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Oblique Grooves avoiding Laminar Flow Separation on Bodies in Positive Pressure Gradients

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Abstract

A new surface texture consisting of grooves obliquely oriented to the flow direction has been investigated. The experimental results confirm two key characteristics of the arrangement:
1. avoiding separation of a laminar flow in positive pressure gradients up to local Re of < 200'000.
2. a reduction of surface friction across the texture of over 30% compared to a smooth surface at Re < 100'000.
Prior textures for the same problem known are derived e.g. from the dimples on golf-balls such as used in US Patents 5,378,524 and 5,540,406. The actual texture used has its application for local Re <200'000 down to very low Re-numbers and has a coarse structure of typically some millimeters groove-width. The results of the Fluid Mechanics Lab have been extended and confirmed by an additional investigation at the Lab for Turbomachinery of the Swiss Federal Institute of Technology in Zürich.
The theoretical understanding to allow for correct dimensioning of technical applications is presented. The grooves allow positive pressure gradients below Re <100'000 and act as a supertripping device on profiles for the turbulent flow regimes beyond.

Background

Locusts wings have on their suction surface relatively coarse grooves with dimensions of mm which are with the wings in gliding attitude obliquely orientated to the flow direction. These grooves are closed upstream. Certrain subspecies of locusts are able to glide efficiently in contrast to most of insects. This feat would require that their wings produce real lift with low pressure on the suction side, a feat not possible in classic steady state aerodynamic wing theory with smooth surfaces at low Reynoldsnumbers.
A laminar boundary layer (Re local < 200'000) does not support adverse pressure gradients without special tricks. It is a classic limit of profile design [5], that for the suction side you would have to limit positive pressure gradients up to the transition from a laminar boundary layer to a turbulent boundary layer permitting such positive pressure gradients. State of the art [11] are a multitude of classic tripping devices, that are directed at provoking this transition at a convenient position. However if placed at locations below local Re number <100'000 the effect is generally unpredictable.
The investigated configuration inspired by the locusts wing with oblique grooves has a profound effect: it avoids separation in positive pressure gradients below Re 100'000 effectively and results in a predictable tripping of the boundary layer transition from laminar to turbulent state.

Operating principle

The operating principle as verified is explained below:

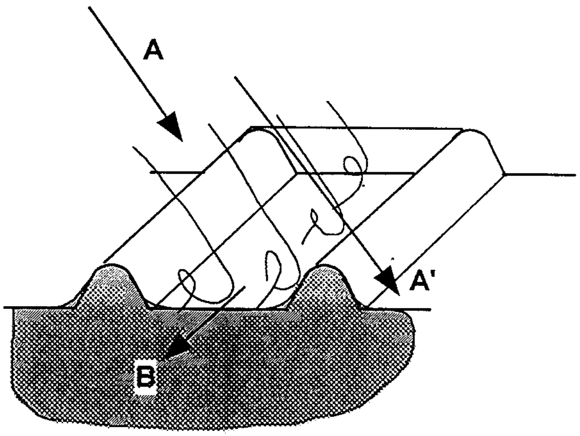

Fig. 1 Oblique grooves operating principle

Grooves which are obliquely oriented to the flow direction A and closed at the upstream end create channels, which are overflown with a free-stream separation layer.The oblique orientation produces at the same time a viscous entrainment force in direction B, which will empty the channel creating a suction effect, because the channel is closed on its upstream end. If the inclination angle between dirction A and B is small enough, this suction effect will work even in the presence of a positive pressure gradient in the direction of A.
In laminar flow such a configuration does exhibit some unusual features to be noted.

A first remark concerns the question of how these grooves should look like. As we found by experimenting it is rather unimportant whether the ridges between the grooves are rounded or not. Best results are usually achieved by rather coarse and angular wall cross-sections.

