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REVIEW ARTICLE

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Fluid Mechanics of Biological Surfaces and their Technological Application

Abstract A survey is given on fluid-dynamic effects caused by the structure and properties of biological surfaces. It is demonstrated that the results of investigations aiming at technological applications can also provide insights into biophysical phenomena. Techniques are described both for reducing wall shear stresses and for controlling boundary-layer separation. (a) Wall shear stress reduction was investigated experimentally for various riblet surfaces including a shark skin replica. The latter consists of 800 plastic model scales with compliant anchoring. Hairy surfaces are also considered, and surfaces in which the no-slip condition is modified. Self-cleaning surfaces such as that of lotus leaves represent an interesting option to avoid fluid-dynamic deterioration by the agglomeration of dirt. An example of technological implementation is discussed for riblets in long-range commercial aircraft. (b) Separation control is also an important issue in biology. After a few brief comments on vortex generators, the mechanism of separation control by bird feathers is described in detail. Self-activated movable flaps (=artificial bird feathers) represent a high-lift system enhancing the maximum lift of airfoils by about 20%. This is achieved without perceivable deleterious effects under cruise conditions. Finally, flight experiments on an aircraft with laminar wing and movable flaps are presented.

Introduction

Biological surfaces exhibit structures which are, at first sight, both appealing and enigmatic (Fig. 1). In particular, the skin surfaces of aquatic animals and the feather structure of birds may promise interesting fluid-dynamic effects. Often, however, these structures only unfold under the microscope. In other cases they are difficult to observe due to the animal's rapid motion. In addition, and rather unexpectedly, interesting fluid-mechanical properties can be found even on plant surfaces. In addition to sheer curiosity, there is scientific motivation for fluid mechanical research related to biology: natural evolution proceeded according to its own laws and with its own possibilities and limitations. One can therefore expect that the universal laws of physics are exploited by nature in a way that is not limited by the present habits of human thought. Escaping the customary avenues of present research could enable us to gain new and useful insights, but access to these insights may be hindered by the very same present habits of thought.

One example of such biased perception is to expect only a single purpose for a biological surface. By contrast, multiple function is the rule in biology. Consider, for instance, the mucus on the skin of aquatic animals. This acts as an osmotic barrier against the high salinity of sea water and protects the creature from various kinds of parasites and infections. Since it is also inherently slippery, it helps the animal escape the grip of a predator. In addition to other useful functions, of which we are not as yet aware, the mucus also operates as a drag-reducing agent on some fast predatory fishes, such as barracuda and smallmouth bass (Hoyt 1975). This particular use of mucus enables the fish to attack more quickly. If the attack on the prey is successful, the loss of mucus due to rapid swimming, and with it the loss of chemical energy, is compensated for. But the existence of mucus on an aquatic animal does not per se necessarily mean that the mucus has a useful consistency for the purpose of drag reduction.

On the other hand, artificial derivatives of fish mucus, i.e., polymer additives for liquids, are used with impressive success in drag reduction technology. For instance, the pumping power required to propel crude oil

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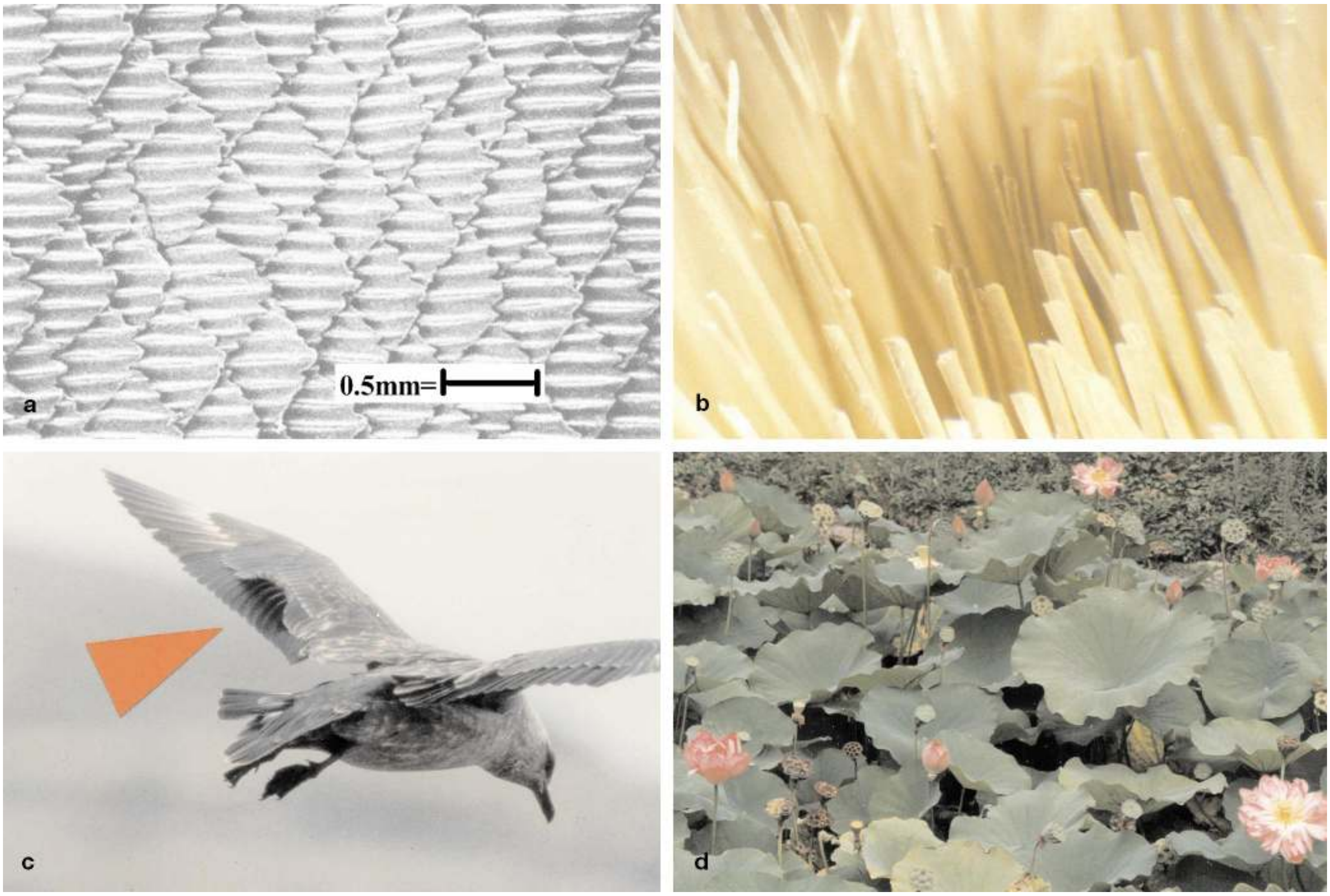

Fig. 1a–d Biological surfaces. a) Silky shark skin photograph (from Reif 1985). b) Sea leopard skin. c) Skua wing in landing approach (from Rechenberg et al. 1995). d) Lotus leaves

through the Alaska pipeline is very significantly reduced (by about 30%) by the injection of a few parts per million of a gooey substance only remotely related to fish mucus (Motier and Carrier 1989). The successful use of this effect clearly demonstrates that one has to understand the physical mechanism at work (Virk et al. 1970). By contrast, the direct use of fish slime or its chemical replica would hardly have yielded a suitable oil-soluble additive for crude oil pipe lines. Likewise, it would be naive to assume that the mere imitation of biology would immediately lead to a technologically viable use of the very same effect.

Moreover, some of the concepts which seem to be used by nature remain tough scientific problems and are only partly understood. One such example is the compliant skin of dolphins. The story started with "Gray's paradox." Gray (1936) suggested there was a huge gap between the speed of the dolphin and its available (estimated) physiological power to achieve this speed. Intrigued by this discrepancy, Max Kramer (1960) hypothesized that, due to the compliance of the dolphin's skin, it would interact with the water flowing over the body's surface in such a way that the flow was stabilized and the transition to turbulence delayed. This delay in the onset of turbulence would in turn dramatically reduce skin friction and drag. Later, theoretical stability calculations supported this hypothesis (Benjamin 1960; Landahl 1962). There followed two decades of both futile and expensive experimental research. Finally, it took the combined efforts of first-class theoreticians and experimentalists to prove that Kramer's original idea did indeed work as a means of stabilizing a laminar boundary layer (Carpenter 1990; Gaster 1988; Lucey and Carpenter 1995).

