Drag reduction: enticing turbulence, and then an industry

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We examine drag-reduction proposals, as presented in this volume and in general, first with concrete examples of how to bridge the distance from pure science through engineering to what makes inventions go into service; namely, the value to the public. We point out that the true drag reduction can be markedly different from an estimate based simply on the difference between turbulent and laminar skin friction over the laminarized region, or between the respective skin frictions of the baseline and the riblet-treated flow. In some situations, this difference is favourable, and is due to secondary differences in pressure drag. We reiterate that the benefit of riblets, if it is expressed as a percentage in skin-friction reduction, is unfortunately lower at full-size Reynolds numbers than in a small-scale experiment or simulation. The Reynolds number-independent measure of such benefits is a shift of the logarithmic law, or ‘ΔU+’. Anticipating the design of a flight test and then a product, we note the relative ease in representing riblets or laminarization in computational fluid dynamics, in contrast with the huge numerical and turbulence-modelling challenge of resolving active flow control systems in a calculation of the full flow field. We discuss in general terms the practical factors that have limited applications of concepts that would appear more than ready after all these years, particularly riblets and laminar-flow control.

Keywords: drag reduction; viscous drag; pressure drag; Reynolds number

1. Introduction

Inventions such as flying wings or laminar-flow control (LFC) have been conceptually available for so long that it is easy for motivated contributors to become discouraged, or to suspect that even the aerospace industry, with its high technology and cost, is not very open-minded. Yet, the testing effort and the design exercises expended on these have been very consequent, as they should when ideas promise drag reductions in the several per cent range at least, and the competitive pressures are so high in our industry. Drag reduction not only cuts down cost for an airline, but also increases the range of the aeroplane. In addition, over the coming decades, regulations driven by climate change concerns could start driving fuel-burn reduction measures beyond what economics leads to. This is already the case for noise, of course. Since the beginning of the jet age, considerable fuel-burn reductions have been provided by engine technology and

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especially higher bypass ratios, and by structures’ technology and especially higher aspect ratios. These are quantitative evolutions, rather than ‘visible’ inventions. The rate of improvement would appear to be naturally slowing (other than the leap allowed by composite materials), but the political authorities do not see it this way. In the recent ‘N+3’ exercise, meaning the third generation beyond aircraft in service, NASA requested a very striking fuel-burn reduction of 70 per cent for a given Boeing 737 mission. Now a 5 per cent reduction represents a very respectable achievement, yet this amounts to combining 23 such reductions. This was found possible with ‘somewhat exotic’ technologies such as wing struts and/or load alleviation, and modest speed reductions. Some teams declared LFC extensively on the wing, but others did not, and instead sought efficiencies in configurations more favourable structurally, and innovations of another type such as boundary-layer ingestion. None mentioned riblets. European institutions via the Advisory Council for Aeronautics Research in Europe have, similarly, set fuel-burn reduction goals in the 50 per cent range, and this with a far shorter deadline. Note how neither authority set any guidelines for the cost of the aircraft. Compare this with the general expectation that a new airliner generation, which is built for decades, needs a cost reduction of the order of 15 per cent to make the business case for its introduction. In short, the pressure towards drag reduction has more than one source and remains very high for management, as does the fascination for engineers including the authors.

We have not concealed a special interest in riblets, which are close to a favourable ‘business case’ with low risk, and LFC, which is being applied over small areas and carries a higher level of risk. We do not intend to discuss all the concepts described in this Theme Issue primarily because their readiness levels are vastly different, as is the completeness of the information provided relative to what industry will need for a sound evaluation.

2. From basic research to aeroplane drag

Researchers not involved in the industry naturally seek simple and preferably striking predictions of the amount of fuel their inventions would save. This often involves straightforward ‘%’ changes, or else textbook values for the turbulent and the laminar skin friction over the proposed LFC area. Independently of the frustrating non-scientific issues which impede applications, and are discussed later, our purpose is to outline as quantitatively as possible using simple tools some phenomena which intervene between a research result such as ‘a 10 per cent skin-friction reduction in our facility’ and the ultimate drag reduction for an aircraft. Many are obvious, such as the fact that skin friction is only one source of drag. Others are not, and fortunately it will be seen that they are not all negative. There are easily explained physical reasons for this. In addition, engineering can take advantage of a change in flow behaviour to reoptimize the design or operation of the system, thus extracting slight further benefits.

