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ACOUSTIC EFFECTS ON FLOW SEPARATION

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ABSTRACT

Flow visualisation techniques were used to study the influence of sound waves on the flow separation from a wing of low aspect ratio 3:1. Two different means of the acoustic excitation have been applied:

1. Spherical sound waves from a loudspeaker within the acoustic far field (Global excitation)
2. Sound waves focused by an elliptical mirror on a small region of the wing (Localised excitation)

The experimental results demonstrate that acoustic excitation in a suitable frequency range can reduce the flow separation, which occurs at high angles of incidence all along the leading edge, to a much smaller turbulent separation region that mainly affects the central part of the wing.

The tests with acoustic waves focused on a small part of the wing give insight into the dependence of the spanwise structure of the separation on the position of the excitation region.

We made video-recordings of the flow visualisation studies which illustrate the characteristic flow features obtained with global and localised acoustic control of the leading edge separation. Also presented are experiments on the control of separation by internal acoustic forcing through a slot in the surface of the model.

INTRODUCTION

Since several years experiments are carried out at DLR Göttingen to investigate the feasibility of controlling the laminar-turbulent boundary layer transition by means of periodic - in particular acoustic - excitation of the unstable laminar boundary layer, see e.g. [1 - 5].
Similar techniques can be applied to diminish the flow separation from airfoils and wings or to shift the onset of separation to higher angles of incidence. This improves the aerodynamic performance of the lifting surface.
Experimental investigations on the control of separation from a two-dimensional airfoil by means of internal acoustic excitation, see e.g. [6, 7], and on control of separation from a three-dimensional wing by external acoustic excitation, see e.g. [8, 9], have been carried out in co-operation with V.V. Kozlov and A.V. Dovgal of ITAM Novosibirsk.
This paper presents work on control of leading-edge boundary-layer separation from a wing of low aspect ratio. Flow visualisation techniques were used to investigate and illustrate the characteristic flow features with emphasis on dynamics of large scale vortices, initiated by separation, with and without acoustic flow control. These are demonstrated in a video film.

EXPERIMENTAL SET-UP

The experiments were made in the large low speed wind-tunnel of DLR-Göttingen. The tunnel has an open test section of 3 m by 3 m cross section and 6 m length. Maximum wind velocity is about 65 m/s. A rectangular wing with NACA 4415 profile was used for the tests, see Fig. 1. Wing chord was 0.6 m and wing span 1.86 m, thus aspect ratio was about 3:1. The wingtips were rounded as indicated in the schematic Fig.1.

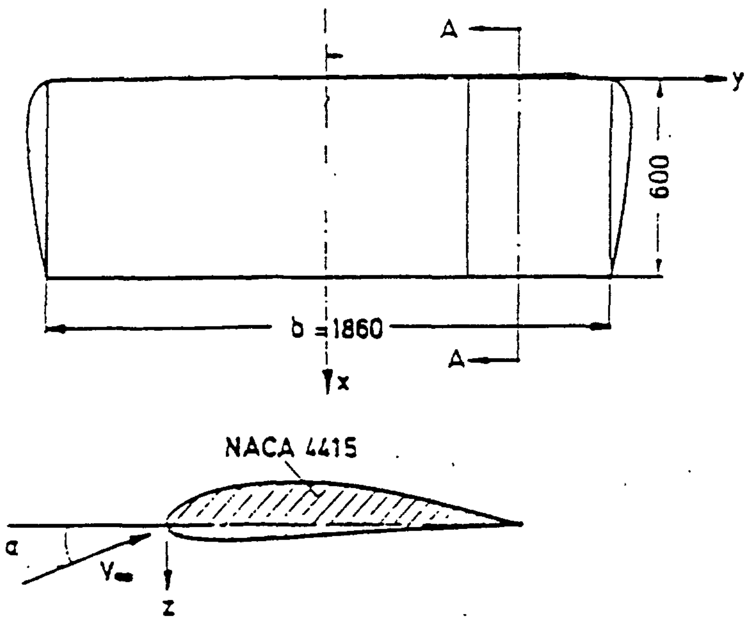


Fig. 1 Wind tunnel model, rectangular wing

The photograph Fig. 2 shows the model mounted in the test section. The nozzle exit of the wind-tunnel is at the right hand side of the picture. The wing was tested at angles of incidence $0° \leq \alpha \leq 25°$ and sweep angles $0° \leq \beta \leq 30°$. This is the set-up for experiments with global acoustic excitation by a loudspeaker within the far-field. The loudspeaker is visible at the lower centre of Fig. 2. It is mounted at about 2 m vertical distance from the model on a horizontal sting extending from the side of the test section.

