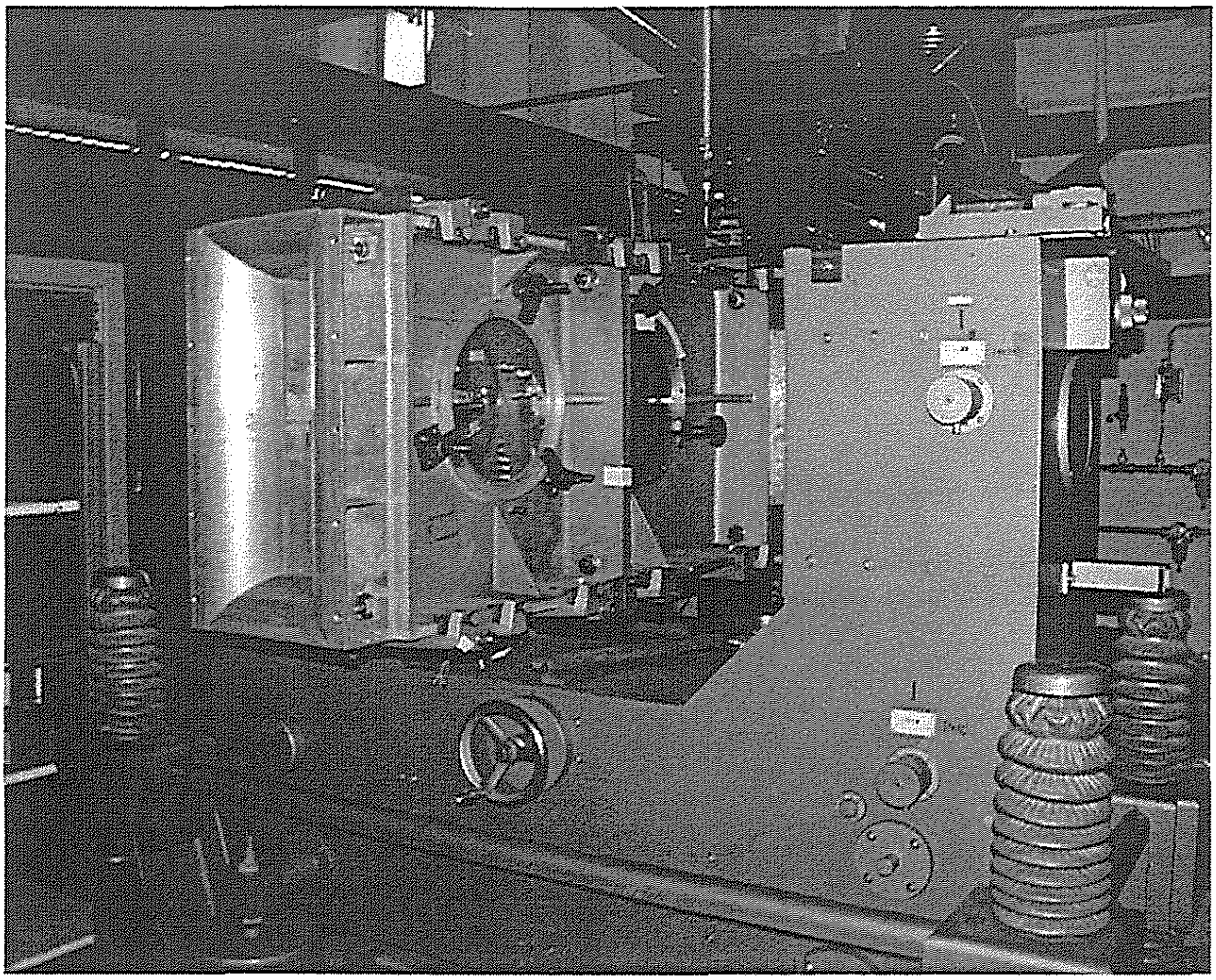


Fig. 8: Research Wind Tunnel VAG equipped with Mach-Zehnder Interferometer and PIV. Investigation of Instantaneous Flow fields at Dynamic Stall and Stall Control

PIV and interferometry will be combined to instantaneously measure both velocity and density fields for comprehensive flow field diagnostics. The tunnel is assumed as a necessary tool for systematic tests of new control devices for rotor airfoils combined with the design- and CFD-tools described above.