(a) Skin-friction reduction: direct and indirect effects

The primary candidates are LFC, which achieves considerable reductions over relatively small areas, and riblets, which achieve slight reductions potentially over the entire vehicle. Future proposals are likely to have one character or
the other. The possibilities for LFC are varied, since it may rely on suction or cooling, be fully ‘natural’, or be hybrid; such proposals may be viewed as distinct. Better riblets may be invented. Proposals exist for body forces to alter near-wall turbulence, and for lateral motion of the surface, but their readiness level is low.

(i) Local and global effects on viscous drag

We begin with a simple phenomenon, most relevant to LFC. What is the ultimate drag reduction due to laminarization, or in fact any reduction by other means, that is limited to the upstream region of a large surface? We consider a flat plate, or a longitudinal cylinder such as a fuselage. This effect can be illustrated for a flat plate with simple explicit formulae given by Schlichting [1]. For the Blasius boundary layer, we have an analytical expression for the momentum-thickness Reynolds number versus the streamwise Reynolds number,

$$Re_\theta = 0.664 \sqrt{Re_x}. \quad (2.1)$$

For the turbulent boundary layer, the formulae are empirical, e.g.

$$Re_\theta = 0.036 (Re_x - Re_{x0})^{4/5}, \quad (2.2)$$

where we have allowed for a virtual origin $x_0$ to reflect a laminar region. Figure 1 shows the distribution of $Re_\theta$, which amounts to the accumulating viscous drag from the leading edge to a position along the plate. We consider cases with no laminar flow, and with laminar flow up to $Re_x = 5 \times 10^6$ and $10^7$. These are typical of current projections [2]. Typical wing chord Reynolds numbers can reach $Re_x = 5 \times 10^7$, and body Reynolds numbers $Re_x = 5 \times 10^8$. The figure is limited to $Re_x = 10^8$ for better visibility, as the behaviour beyond $10^8$ is simple.

The reduction of $Re_\theta$ due to maintaining laminar flow from $Re_x = 0$ to $Re_x = 5 \times 10^6$ is 6747; for $10^7$, it is 12232. The numbers are the difference between equations (2.2) (assuming $x_0 = 0$) and (2.1). These can be called the ‘face value’ benefit of laminar flow and are considerable when viewed locally, as is evident.
in figure 1: at $10^7$, the reduction is by 85 per cent. However, the ultimate $Re_\theta$ reductions at $Re_x = 5 \times 10^8$ are only 2315 and 4776, respectively. Not only are they smaller relative to the total drag, but also they are smaller in absolute terms, because of the convexity of the dependence in equation (2.2). The benefit is about 60 per cent lower. If we consider a wing rather than a body, the $Re_\theta$ reductions at $Re_x = 5 \times 10^7$ are 3700 and 7705, respectively: the erosion of the benefit is still about 37 per cent, which is very consequent. Physically, the thickness reduction is self-mitigating because it reduces the thickness Reynolds number, which raises the skin-friction coefficient at a given station over the turbulent part of the plate. Riblets or other devices suffer from this same effect, but not as strongly. Conversely, features which increase drag near the nose of the aircraft, such as a windscrew wiper, cause an ultimate drag penalty that is much lower than their drag proper is. Naturally, industrial computational fluid dynamics (CFD) studies of the entire flow with credible representations of the device’s effect capture these facts, but even in research contexts with treatments of isolated regions there is value in keeping such effects in mind.

(ii) Effect on pressure drag

The pressure drag of an aeroplane is increased by the displacement effect of the boundary layer, although by a small amount compared with the induced drag. This is the viscous pressure drag. As a result, a reduction of the boundary-layer thickness, as provided by LFC or riblets (and very similar to an increase in Reynolds number), almost always reduces this part of the drag. Unlike in our first example, a more complete description of the physics leads to the expectation of better benefits. This is especially true if the boundary layer is brought close to separation, and thickens appreciably for instance at the foot of a shock wave. Therefore, there is a sort of ‘efficiency factor’ of viscous drag reduction, larger than 1. Again, good design estimates for complete configurations can be obtained by CFD, with appropriate care for numerical and turbulence-modelling accuracy, and scepticism. Specific values for this factor on a transonic wing are a matter of competitive advantage, and will not be discussed here.

