GENERATION AND BREAKDOWN OF AERODYNAMIC LIFT:

PHYSICAL MECHANISM

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INTRODUCTION

At high angles of attack the condition of attached flow is dependent upon the balance between forces on the leading edge and on the trailing edge of the wing. In the case of low-speed flight the wing operates at the upper limit imposed by this balance. In order to calculate and possibly influence this limit, a detailed understanding of the physical mechanism is required. We do know how to generate lift forces and we are able to calculate their magnitude as well as their distribution along the wing span. We do not know, however, the real physical mechanism of lift generation.

THOMSON'S THEOREM

The lift force is a result of circulation, i.e., a net flow around the airfoil. A differential pressure results with a corresponding force perpendicular to the main flow; this lift force is proportional to the airspeed and to the intensity of the circulatory flow. In order to discuss the problem of lift generation, attention has to be focussed on the circulation itself.

We learn from standard literature (refs. 1 and 2) the way circulation is produced: A layer of separation arising at the trailing edge coils up to a starting vortex. According to Thomson's theorem (ref. 3) the circulation along a closed flow path situated in a homogeneous inviscid fluid remains constant with time. Consequently the formation of the starting vortex requires the generation of an opposite circulatory flow. Since the total circulation is zero to begin with, the magnitude of the opposite circulatory flow is such as to compensate the starting vortex. Hence the starting vortex gives rise to a superimposed additional velocity of the fluid particles in the vicinity of the wing surface.

At this point one may have difficulties realizing the logical sequence of events. Of course there are no doubts about the validity of Thomson's theorem. The application of this theorem, however, does not explain the physical origin of additional forces acting on the fluid particles. Presently we need some kind of electrodynamic "far field effect" to explain this fluid dynamics problem.

FLOW AROUND THE TRAILING EDGE

The fluid particles pass the trailing edge with extremely high and localized velocities, especially during the early phase of the motion. Figure 1 illustrates the corresponding flow pattern and the resulting low pressure zone. Static pressure differences are produced in the vicinity of the trailing edge. As a result more and more of the flow close to the surface moves towards the low pressure region even against the main flow. The "depression zone" is filled up by spirally moving particles forming a vortex sink. With increasing vortex diameter the flow velocity around the trailing edge decreases. This in turn reduces the suction and the transport of material towards the sink will decay as shown in figure 2. Finally the vortex reaches a critical size which is characterized by zero suction and vanishing flow around the trailing edge. At this moment the vortex is free; it separates from the wing surface (fig. 3).

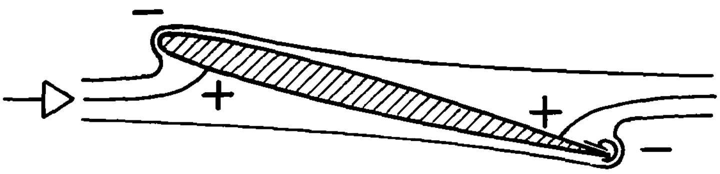

Figure 1.- Suction head at the trailing edge.

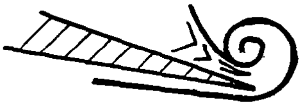

Figure 2.- Accumulation in a vortex sink.

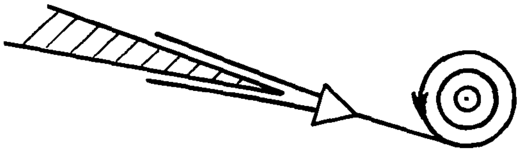

Figure 3.- Separation of vortex.

As soon as the starting vortex drifts away, the condition of attached flow is attained. Smooth flow is established all the way down to the trailing edge. A combined local suction and material transport mechanism has been able to initiate a circulation. "Far field effects" are no longer required.

VORTEX ROLL

Filling up the suction zone is characterized by the formation of a typical flow pattern which generates what may be called a vortex roll. The intermittent phenomena taking place at the wing surface can be simulated by a continuous source-sink mechanism as shown in figure 4.

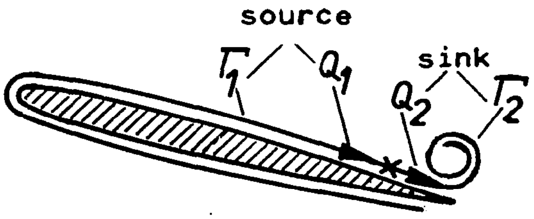

Figure 4.- Source-sink mechanism.

The mass flow $Q_1 \rho$ discharging from the source equals the one $Q_2 \rho$ entering the sink at any instant of time. Continuity of the incompressible flow requires (dots denote partial differentiation with respect to the time)

$$dQ_1 + dQ_2 = \dot{Q}_1 \, dt + \dot{Q}_2 \, dt = 0 \tag{1}$$

In addition to this the stimulated circulation Γ is directly proportional to the volume flow according to

$$dQ = -S \, d\Gamma \tag{2}$$

The quantity S represents the active span of the wing.