A second remark concerns the friction losses incurred by applying relatively coarse oblique grooves. The total friction (of the fluid against the wall with grooves) has conceptually two components: the friction of the free jet layer across the grooves and the friction in contact with the ridges between the grooves. In turbulent flow regime the arrangement would result in much increased total friction. For laminar flow the result is that we get even smaller total friction compared to a smooth wall.

To analyse the situation we consider the energy dissipation of boundary layers as a function of the Re_delta, the Re number calculated for the

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momentum deficiency thickness for laminar and turbulent boundary layers, Fig 2.
The diagram presented is compiled from the catalog Tani [4] has prepared and the Blasius formula for laminar boundary layers and compares energy dissipation (a measure for kinetic energy loss) for wall- and jetlayers.

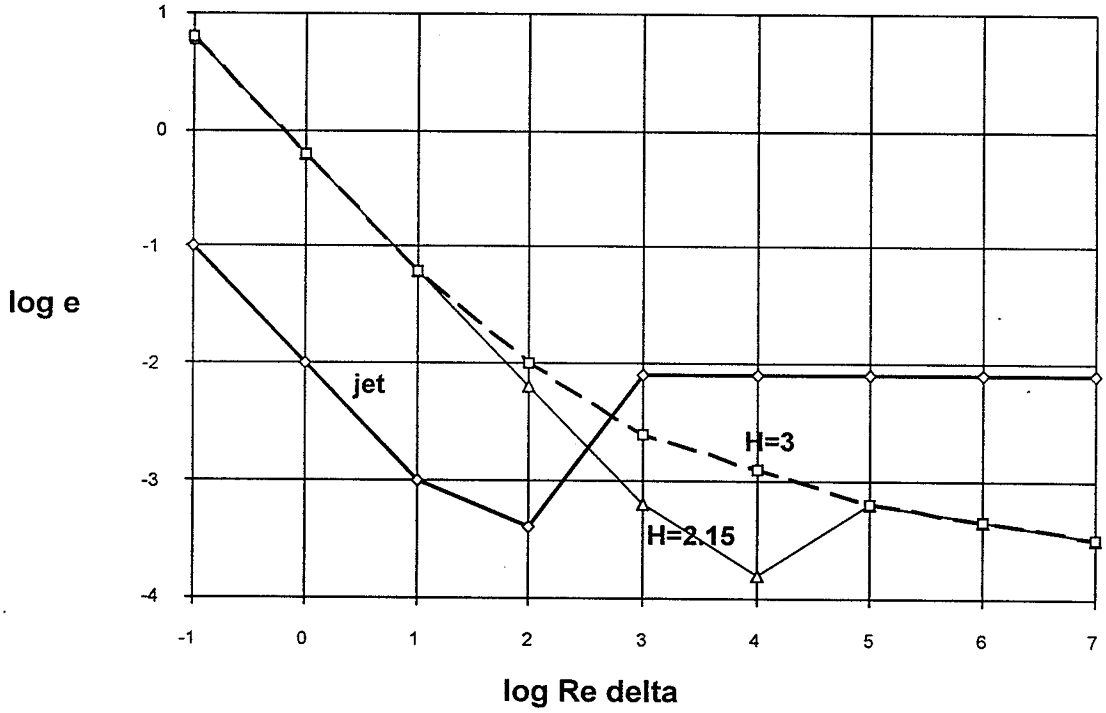


Fig. 2 gives the Dissipationsdiagram for twodimensional boundary layers as put together by the author (Diss. U. La Roche 1965) [1] on basis of the catalog of turbulent B.L. profiles by Tani [4] and the formula given by Blasius for laminar B.L. [5].
jet: means a free jet layer
H=.. are respective Form-parameter values selected for presentation
Parameters H=3 and H=2.15 describe e.g. different wall-boundary-layers in transition from laminar to turbulentflow [4].

For small Reynoldsnumbers i.e. below laminar-turbulent transition (2 < log Re delta < 3) the energy-dissipation of free jet layers at the same Re_del is almost 90 times less than of wall-layers. This is in sharp contrast to turbulent boundary layers, where the same ratio is very much bigger than 10.