In addition to this transition delay mechanism, it has been assumed that dolphin skin would also work under fully turbulent flow conditions. The expected effects are, however, much smaller than those from transition delay and are assumed to amount to skin friction reduction of only a few percent (Kulik et al. 1991). What mechanisms the dolphin really uses is still not clear. The actual margins of dolphin drag reduction are, nevertheless, much smaller than "Gray's paradox" would lead one to believe. In experiments with trained dolphins Lang (1975) exposed a crucial deficiency in Gray's considerations: one cannot extrapolate the physiological performance of human athletes to that of dolphins. Dolphins seem to perform better, and this puts into question "Gray's paradox." On the other hand, the limited accuracy of Lang's measurements does not eliminate the possibility that the dolphin's skin does in fact produce *some* drag reduction. Thus, further investigations of this phenomenon could prove fruitful.

This leads to the issue of wishful thinking in conjunction with biological observations. As a matter of fact, drag reduction research usually is motivated by high expectations. The actual effects, however, are generally modest; one of the few exceptions is the influence of polymer additives on turbulent flows. Nevertheless, there is nothing wrong with small improvements, particularly if several of them are used at once. In human technology, aircraft engineers or computer technologists have improved their creations in many small steps to arrive at something which finally appears as a breakthrough. Natural evolution proceeds very successfully in the same way (Rechenberg 1973; Schwefel and Bäck 1992).

In the present paper, we will focus on two issues: (a) wall friction reduction in turbulent flows caused by surface properties related to natural skin structures, and (b) separation control devices derived from observations on animals. In addition to discussing biofluid-dynamic mechanisms, we also consider technological applications. Eventually, and as a by-product, this leads to a better understanding of the observations with which we began. With a few exceptions (e.g., the "lotus mechanism") we report mostly on our own findings. In order to provide a clear distinction between that which has been confirmed scientifically and that which remains merely plausible, we note the unconfirmed ideas in italic print. This is because biological research related to engineering applications is pervasively contaminated by wishful thinking. Therefore we consider it useful to draw a clear line here.

Wall shear stress reduction

Drag reduction of a moving animal or vehicle can be achieved by reducing wall shear stress and, in some cases, by separation control. This section of the paper will mainly focus on *turbulent* wall shear stress reduction. Obviously, laminar flow offers the lowest attainable wall shear stress. This has been introduced successfully in glider aircraft wings. In commercial aircraft, however, the problems associated with the implementation of laminar flow on swept transonic wings have not yet been completely solved. Even if laminar flow is maintained over a major proportion of the wings, most of the aircraft surface will still be exposed to turbulent flow. Thus, turbulent wall shear stress reduction is obviously important in all contexts of future aircraft design.

Shark skin or "riblets"

The mechanism

By about a decade ago it had become clear that a turbulent boundary layer on a surface with longitudinal ribs can develop a lower shear stress than that on a smooth surface (Nitschke 1984; Walsh 1980, 1990). While scientists in the United States invented ribbed surfaces on the basis of fluid-dynamic reasoning, parallel work in Germany was motivated by observations on shark skin (Dinkelacker et al. 1988; Nitschke 1984; Reif 1985; Reif and Dinkelacker 1982). When we started working in this field, we first confirmed the effect in our wind tunnel using a direct shear force measurement (Bechert et al. 1985). We subsequently developed a theoretical model, together with a group from the University of Naples, (Bechert and Bartenwerfer 1989; Bechert et al. 1990; Luchini et al. 1991). This model is outlined below.

The turbulent flow close to a plane smooth wall exhibits very significant instantaneous deviations from the average mean flow direction. Figure 2 shows an instantaneous streamline pattern very close to a smooth wall, as calculated by Spalart and Robinson (Robinson 1991).

The actual size of the flow regime shown in Fig. 2 would usually be very small. For the water flow on a shark or for the air flow on an aircraft the actual dimensions of Fig. 2 would be in the millimeter range. In order to obtain generally valid data, quantities are defined in dimensionless wall units. For instance, the distance y perpendicular to the wall takes the form $y^+ = y \cdot u_\tau / \nu$. This is a Reynolds number defined with the velocity $u_\tau = \sqrt{\tau_0/\rho}$, where τ_0 is the average wall shear stress; ρ and ν are density and kinematic viscosity, defined as usual. In normal circumstances, u_τ assumes a value of a few percent of the free-stream velocity. The streamwise distance x and the lateral length z are nondimensionalized in the same way as y. In Figure 2, instantaneous pressure levels are also given. The pressure is nondimensionalized as $p^+ = p/\tau_0$.

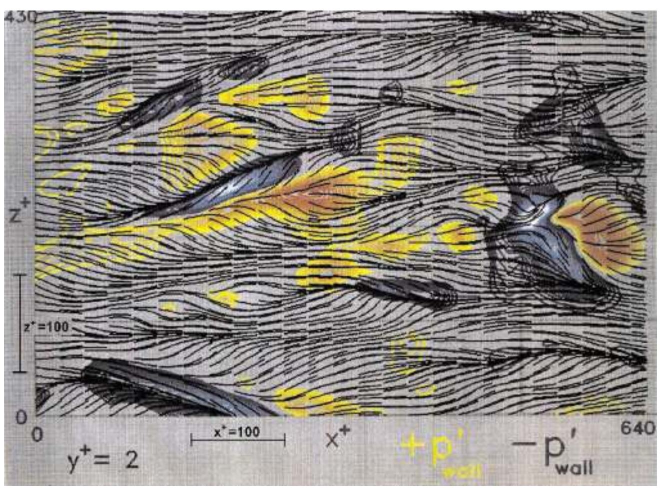

Fig. 2 Instantaneous streamline pattern near a smooth wall, at an elevation of $y^+ = 2$, underlaid with contours of wall pressure. Yellow to red: $p^+ = 3$ to 25; blue to white: $p^+ = -3$ to -25 (from Robinson 1991). Flow from left to right

The strong exchange of momentum in a turbulent boundary layer is produced by high-speed flow lumps approaching the surface ("sweeps") and by low-speed flow moving away from the surface ("ejections") into the high-speed regions of the flow (Fig. 2). Regions of impinging flow ("sweeps") mostly occur in regions of elevated pressure (yellow to red) while "ejections," i.e., where the flow moves away from the surface, correspond mostly to regions of lower pressure (blue to white). This exchange of fluid normal to the surface generates the enhanced shear stress of a turbulent flow because high-speed flow is decelerated efficiently when it is swept towards the surface. By contrast, such an exchange normal to the surface does not occur in a laminar flow where the streamlines are essentially parallel, and the flow lacks such violent local events.

It is also obvious from Figure 2 that local events such as "sweeps" and "ejections" require fluid motion in the lateral z-direction. Thus, hampering w-velocities in the z-direction will reduce momentum transfer and skin friction. It is plausible that this can be achieved with ribs on the surface which are aligned in the mean flow direction. On the other hand, it is known that surfaces exhibiting protrusions higher than about $y^+ \approx 5$ do increase the wall shear stress (Schlichting 1979). However, for protrusions smaller than $y^+ \approx 3$–5, ribs or other roughnesses are embedded in the viscous sublayer. In this layer, very close to the wall, any fluid behaves like a highly viscous fluid, e.g., like honey. Therefore it is admissible to calculate the flow around very small ribs with a viscous theory. Under viscous flow conditions it turns out that the ribbed surface appears as a smooth surface located at a virtual origin (Fig. 3). However, the location of the origin, i.e., its elevation above the groove floor depends on the flow direction. For cross-flow on the ribs, the virtual origin is closer to the rib tips than for longitudinal flow. The difference between these two heights, Δh, we call the "protrusion height difference." The existence of this difference has interesting consequences: if a flow motion is generated by a fluid lump in a plane at a height y^+ above the surface, the fluid lump experiences greater resistance if it moves laterally than if it moves longitudinally. In this way the cross-flow is hampered by the ribs, as desired, and thus ribs do indeed reduce momentum transfer and shear stress. Therefore, for an optimization of the shear stress reduction, we have to select a ribbed surface which exhibits a maximum difference of the virtual origins for longitudinal and cross-flow. As the theory shows (Luchini et al. 1991), the maximum height difference is obtained for very thin bladelike ribs. The rib height should be $h \geq 0.6\,s$, where s is the lateral rib spacing. For this value of the rib height, the maximum difference in the elevation of the origins, or the protrusion height difference is $\Delta h_{max} = 0.132$ s. Careful experiments in our oil channel (Bechert et al. 1992) with an adjustable blade rib height (Bechert et al. 1997b) have shown that the optimal rib height is actually slightly lower, at $h = 0.5$ s. With this surface a turbulent shear stress reduction of 9.9% below that of a smooth surface has been achieved (Bechert et. al 1997b).

