DRAG MEASUREMENTS ON AIRFOILS

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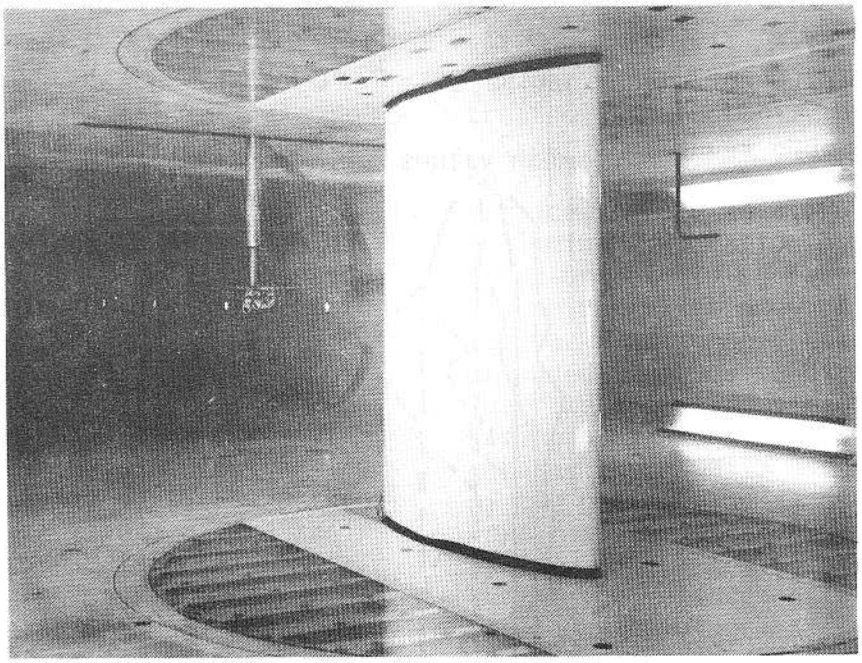
The drag of airfoils is evaluated from the loss of total head in the wake. This is achieved either by an integrated rake positioned vertical to the trailing edge at some distance from the airfoil trailing edge, or the wake is traversed by a single Pitot-tube point by point and the readings are integrated subsequently. In both cases the drag is evaluated only for a particular plane in spanwise direction z. If the drag was measured by a balance, the mean value over the whole wind tunnel model could be attained. But, because of the undefinable influences of the tunnel walls, this procedure cannot be used satisfactorily.

In the laminar wind tunnel at the Institut for Aerodynamics, University of Stuttgart, drag is measured by an integrating rake which includes static tubes and tubes for detecting the direction of flow (Fig. 1). The rake can be moved vertically relative to the trailing edge of the model and can be rotated in the direction of flow. It automatically positions in the middle of the wake and in flow direction. Originally, the rake was fixed at half of the span of the wind tunnel model in the middle of the test section. Recently, the traverse installation was completed to allow for movement of the rake in the spanwise direction. It's position is controlled by an electric potentiometer. When measuring the drag coefficient in the spanwise direction, the rake is moved with a small constant velocity along the span. Pressure data are sampled by an analog-digital converter with a frequency of about 20 Hz and stored by digital computer. Drag values are evaluated and plotted on an x-y plotter on line. At the end of the traverse, the data for a length of 30 cm are integrated and plotted as a mean value line. Fig. 2 shows an example of the measurement of drag coefficient c_D in the spanwise direction z at a constant angle of attack $\alpha = 3^o$ and 4 Reynolds numbers on an airfoil. At small Reynolds numbers, the drag shows considerable, nearly periodic variations along the span. In the example shown, the maximum deviations from the mean are about ±15%. With increasing Reynolds number, the amplitude becomes smaller. At about Re = 3 million, the drag coefficient is nearly constant along the span.

If the drag of an airfoil is only measured in a single spanwise plane, considerable differences can arise. With this in mind, the reason was understood for why retesting of wind tunnel models resulted in different drag coefficients: the rake was not installed at the same position z after a change in installation. Furthermore, an additional explanation is given for why in different wind tunnels, or in flight tests, different drag coefficients are measured for the same airfoil.

Periodic oscillations of drag in the spanwise direction are found on nearly all airfoils. At first, irregularities in the wind tunnel flow were thought to be the cause. However, not even by artificial disturbances simulated by 5 cm wide rods behind the last screen in the contraction part of the tunnel, could any variations in drag be generated. The fact that the amplitudes become smaller with growing Reynolds number does not hold with this assumption.