According to the dissipation diagram supplied, the resulting "wall friction" on such an arrangement is surprisingly much less than in a laminar boundary layer on a comparable smooth wall.
This together with the viscous entrainment effect on the material in the grooves would be a plausible explanation of the locusts gliding wings suction side at the observed gliding with Re <2'000.
Relatively coarse oblique grooves in laminar flow will have therefore a small energy-dissipation, which means small friction.

Nomenclature

Cf	friction coefficient
Cl	lift coefficient
H	Boundary layer formparameter=delta/d
delta	momentum loss thickness
d	displacement thickness
e	energy-disspation coefficient of boundary layer
k	height of groove-ridge
alpha	inclination between grooves and free stream direction, 90 degrees would mean perpendicular to free stream direction
L	length along profile to point considered for calculation of local Re number
Re	local Re number calczulated with L
Re_k	Re number calculated with k-value
Re delta	Re number calculated with imonemtum loss thickness
other	to be found in the text and literature cited

Transfer to technical applications

The following is a description how to transfer the locusts lesson to general technical applications. The understanding condensed in the transfer prescription was also the subject of the experimental verifications reported.

For correct operation, the separated flow over the grooves must be laminar. From the work of Kottke [3] it is known, that the flow over a step is laminar, if the Re number calculated with the step height Rek is < 6000. It is further known, that the separation region following such a step has a length of between 6 to 12 times the step height k. In order to operate in the proper regime, the following conditions have therefore to be met:
Groove dimensions height and width: see diagram summary Fig. 3 below

- k the groove-height must give a Reynoldsnumber < 6000 [3]
- The groove width in flow direction shall be smaller than 6 to 12 k [3]
- The minimum groove height d should be > than about 3 times displacement thickness of comparable wall boundary layer. As the experimental verification shows a recommendable lower limit would be a step height (the groove depth) k as big as practical, e.g. giving Re_k >1000