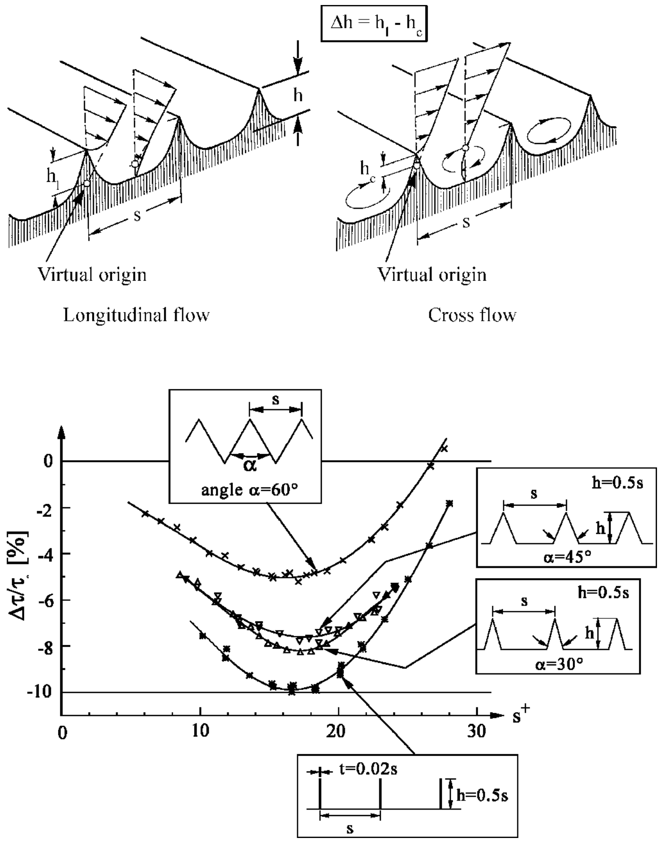

Fig. 3 Above: Longitudinal and cross-flow on a ribbed surface; below: drag reduction performance of various rib geometries

Figure 3 shows the data of optimal blade rib surfaces as compared to "riblets" with a triangular cross-section, which had previously been considered as optimal. Clearly it is difficult to manufacture surfaces with blade ribs. Therefore we devised wedgelike ribs which still produce an impressive wall shear stress reduction (Fig. 3). Ribbed surfaces such as those shown in Fig. 3 perform well over a certain s^+ range, which corresponds to a particular velocity range. By selecting an appropriate spacing s of the ribs, one can adjust the ribbed surface to the flow conditions at hand. In Fig. 3, $\Delta\tau$ is the difference between shear stress τ on the ribbed surface and τ_0 on a smooth reference surface, i.e., $\Delta\tau = \tau - \tau_0$. Negative values of $\Delta\tau/\tau_0$ refer to drag reduction and positive values to an increase in drag.

"Brother and sister riblets"

The viscous theory (Bechert and Bartenwerfer 1989; Bechert et al. 1990, 1997; Luchini et al. 1991) appears to provide a useful prediction for an optimal rib height, i.e., $h/s \geq 0.6$. As a guideline for the experiments this has turned out to be very useful. However, for deeper

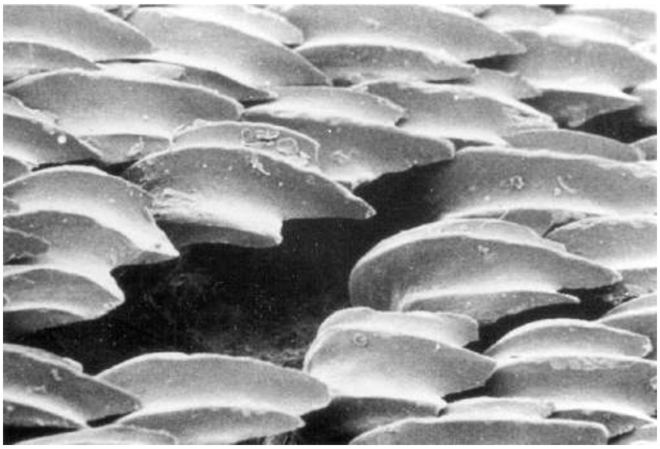

Fig. 4 Scales of the great white shark (from Reif 1985)

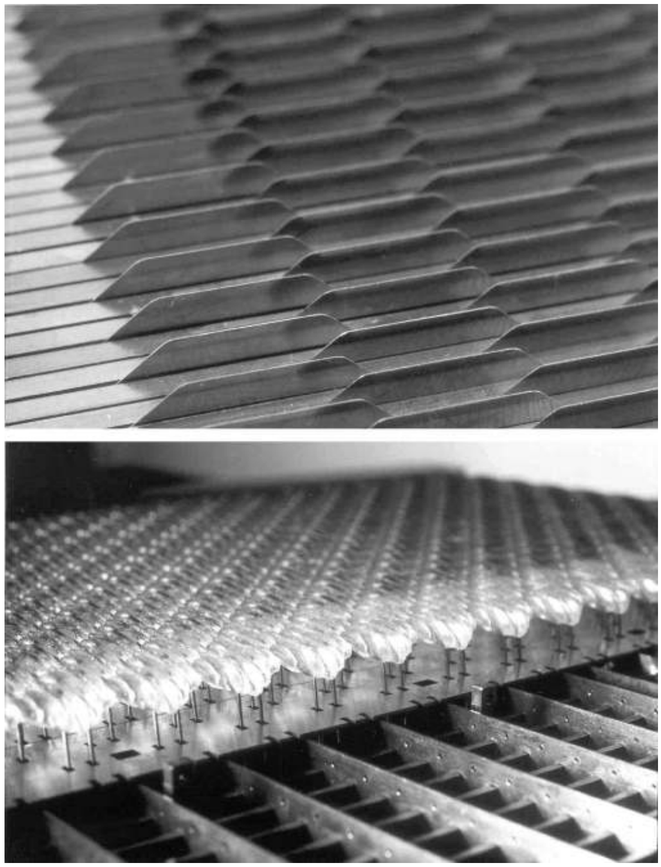

Fig. 5 Above: Photographs of a test surface with three-dimensional ribs; below: a partly assembled artificial shark skin

grooves, those exceeding $h/s \approx 0.6$, the measured performance deteriorates rapidly, a fact which is not predicted by the simplified viscous theory. This deleterious effect is probably due to increased sloshing of the fluid in the grooves. Sloshing is excited by the fluctuating pressures of the turbulence above the surface. Sloshing entails enhanced momentum transfer and, as a consequence thereof, increased wall shear stress occurs.

The above physical description led to the idea that sloshing in the grooves might be reduced by inserting an additional small rib on the floor between the previous ribs. For this arrangement we have coined the term "brother and sister riblets". A careful parametric study was carried out with this configuration (Bruse et al. 1993). This study was later repeated in our laboratory with different hardware and improved data corrections. The result is neither encouraging nor disappointing: "brother and sister riblets" can be as good as the best previous riblets, i.e., blade riblets having uniform height. There is a broad regime of parameters for which the drag reduction remains practically unchanged, with values around and slightly above 9% (Bruse et al. 1993). It is conceivable that "brother and sister riblets" may even be better than blade riblets by a few tenths of a percent. However, it would not be possible to prove this with our present measuring accuracy, although this is excellent ($\pm 0.3\%$).

If there is such a broad range of optimal configurations, we should also see ribs of differing height on real shark skin. Figure 4 is a photograph of the skin of a white shark (Reif 1985). This skin sample exhibits only three ribs on each scale (as opposed to the five to seven ribs per scale of other species; Reif 1985). It is clearly visible here that the height of ribs does indeed vary. In addition, the ribs of consecutive scales seem to interlock. As we were curious about this particular feature, this led to the next set of configurations, namely interlocking three-dimensional riblets.

Three-dimensional riblets

Observations on shark skin and ideas similar to those of "brother and sister riblets" led us to investigate three-dimensional riblets to determine whether the use of interlocking riblets of finite length offers a viable method for reducing turbulent shear stress. In these experiments we again used thin blades as ribs. The blades were formed by electric discharge machining to obtain the shape shown in Fig. 5. Subsequently the blades were inserted into an array of slits in a flat plate. Then the blades were locked to a second plate below the slit plate. By moving the two plates relative to each other, the rib height of the blades could be varied during the experiment. We tested three different rib lengths. In addition to the shape shown in Fig. 5, we also tested ribs with vertical leading and trailing edges, i.e., rectangular shape. The measured wall shear stress data have recently been presented in some detail (Bechert et al. 2000). The maximum shear stress reduction obtained was 7.3%. This falls somewhat short of the 9.9% which we obtained with straight two-dimensional blade ribs.