Combining equations (1) and (2) yields

$$d\Gamma_1 + d\Gamma_2 = \dot{\Gamma}_1 \, dt + \dot{\Gamma}_2 \, dt = 0 \tag{3}$$

which indicates that flow continuity and the proportionality (2) are reflecting the relevant physical phenomena at the wing; in particular, equation (3) satisfies Thomson's theorem at any instant of time.

Finally at a time T the formation of the vortex roll is terminated which is characterized by

$$\Gamma_{1_T} + \Gamma_{2_T} = 0 \tag{4}$$

Consequently a circulation around the wing has been built up, having the same magnitude but different orientation from the final vortex roll drifting away.

LIFT

The lift force at the wing can be directly calculated from the properties of the vortex roll. According to Kutta's theorem the fluid velocity V produces a lift force F at the active wing span S of

$$F = \Gamma \rho V S \tag{5}$$

Γ represents the steady state circulation around the airfoil, which according to equation (4) is replaced by $-\Gamma_{2_T}$. Following figure 5 the vortex-roll circulation Γ_{2_T} is

$$\Gamma_{2_T} = -\pi D W \tag{6}$$

where the quantity D represents the final diameter of the vortex roll and W is the local fluid velocity passing the trailing edge.

Therefore the lift force is

$$F = \pi D W \rho V S$$

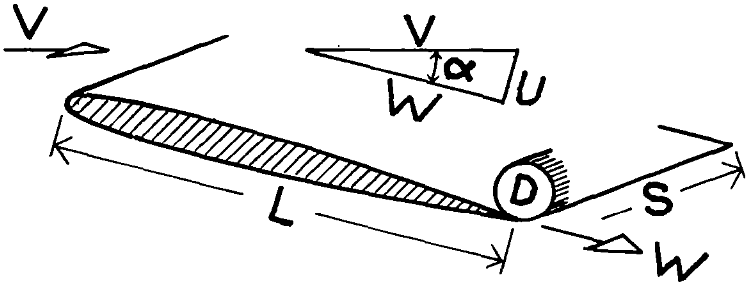

Figure 5.- Properties of wing and vortex roll.

Mechanical similarity requires a simple proportionality between geometry and velocity ratios as shown in figure 5:

$$(D/L) = m(U/W) = m \tan \alpha \tag{7}$$

Herein L is the wing chord and U is the transverse velocity component at the trailing edge according to the angle of attack α. The factor m is a dimensionless coefficient.

With the relations,

$$D = m L \tan \alpha$$

$$W = \cos \alpha V$$

it is possible to calculate the lift force

$$F = m \pi L \tan \alpha V \cos \alpha \rho V S = m \pi \sin \alpha \rho V^2 S L$$

or specializing for small angles of attack α (wing area $S L = A$),

$$F = 2 \pi m \alpha (\rho/2) V^2 A$$

For the lift coefficient C_A one obtains

$$C_A = \frac{F}{(\rho/2)V^2A} = 2\,\pi\,m\,\alpha \tag{8}$$

Experiments indicate that the dimensionless coefficient m is close to 1.0 so that the following approximation is justified:

$$C_A \approx 2\,\pi\,\alpha$$

THE TRAILING-EDGE MECHANISM

The condition of attached flow dominates just after separation of the starting vortex. This condition, however, is not stable since dissipation and other effects are disturbing the flow. Consequently, the fluid again passes the trailing edge causing suction, which is able to correct for the disturbance. This mechanism at the trailing edge continuously and effectively maintains the condition of attached flow. The sharper the edge is, the more effective the mechanism is.

At high angles of attack, however, a counteracting effect is initiated at the leading edge.

BREAKDOWN

Usually the leading edge is rounded; nevertheless similar processes take place as at the trailing edge. High fluid velocities are accompanied by strong suction. Local backflow is initiated in the boundary layer, but no vortex roll can be formed in the front. This is not due to rounding of the leading edge but to the fact that the front depression zone has no direct contact with a region of significantly higher static pressure which is able to fill a vortex roll. With increasing angle of attack there is an increasing static pressure gradient from the front to the back of the upper wing surface. But the boundary layer is able to resist a major backflow. So in spite of this pressure gradient, the front low pressure zone remains isolated.

As far as this isolation is concerned, there is a fundamental difference between the processes at the leading edge and those at the trailing edge. In the case of the back depression this zone is being rapidly filled from a very close reservoir, the high pressure stagnation zone. In the case of the front region the low pressure is continuously maintained since there is no high static pressure reservoir available which could form and fill a vortex roll.