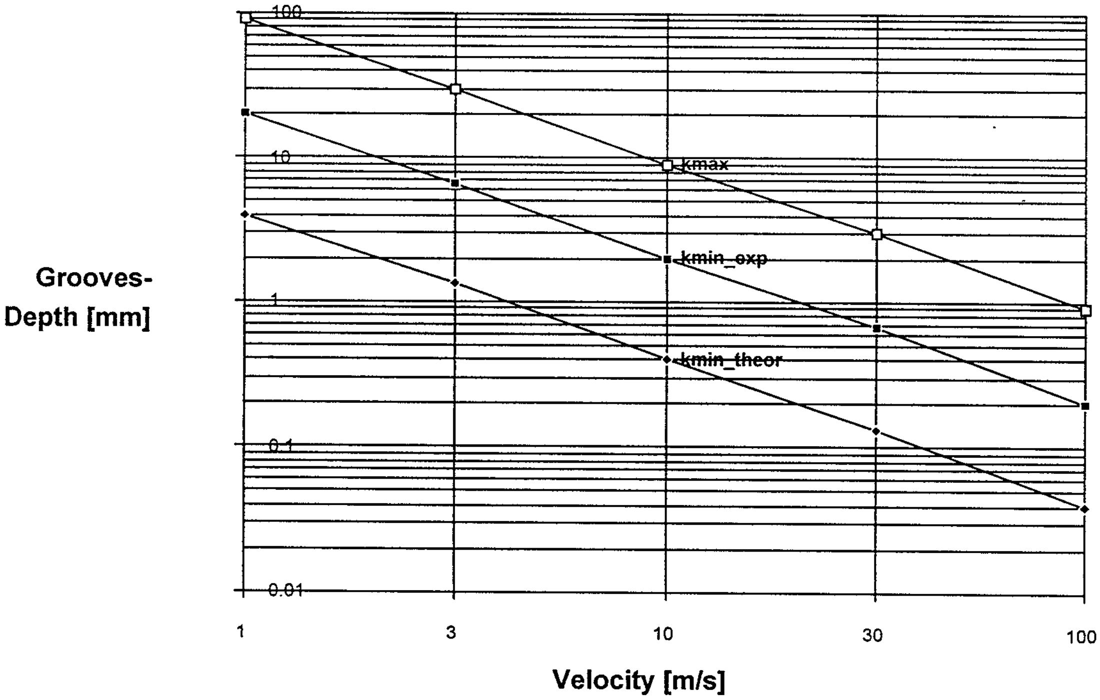


Fig. 3 Diagram for air at normal pressure

The diagram Fig. 3 summarizes these relationships for a practical speed range in air at normal conditions. For other fluids and/or conditions just make correction for the dynamic viscosity. (in the diagram the value used is 1.5e-5).

An example for use of the diagram:
For a flow speed of 3 m/s in air we get the dimesions of the groove as:

- minimal theoretical* groove height d
  :k=1.5 mm
- minimal practical groove height d
  :k=7 mm
- maximal groove height k
  :k=30 mm

*(limit set plausibly at 3 times displacement thickness of B.L.)

With an inclination angle of 45 degrees the value for the grooves width (perpendicular to groove direction) would be e.g.: 7mm*6/1.4 = 30mm, (7*6 is groove width in flow direction)

Experimental verification

The starting preliminary check on the whole concept leading to oblique grooves was made on the statements of Fig. 2:

We should be finding reciprocal dissipation values in laminar vs turbulent regimes for jet shear layer and wall boundary layers. In laminar flow the energy dissipation of the wall layer would be bigger than the jet layer and in turbulent flow the relation would be inverse. To test this relation a pipe with diaphragms inserted at regular intervals was compared to a smooth pipe with identical free inner diameter [2]. In laminar flow below Re <2000 pressure loss in the smooth pipe was distictly higher, confirming qualitatively the expectations.
So the next step was concentrating on concepts using this phenomenon. At the HTL Fluid Mechanics Lab we conducted several investigations on oblique grooves starting in 1996.

A first phase was dedicated to understanding of the phenomenon. To this end parallel investigations were done on visualization with a laminar water table at Re 20'000 and preliminary pressure measurements on a plate in windtunnel tests in air at Re 100'000. [6]
The groove dimensions were taken from diagram Fig. 2 and worked well.

Result shows non-separation in positive pressure gradient up to a Cl of 1.0 on a thick plate with rounded nose from Re 2e4 to 1e5. The Cl-value is inferred from the pressure measurements. Visualisation showed markedly less mixing in B.L. over grooves. The inclination angles for the grooves used were 45 and 60 degrees. The results of windtunnel measurements and watertable agree sufficiently well, when the appropriate windtunnel corrections [10] are applied for angle of attack used. The similarity assumptions (diagram) worked well for the Re numbers choosen.

A second phase was aimed to more quantitative work on the phenomenon identified.
To this end we had two investigations, one on a wing profile producing pressure gradients and one for verification of Cf-values in a tube. The latter was also modeled with an available CFD code.
The real profile tests in a free jet windtunnel [8] were designed to check for separation for extended Re. Measurements with 45 degrees grooves confirmed, that at around Re 100'000 transition to a turbulent B.L. takes place within a very narrow space. It became apparent, that with higher positive pressure gradients the location of boundary layer transition shifted upstream, which at the time was not correctly identified as breakdown of the postulated entrainment of material in the grooves. We expected that with changing to coarser grooves this problem could possibly be alleviated.
To test friction coefficient at low Re numbers we used a tube with grooves at 90 degrees to flow direction [7]. It shows distinctly less friction drag compared to a smooth tube with the same free inner diameter below Re 700 to 1100. The smaller value for wider spaced ridges of the groove-geometry. This result would be the indirect confirmation of the diagram Fig. 2 showing B.L. dissipation for laminar and turbulent cases.
The CFD simulation [7] confirmed some insigths on grooves geometry, e.g. formation and location of vortex in grooves. The optimization however was confined to rounded grooves ridges only. The available experimental evidence shows, that in the laminar flow regime even sharp ridges separating the grooves work very well. The findings further show very weak influence of these vortices, not supporting a possible model concept of vortex-rollers of the flow over the grooves as postulated elsewhere. Because of laminar flow regime the viscous decay of vortex energy prevails and no important kinetic energy is stored in the vortices filling the grooves.