Recent viscous flow calculations by Luchini and Pozzi (1997) have indicated, however, that we may have narrowly missed a more suitable configuration. This configuration would have a slightly wider gap between the trailing edge of one rib and the leading edge of the next interlocking rib following in the streamwise direction. Thus there is some hope for a modest improvement. On the other hand, this does not necessarily mean that the data of the best two-dimensional riblets can be exceeded.

Experiments with a shark skin replica

After confirming that riblets do indeed work, optimizing their shape, and developing a theory, we considered the next crucial question to be: Are there other mechanisms at work on real shark skin? In simplistic terms: Is there any intriguing mechanism at work which may render actual shark skin superior in a novel and impressive way? Our oil channel (Bechert et al. 1992) offered a unique tool for answering this question. The viscosity of the oil makes it possible to emulate the microscopic features of actual shark skin in a dimension magnified × 100. Therefore we were able to emulate: (a) the detailed shape of typical shark scales, (b) the flexible anchoring of the individual scales, and (c) a variable angle of attack of the scales with a global adjustment for all scales.

Previous knowledge of this area was scarce. In the first investigation of this kind Gren (1987) built an array of magnified plastic model scales and collected laser Doppler data in an oil channel. He was already able to change the angle of attack of the scales. The only (rather minor) criticisms of his previous work were that: (a) he used scale models of a slow shark, the spiny dogfish, and (b) he determined the wall shear stress indirectly using velocity measurements above the surface. In addition, he did not have compliant anchoring of his scales. Independently and at about the same time, we had attempted to carry out wind tunnel experiments with a similar aim (Bechert et al. 1985). We built plastic surfaces with a large number of tiny emulated shark scales and tested these on a shear stress balance (Bechert et al. 1985). The various cast plastic surfaces exhibited scales with different angles of attack. The limitations of these latter experiments were: (a) the rather poor quality of the artificial shark scale pattern due to imperfections in the microscopic production process, (b) that the surface was again rigid, and (c) that the gaps between the scales were not modeled, which occur particularly at higher angles of attack. In both of these previous investigations, however, the findings were identical: at higher angles of attack of the scales the wall shear stress increased dramatically. Only at zero angle with an almost riblet-type surface could one hope for a very modest wall shear stress reduction.

The prospect of carrying out new experiments on scales with compliant anchoring, however, was most intriguing. With high expectations, we laboriously built a surface with 800 individually movable scales which could also be adjusted globally to different angles of attack (see Figs. 5, 6). Anchoring of the individual scales was achieved by the mechanism displayed in Fig. 6.

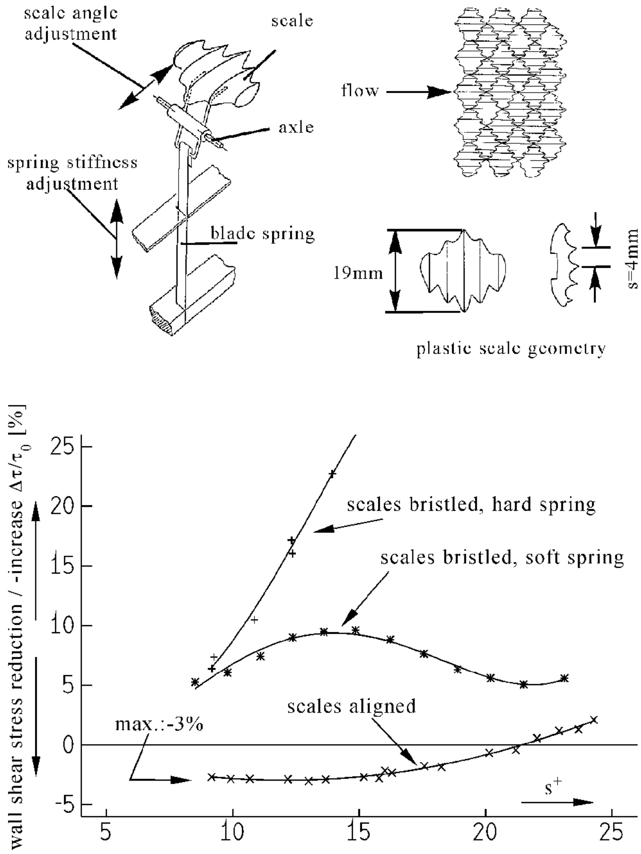

Fig. 6 Plastic scale suspension and typical wall shear stress data of artificial shark scales

Blade springs with variable clamping conditions were used to alter the degree of softness of the suspension. The spring constant could be varied between "hard" and "soft" suspension over three decades; this was achieved with two sets of blade springs. Figure 6 is a schematic presentation of a plastic scale with five ribs designed according to our own microscopic observations of hammerhead shark scales. The manufacturing process consisted first of constructing a 600 : 1 hand-sculptured clay model. From that model a negative mold was cast. With a pantograph-copy milling machine, the mold was reduced in size to a 100 : 1 scale. This mold was inserted into a plastic casting machine, and 800 polystyrene scales were subsequently produced. In addition, tiny brass wire legs and the other parts of the suspension mechanism were manufactured using suitable tools, then soldered together and glued onto the scales. Note that both suspension stiffness and scale angle can be varied during the measurement by remote tooth belt operation.

A few typical wall shear stress data as measured on our artificial shark scale surface can be seen in Fig. 6. The data are consistent with previous results for high spring stiffness and with bristled scales (Bechert et al.

1985; Gren 1987). On the other hand, when the scales are not bristled but are well aligned so that the scales interlock and leave almost no gaps, we find a modest amount of shear stress reduction (3%). This is when shark scales operate as "riblets." The comparatively modest performance may be due to the residual tiny gaps between the scales and other imperfections. This was the first time that shear stress reduction had been measured on a shark skin replica. An interesting situation arises when the scales are anchored with a soft mounting. In this case observations in the oil-channel showed that the scales undergo collective erratic motion caused by the locally varying instantaneous shear stresses within the turbulent boundary layer. Nevertheless, the curve for soft spring suspension in Fig. 6 can still be explained with quasistatic considerations. Incidentally, for aligned scales there is no difference between rigid and soft suspension. For the aligned condition the scales actually do have mechanical contact, and the surface is indeed rigid, even for the soft suspension. Consider the curve for the soft spring suspension in Fig. 6. For bristled scales at low s^+, i.e., at low velocity and low shear stress, the scales remain bristled and again behave like a stiff and rough surface. However, velocity and shear stress increase with increasing s^+. As a consequence, the scales are bent in the streamwise direction, and thus the curve approaches that of the aligned case. This results in a lower friction coefficient, and hence the surface behaves more like a smooth surface.

We can summarize these data with the statement that, even with a detailed and compliant shark skin replica, we did not find a striking effect, at least as far as shear stress reduction is concerned. As a matter of fact, our synthetic two-dimensional blade rib surfaces do perform significantly better than our ambitious shark skin replica. *There remains, however, the possibility that actual shark skin of, say, a silky shark with its very regular ribs (Reif 1985), may perform better and indeed closer to our optimized synthetic two-dimensional riblets.*

On the other hand, the data on the softly suspended scales provide some basis for further speculations. A shark does not move in a straight line and does not have a rigid body, as a ship does. Actually a shark wiggles a lot. Therefore the flow conditions on the body and fins vary periodically and considerably with time. In addition, agility is an important prerequisite for survival. Consequently, separation control may be more important than shear stress reduction. Consider a situation approaching flow separation: For attached flow, the wall shear stress is high. This would refer to a high s^+ in Fig. 6, upper curve, trough regime. However, close to separation, the wall shear stress would be reduced, corresponding to a lower s^+. With low spring stiffness, the scales would then bristle. They would operate as vortex generators enhancing the mixing in the boundary layer. This would help to keep the flow attached. Maintaining attached flow reduces the overall drag (in spite of a locally increased shear stress) and permits higher lift generation on the fins. Both features enhance agility and speed. We will discuss separation control later in this paper, but here, it might be worthwhile to draw the attention of the reader to the striking similarity (if not identity) of vortex generators as devised by Wheeler (1989) and shark scales (Bechert et al. 1986; Bone 1975; Reif 1985) or the skin structure of billfishes (Nakamura 1985). Efficient separation control by these scalelike structures has been demonstrated in several laboratories (Barret and Farokhi 1993; Lin et al. 1989; McCormick 1992; Wetzel and Farokhi 1996).