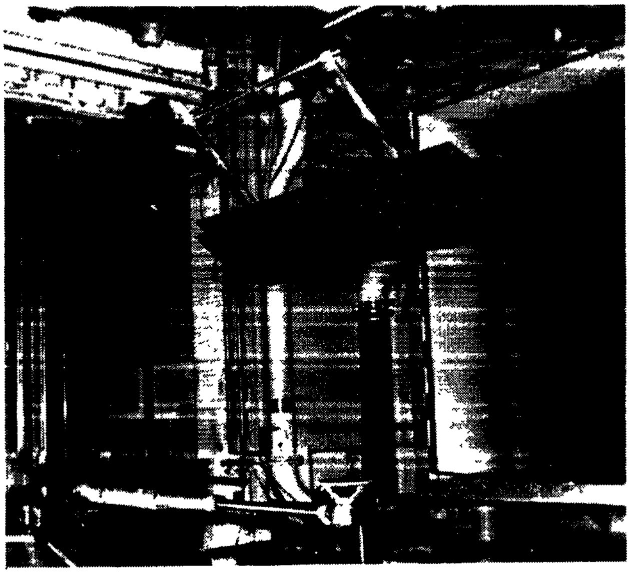


Fig. 2 Set-up for global acoustic excitation with loudspeaker 2 m below model

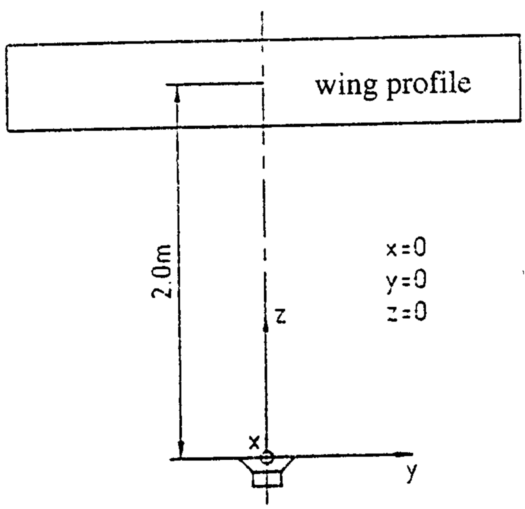


Fig. 3 Schematic view from downstream, configuration for global excitation by spherical waves from loudspeaker below the wing

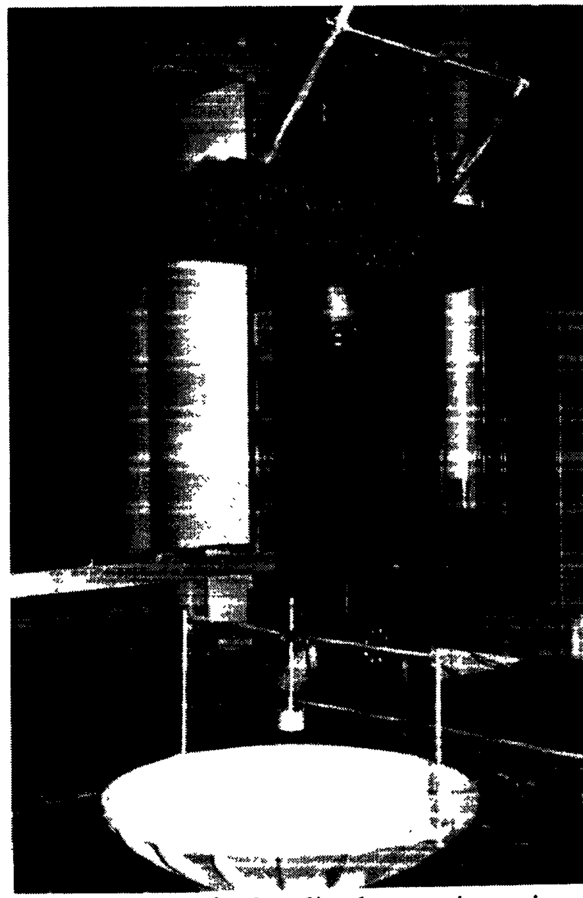


Fig. 4 Set-up for localised acoustic excitation, sound waves focused on a small region of the wing by an elliptical mirror