After these results we had still unsolved questions:
a) how to upheld the entrainment effect of oblique grooves against positive pressure gradients
b) influence of pressure gradients and friction for flat plates/profiles

Continuation took place in 1997 with the ETHZ Turbomachinery Fluid Lab for the remaining questions.
Investigated were grooves on a flat plate in different pressure gradient setups combined with boundary layer profile measurement. In additon a greater range of obliqueness alpha was investigated, from 30 to 90 degrees [9].

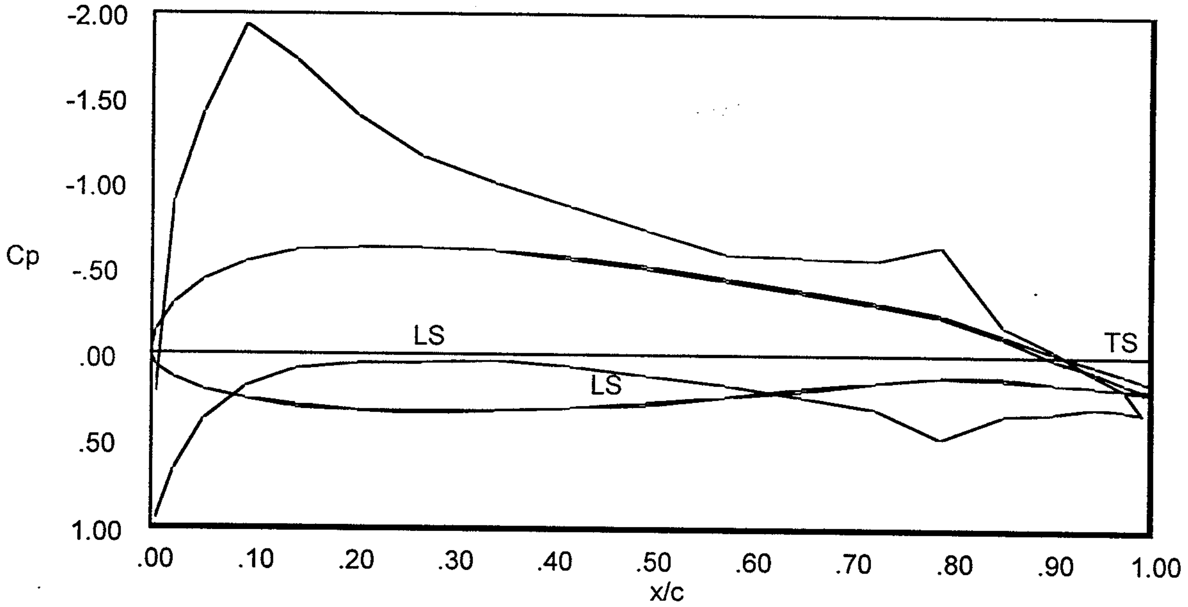
Summary:
The arrangement with oblique grooves is working up to Re 80'000 to 120'000 depending on pressure gradient, followed by a clean transition to turbulent B.L. with a convex velocity profile (low H-values).
The integrated surface friction up to transition point is down to about 60% percent of a comparable smooth wall between Re 40'000 and 100'000.
The measurement setup did not check for separation, since the pressure gradient was forced on a flat testplate with channel inserts.
Measurements with various grooves inclinations vs. pressure gradient showed, that for positive pressure gradients high inclinations should be applied, e.g. angle between grooves and flow direction less than 30 degrees. If so, the viscous transport of material inside the grooves stays pointing downstream, which is a condition for non-separation. If inclination less than 30 degrees, e.g. 45 degrees are applied, the boundary layer will make an earlier transition to turbulent state at the point, where the material in the grooves is not any more transported against the pressure gradient outside the boundary layer. This was cofirmation of the profile tests at the HTL fluid mechanics lab.
An additional result obtained was the fact, that there is no big difference between rounded grooves ridges or sharp ones, which is plausible for a laminar flow regime, see locusts wings.
Similarity assumptions are again confirmed (diagram Fig. 2).
Optimum parameters near upper size of step k [3] are confirmed: (as coarse as possible)