There are more mechanisms which may come into play. If local flow separation occurs, this will also entail local regimes of flow reversal. Under reversed flow conditions, movable scales will bristle and exert an enormously increased resistance to the reversed flow. From our research on separation control with artificial bird feathers we know that this will indeed hamper flow separation.

It has been suggested previously (Chernyshov and Zayets 1971) that mucus also plays an important role on shark skin. One may have doubts about this when one touches a freshly killed shark. Shark skin feels only wet and rough, and virtually no slime is found upon inspecting the skin. However, one should be cautious here. The shark may perhaps use its mucus more efficiently and therefore less visibly. The combination of riblets and polymer additives does indeed work very well. Data reported by Virk and Koury (1995) indicate that the combination of riblets and polymer additives actually works better than the algebraic sum of the two effects. Due to the strong effect of polymer additives, however, the lateral rib spacing must be adjusted to the modified flow situation. That entails a wider spacing for the same flow speed, or it requires an increased flow speed for the same rib spacing. *The latter property would suggest the use of polymer additives only for high-speed emergency situations. This also makes sense in terms of energy conservation because the use of polymer additives is associated with a loss of chemical energy.*

Hairy surfaces

The first-ever suggestion for a drag-reducing surface was made by Max Kramer in 1937 . His model consisted of strings stretched in the streamwise direction above a flat surface. His reasoning was that the shear stress being exerted by the flow would be concentrated on the strings and kept away from the flat surface. Obviously this is correct, but it is not a consistent scheme for drag reduction over the entire surface, including the strings. Nevertheless, our concept of cross-flow resistance of riblets also applies here. The viscous flow calculations which show this phenomenon have been carried out previously (Bartenwerfer and Bechert 1991; Luchini et al. 1992). Actually, the fact that on a string, a viscous cross-flow generates a higher resistance than a longitu-

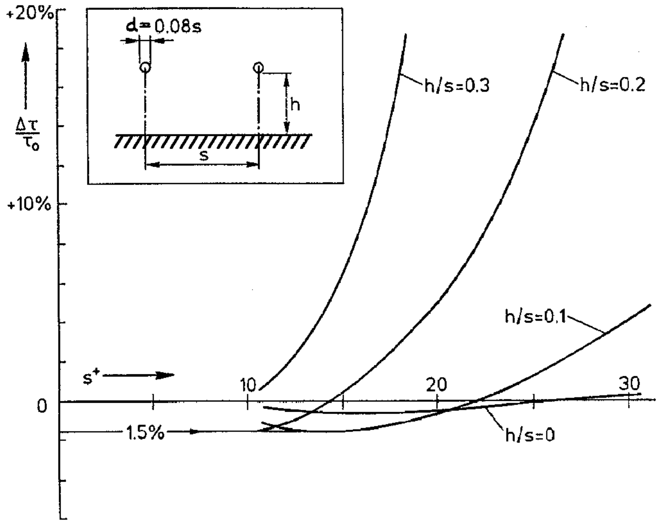

Fig. 7 Test data with a "hairy" surface

dinal flow is well-known; this is at the core of the theory of the locomotion of micro-organisms by flagellate motion of their tails (Higdon 1979).

Thus, with the help of previous theory, we could select a suitable geometry for our experiments with stretched strings above a flat plate. Nevertheless, our experimental surface was equipped with a mechanism for varying the height of the strings above the surface. Figure 7 presents the data from our oil channel experiments; it is evident that a very modest shear stress reduction can be obtained (1.5%).

At lower string elevations, *h/s*, the strings appear to work similarly to riblets. However, at higher string elevations a disastrous increase in shear stress is found. *We argue that sloshing of fluid underneath the strings in the lateral direction is not sufficiently inhibited by the strings as is the case with riblets.*

The question then arises whether this rather marginal drag reduction mechanism may indeed be utilized by animals moving in water or air. We are not in a position to answer this conclusively, but, again, we must recall that biological devices usually serve several purposes simultaneously. Thus a marginal drag reduction may possibly be not that relevant here. Other purposes could be much more important. For instance, the very fine, dense fur of otters serves as a heat insulation device, even in water (Wolkomir and Brimberg 1995). On the other hand, the coarse fur of sea leopards exhibits a quite peculiar hair structure (see Fig. 1). The cross-section of the comparatively stiff hairs is not round, but flat. As one fluid-dynamic purpose of this structure, one could speculate that this type of hair also may inhibit reversed flow and thus may be able to limit flow separation. An (albeit marginal) effect of this kind has been demonstrated for the fur of a certain flying squirrel (Nachtigall 1979). A rather obvious purpose, however, is the enhanced ability of sea leopards and seals to move on ice and snow with such a coarse fur. The short length (about 6 mm) and the exceptional stiffness of the hairs support this latter assumption. Skiers may recall that, before artificial seal fur became available, natural seal fur was attached under the ski for ascending steep slopes. A referee suggested another obvious biological purpose: protection against injuries.

Meddling with the no-slip condition

One usually assumes that the fluid on the surface of a moving body assumes the same velocity as the moving body itself. This is what fluid-dynamicists call the "no-slip condition." It sets the limits for the range of fluid-dynamic shear stress and drag. There are, however, ways to circumvent this confining condition:

- If the skin is not fixed to the body but can move relative to it, the drag of the body can be reduced. Assume, for instance, that the rigid surface of a body is replaced by a belt driven by the shear stress of the flow itself. In this case, we have demonstrated experimentally that a reduction in the drag is possible (Bechert et al. 1996).
- The motion of a spherical oil droplet in water cannot be correctly predicted by Stokes' law for the motion of a rigid sphere in a liquid. This is because the oil inside the droplet takes part in the fluid motion. Therefore the drag of the liquid droplet is lower than that of a rigid sphere (Happel and Brenner 1965).
- The ejection of air at the surface of a body moving through water efficiently reduces the drag (Merkle and Deutsch 1990). A recent video-documentation of swimming penguins (Bannasch 1997) clearly shows that this mechanism is also used in nature: the penguins exhale air before emerging at high speed from the sea. Even more intriguing is the observation (Bannasch 1997) that exhaled air sometimes agglomerates in rings or patches around the body of the penguins and remains there for several seconds. *The wavy contour of the penguin body may contribute to the stability of these air rings. For a limited time exhaled air may thus further reduce the drag of penguins, which is already very low (Nachtigall and Bilo 1980).*

Lotus leaves: a self-cleaning system

The particular cleanness of the sacred lotus (Nelumbo) has been observed since early in history. It has made the lotus a symbol of purity in Asian religions, as early as in Sanskrit texts. Nevertheless, this cleanness has only fairly recently received a satisfactory scientific explanation by Barthlott (1990) and Barthlott and Neinhuis (1997). Not entirely unexpectedly, the cleaning is caused by rain drops. However, the plant surface is water repellent. The ability to avoid wetting of the leaves is further enhanced by a rough surface structure exhibiting microscopic wax knobs (Fig. 8). The way in

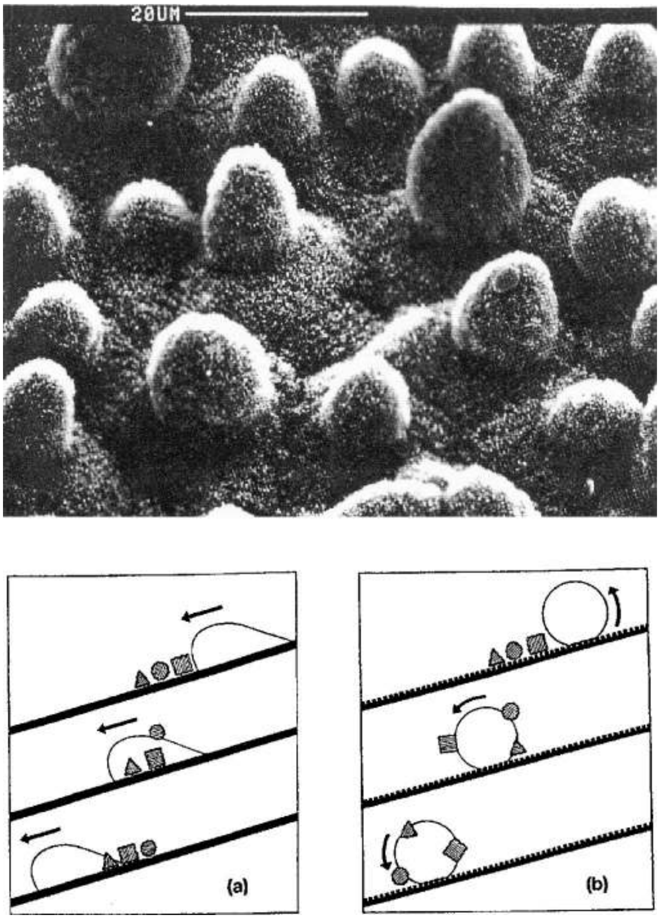

Fig. 8a,b Microstructure and self-cleaning mechanism of the lotus plant (from Barthlott and Neinhuis 1997). a) On a smooth surface dirt particles are merely redistributed by a water droplet. b) When droplets run off a rough water-repellent surface, dirt particles are efficiently removed

which dirt particles are removed from the surface can be also seen in Fig. 8. This self-cleaning "invention" is not restricted to the sacred lotus alone but is also found on various other plants, among them the well-known garden flower nasturtium (Indian cress, *Tropaeolum majus*, German: *Kapuzinerkresse*) and even on the surface of insect wings (Barthlott and Neinhuis 1997).

