Helicopter Aerodynamics with Emphasis Placed on Dynamic Stall

Wolfgang Geissler, Markus Raffel, Guido Dietz, Holger Mai

DLR-Göttingen, Bunsenstr.10, 37073 Göttingen, Germany

Abstract

Dynamic Stall is a flow phenomenon which occurs on helicopter rotor blades during forward flight mainly on the retreating side of the rotor disc. This phenomenon limits the speed of the helicopter and its manoeuvrability. Strong excursions in drag and pitching moment are typical unfavourable characteristics of the Dynamic Stall process. However compared to the static polar the lift is considerably increased. Looking more into the flow details it is obvious that a strong concentrated vortex, the Dynamic Stall Vortex, is created during the up-stroke motion of the rotor blade starting very close to the blade leading edge. This vortex is growing very fast, is set into motion along the blade upper surface until it lifts off the surface to be shed into the wake. The process of vortex lift off from the surface leads to the excursions in forces and moment mentioned above.

The Dynamic Stall phenomenon does also occur on blades of stall regulated wind turbines under yawing conditions as well as during gust loads. Time scales occurring during this process are comparable on both helicopter and wind turbine blades.

In the present paper the different aspects of unsteady flows during the Dynamic Stall process are discussed in some detail. Some possibilities are also pointed out to favourably influence dynamic stall by either static or dynamic flow control devices.

Introduction

Although a lot of efforts have been undertaken, [7,1,6] the process of Dynamic Stall with all its different flow complexities is still not completely understood nowadays.

The flow is strongly time-dependent in particular during the creation, movement and shedding of the Dynamic Stall Vortex. These rapid flow variations have to be addressed in both numerical as well as experimental investigations. Numerical codes, [3] have to be based on the full equations, i.e. the Navier-Stoke equations to solve these problems by taking into account a suitable turbulence model, i.e. [8]. In low speed flows transition plays an important role as well and has to be taken into account by a transition model, [4]. In helicopter flows the problem of compressibility is present even if the oncoming flow has a Mach number as small as M=0.3. In this case local supersonic bubbles are present during the up-stroke motion. These bubbles are terminated by small but strong shock waves, [2] which trigger the start of the Dynamic Stall process.

The phenomenon Dynamic Stall.

The advancing helicopter rotor blade encounters the sum of rotation and forward speeds and runs into transonic conditions with the creation of moving shock waves on the blade upper surface. On the retreating blade the difference of rotation and forward speed leads to small local Mach numbers but in order to balance lift on the rotor the incidence has to be increased at this time-instant and Dynamic Stall occurs during this part of the rotor disc.

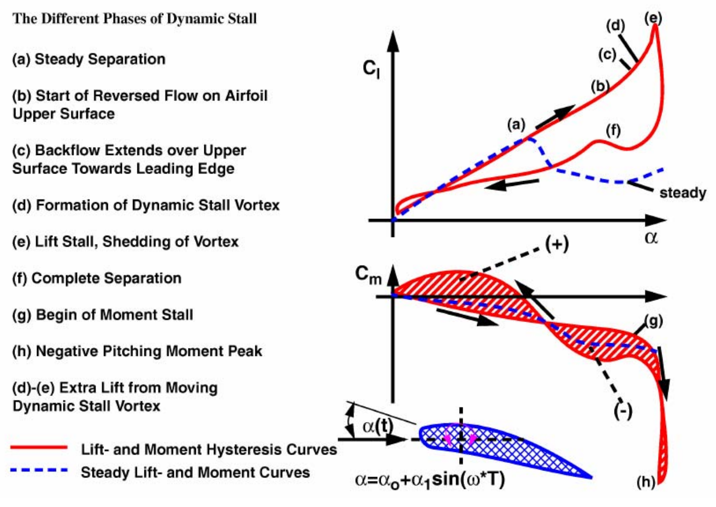

Fig.1 *Problem-zones at a helicopter in forward flight*

Fig.1 shows the different flow events during Dynamic Stall. The blue curves indicate the static limit. The lift curve does extend the steady C_{Lmax} by almost a factor of two with an extra peak which is caused by the Dynamic Stall Vortex. After its maximum the lift decreases very rapidly and follows a different path during down-stroke. Of even larger concern is the pitching moment hysteresis loop of Fig.1. It can be shown that the shaded areas between the different parts of the moment loop are a measure of aerodynamic damping. If these loops are travelled in anti-clockwise sense, the situation is stable, i.e. energy is shifted from the blade into the surrounding fluid. However if the loop is traversed in the clock-wise sense (see indication in Fig.2) an unstable flow condition occurs and energy is transferred from the flow to the blade structure. This is a critical situation insofar as dangerous stall flutter may occur.