An instructive estimate can, however, be obtained from a seminal article by Nash & Bradshaw [3]. They were considering drag increases due to a roughness element or patch, but drag reductions simply have the opposite sign. In either case, the local flow alteration is encapsulated in a change in the momentum thickness of the boundary layer, after it recovers to a normal state. Using an empirical closed formula due to Spence for turbulent boundary-layer development in pressure gradients, they arrive at the following efficiency factor, which they denote by $m$ and which is the ratio of the momentum-thickness change at the trailing edge over the change at the origin; in other words, the same measure we derived from figure 1,

$$\frac{\Delta \theta_T}{\Delta \theta_0} = m = \left( \frac{u_0}{u_\infty} \right)^{4.2} \left( \frac{u_\infty}{u_T} \right) \left( \frac{\theta_0}{\theta_T} \right)^{0.2}.$$  

(2.3)

Here, the subscript 0 refers to a location where a skin-friction modification is effected, and the subscript T refers to the trailing edge. Note the slight difference from Schlichting’s empirical formula above: on a flat plate $m$ reduces to $(\theta_0/\theta_T)^{0.2}$. 

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but Schlichting’s formula would have the power 0.25 rather than 0.2. This reflects the empirical scatter in power laws for the turbulent velocity profile, both of which have arguably been superseded by the logarithmic law.

For a two-dimensional transonic aerofoil with skin-friction reduction in the first 10–20% of chord, at the beginning of the supersonic ‘roof top’, typical values may be \( u_0/u_\infty = 1.65 \); \( \theta_0/c = 0.0001 \); \( u_T/u_\infty = 0.95 \); and \( \theta_T/c = 0.005 \). These give \( m \) a very large value: almost 4. The power 4.2 applied to \( u_0/u_\infty \) in equation (2.3) dominates. A simple local analysis of the flow alteration would take into account only the local overvelocity \( u_0/u_\infty \), which raises the dynamic pressure by a factor 1.65\(^2\) (using low-speed formulae). Therefore, the magnification actually due to the subsequent non-trivial boundary-layer development in adverse pressure gradients is only a factor of about 1.5. This is still appreciably larger than 1. Pressure gradient effects easily overpowered the Reynolds number-related loss explained in §1.

In the modern world, CFD methods are applied to calculate these effects without the user even conceiving of \( m \). Note that we used a formula intended for low speed through a shock–boundary-layer interaction, which has its dangers. The Nash–Bradshaw analysis also does not distinguish between drag changes at a fixed angle of attack and at a fixed lift coefficient (a key distinction in the design world), simply requiring the pressure distribution not to change enough to, in itself, alter the boundary-layer development. However, in this same region CFD uses Reynolds-averaged Navier–Stokes (RANS) turbulence models that have no specific calibration in such extreme stimulation as a shock–boundary-layer interaction. Thus, CFD renders inviscid effects better than Spence’s approach, but, until proven otherwise, not all the turbulence physics. There is almost no knowledge of the state of the boundary layer exiting the interaction, for instance. This justifies care in interpreting CFD results, not limited to trying different turbulence models and grids.

(b) Riblets and other ‘viscous region modifiers’

(i) Overall assumptions

Riblets are the prime example of modestly ‘enticing turbulence’ with a simple, passive and small (without, however, requiring nanoscales) device that promises to reduce a major part of an aeroplane’s drag by an amount of the order of 10 per cent, if the more bullish claims in the literature are considered. It is likely that a retrofit to any plane would be possible without affecting safety, and with minimal weight consequences. Manufacturers have conducted promising tests over many years; we shall return to the reasons why no riblets are in service (not counting racing yachts), but first we explore the precise quantitative knowledge of riblets, which is not as simple as many people expect. Some of the thinking applies to similar inventions, existing or future.

We start with physical remarks. In this Theme Issue, García-Mayoral & Jiménez [4] reiterate the point that riblets work with sizes of the order of 10–20 wall units, and start failing for larger sizes. In other words, we are working only on the inner, viscous region. In spite of decades of detailed studies of its statistics and structure, humankind has failed to invent a device which favourably alters turbulence in the bulk of the most important turbulent flow, namely the boundary layer. Large-eddy break-up devices and compliant surfaces are not

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being studied any more, to our knowledge. This durable difficulty motivates the word ‘enticing’ in our title. Turbulence can be fairly described as very ‘robust’ and ‘stubborn’.