This self-cleaning ability can be emulated on technological surfaces to reduce maintenance. For instance, a paint for buildings based on this principle already exists. The cleaning of these novel surfaces works well only when soap or detergents are not used. Consequently the result is a two-fold beneficial environmental effect: water for cleaning is saved, and water pollution is reduced.

A water-repellent surface with micro-roughness (with knobs <10 μm height) is also an interesting option for laminar wing surfaces on aircraft. A clean, smooth surface is a crucial prerequisite for the proper operation of a laminar wing.

On the other hand, for turbulent shear stress reduction, plastic riblet film is currently used on one Airbus A340 commercial aircraft (Cathay Pacific Airways). The riblet film used here has a lateral rib spacing of about 60 μm. An unexpected finding is that this aircraft remains cleaner than others without riblet film. This cleanness suggests an inadvertent utilization of the "lotus effect."

Differing from the "lotus effect", shark skin usually appears remarkably clean. Compare, for instance, the skin of whales and that of sharks. It is possible that, on the ribbed surface of sharks, suction caps and other attachment techniques of parasites might not work so well either. We speculate that the high local shear stress on the rib tips also may help to prevent dirt particles from settling on the surface. Thus the initial concerns about possible dirt agglomeration on riblet films on aircraft and the ensuing increased maintenance costs may not materialize after all. By contrast, a reduction in maintenance costs by the introduction of new surfaces now appears as a real possibility.

Technological applications on aircraft

Artificial shark skin, i.e., riblet film, is on its way to being implemented on long-range commercial aircraft. On long-range aircraft (a) the fuel costs contribute perceptively to the direct operating costs and (b) the fuel weight exceeds the payload by far.

Consider an application on the Airbus A340-300. What are the implications of riblet film for its economic performance? The contribution of skin friction to the total drag of this aircraft is about 48%. Using our optimized riblets with trapezoidal grooves could reduce this component by 8.2%. Covering the entire aircraft would reduce the aircraft's total drag by about 4%. For various reasons, however, the entire surface of the aircraft cannot be coated. Dust erosion, for example, at the leading edges of the wings and in the vicinity of the landing gear has a long-term effect similar to that of sand blasting. In addition, at the leading edges of the wings, the riblet film would interfere with the de-icing system, and it would be incompatible with the laminar flow there. Locations at which fuel or hydraulic fluid comes into contact with the plastic riblet film should also be avoided. Obviously, the windows cannot be covered either. Thus, only about 70% of the aircraft could be coated with riblet film. In addition, in some places riblet spacing and alignment would be suboptimal. On the other hand, some of the roughness on the aircraft surface would be covered and thus be smoothed by the film. Moreover, a reduction of the wall friction ensues a slightly thinner boundary layer which, in turn, causes a reduction of the form drag in the rear part of the fuselage. This means that a 3% reduction in total drag of the aircraft is probably achievable.

The weight of the riblet film is in the order of the weight of the paint which it replaces, i.e., 100–250 kg, depending on the percentage of the surface being covered. Additional technological issues, such as durability and UV radiation tolerance, have been solved in the meantime. One particular concern has fed the reluctance of innovation-skeptical businessmen: at present, it takes one week to coat an aircraft with riblet film, during which time the aircraft earns no money. Plausible as this consideration may sound, it is indeed a spoof argument. Clearly, it is possible to coat the aircraft in steps parallel to other mechanical or maintenance work. In addition, if the riblet film replaces the paint, the time required for painting and the time required for attaching the riblet film do not differ significantly. Moreover, the producer of riblet film (3M, St. Paul, Minn., USA) has developed a film that can be removed more conveniently than paint. The prospect of having an aircraft with a dirt-repellent film surface, resembling the lotus, may be an additionally attractive item in terms of maintenance costs.

The basic data on the A340-300 long-range aircraft are:

- Empty weight: 126 t
- Fuel: 80 t
- Payload: 48 t, 295 passengers
- Maximum take-off weight: 254 t

On long-range aircraft, fuel costs currently account for about 30% of the direct operating costs. One would thus save about 1% of the direct operating costs by a 3% reduction in the fuel consumption (resulting from a 3% reduction in total drag). More importantly, however, about 2.4 tons of fuel could be replaced by 5% more payload, the equivalent of 15 more passengers. Consequently, including fuel savings, the airline could earn up to 6% more per flight. This would add up to something in the order of US$ 1 million more profit from each aircraft per year. Incidentally, this would be roughly equivalent to the total expenditure for research money on this issue. Now one wonders whether this research has been too expensive.

Apart from this application and considering the many requests that we have obtained in the meantime, we would like to stress the following point: drag reduction by riblike surfaces makes sense only where turbulent wall friction makes an important contribution to fluid-dynamic losses. However, in other cases, such as in automobile aerodynamics, which is governed by separated flow and form drag, the application of riblet film would be useless.

Separation control

As we have noted in the preceding sections, biological surfaces sometimes combine shear stress reduction with separation control. Indeed, it is conceivable that separation control itself is most important for the survival of living creatures moving in air or water. There may conceivably be many biological devices which serve this purpose, but, unfortunately, only few of them are sufficiently well understood that one can do more than utter some vague speculations (Pychakwiat and Ziarnko 1997). The few instances in which we can do more than speculate are those in which aeronautical research has paved the way for a partial understanding at least. Moreover, in the following, it will become apparent that technology-motivated research leads to an appreciation of even rather subtle details of biological devices.

First, we provide an apparently simple example to highlight the problems which we encounter. When a bird lands, a few feathers are deployed in front of the leading edges of the wings. (We do not discuss here the function of the feathers at the wing tips, i.e., the "winglets". These help to reduce the induced drag on the wing, in particular for slow predatory land birds with a low aspect ratio of their wings.) This helps to keep the flow attached, probably in the same way as slats do on wings of commercial aircraft (Lachmann 1961). However, Liebe (1996/1997, personal communication) maintains that these feathers may rather operate as boundary layer fences. Or do they work also as vortex generators? Or rather with all three mechanisms combined? Thus, we are caught in the middle of competing and equally plausible ideas, and in this case we do not have a conclusive answer. We believe, however, that these small feathers are important for the flight control of birds at high lift conditions during landing.

Vortex generators

Vortex generators are very efficient devices for suppressing or delaying flow separation. They create vortices that are oriented with their axis in the streamwise direction. This enhances the exchange of momentum and leads to an increased flow velocity near the wall. Therefore the boundary layer can tolerate higher pressure gradients and is less prone to flow separation. For instance, vortex generators can increase the lift of an airfoil by 30% (Chang 1976). Our wind tunnel measurements have provided similar data. The scientific history of these devices, however, is cluttered with widespread prejudices. The use of vortex generators is believed to be an admission of failure on the part of aerodynamic design. On the other hand, aircraft manufacturers have used vortex generators with considerable success (Hemker 1996). Vortex generators also have significantly improved the performance of wind turbines (Bovarnik and Engle 1985). The appearance of vortex generators can vary widely. They can be either small fish-scalelike structures immersed in the boundary layer (Barret and Farokhi 1993; Bechert et al. 1986; Bone 1975; Nakamura 1985; Lin et al. 1989; Schubauer and Spangenberg 1960; Wetzel and Farokhi 1996; Wheeler 1989) or finlike structures which protrude into the potential flow regime (Bovarnik and Engle 1985; Chang 1976; Hemker 1996). The latter can presently be seen on the wings of many commercial aircraft.