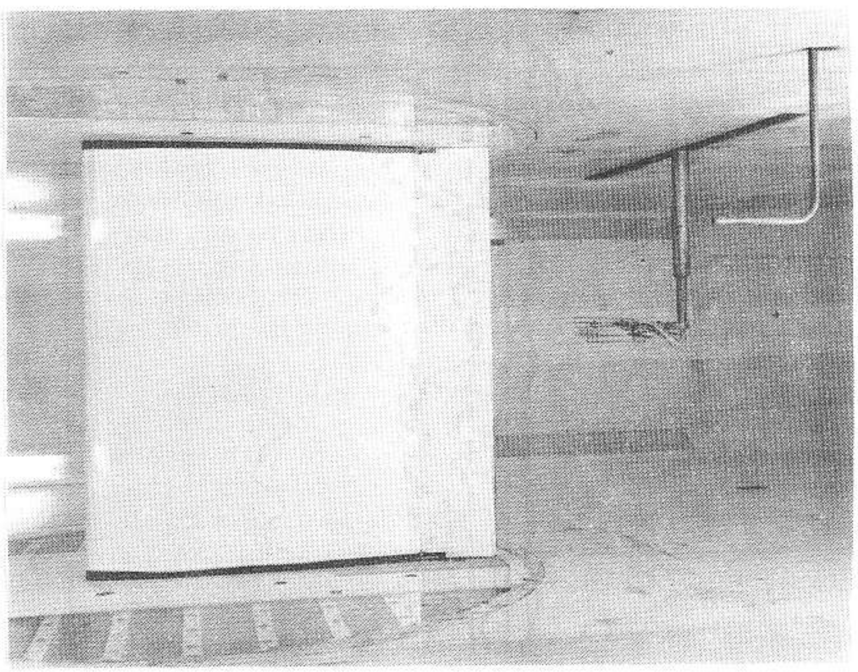


Fig. 1 Airfoil in the test section of the laminar wind tunnel with the rake in the background.

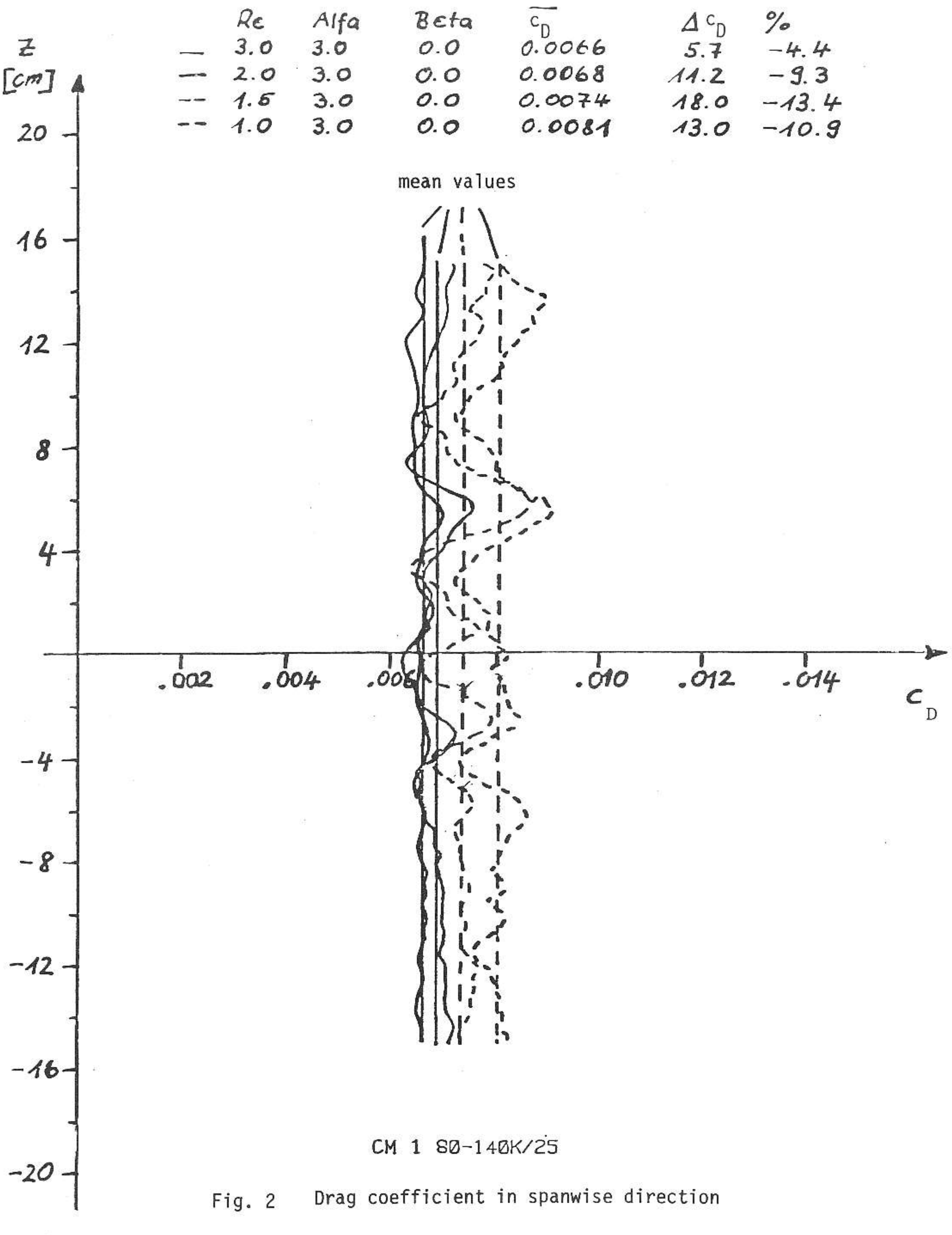


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Fig. 2 Drag coefficient in spanwise direction