8. Successful application of tools.

In recent years most of the tools discussed above have successfully been used in a combined effort for the project RACT (Rotor Active Control Technology, [13]). RACT was a joint project of industry represented by ECD (Eurocopter Deutschland), DB (Daimler Benz Research Institute) and DLR institutions. In the project RACT a 2D-blade model was equipped with a 15% chord moving trailing edge flap as the control device. The flap was driven by Piezo-electric actuators installed inside the model. The test set-up for oscillating models of the DLR-Institute of Aeroelasticity has been used for these tests (see Fig.5). A discussion of numerical and experimental results of the RACT-project is included in [7].
Fig. 9 shows typical results of the RACT project including numerical and experimental force- and moment coefficients for the oscillating blade model (7Hz frequency) and the flap oscillating with 4/ref (28Hz).The time dependent lift shows a 1/ref variation with a 4/ref modulation due to the flap motion. The moment coefficient shows almost a 4/ref variation which is in good correspondence with the experimental data. Differences in the extreme values of the unsteady lift coefficient must

Fig. 9 (right): Force- and Moment Distributions versus Time. Blade Oscillation with 1/ref, Flap Oscillation with 4/ref.

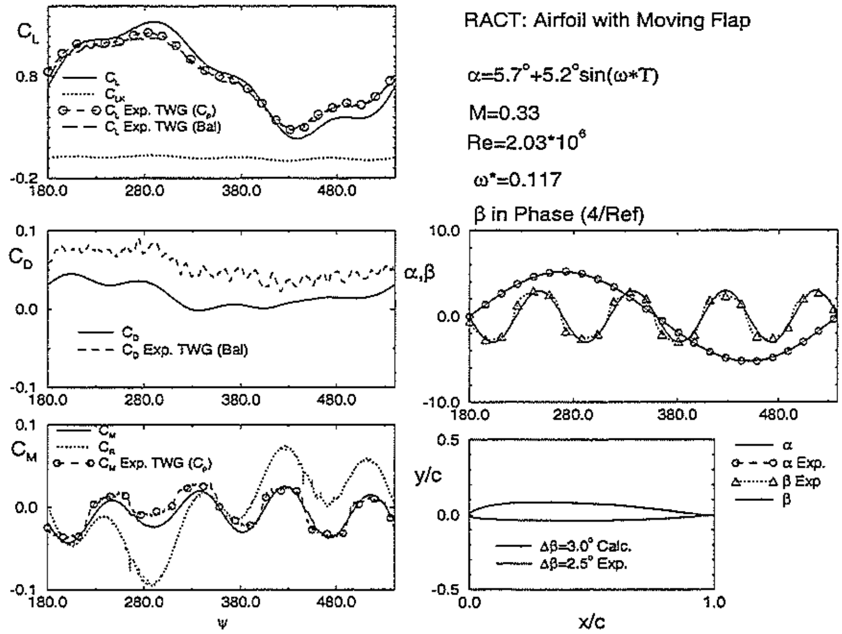
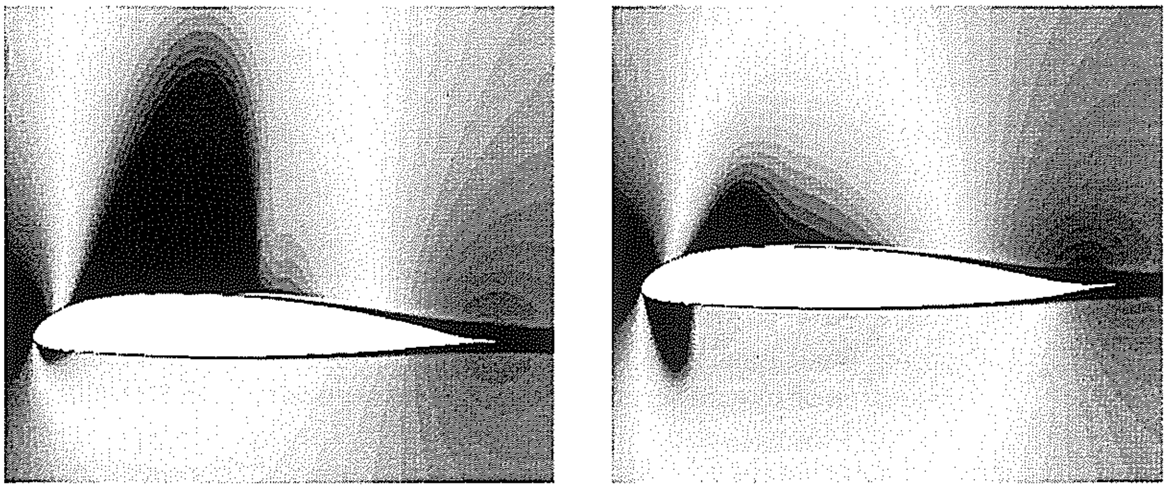