The riblets are required to be much smaller than the boundary-layer thickness, with dimensions proportional to the viscous length scale. Their effects are also confined to the buffer layer of the turbulent boundary layer, and are accurately rendered by an increase in the intercept \( C \) of the logarithmic velocity profile in the law \( U^+ = (\log y^+)/\kappa + C \). Thus the figure of merit is a quantity \( \Delta C \), also evocatively denoted by \( \Delta U^+ \); positive values provide a drag reduction, and negative values denote a badly designed or badly used riblet, or in fact common roughness. Except at low Reynolds numbers it is also adequate to model riblets in CFD by still using a virtual smooth surface and adjusting the buffer-layer region of the velocity profile produced by the RANS turbulence model (at low Reynolds numbers, the influence of the mass flow in the buffer layer cannot be ignored; see [5]). Thus, RANS predictions of the riblet effect for the full aeroplane have become routine.

(ii) Reynolds number effect

Here, the engineer with a complete view of the aircraft at a normal Reynolds number arrives at a benefit that is lower than that in numerous simple statements found in the literature. Let \( U_e \) be the velocity at the edge of the boundary layer, and for now neglect any differences in thickness \( \delta \) between the baseline case and that with riblets, in the shape of the outer part of the velocity profile, and even in the friction velocity \( u_t \) as it influences the outer region. The log law gives for the skin-friction coefficient \( C_f \),

\[
\sqrt{\frac{2}{C_f}} = \frac{1}{\kappa} \log \delta^+ + C + C',
\]

where \( C' \) depends only on the outer region. If \( C_{f0} \) and \( C_{f1} \) are the baseline value and the riblet value, we have simply

\[
\sqrt{\frac{2}{C_{f1}}} - \sqrt{\frac{2}{C_{f0}}} = \Delta C. \tag{2.5}
\]

If the difference is relatively small, this leads to

\[
\frac{C_{f1}}{C_{f0}} \approx 1 - \sqrt{2C_{f0}\Delta C}. \tag{2.6}
\]

Recall that \( \Delta C \) is fixed for a given riblet type, with its size adjusted to be the same in wall units at the different flow Reynolds numbers. The major point here is that the relative gain \( 1 - C_{f1}/C_{f0} \) is not a fixed percentage (say 10%) but instead is Reynolds number dependent and is eroded when \( C_{f0} \) comes down, which is precisely what happens at flight Reynolds numbers: \( C_{f0} \) takes values closer to 0.0025 than to the 0.005 that is typical of low Reynolds number direct numerical simulations and laboratory experiments, and \( \sqrt{0.0025}/0.005 \) is

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appreciably smaller than 1. Again, this effect is naturally reproduced by full CFD studies, but, even in research publications, using equation (2.6) as a simple rule of thumb would contribute some perspective.

This effect cannot be ignored in the evaluation of riblets but it often is, in even recent literature, and even in papers published by industry individuals. Equation (2.6) shows that a 10 per cent reduction when \( C_f^0 = 0.005 \) corresponds to a \( \Delta C \) near 1, and this is the measure to remember. It can be determined well from low Reynolds number studies, although it is preferable to have at least a range of 2 in \( Re \) to firm up the determination of \( \Delta C \).

If we seek a finer estimate and include the reduction in \( d^+ \) at a fixed distance \( x \) for the riblet-treated flow, we see that the benefit is in fact slightly smaller than even predicted by equation (2.6). In other words, the thickness Reynolds number of the flow is reduced, which is unfavourable, as discussed in §2a. This is a higher order effect.

