A REVIEW OF DRAG REDUCTION BY RIBLETS AND MICRO-TEXTURES IN THE TURBULENT BOUNDARY LAYERS

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Abstract

Drag reduction in wall-bounded flows can be achieved by the passive flow control technique, riblets. In this article, possible physical mechanisms responsible for turbulent drag reduction have been summarized. The modeling and experiments concerning the relationship between the riblets features and the turbulent boundary layer structure has also been reviewed.

Keywords: Turbulence, drag reduction, riblets, boundary layers, skin friction

Introduction:

In recent years, turbulent boundary layer drag reduction has become an important area of fluid dynamics research. Specifically, rising fuel costs greatly emphasized the usefulness and necessity of developing efficient viscous drag reduction methods. Therefore, this study explores concepts for control of turbulent boundary layers leading to skin friction reduction by featured surfaces. Riblets as a passive method reduce drag approximately 6-10% in turbulent flow.
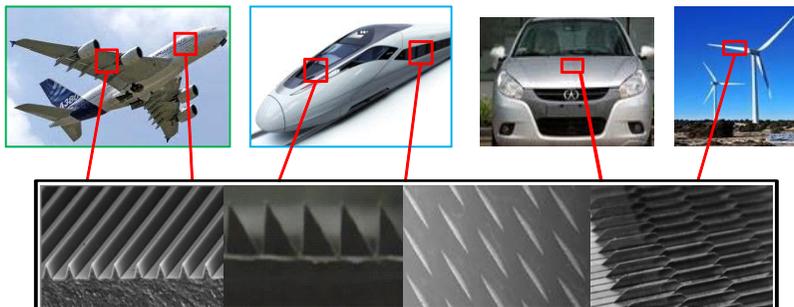
Figure1: Riblets and Micro-texture applications in Aerospace, Automotive and Enrgy

The essential feature of the structure of a turbulent boundary layer, presented by Head and Bandyopadhyay (1981), is the existence of large number of vortex pairs, or hairpin vortices. The boundary layer can be basically partitioned into three layers. "Viscous sub-layer" is defined in $y^+ < 5$, where the viscosity dominates and as a result the flow is almost laminar. The viscosity and turbulent momentum play equally significant roles in the second layer called "buffer layer" which is $5 < y^+ < 30$. In the region $y^+ > 30$, called "outer layer" or "log-layer", momentum plays a dominant role and the normalized mean velocity has a log relation with the distances.

(a)   (b)
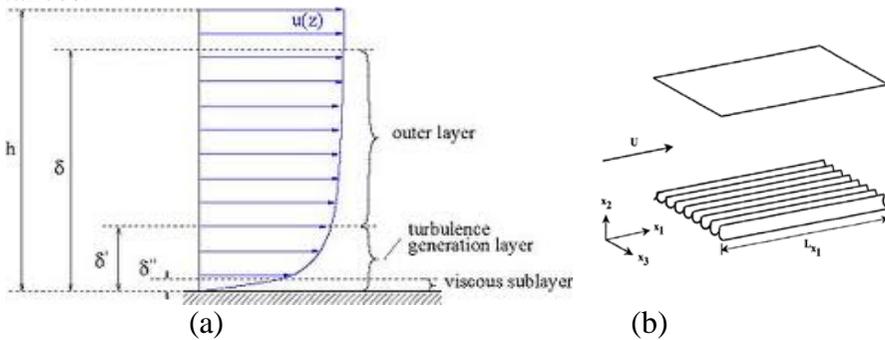
Figure 2: (a) Turbulence Boundary Layer, (b) semi-circular or U shape riblets