Fig.10 (down): Mach number Contours at compressible Flow (M=0.745): Blade at Fixed Position, Flap Oscillating with 1/ref.



be attributed to wind tunnel wall interference effects: A wall correction has only been applied for the steady mean incidence (see section 6) . A correction of the unsteady airloads is a difficult task which remains to be investigated in the future.

Fig. 10 shows calculated Mach number contours for M=0.745 with the airfoil in a fixed mean position and the flap oscillating with 1/ref.

The left figure shows the flap in its extreme downward position: a strong shock wave exists on the airfoil upper surface which has almost disappeared for the flap in its extreme upward position (right figure). In this case a supersonic area develops on the airfoil lower surface.

Of major concern for the RACT project was the investigation of flap efficiencies $dC_L/d\beta$ ($C_{L\beta}$) and $dC_M/d\beta$ ($C_{M\beta}$). Due to the special arrangement used for the experiment (Fig.5) it is obvious that integrated pressures at the mid chord of the model will not exactly represent a 2D situation. Therefor 3D calculations have been carried out in addition taking into account the finite length of the flap. For these calculations a 3D-Panel code has been used. This code is based on unsteady compressible thin flat plate theory and gives directly the lift- and moment derivatives with respect to the flap motion as a function of reduced frequency.

Fig. 11 shows amplitudes (left) and phase angles (right) for three different numerical approaches:

- 3D Panel Method
- 2D Navier-Stokes Code
- 2D Theodorsen Function (2D lifting line theory)