(iii) Laboratory tests

We mentioned already the pitfall of testing riblets at low Reynolds number and extrapolating to flight Reynolds number without consideration for the effect in equation (2.6). Here, we wish to draw attention to a separate issue. Consider an untreated plate followed by a section equipped with riblets. Let \( U_e \) be the edge velocity of the boundary layer, and manipulate equation (2.6), which gives \( U_e/u_r \), and the log law itself. At a fixed distance from the wall \( y \), once the riblet effect has propagated up the logarithmic layer, the velocity will change by an amount \( \Delta U \), with

\[
\Delta U \approx \left[ U_e - U - \frac{u_r}{\kappa} \right] \sqrt{\frac{C_f^0}{2}} \Delta C, \tag{2.7}
\]

where \( U(y) \) and \( u_r \) refer to the baseline state. There are other forms of this equation, which takes a few steps of algebra, but this one is especially revealing. It is easy to see that the quantity \( [U_e - U - u_r/\kappa] \) is positive over most of the layer (and more so near the wall) as \( (U_e - U)/u_r \) is large when compared with \( 1/\kappa \), and recall that, for effective riblets, \( \Delta C > 0 \). Therefore, the flow is accelerating after entering the riblet-treated region \( (\partial U/\partial x > 0) \), and this momentum increase must be allowed by a local reduction in skin friction, above and beyond the reduction that will exist in the new established state. As a result the early, apparent drag reduction is exaggerated over the distance needed for the change to propagate. A fair estimate for the propagation velocity is the friction velocity \( u_r \), which sets the root mean square of wall-normal fluctuations, \( v' \). Then, the distance will be commensurate with \( \delta U_e/u_r \), where \( \delta \) is the boundary-layer thickness, which is significant. Similarly, a time-developing simulation with sudden application of riblets should create a transient of duration commensurate with \( \delta/u_r \). If this reasoning is confirmed by measurements and/or simulations, it casts a doubt on the fine accuracy of experiments that measure the skin friction near the beginning of the riblet treatment.

RANS solutions using the riblet modification of Aupoix et al. [5] in the Spalart–Allmaras (S–A) turbulence model, which coincides with one formulated privately by P.R.S., agree with this conjecture. Figure 2, kindly provided by Dr C. Mockett of T. U. Berlin, shows results in a channel with \( Re_T = 18\,000 \). The S–A turbulence model constant \( c_{v1} \) is discontinuous at \( x = 0 \), on one wall
Figure 2. Skin friction on two walls of a channel, at the beginning of riblet treatment on the lower wall only. RANS solution. Red solid line, lower wall, riblets at \( x > 0 \); green dashed line, upper wall, smooth. (Online version in colour.)

only, adjusted to produce the right \( \Delta C \). The slight reduction in skin friction on the untreated wall is consistent with the acceleration near the treated wall, predicted by equation (2.7); the mass flux being conserved, this acceleration causes a deceleration near the other wall, which reduces the skin friction. The skin friction on the treated plate discontinuously drops to a low level, and recovers upwards. The average reduction over the first \( 4\delta \) is about 30 per cent higher than the ultimate value; this effect is too large to be ignored. We recognize that this is ‘only the RANS answer’ to a somewhat subtle question, but a RANS answer is better than none.

This transient regime is preceded by a shorter one as the riblets begin to interfere with the buffer-layer motion. It depends on the exact vertical position of the treated plate, relative to the untreated one. It is common to recess the basis of the treated plate, so that the riblets protrude only partially at the border between the two plates, and the cross-sectional area changes as little as possible. The length of this transient must scale in wall units, since it allows for the reorganization of the buffer layer. The length in wall units \( x^+ \) is most probably a large number, in the hundreds, so that a high Reynolds number is needed to distinguish the two (RANS results suggest that it is about 200 wall units long, but the RANS solution has little of the buffer-layer physics, and far less than in the region, which dominates in equations (2.6) and (2.7)). Note that equation (2.7) assumed the same virtual origin in \( y \) for the smooth wall and the riblet velocity profiles, again because their difference is of order 1 in wall units. The current riblet-modified RANS models all make this approximation.

(c) Optimal use of skin-friction reductions

Since the economics of airliners are very sensitive, every per cent in fuel burn can make the difference between success and failure of inventions, such as riblets, or winglets for instance.

We envision the same model of aeroplane on the same mission, with and without riblets. Earlier estimates in §2b lead us to expect roughly a 6 per cent reduction in the skin friction, assuming full coverage. Knowing that this drag is, in
simple terms, half of the total drag we then at first expect a 3 per cent reduction in drag and, therefore, fuel burn, and explore how to extract more than this ‘face value’ from the invention.