Fig.2 shows the calculated details of the vorticals flow at two instants of time during the up-stroke motion. In the left figure the vortex has just been created close to the blade leading edge, has started to travel along the upper surface but is still attached to the surface. In this phase the vortex creates extra lift (see Fig.1). Very short time later (right sequence of Fig.2) the vortex has been lifted off the blade surface, stall has been started and negative vorticity is created at the blade trailing edge moving forward underneath the Dynamic Stall Vortex. In this phase the complex flow phenomenon occur which cause the strong decay of lift and creation of negative aerodynamic damping.

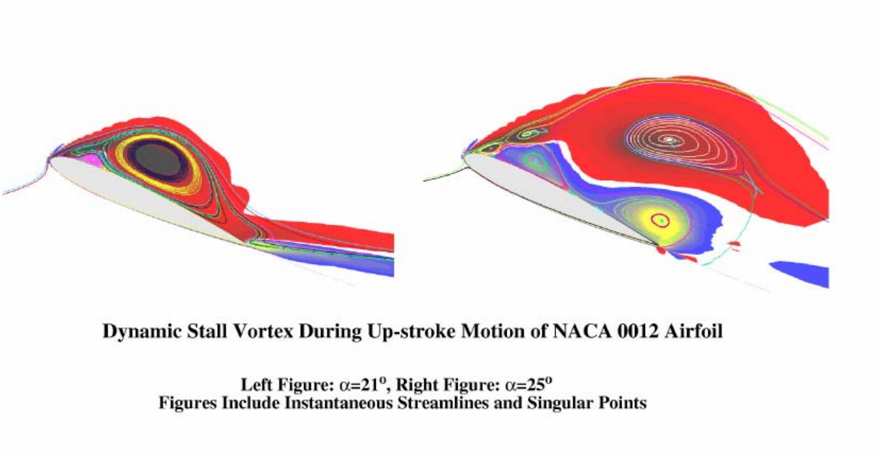

Fig.2 *Vorticity contours at two time-instants during up-stroke*

Numerical and experimental results for the typical helicopter airfoil OA209.

In October 2004 DLR has done experiments in the DNW-TWG wind tunnel facility located at the DLR-Centre in Göttingen. These tests are part of the DLR/ONERA joint project "Dynamic Stall". Within this project it was decided to use the OA209 (9% thickness) airfoil section as the standard airfoil. The OA209 airfoil is in use on a variety of flying helicopters. Measurements on a 0.3m chord and 1m span blade model (extended between wind tunnel side-walls) have been carried out. The objectives of these almost full size tests have been to study the details of the dynamic stall process by both numerical as well as experimental tools. From this knowledge base together with former investigations on this subject possibilities are explored to favourably ***control*** Dynamic Stall.

Fig.3 displays lift-, drag- and pitching moment hysteresis loops as measured from integrated signals of 45 miniature pressure sensors arranged at mid-span of the blade model. In the plots the force and moment data of all measured 160 consecutive cycles are simply plotted on top of each other. Two sets of data are included:

1) Measurements with straight wind tunnel walls (black curves)

2) Measurements with steady wind tunnel wall adaptation at mean incidence (red curves).

It is observed that a shift of the lift curve (left upper Figure 3) occurs due to wind tunnel wall interference effects. The results with wind tunnel wall correction do better fit to the numerical curves indicated in the plots as well (green curves).