The wall surface conditions, such as surface roughness, play an important role in influencing the characteristics of turbulence structure in the near-wall region of the flow. According to Perry et al. (1969), roughness elements, depending on the flow characteristics, can be subdivided into k-type and d-type. For instance, when the cavities between the roughness elements are narrow, and the roughness shift depends on an outer scale (e.g. pipe diameter), it is called d-type, while for a k-type flow the roughness shift depends on the roughness height. Additionally, based on the physical geometry of the wall, experimental evidence has shown that three flow regimes exist for turbulent flow over rough surfaces, (hydraulically smooth, transitionally rough and fully rough flows) primarily depending on the size of the roughness elements relative to the viscous sub-layer (Akinlade, 2005). Following Schlichting (1968) has shown that, for k-type roughness, the equivalent sand grain roughness Reynolds number $k_{eq}^+ = U_\tau k_{eq}/v$ (where U_τ is the friction velocity, k_{eq} is the equivalent sand grain roughness height, and v is the kinematic viscosity) can be used as an indicator of the rough wall turbulence regime as follows: hydraulically smooth wall for $0 < k_{eq}^+ \leq 5$, transitionally rough regime for $5 < k_{eq}^+ < 70$, and completely rough regime

for $k_{eq}^+ \geq 70$. The scaling of the surface has been studied by many researchers (George and Castillo 1997, Seo et al. 2004, Tachie et al. 2003, and DeGraaff and Eaton 2000). The use of the friction velocity, U_τ as the scaling parameter for assessing the effect of surface roughness on the mean velocity and turbulence fields is often adopted in the literature. Ribbed surfaces which are used for drag reduction can be considered as transitionally rough (Tani 1988).
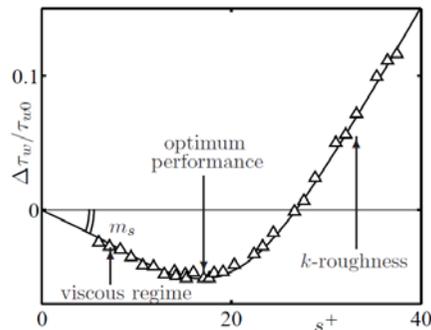
Figure 3: Effect of the peak-to-peak distance (S^+) on the skin fiction of a triangular riblet with 60^0 peak sharpness (Bechert et al, 1997)

1. Theoretical treatments of the riblets mechanisms

The physical mechanism of the drag reduction by riblets has been investigated in detail by many researchers, such as Wilkinson et al. (1987), Walsh (1990), and Coustols and Savill (1992), although some aspects remain controversial. It has been demonstrated that riblets can delay the transition to turbulence of an excited laminar boundary layer (viscous sub-layer) (Starling and Choi, 1997). Therefore, studies of the mechanism of drag reduction by riblets focus on creating a viscosity dominated region in the base of the riblets valleys where the wall shear stress is very low. In other words, the growth rate of the momentum thickness during the non-linear stage of the transition over smooth surface is greater than over the ribbed surface; additionally the turbulence intensity is reduced by riblets, supporting the fact that the transition to turbulence has been delayed (Tullis, 1992). Kramer (1937) presented the first hypothesis on drag reducing surfaces, although he did not provide a satisfactory explanation of the influence of riblets (Granola, Murcsy-Milian and Tamasch 1991).

There are few theories proposed in the literature for the performance of riblets whereas most of them focus on the behaviour of the cross-flow. The first theory suggests that the generation of secondary vortices with the riblets valleys weakens the stream-wise vortices immediately above the riblets (Bacher and Smith, 1985). Robinson (1988) and Smith et al. (1989) suggested that riblets interfere with the span-wise motion of the low speed

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streaks at the wall. Similarly, Choi (1987) and Crawford (1996) confirmed that riblets reduce the skin-friction drag by impeding the span-wise movement of longitudinal vortices during the sweep events. Karniadakis and Choi (2003) concluded that the paired vortices over the riblets surface tend to be shorter compared to their counterpart over a smooth surface; and the span-wise spacing between them is wider, supporting the above findings that skin friction is reduced by passive span-wise forcing. Also more recently, Goldstein & Tuan (1998) and Goldstein, Handler and Sirovich (1995) proposed that the deterioration is due to the generation of secondary stream-wise vorticity over the riblets, as the unsteady cross-flow separates and sheds small-scale vortices that create extra dissipation. Although this theory has been supported by many researchers as mentioned above, evidence by span-wise oscillations of the wall weaken the acceptance of it (Jung et al., 1992; Jimenez, 1992). They found that introducing small-scale stream-wise vorticity near the wall decreases drag by damping the larger stream-wise vortices of the buffer layer, and that inertial cross-flow effect need not be detrimental to drag reduction (García-Mayoral, 2011).