The first reason for a better gain is that the pilot will adjust the flight altitude and therefore the air density, to reoptimize the balance between viscous and pressure drag. We are here assuming an ideal situation without air-traffic or thrust constraints, and also the ideal parabolic drag polar. This has the perverse effect of bringing the viscous drag back to half of the total drag, but the pressure drag is now also lower. Neglecting subtle effects of engine-specific fuel consumption and practical issues with flying slightly lower, this brings the benefit from 3 to 3.1 per cent, which is modest because the baseline flight condition is so close to optimal even after the change in parasite drag coefficient.

The second reason for a better benefit is that the improved aeroplane will carry less fuel, and therefore have less drag than the baseline aeroplane for that reason. On a 10000 km flight, the fuel burned is over 30 per cent of the take-off mass, so that a 3 per cent reduction, averaged over the flight, in itself reduces the average weight and drag by about 0.5 per cent. This is quite significant.

If we now envision a different mission, the range of the plane indicated by the Breguet formula is also increased, making it a more capable product. The point here is that the facts of flight mechanics would be used to best effect by the engineers, appreciably extending the benefits beyond the sometimes simple academic expectations.

It is clear from the many points made in this section, often introducing conflicting corrections, that for instance the ultimate benefit of riblets in terms of drag is not ‘10 per cent of 50 per cent of the fuel burn’. Manufacturers are engaged in determining the precise number, using full-aeroplane CFD and fine experiments, but the leading-order corrections can be appreciated intellectually and estimated with simple mathematics, except for the full pressure-drag effect.

\((d)\) Separation control

The proposals discussed until now tend to provide a relatively small drag reduction, during the entire flight; separation control tends to promise large drag reductions and lift increases, in a small but crucial region of the flight envelope, for instance landing. These may make a mission possible that would otherwise not be. They can also be interpreted as an increase in lift coefficient, which allows a reduction in wing area; this reduction can be beneficial during the rest of the mission.

Dramatic improvements from very small inputs are typically claimed for separation control, and this is a hallmark of active flow control (AFC). However, there are pitfalls in basic research in this domain. To begin with, we guard against generalizing gains derived from flow control when the baseline flow has laminar separation; it is not the norm in full-size applications. We also suggest a distinction between ‘separation control’ and ‘post-separation control’. There is a class of flow-control proposals which do not suppress separation, but instead reduce the ‘massiveness’ of the separation, or merely accelerate reattachment. This is achieved by deliberately enhancing the mixing in the separated shear layer, above even what natural turbulence does (i.e. with higher intensity than in
boundary layers). It is debatable whether it is correct to describe the input level in such systems as ‘very small’, in part because the momentum coefficient $c_m$ is an obscure quantity to many observers.

We also suggest reserving the term ‘synthetic jets’ to those that alternate suction and blowing at high frequencies relative to the natural frequency of the separated flow (we are also troubled by the identification of the physics of a synthetic jet in still air, and the same device under a cross flow, usually stronger than the jet). Some successful systems, we would argue, instead cycle between the benefits of suction and those of blowing, at rather low frequencies. In other words, we believe flow control could also be obtained with constant tangential blowing, or with constant suction, as in older concepts. A system that alternates suction and blowing has a practical advantage over those which require a sustained source or sink of air, but not if the frequency is so low and/or the flow rate so high that the actuator volume is excessive. This volume is often ignored in CFD studies, and in some experimental studies. If the system takes away a significant portion of the fuel volume, this becomes a serious issue; another issue is actuator weight, of course. This was a key issue in the AFC system flight-tested on the XV-15 tilt-rotor aircraft, and in the hybrid LFC system flight-tested on the Airbus A320. We recognize the difference between a proof-of-concept installation and an optimized production installation. All companies have been discreet regarding insect protection of LFC concepts. Synthetic-jet concepts may also face a serious noise problem; we have not yet made estimates of that, as actual applications in our field have not come to life. Finally, reliability is paramount, particularly since a sizeable share of the total aircraft lift presumably depends on the operation of the system. In a worst case scenario, a failure of the system proper or of the aircraft’s power supply could make landing on the projected runway impossible. Redundancy will have to be carefully verified, as it has for mechanical high-lift devices which would cause the same problem.