During the up-stroke phase all measured curves are on top of each other. The flow in this region is non-separated. Close to maximum lift the Dynamic Stall Vortex starts to develop and the different measured curves deviate from each other. This trend continues and is exceeded during the down-stroke phase. The experimental curves show a wide area of distribution until all curves are merging again into a single line at the end of the down-stroke. The numerical curve does fit very close to the experimental results during up-stroke and the first phase of down-stroke. The spreading of the experimental data is caused by turbulence activities at flow separation. This can not be calculated with the present numerical code using turbulence and transition modelling. Nevertheless the correspondence between calculation and measurement in Fig. 3 also for drag (upper right Figure 3) and pitching moment (lower Figure 3) is quite satisfactory. All calculated details like surface pressures and skin friction as well as field data (vorticity, density, pressure, etc., not displayed) can be studied and interpreted. Some discussions are included in [5].

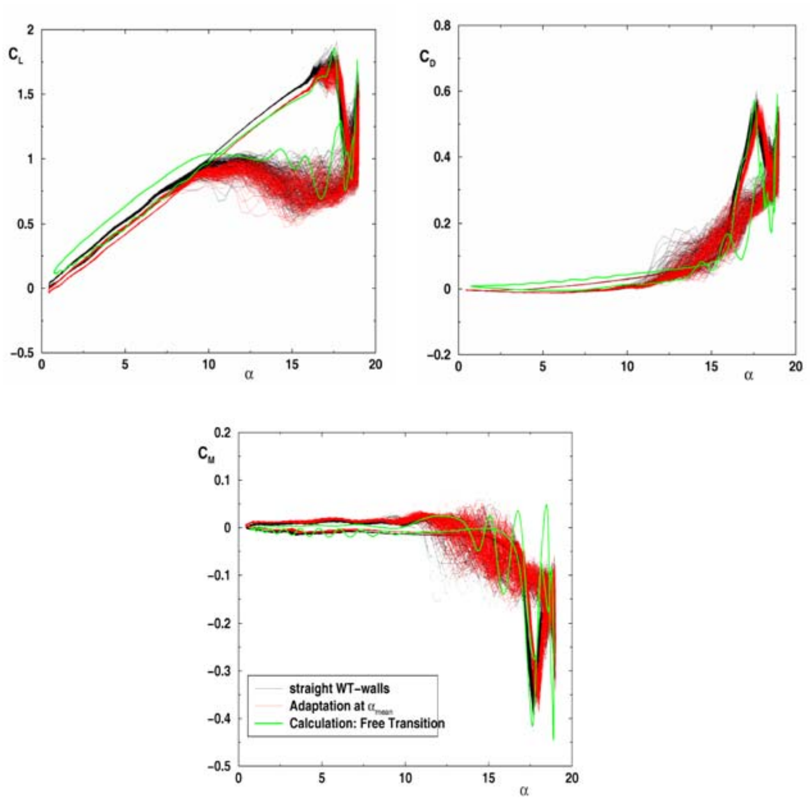

Fig.3 *Lift-, drag- and pitching moment hysteresis loops; comparisons of calculation and measurement;*
M=0.31, α=9.8^o+/-9.1^o, k=0.05

Conclusions

The flow phenomenon Dynamic Stall has been described in some detail and the advantages (high lift) as well as the disadvantage (excursions of drag and pitching moment) have been addressed. Recent experimental data and comparisons with numerical results have been discussed. A good comparison between the 2D-calculations and experimental data has been shown. From this knowledge base the important step to ***control*** Dynamic Stall in a favorable way is straightforward. Dynamic flow control devices

by droop the leading edge of the blade led to considerable improvements. However dynamic control needs actuators strong enough to do the job. The implementation into rotor blades is a formidable task. Therefore passive controlling devices have been considered at DLR and Leading Edge Vortex Generators have been studied. It was found that this type of devices has considerable potential to improve the Dynamic Stall characteristics. Beside of the shape of the leading edge vortex generators their positioning at the blade leading edge is of crucial importance. Due to the fact that the generators may be implemented even on existing blades and that later maintenance problems do not occur, it should be of considerable interest to install the devices also on wind turbine blades to improve its Dynamic Stall characteristics.
In the future considerable effort is planned at DLR both experimentally and numerically to investigate and optimize the effects of leading edge vortex generators.

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