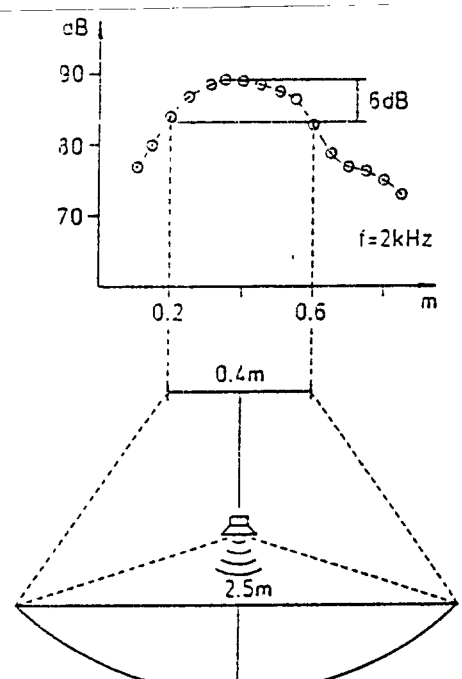


Fig. 5 Schematic view from downstream, focusing of sound waves on a small region of the wing by an elliptical mirror. Sound pressure level distribution at the model for 2 kHz tone

A schematic view of this set-up is given in Fig. 3. The spherical sound waves from the loudspeaker render an almost uniform sound pressure distribution all over the suction side of the wing.

Fig. 4 and Fig. 5 illustrate the set-up for the experiments with localised sound excitation on the wing. An elliptical acoustic mirror with 1.6 m diameter focuses the sound waves emitted by the small loudspeaker mounted in the appropriate position above the mirror onto a part of the wing surface. The mirror with the loudspeaker is shown in the lower part of the figures. The upper part of Fig. 5 gives the sound pressure level distribution measured at the position of the wing at a sound frequency f = 2 kHz. A 6 dB decrease of sound pressure level is observed at a distance of 0.2 m from the maximum, or within a diameter of 0.4 m. This is less than ¼ of the wing-span. The focus could be shifted to different positions on the wing by traversing the mirror-loudspeaker unit. The focus position on the wing was made visible for the video-recordings by illumination using a flashlight mounted suitably on the mirror-traverse.