3. Airline industry considerations

(a) Laminar-flow control

The success story in our industry consists in the partial natural LFC on the engine nacelles of the Boeing 787 [6]. The high engine bypass ratios now in effect have increased the nacelle viscous drag and, therefore, the possible gains. Evidently, the compromise imposed on the pressure distribution was found acceptable. This system is passive, and the flow is immune to the cross-flow instability so that insect contamination is a lesser issue than for a swept wing. The principal difficulties included maintaining sufficient surface quality and accounting for degradation due to insects, roughness, steps and gaps while not squandering the drag benefit by incurring an excessive cost.

The next steps in LFC may be to treat similar modest regions, as tested by Airbus for the vertical tail. It was just revealed that the Boeing 787-9, a stretched version, will in addition have hybrid LFC on the horizontal and vertical tails. The novelty is the absence of mechanical pumps, which benefits cost, weight and reliability. This concept does not constitute natural LFC, but it has been described as passive. There is also work towards much wider laminar regions, and on the upper surface of the wing, where the dynamic pressure and, therefore,
the skin friction are high [7,8]. The Boeing 757 flight test of 1990 addressed precisely this region and was technically successful, yet the company has not followed up in its products, even on the 737NG, which is smaller and has slightly less sweep angle.

The LFC choices are wide, and it may be a surprise in such a mature field that both natural and hybrid LFC are in contention, as is the ‘distributed roughness element’ idea [2]. The uncertainty level remains high. To begin with, at least for natural LFC on jetliners, the compromises become glaring: avoiding the cross-flow instability demands unsweeping the wing, and therefore sacrificing speed and aerofoil thickness. Unmanned aerial vehicles are more amenable, and we admit that successful military applications may be unknown to us. Wind turbines appear to derive some benefit from laminar regions. Less obvious is the compromise on the pressure distribution on the upper surface, as the demands of natural LFC lead to a loss of lift or an increase in wave drag (M. Drela 2010, personal communication). Insect protection typically dictates a leading-edge high-lift device of Krieger type, when the slat would otherwise be the device of choice with few exceptions. This illustrates the strong interaction between disciplines in the design of aircraft, and here we agree that academic scientists do not have access to enough of the issues.

(b) Riblets

Riblets have no success stories in the airliner industry. The tests conducted by the major airliner companies have been somewhat successful, as far as their results were made public, but durability tests in airline service revealed significant problems. The drawbacks of riblets include cost and labour to install, initially and over the life of the plane after erosion takes place and/or the riblets peel off. Remarkably, when making the business case the interest on the value of the aircraft during the few days of a riblet installation is not insignificant. Riblets are affected by leaks due to pressurization, and interfere with paint and general appearance and with access to the wing including for crucial structural inspections. Knowing the intense competition between the dominant companies (and now a number of ambitious low-cost rivals) and among airlines it appears clear that complacency cannot be the reason riblets are not yet in service. New materials or methods are almost certain, sooner or later, to bring riblets into use. Naturally, a new riblet design that provides a $\Delta U^+$ substantially larger than 1 would also tip the balance earlier. Research goes on.

(c) Active systems

Riblets are small and, therefore, very numerous, but still inexpensive. Other systems are not, and guessing their cost within an order of magnitude is not an idle exercise. An estimate made for another purpose (predicting the advent of large-eddy simulation (LES), [9]) appears relevant to active systems, particularly those dependent on feedback. It centred on $N_{\text{cubes}}$, defined as the ‘number of cubes needed to fill the boundary layer’. It was defined as the integral over the surface of $1/\delta^2$, where $\delta$ is the local boundary-layer thickness. On a full-size wing, it is very large: in excess of $10^7$. Most control devices are far smaller than $\delta$; as we mentioned, no device that addresses the bulk of the boundary layer has succeeded. Therefore, $10^7$ is a generous underestimate of the number of separate devices, presumably each with ‘intelligence’, which would be needed to cover...
the wing. Unfortunately, successful drag reduction further increases $N_{\text{cubes}}$, which can be thought of as scaling the non-dimensional ‘size’ of the AFC problem. The numbers are not as huge for ground vehicles, for instance, but the value of skin-friction reduction is also not as high as it is for aeroplanes, because of separation-induced drag and rolling resistance.