At high angles of attack the pressure gradient along the upper surface rises considerably; this changes the situation drastically: The thickness of the boundary layer increases, giving rise to a backflow at the wing surface. This reverse wedge flow expands from the back and reaches the front depression zone. At the moment of contact a rather violent inflow takes place towards the centre of the zone. A flow unbalance results since the depression zone takes in more material than the main flow is able to deliver. As a consequence the low pressure region is filled very fast, which in turn leads to a rapidly growing vortex roll. Finally the flow separates as indicated in figure 6.

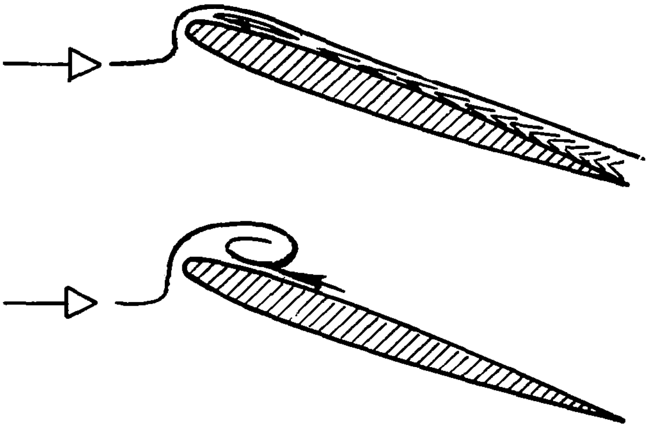

Figure 6.- Above: Expanding reverse flow.
Below: Contact - the flow separates.

These phenomena now correspond directly to what has previously been described as happening at the trailing edge, except for one important difference: There is a net flow around the airfoil which reduces the circulation and causes lift breakdown.

It has been shown that flow separation is not only initiated by static pressure rise and friction; a third condition has to be satisfied: The condition of contact between the low pressure zone with regimes at a higher static pressure.

COUNTERMEASURES

The range of steady lift generation could be extended if one were able to prevent contact of flow from the trailing edge with the front depression. One device for this purpose is shown in figure 7.

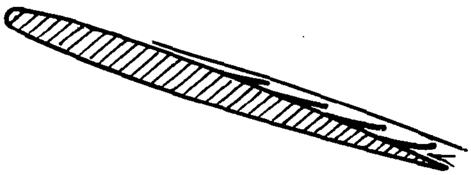

Figure 7.- Pockets at the upper surface.

Such "pockets" at the upper wing surface are well known from the wings of birds. At high angles of attack the backflow in the boundary layer causes these elastic elements to raise. This way the expansion of the backflow is effectively stopped; contact is prevented and lift breakdown is delayed.

The outlined principle is not yet in use in aeronautics, but it has proven successful in biotechnics (fig. 8). So far only one case is known where such a pocket-type device has been tested on a stalling airplane — with good results.

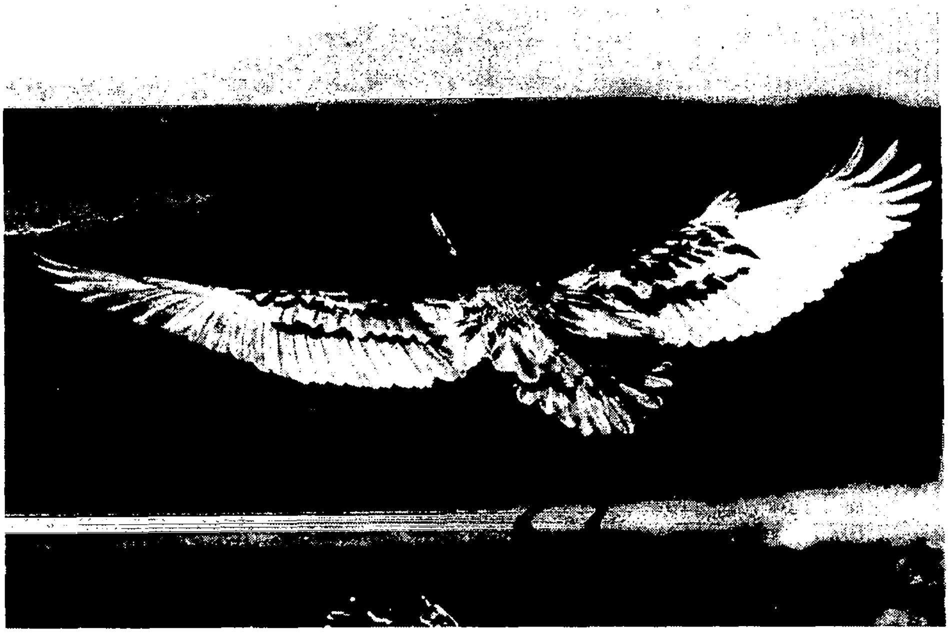

Figure 8.- Heron during approach for landing.
(G. Rueppell, Vogelflug, Kindler 1975)

Up to now only two-dimensional flow conditions were considered. In real situations lift breakdown mostly starts locally somewhere along the wing span. Localized lift breakdown, however, being limited to a short part of the span may lead to a three-dimensional flow. Now the low pressure zone in the vicinity of the local breakdown fills up from separated regions causing sideways inflow of material. At high angles of attack that sideways influx rapidly propagates to the wing tip. Like a chain reaction the lift collapses all of a sudden along the whole wing as shown in figure 9.