The other theory emphasizes the scale of the turbulent structures in the unperturbed turbulent wall region to optimize spacing (Choi et al., 1993; Suzuki and Kasagi, 1994; Lee and Lee, 2001). Although they showed that the streamwise turbulent vortices embed within the grooves for riblet in the early drag-deterioration regime, their suggestions suffer from persuasive arguments for a drag increase above break down region (García-Mayoral, 2011).   Besides the mentioned theories, techniques proposed for theoretical analysis is worthy of review. Bechert and Bartnwerfer (1989) determined an effective location for the origin of the velocity profile and a "protrusion height" which is the distance between this effective velocity profile origin and the tips of the riblet peaks. This technique can provide a wall shear stress distribution by averaging wall shear stress value; but cannot obtain any drag reduction predictions. With this technique, Bechert et al. (1997) concluded when the fluctuating cross-flow component is reduced, the turbulent momentum transfer will also reduce; therefore, the shear stress will be decreased.
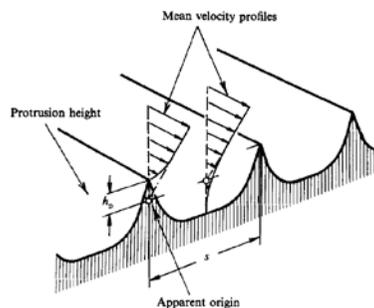
Figure 4: Apparent origin of a riblet surface (Bechert and Bartnwerfer, 1989)

The work of Bechert and Batenwerfer has been continued and elaborated upon by a group of researchers at the University of Milan (Luchini et al., 1991; Luchini and Trombetta, 1995). They proposed that the drag reduction can be optimised by maximising the difference between the protrusion height of riblets for the longitudinal flow and that for the cross flow. In addition, Luchini studied the effects of riblets on the boundary layer stability using the e^N method. His investigation demonstrated that the Tollmien-Schlichting (T-S) waves over the triangular riblet surface are found to be excited at a lower critical Reynolds number. Another group, who followed Bechert and Batenwerfer, defined the concept that the drag reduction of riblets could be related to the difference between the normal (stream-wise) protrusion heights and the cross-flow protrusion height (Baron, 1993).

Most recently, García-Mayoral and Jiménez (2012) suggested that the existing experiments for the location of the breakdown collapse better with a new length scale, based on the groove area, than with the riblet spacing or depth. They claim that "the degradation for large riblets of the linear regime of drag reduction is not connected with the breakdown of the Stokes behaviour of the longitudinal velocity along the riblet grooves".

(a)   (b)
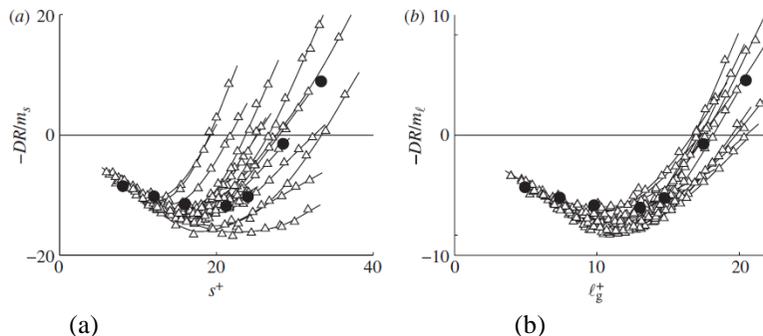
Figure 5: Drag-reduction curves of diverse riblets, reduced to a common viscous slope. Drag reduction (a) as a function of the spacing s+ and (b) as a function of the square root of the groove cross section, $L_g^+ = A_g^{+\,1/2}$. Open triangles, experimental results from Bechert et al. (1997); filled circles, direct numerical simulation results from García-Mayoral & Jiménez (2012).