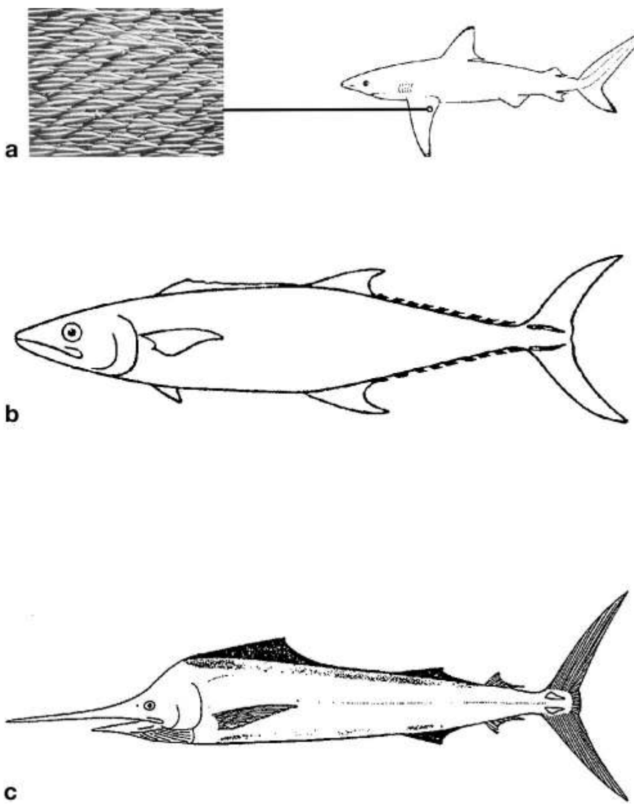

Fig. 9 a) Scale structure on a pectoral fin of dusky shark (*Carcharhinus obscurus*; from Reif 1985; Bechert et al. 1986). b) Fin array and dual keel on mackerel (*Scomberomorus commersoni*). c) Dual keel on billfish (*Istiophorus platypterus*; Nakamura 1985)

In biology it is not so obvious which devices actually operate as vortex generators. For shark scales we assume that this is one of their purposes, as has been suggested previously (Bone 1975). In particular, on the pectoral fins of sharks (Fig. 9) we have identified scale structures that we interpret as vortex generators (Bechert et al. 1986; Reif 1985). Obviously all of these surface structures are embedded in the boundary layer. The larger type of finlike vortex generators appears to be seldom used in nature. However, the arrays of small fins on the rear body of tuna and mackerel (Fig. 9) may be interpreted as vortex generators, with the function of keeping the flow attached there. In addition, the dual keel on the tail fin of several species of billfishes (e.g., marlin, spearfish, sailfish; Nakamura 1985) may be understood as a cross-breed of vortex generator and boundary layer fence. We suggest that the keels prevent the slow fluid of the body boundary layer from contaminating the flow on the tail fin (Fig. 9). Admittedly, however, the latter biology-related ideas are plausible ideas rather than proven facts.

While this section on vortex generators is rather brief, the following section on artificial bird feathers is comparatively detailed. This is because the present paper is our first journal publication on the issue. In addition, previous research is scarce, and for the basic facts we cannot refer to previous work.

Movable flaps on wings: artificial bird feathers

Once our attention is drawn to it, it is comparatively easy to observe: during a landing approach or in gusty winds the feathers on the upper surface of a bird's wings tend to pop up (see Fig. 1). Liebe (1979) has interpreted this behavior as a biological high lift device. At the former German Aeronautical Establishment DVL (=Deutsche Versuchsanstalt für Luftfahrt, the predecessor of the present DLR) and at Liebe's suggestion, flight experiments with a fighter airplane, a Messerschmitt Me 109, were carried out as early as 1938. A piece of leather was attached to the upper side of one wing. The ensuing aerodynamic asymmetry of the wings caused the aircraft to be difficult to handle, particularly at high angles of attack. The problems occurring in this initial test kept the German Air Force from pursuing the idea further. Much later Liebe (1979) presented his ideas in a journal article. His original idea was that, once separation starts to develop on a wing, reversed flow is bound to occur in the separation regime. Under these locally reversed flow conditions, light feathers would pop up. They would act like a brake on the spreading of flow separation towards the leading edge. Liebe was aware of the fact that flow separation is often a three-dimensional effect with variable patterns in the spanwise direction. He therefore considered it essential to be able to interact even with local separation regimes (see Fig. 1). For this reason Liebe suggested the term "reverse-flow pockets" (*Rückstromtaschen*). Following Liebe's ideas, a few tentative flight experiments were carried out in Aachen with small movable plastic sheets installed on a glider wing on the upper surface near the trailing edge (Malzbender 1984). *The glider aircraft is reported to have exhibited a more benign behavior at high angles of attack.*

This issue was taken up again in early 1995 in a joint effort by four research partners: the DLR in Berlin, the Institutes of Bionics and of Fluid Mechanics at the Technical University of Berlin, and the Stemme Aircraft Company in Strausberg, near Berlin. Previous preliminary experiments in the wind tunnel of the Bionics Institute with paper strips on a small wing had suggested an appreciable effect.

Our first wind tunnel trials of naively attempting to simulate bird feathers by attaching plastic strips to the wing surface produced rather confusing results. Therefore, we continued our experiments with a simpler device, i.e., thin movable flaps on the upper surface of a glider airfoil. These flaps consisted either of elastic plastic material or thin sheet metal. The flaps were attached in the rear part of the airfoil and could pivot on their leading edges (Fig. 10). Under attached flow conditions, the movable flap is very slightly raised. This is because the static pressure increases in the downstream

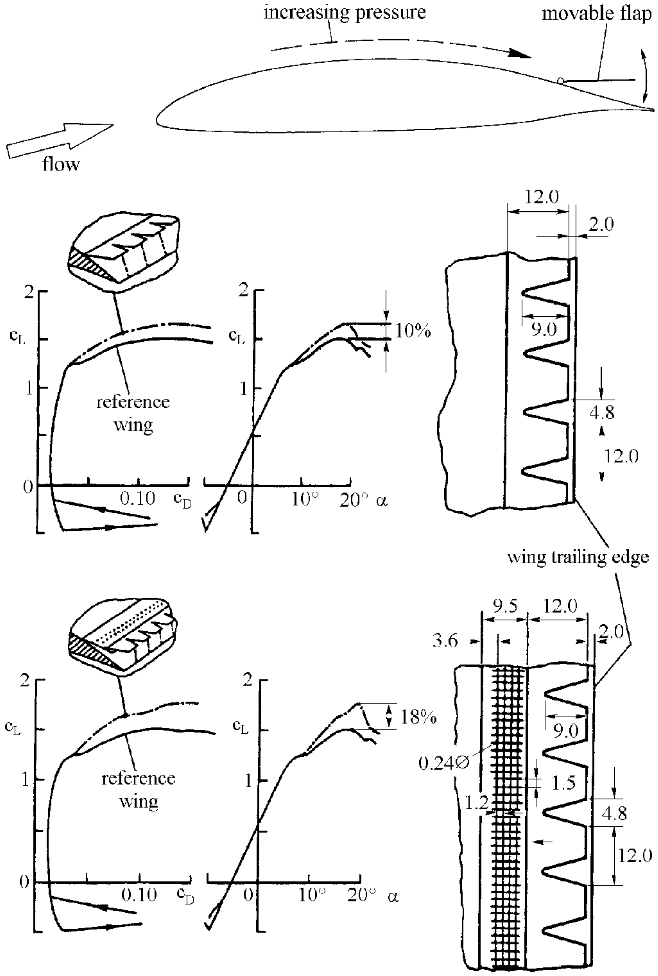

Fig. 10 Configuration and data of movable flaps installed on a laminar glider airfoil (HQ41). Flap dimensions (in percentage) of the chord length

direction in the rear part of the upper surface of the airfoil. The space under the flap is thus connected to a regime of slightly elevated static pressure. In most places the pressure is consequently higher beneath the movable flap than above it. This is the reason why the flap is slightly lifted. However, this behavior is not at all advantageous. The drag is obviously slightly increased due to the small separation regime at the end of the flap. In addition, there is a slight decrease in lift because the angle of the airfoil skeleton line at the trailing edge is decreased, and the effective angle of attack of the airfoil is also decreased. So far the impact of the movable flap is therefore a slightly deleterious one.

However, there are several ways in which to deal with this problem. The first and most obvious one is to lock the movable flap onto the airfoil surface under attached flow conditions. The second is also rather simple: make the flap porous in order to obtain equal static pressure on both sides of the flap for attached flow conditions. A third method is to make the trailing edge of the flap jagged, as can be seen in Fig. 10. This leads to an exchange of pressures as well. Incidentally, the latter two "inventions" are indeed found on bird wings. The various aspects of bird feather aerodynamics have been studied in detail at the Institute of Bionics (Müller and Patone 1998; Patone and Müller 1996).