Fig. 3 shows drag measurements in the spanwise direction for another airfoil. In addition, the behaviour of the drag portions of the upper and lower sides of the airfoil, measured by a rake sliding on the airfoil surface at the trailing edge, are shown. These portions of drag, called c_D', are not in scale with the total drag coefficient c_D. The drag along the lower side is constant, while on the upper side periodical variations of drag with a wave length of about 3 cm are observed. They show again in the variation of the total drag coefficient c_D. Further experiments and boundary layer measurements made on different wind tunnel models revealed that these oscillations are caused by counter-rotating longitudinal vortices in the turbulent boundary layer, having their origin in the laminar separation bubbles. With growing Reynolds number, the laminar separation bubbles become smaller, boundary layers become thinner, and the amplitudes of the drag oscillations diminish (Fig. 1). When the laminar separation bubble disappears, the vortices fade away too. The development of the amplitudes of the waves depend on the curvature of the surface; amplified by a concave curvature, damped by convex. Owing to these longitudinal vortices, all boundary layer parameters show oscillating characteristics in z-direction. No boundary layer theory could account for this effect until now. In addition, laminar separation bubbles cannot be treated satisfactorily by theory.

Experience shows that there is almost no airfoil without longitudinal vortices. Such an airfoil should have no laminar separation bubbles or convex curvature of its surfaces. Before measuring a lift drag polar in the laminar wind tunnel, the drag is measured in spanwise direction (Fig.1). The rake then is positioned at a point z having a mean drag coefficient, and remains there while measuring the rest of the polar. The z-position of the vortices merely varies with the angle of attack. The z-position of the rake during the measurement of the polar is noted on the diagrams.

Because of the appearance of longitudinal vortices in turbulent boundary layers, and the associated drag oscillations in spanwise direction, comparison of various drag measurements is only comparable if drag measurements in the spanwise direction are available as well.

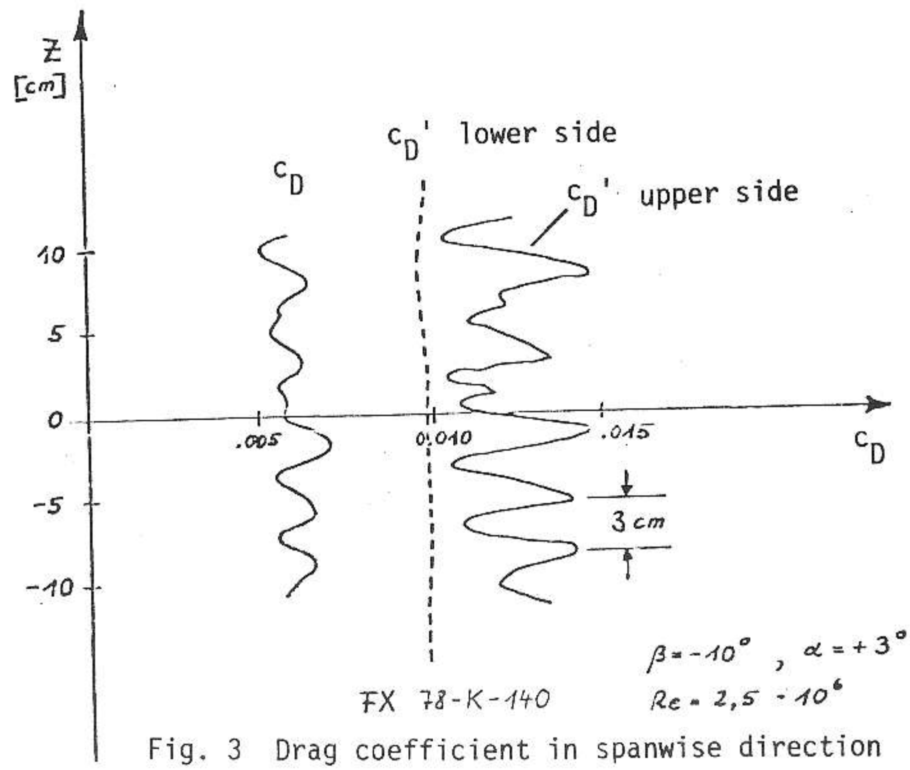

Fig. 3 Drag coefficient in spanwise direction

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