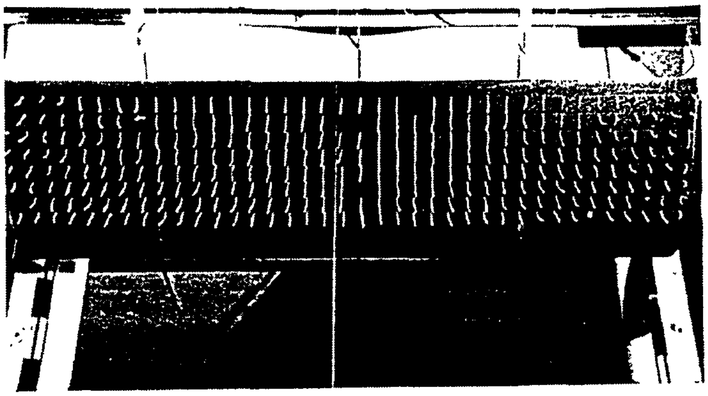
EXPERIMENTS

Several visualisation techniques were used for observation of the effects of acoustic forcing on the boundary layer separation. These included tufts, smoke injection and identification of surface streamlines by oil flow patterns. Some hot wire measurements were carried out in addition to the visualisation experiments.
The tufts were 50 mm long and positioned 50 mm apart in spanwise and chordwise direction. The nose region up to 0.2 m from the leading edge of the wing was left free of tufts in order to avoid perturbation of the boundary layer in this sensitive region. Smoke was injected through a probe which could be positioned within the flow field by a traversing unit.
The flow patterns, visualised by the above techniques, were recorded by a video system and arranged as a movie, in addition to still photographs. Positions of the cameras were below and immediately downstream of the model or downstream of the model at the side of the test section.
Acoustic effects on the flow separation were investigated, using flow visualisation and video recordings, at Mach numbers $M < 1$ within the chord-Reynolds number range $6 * 10^5 \leq Re \leq 1.2 * 10^6$, at angles of incidence up to 25 degrees and yaw angles up to 30 degrees. Both the tests with global excitation (Fig. 2,3) and with localised excitation (Fig. 4,5) were made at these conditions. For global excitation, sound frequencies between f = 1.0 kHz and f = 2.05 kHz were applied. The small loudspeaker used with the acoustic mirror for localised excitation permitted only high sound frequencies around 2 kHz, because the focusing effect of the mirror and the sound power output of the loudspeaker decrease with frequency.

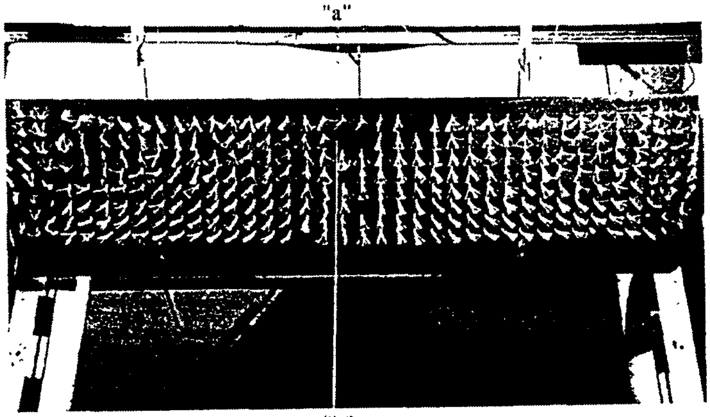
RESULTS

At high angles of incidence, $\alpha > 20°$, and within the Reynolds number range investigated, laminar flow separation occurs all along the leading edge of the wing. The acoustic excitation of the flow as described in the previous chapter reduced the leading edge separation to a much smaller turbulent separation region which mainly affects the central part of the wing.

Strong hysteresis effects were observed in the case of global excitation. Once the separation region was reduced by the sound, the flow remained attached even if the sound excitation was switched off.
In the case of localised excitation, attachment of the flow could be obtained on one side of the wing only by directing the sound waves to that area. In this case, there was no hysteresis effect. Directing the sound beam onto the centre of the wing the results were similar to the effects found with global excitation.
The flow visualisations, in particular the video recordings, reveal clearly the three-dimensional structures and the unsteady characteristics of both the natural and the acoustically influenced flow separation.
Some typical examples of the flow visualisation results are shown in the following figures.



"a"



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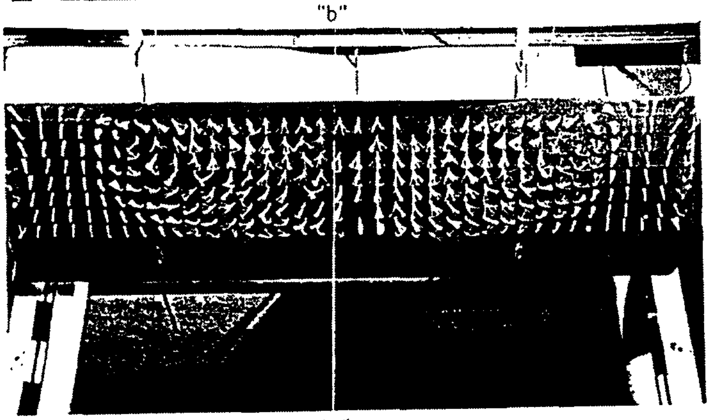


"c"

Fig. 6 Photographs of model with tufts. Camera below and downstream of the wing:

Upper part: Without flow, arrangement of tufts on the model

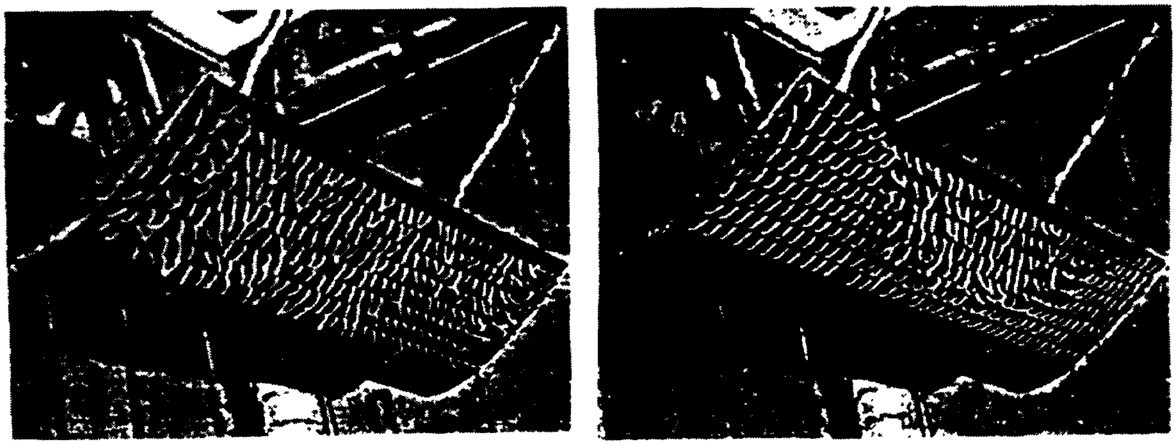
Centre part: and lower part: With flow, Re = $6*10^5$, α = 25°, Sweep angle $\beta = 0$

Centre part shows „natural flow" without acoustic excitation

Lower part shows effect of global acoustic excitation on the flow.
Excitation freq. f = 1980 Hz
SPL at the wing: L = 113 dB

The photographs given in the centre part and lower part of Fig. 6 indicate clearly the effects of acoustic excitation on the topology of the separated flow. In particular, the reduction of the separation region from a global leading edge separation to a smaller turbulent separation region can be observed. The unsteadiness of the flow field is indicated by the blurred images of the tufts in certain regions.

Another example is given by Fig. 7, showing the flow patterns without and with global acoustic excitation as viewed from a different camera position.

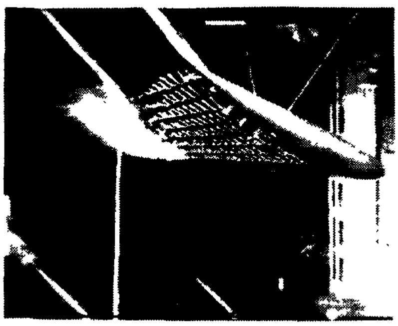


without acoustic excitation   with acoustic excitation

Fig. 7 Photographs of model with tufts. Camera below and downstream of the model at the side of the test section.
$Re = 6*10^5$, $\alpha = 22°$, $\beta = 0°$, excitation freq. f = 1.8 kHz, SPL = 117 dB

The figure shows the reverse flow over the wing without acoustic forcing, and a small separation region with acoustic excitation.

A



B

An example of the results of smoke visualisation is presented in Fig. 8. For smoke injection, a slender smoke tube was inserted into the separation region producing only insignifant disturbances to the flow. The angle of sweep was 15 deg. in this case. Smoke and tuft patterns demonstrate the reduction of the separation region by the sound also in this case.

Fig. 8 Smoke visualisation. $Re = 6*10^5$, $\alpha = 25°$, $\beta = 15°$, excitation freq. f = 2.05 kHz, SPL = 113.5 dB
A: Natural flow
B: With acoustic excitation

CONCLUSIONS

A combination of different visualisation techniques and video recording of the visualised flow patterns was applied in this investigation of the effects of acoustic excitation on the flow separation from a wing of low aspect ratio at high angles of incidence. The visualisation reveals the three-dimensional structures and the unsteady characteristics of the flow fields. The tests with acoustic excitation focused on a small part of the wing give some insight into the dependence of the spanwise structure of the separation on the position of the excitation area.

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