Applications

In general the most interesting effect is avoiding laminar flow separation in positive pressure gradient, a feature which overturns a classic limitation of aerodynamic design for low local Re numbers. As a wellcome by-effect there is no important friction increase caused by the proposed oblique grooves, in most cases friction will remain comparable or even less important than with a smooth wall.

•retrofit on laminar part of airfoil profiles, slats and/or flap-arrangements replacing classical tripping devices with a superior tripping device assuring complete avoidance of laminar separation in positive pressure gradient and giving clean transition to turbulent B.L. at local Re of around 100'000. A case in question would be making control surfaces more efficient and safe in low speed operation.

- hangglider profiles with a supertripping device on suction side near the leading edge will allow flying not like a kite, but dependably as an airplane. Tugging down the aft part of the gliders profile e.g. on your right side will not start turning to right with stalling right wing part, but will turn you to left with much reduced loss of height.
The price to pay is a slightly increased Cd-value with fully turbulent bondary layer on suction side, which as an additional return improves however general stall resistance in gusts.



Angle of attack = 1.50
CL = 1.002
Cm = -.131
CD = .0111
t/c = .162

Fig. 4 An exemple of a profile with laminar separation LS triggered by actuating the flap deformation on the paragliders wing profile. Oblique grooves at around x/c location 0.1 would allow to get Cl of 1.0 without laminar separation, triggering turbulent transition around location x/c 0.15.

- New airfoil profiles with high Cl-loading at low Re feasible leading to increase of aspect ratio and decrease of friction drag, no laminar separation. Thereby the classic limits of profile design as e.g. summarized by H. Schlichting und E. Truckenbrodt [5] can be overcome.

an exemple:
- WINGGRID [12] for small chord winglets. No lower limit due to Re as with smooth profiles. Allows high span_efficiencies also at very low speed and high number of winglets. A high number of winglets will reduce the relative span a WINGGRID has to have for a specified span_efficiency.

- Ventilation propellers with much increased efficiency and low noise. The device would practically achieve more than 2 to 4 times blade loading at the same low Re number.

- Mixers of all kinds in laminar flow in process industry. The grooves will result in a drastic improvement of mixing efficiency with ordinary mixers, e.g. more mixing with less energy required.

- Inlet ducts of diffusors, allowing wider divergence and shorter duct length for a given pressure recovery.

- Water craft fins and control surfaces avoiding loss of control in starting and turning at low speed due to laminar flow separation.

Patents

PCT publication WO 97/21931 phase finished.
Nationalizing phase under way.

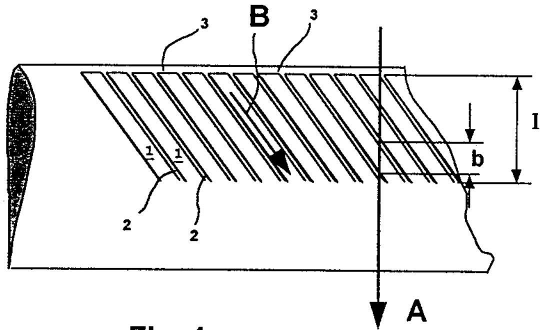


Fig. 1

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