2. Experimental investigation over riblets

This section will briefly discuss some of experimental measurement techniques, such as Hot-Wire, VITA and visualization, which have been used on the flows over riblets. The advantages of using riblets in many engineering applications have been notified. For instance, the flight testing of aircraft with riblets by Boeing (McLean et al., 1987), Airbus (Coustols and savill, 1992) and NASA (Walsh et al. 1989) demonstrated the importance of the effect of riblets. Robert (1992) summarized some tests on airfoils by

researchers, such as Szodruch (1991), who estimated an overall 2% drag reduction on the flight tests of a commercial aeroplane (Airbus 320) with riblets over 70% of its surface. Sareen (2012) imployed diferent size of sawtooth riblets applied to DU 96-W-180 airfoil for wind turbine. An average drag reduction of 2-4% was observed for a range of riblet sizes and Reynolds numbers. The optimal riblet size was found to be 62 µm. Also, Lee and Jang (2005) reported reduction of the overall drag of airfoils by riblets with optimum spacing of 30-70 µm. Similar results on aircraft have been obtained by Viswanath (2002).

Re	Percentage Drag Reduction			
	44 μm	62 μm	100 μm	150 μm
1,000,000	0–1%	2–4%	2–4%	+
1,500,000	1–2%	4–5%	2–4%	++
1,850,000	0–1%	1–2%	++	++

(a)   (b)
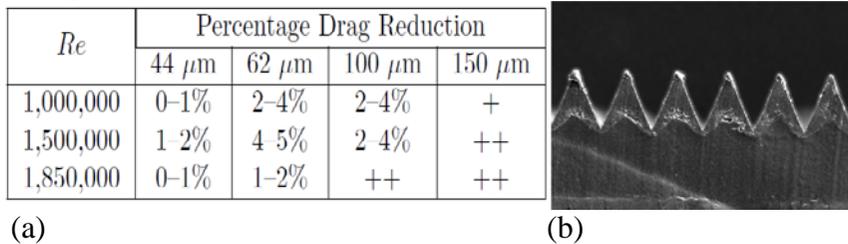
Figure 6: (a) Measured Percentage Drag Reduction with Riblets on the DU 96-W-180 Airfoil, (b) 62 µm riblets (Sareen, 2012)

Not only the aeronautical application but other industrial applications such as high speed trains have shown an interest in the use of riblets (GEC Alsthom, 1991). Biological surfaces are another type of applications with geometrically complex textures (Hahn et al., 2002; Kong and Schetz, 1982; Jimenez et al., 2001). Itoh et al. (2006) investigated the flow over seal fur with a dependence on mean hair separation similar to that of riblets. They could obtain drag reductions of up to 12%. A broad review of the effect of riblets with different geometries in wind tunnel was that of Walsh (1990), Choi (1999), Bushnell (2003), Vukoslavcevic et al. (1992), Park and Wallace (1994), Walsh & Lindemann (1984), and Lee and Lee (2001).

The initial drag reduction studies with riblets were those of Walsh and Weinstein (1978) and Walsh (1980, 1982) at NASA Langley. They results demonstrated that the aspect ratio h/s of the riblets appears to have a major effect on the drag reduction. Dubief et al. (1997) have measured the statistics of $\partial u/\partial y$ over a smooth wall and a riblet surface using parallel hot wires. They observed that the mean square span-wise vorticity is reduced near a riblet surface. Generally in experimental study of the flow over riblets, the law of the wall relationship can be applied. The normal law of the wall (Coles, 1956) gives the mean stream-wise velocity profile over a flat wall as:

$$u^+ = \frac{1}{k} ln y^+ + C - F$$

where k~0.41 is von Karman's constant, C~5.0 is the smooth wall constant and F is roughness factor. Some researchers, such as Tani (1988), Sawyer

and Winter (1987) and Choi (1989), considered the effect of riblets as an "upward" shift of the profile corresponding to negative values of the F term. Among all the experimental measurements which have been taken over riblets walls, only two groups, Vukoslavcevie et al. (1987) and Benhalilou et al. (1991), considered the measurements within riblets valleys. They results appear to be confirmed by the hot-film measured wall shear stresses in the valleys of similarly sized L groove riblets by Choi (1989). Other researchers, including Sawyer and Winter (1987) and Coustols et al. (1987), measured drag reduction for approximately the same riblets geometry.

In particular, mean and local velocity profiles and turbulent statistics within and above the riblet grooves have been reported for experiments in water and oil channels by Bechert et al. (1997), Bruse (1993), Bechert (1997) and Suzuki and Kasagi (1994).
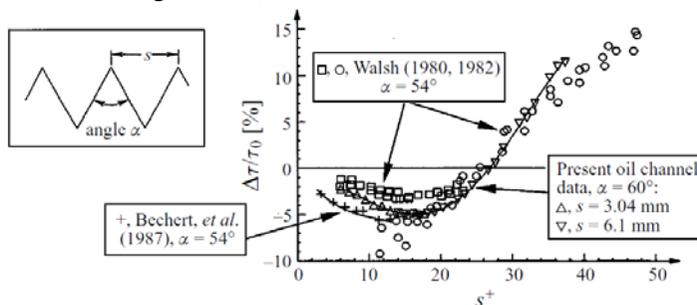
Figure 7: Measurements with sawtooth riblets (Bechert et al. 1997)
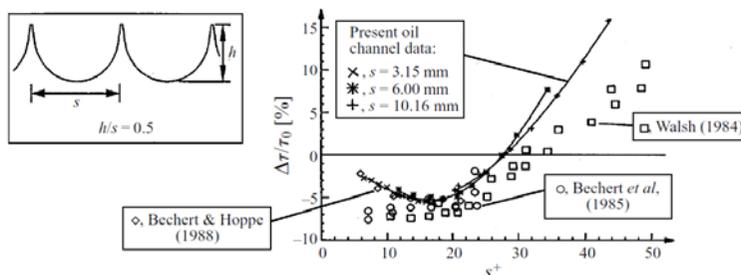
Figure 8: Measurements with semi-circular scalloped riblets (Bechert et al. 1997)

One of the standard techniques in the investigation of turbulent boundary layer flows over flat plates and riblets is the use of variable interval time averaging (VITA). In this method a short time interval r.m.s. value is compared to the long term r.m.s value, where the used value is typically the stream-wise velocity that has been measured at a fixed point (Blackwelder and Kaplan, 1976). In conditional averaging techniques, a burst event should be defined by establishing threshold criteria in the measurement of some turbulence quantity (Kim et al., 1971). The VITA has been used by

Hooshmand et al. (1983), Choi (1989), Walsh (1982) and Gallager and Thomas (1984) to compare burst frequencies over flat and riblets walls.

Another way to study the effect of riblets is to investigate the sweep and ejection events using the quadrant detection technique (Schwarz-van Manen et al. 1990). Bogard and Tiederman (1986) defined a critical time between events to characterize these Reynolds stress producing events as either grouped (multiple) or single events. Tang and Clark (1992) confirmed the same conclusions using similar techniques.