4. Numerical predictions

We have mentioned that CFD studies with suitably equipped turbulence models are good resources to calculate the system-level drag reductions for some concepts (more easily than the absolute drag, in fact). This is easy for riblets, and somewhat more difficult for LFC, but not because it would inflate the computing cost excessively. Figure 1 would be very similar had it been obtained from CFD rather than empirical correlations. Other viscous region modifiers would be represented in a Reynolds-averaged sense just like riblets have been, in view of their small size and huge population, and so would distributed suction.

The situation is far more difficult for AFC, for instance using small jets and suction openings. There are major issues with computing cost, and with turbulence modelling. The cost issues are easy to explain, but extreme. Representing a small opening is not too difficult in itself, with modern CFD methods accepting unstructured or multi-block grids. The problem is primarily in the time scales of AFC: normally the frequency is of order 1 if normalized with the flow velocity and boundary-layer thickness. It is therefore high when normalized with the chord of the wing, and very high when normalized with its span, or more precisely with the distance needed to establish the vortex system of the wing, or to obtain an appropriate sample for averaging if the flow is massively separated and unsteady. CFD with active systems is not very compatible with strategies to accelerate the convergence to steady state. As of today, this tends to limit CFD studies of AFC to elementary components rather than complete systems and possibly to low Reynolds numbers [10,11], which is a serious impediment to industrial work.

The concern deepens once we observe that a boundary layer strongly modified by an AFC device is far from standard in terms of its turbulence. Consider a boundary layer with the periodic release of vortices of both signs. RANS turbulence models have no particular reason to be accurate enough in this region, but it controls the entire flow. Therefore, the RANS calculation is not only very expensive, but also untrustworthy. A simulation with arguable chances of being accurate would involve resolving the locally dominant eddies, presumably with a hybrid RANS–LES approach, using a grid much finer than even the boundary-layer thickness, including in the direction parallel to the slot and span. The ratio of the span to grid spacing and of the global time scale to the time step have both increased again, if we demand a believable treatment of the turbulence. This will be a serious obstacle; for years, AFC studies will be dependent on fundamental experiments and very cautious extensions to the aircraft flow. It is not that such extensions are a trivial matter in CFD. Even if we can count on separation being controlled, it is not easy to ‘model’ the suppression of separation in a CFD code by artificially steering the boundary layer.

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A milder form of this difficulty affects studies of vortex generators (VGs). The time scales are no issue, but the length scales are: a grid fine enough to resolve the vortices at the source and over the entire length of their mission is needed. The turbulence-modelling issue is also present. The known corrections to RANS models aimed at the flow inside vortices have received only the most preliminary of calibrations. We have very few flow-field measurements and direct numerical simulation or LES studies. The evidence that CFD captures the effects of VGs remains indirect and slight.

5. Parting comments

We hope that we have given the impression that the airliner industry is very aware of the majority of drag-reduction research and proposals, and that its attitude is prudent rather than complacent in this domain. We do not believe in a distinction between scientists and engineers. For inventions such as riblets and LFC, comprehensive studies are conducted now and then to predict whether they ultimately give a better product, worth offering the airlines. Sometimes the correct attitude is to wait for progress in non-aerodynamic fields, such as materials and manufacturing, for instance as they impact surface quality or perforations in the skin. We emphasize the multi-disciplinary nature of designing and manufacturing large complex systems with extremely high safety, as well as the extensive efforts applied towards drag reduction by other means, such as span increases and lowered structural weight.

We also hope our discussions will help basic researchers tailor their presentation to the legitimate information needs of the industry, in order to first entice its technical staff, and ultimately its management. For instance, an active system presented with no discussion of the power needed to operate it has little appeal, as observed by Quadrio [12]. Preferably, the power will be expressed non-dimensionally, for instance as an effective drag coefficient. If the purpose of the device is to save energy, the energy spent and energy saved will be directly compared. Plasma and Lorentz-force systems are particularly suspect in this regard, in our view, and intuitively synthetic jets also appear likely to consume excessive power. This needs to be compared with the advantage they offer of working ‘on demand’, in contrast with fixed devices. Similarly, presenting synthetic jets without mention of the ‘breath’ volume is negligent. System weight estimates are more difficult to produce, not to mention cost estimates, and these will remain the industry’s responsibility. We look forward to productive community efforts towards the universal goals of burning less fuel and producing more clean power.

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References