As a countermeasure an effective device has been suggested: The boundary layer fence. A simple shroud is mounted on the wing in order to protect the outer part of the wing against infiltration. Thin threads have been fastened to the wing surface to make the flow pattern visible during flight (fig. 9). The fence does prevent sideways contact and subsequent lift collapse.

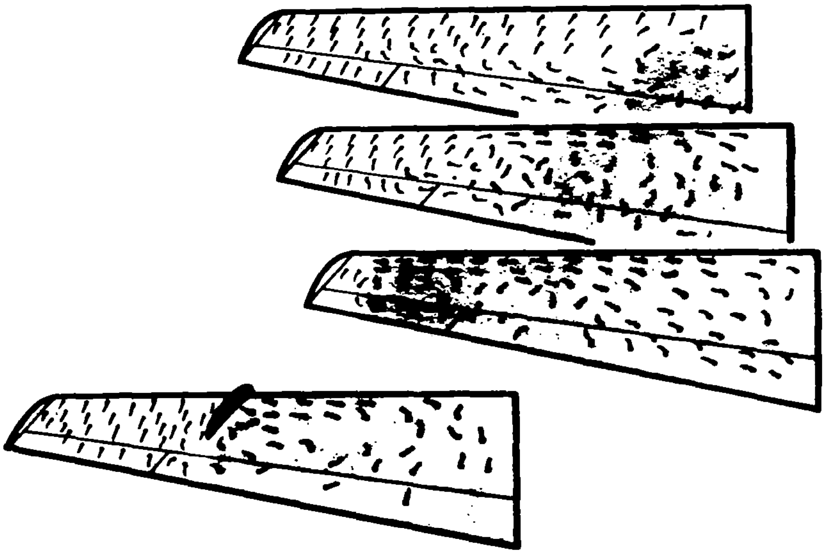

Figure 9.- Flow pattern on a stalling airplane. Right: Sideways influx rapidly propagating to the wing tip. Left: A fence protects the outer part against infiltration.

Quite frequently the boundary layer fence is used in conjunction with sweptback wings. Sweepback means shifted airfoils which is accompanied by sideways pressure gradients. Thus the low pressure zone is filled sooner from the adjacent side, causing not only reduced lift but also unfavorable pitching moments. These inherent effects can be prevented by fences.

WING FLAPPING

The outlined extremely high velocities around the trailing edge can be provoked by a transverse motion of this edge relative to the main flow, for example by moving a trailing edge periodically up and down. Corresponding vortex rolls are generated and material is absorbed from the boundary layer, thus reducing its thickness. The reverse wedge flow decreases and again lift breakdown is delayed.

The volume flow due to wing flapping can be calculated from the following relation:

$$Q_f = 2\ \pi^3\ k^2\ \rho_0^2\ n^3\ \frac{r^2 S\ L^2}{V^2} \tag{9}$$

where

Q_f	volume flow due to flapping
k	dimensionless coefficient
n	flapping frequency
ρ_0	angular amplitude of flapping
r	radius of moving edge
S	span of active wing
L	wing chord
V	fluid velocity

The material taken out from the boundary layer is accelerated backwards by flapping, which as a reaction produces wing propulsion. The thrust attained in this manner is negligibly small in gases; in high density fluids it is possible to produce significant propulsive forces by this technique.

SUMMARY

A contribution has been given to an old problem: The explanation of the generation of aerodynamic lift. New physical models are described which provide a better understanding of the phenomena involved. The suggested viewpoint leads to new technological implications. The formation of both a starting vortex and a circulation can be conceived as the filling of a vortex sink at the trailing edge. Fluid is absorbed by the vortex, which causes it to expand to a vortex roll. The lift force can be calculated from the properties of the vortex roll.

Once the starting vortex drifts away, the condition of attached flow is attained. With increasing angle of attack this condition is disturbed by low pressure close to the leading edge. Finally this depression zone fills from the back of the wing, which induces a countercirculation and lift breakdown.

Filling requires the low pressure region to have contact with flow regimes of higher static pressure. Flow separation caused by filling of the vortex at the leading edge can be influenced by anti-contact devices such as pockets or fences.

A periodic flow can be superimposed around the wing by a forced oscillatory motion of the trailing edge. The periodic formation and separation of small vortex rolls reduce the drag or even produce propulsion.

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