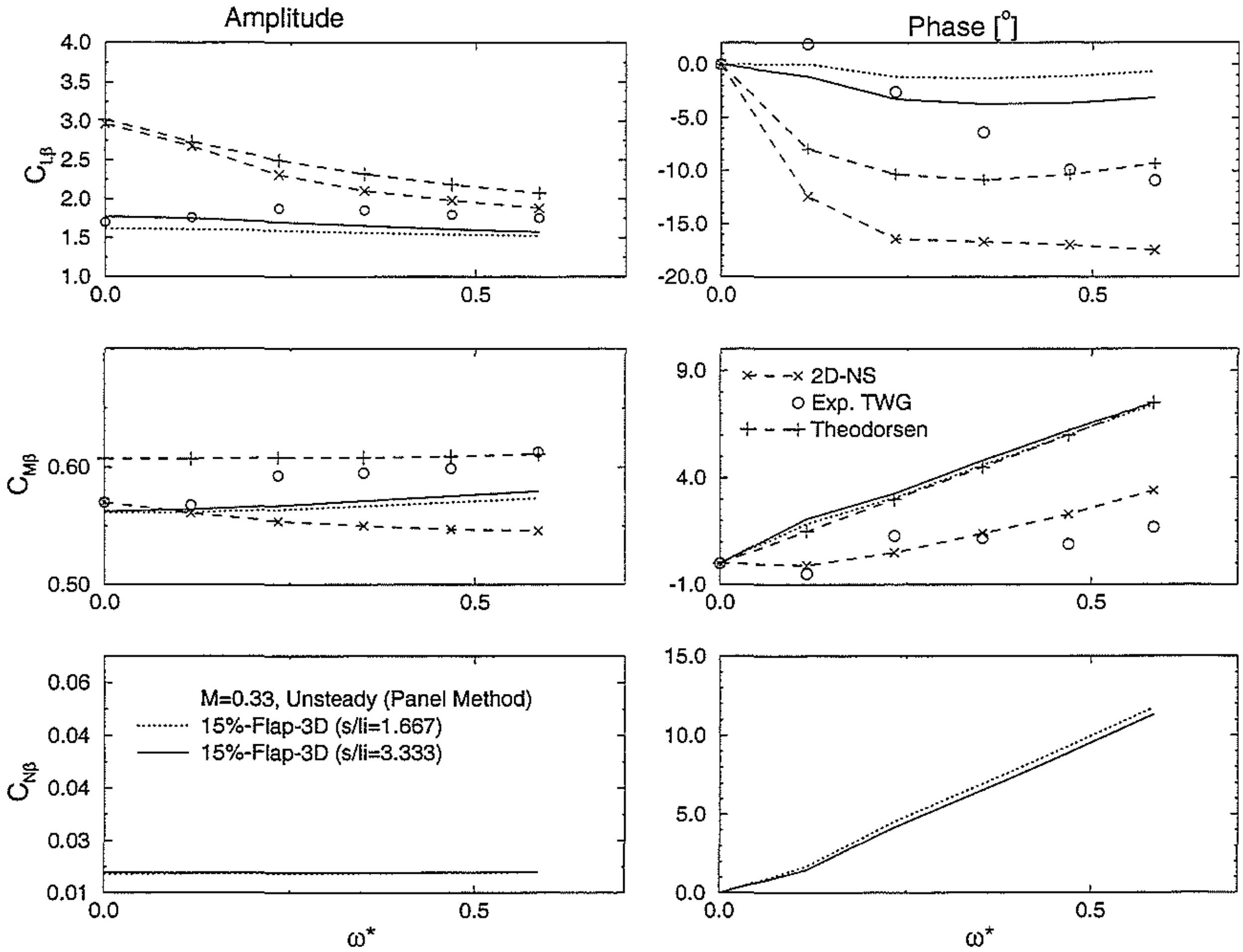


Fig.11: Amplitude and Phase of Flap Efficiency with Respect to Reduced Frequency

as well as the corresponding experimental data from the TWG experiments.
A large gap between the experimental data and the 2D-calculations is observed for the amplitude of the quasi-steady lift-derivative. The results with the 3D-panel method show a very good correspondence with the data. Also the phase of the 3D calculation is in much better agreement with experiment compared to the 2D results. The improvements for the moment derivative are not so obvious but especially the amplitudes show improvements compared to the experimental data. It must be concluded from these investigations that the flap efficiencies are strongly influenced by 3D-effects. In real rotor applications a flap of finite span will always operate as a 3D-device.

9. Conclusions, Future Activities.

Recent investigations on active blade control have focused on local or on-blade control devices like oscillating trailing edge flaps or leading edge deformations to favorably influence noise- and vibration levels as well as improve rotor performance. DLR-Göttingen has developed a set of aerodynamic tools to systematically investigate the complex flows about oscillating and deforming rotor airfoils and blades:

- Geometry Generator to define the time-dependent shape variation of the airfoil,
- CFD-tools based on the time-accurate Navier-Stokes equations to calculate the unsteady flows,
- Measuring techniques to measure instantaneous pressures and flow fields by in-situ pressure tabs, pressure sensitive paint (PSP), Particle Image Velocimetry (PIV) and interferometry. Unsteady overall forces and moments are measured by special Piezo-Electric Balances.
- Steady/ Unsteady test rigs for blade model oscillation,
- Wind tunnel facilities for full size blade models (TWG) and research facilities (VAG) for BVI and dynamic stall investigations.

All tools are operational and have proven to work with high efficiency. It is planned for future activities to improve the tools systematically:
Geometry Generator and CFD tools have to be combined such that closed loop investigations of dynamic airfoil deformations are possible. Measuring techniques like PIV will be further developed to measure complete 3D-flow fields. A combination of PIV and interferometry is envisaged to better understand the complex flows during dynamic stall.

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