Now, how do the movable flaps respond to reversed flow? First, it should be mentioned that the flow velocities of the reversed flow are considerably less than the mean flow velocity. Thus the movable flaps must be very light and should respond with high sensitivity to even weak reversed flows. A very soft trailing edge of the movable flaps facilitates a sensitive response there. Again, this feature is found on bird feathers.

Once the flow starts to separate, the movable flap follows gradually. It does not, however, protrude into the high-speed flow above the separation wake. This high-speed flow would push the flap back to a lower elevation. At the same time, the effective shape of the airfoil changes due to the slightly elevated flap and a lower effective angle of attack results. The pressure distribution on the airfoil is therefore adjusted in such a way that the tendency for flow separation is reduced. Consequently the flow remains attached to higher (real) angles of attack, and the lift of the wing is increased.

Nevertheless there are limits to everything. At very high angles of attack, the reversed flow would cause the flap to tip over into the forward direction, and the effect of the flap would vanish. This can be prevented, however, by limiting the opening angle of the flap. Very simply, we achieved this by attaching limiting strings to the movable flap. In our experiments we determined the optimal maximum opening angle of the flaps. This was found to lie between 60° (for solid and porous flaps) and about 90° (for flaps with jagged trailing edges). Once the full opening angle is reached, the separation jumps forward over the flap. Hence for very high angles of attack the effect of the movable flap finally decreases and vanishes. Tipping over of the feathers is not observed on birds; their feather shafts are probably sufficiently stiff and well anchored to prevent such a deleterious situation.

An important question is where on the airfoil a movable flap should be installed. We started our experiments with movable flaps being located at the downstream end of the airfoil. This appeared reasonable because on laminar airfoils such as ours the first 60–70% of the upper surface is designed to be laminar. Any attachment or other deviation from a perfectly smooth surface in this laminar regime would cause transition, entailing significant additional drag. By contrast, on the rear part of the airfoil and downstream of the laminar regime, minor changes in the surface quality do not produce a detectable increase in drag. In our experiments, we found that the trailing edge of the movable flap should be located slightly upstream (≥1% chord) of the trailing edge of the airfoil. Otherwise it would not respond properly to flow separation. On the other hand, the farther upstream the flap is located, the farther upstream the flow separation would have already spread once the flap starts to respond. Thus, if one wants to interfere with incipient separation the trailing edge of the flap should be located close to the trailing edge of the airfoil.

Another intriguing question is that of the appropriate size of a movable flap. We started our wind tunnel experiments with comparatively small flaps, having a length of about 12% of the airfoil chord length. The effect was significant (Fig. 10) and resulted in an increase in maximum lift of 10%. Increasing the flap length produced a further increase in maximum lift. For instance, a flap length of 22% resulted in an increase of 18% in the maximum lift. However, for large movable flaps (which are not flexible), the self-adjustment to the flow situation becomes less satisfactory. Typically, a movable flap starts to raise when the flow separation has already reached its upstream edge. On the other hand, full reattachment of the flap is obtained at that lowered angle of attack when the reattachment line of a reference wing (without movable flap) has moved downstream to the location of the flap trailing edge. This causes a significantly different behavior with increasing angles than decreasing angles. This hysteresis in the airfoil data is not desired because it would make an aircraft difficult to handle. One way to avoid this problem is to divide the flap into movable parts attached to each other (Fig. 10). Indeed, this double flap adjusts itself much better, and the hysteresis is practically eliminated. Nevertheless, the impressive increase in maximum lift is still maintained.

Going back to bird feathers: they are obviously flexible and likely to have the required properties. Birds possess, however, several consecutive rows of covering feathers on their wings, and several of these can pop up at once during the landing approach. Our experiments with more than one movable flap, however, turned out to be tricky. In some cases, when the rear flap rose, the additional forward flap also popped up immediately. Thus, the forward flap tended to behave like a conventional spoiler, causing a sudden drop in the lift force of the airfoil. Things seemed to work better when rather flimsy, thin plastic flaps were used. This drew our attention to the significance of fluttering of the flimsy flaps. As a preliminary conclusion, we now think that two movable flaps combined work best if the first flap flutters when being activated. In a more detailed report (Bechert et al. 1997a) we have presented the results of these experiments. In addition, we have shown in preliminary wind tunnel tests that even three-dimensional separation on a wing can be handled if the movable flap is divided into sections in the spanwise direction, i.e., as feathers on the wings of birds.

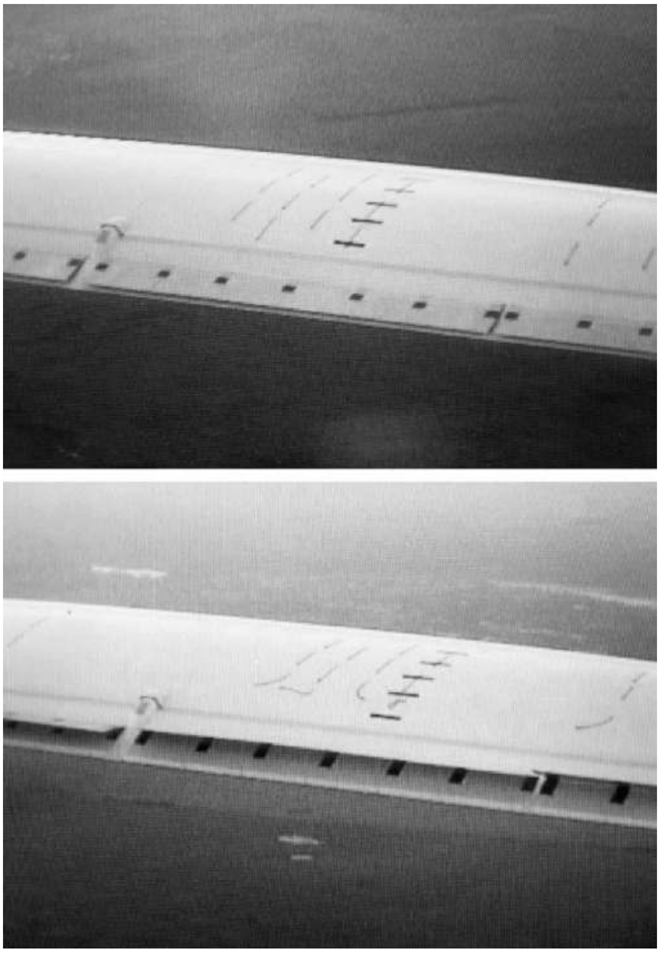

Fig. 11 In-flight video-recording. Above: Attached flap and attached flow; below: woolen threads indicate partial separation, and the movable flap has raised by itself

Flight experiments with movable flaps

For our flight experiments, the aircraft available to us was a Stemme S10 motor glider. Its laminar wing is equipped with conventional flaps which also operate as ailerons. As a specific preparation for flight experiments with this aircraft we made sure that our movable flaps would also work properly in combination with the conventional flaps on the wings. During the flight experiments the intention was to fly at very high angles of attack just into the regime of total stall. Usually, for tests of high-lift systems, one does not go that far in order to avoid such dangerous situations as spinning of the aircraft. Our flight tests, however, included such situations, with the purpose of demonstrating the inherent safety of our movable flaps. In order to highlight the flow situation on the wing of the aircraft, woolen threads were attached to its surface. These and the motion of the movable flaps were recorded by a videocamera on the empennage; the flight speed was also recorded on the video-tape. Figure 11 presents typical flow situations. The video-images in Fig. 11 are fully consistent with parallel experiments in the wind tunnel at identical air speed and Reynolds numbers.

In flight experiments, the increase in maximum lift coefficient can be documented by recording the minimum attainable speed before stall. Therefore, during the tests, the flight speed was reduced very gradually until total stall occurred. The reduction in minimum speed due to the movable flaps was recorded in this way. For comparison, test flights were also carried out with the movable flaps locked. The reduction in minimum speed due to the movable flaps was 3.5%. That corresponds to a 7% increase in lift. Taking into account that only 61% of the wing area was equipped with movable flaps, one obtains an 11.4% increase in maximum lift for the airfoil. This is exactly the same value that had previously been obtained in the wind tunnel with the same movable flap.

The comments of the pilot were also positive. Permanent spinning did not occur following a straight-flight stall situation. By contrast, permanent spinning did develop in this situation with locked movable flaps. However, due to our caution, the flaps were installed only in the inner part of the wing. Therefore the changes in flight behavior were only moderate, albeit positive. Another observation was that maintaining the flight speed at low and near-stall values appeared to be easier with movable flaps. More detailed information can be found in a recent report on this subject (Meyer et al. 1997).

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