In addition, flow visualization is the technique that has been used to measure the flow over riblets with particular attention to the behaviour of the flow in the riblets valleys. Gallager and Thomas (1984) and Bacher and Smith (1985) noticed a "quiescent pooling" of low speed flow in dye marked water flows in the V groove riblets valleys with dimension of $h^+ = s^+ = 15$. Similar results have been observed in smoke marked air flows over riblets with sizes of $2h^+ = s^+ = 16$ and $2h^+ = s^+ = 30$ by Hooshmand et al. (1983) and Clark (1989), respectively. Moreover, near wall low speed streaks can be investigated by flow visualization on the effect of riblets. These streaks over flat walls have a spacing that increased with distance from the wall (Smith and Metzler, 1983); but this method is not reliable since the riblets surface location and the influence of the decreased friction velocity lead to difficulties in comparing the various riblets geometries with flat walls (Gallager and Thomas, 1984; Bacher and Smith, 1985; Choi, 1989). In addition, Hooshmand et al. (1983) did not observe any change in the low speed streak spacing. Although most of the existing experiments for drag reduction on the surface considered two dimensionally longitudinal grooves, there are few attempts that investigated three-dimensional rib patterns. Bechert et al. (2000) examined the texture similar to the skin of fast sharks, sharp edged fin-shaped elements arranged in an interlocking array. They claimed that the 3D riblet surfaces do indeed produce an appreciable drag reduction but they do work reasonably as drag reducing devices.

(a)   (b)
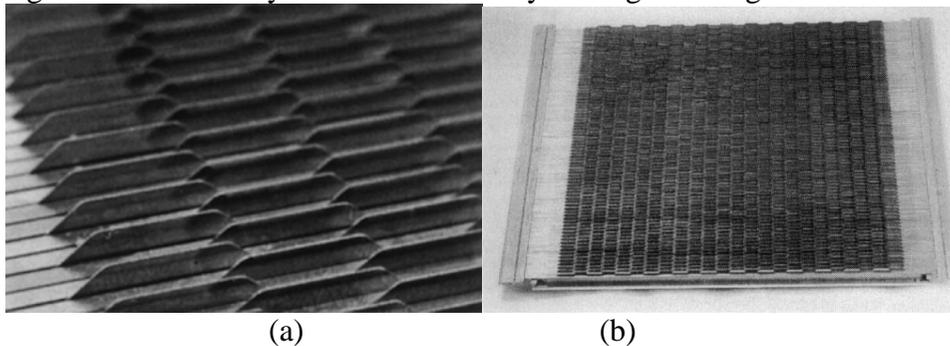
Figure 9: (a) Detail photograph of the staggered fins on the test plate (b) Test plate for oil channel measurements (Bechert et al., 2000)

Fin geometry, dimensions in mm
Fin thickness t = 0.1 mm
Fin spacing s = 4.6 mm

(a)   (b)
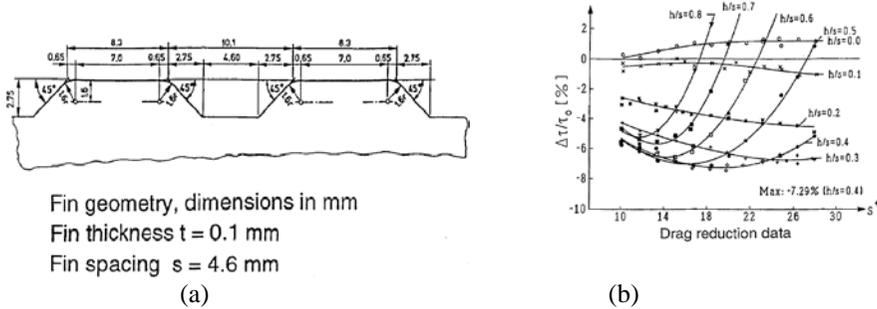
Figure 10: (a) Trapezoidal fin shape, (b) Two different Fins' shapes, Trapezoidal and rectangular, with three different lengths for each of them have been compared. Trapezoidal Fins of medium length (l=2s) perform slightly better (7.3%) than long Fins. The optimum s+ lies at higher s^+ =19. On the other hand, the optimum rib height is lower, at h = 0.4s

(Bechert et al., 2000)

3. Simulation methods over riblets

Similar to the most turbulent flow simulations, CFD over riblets can be classified in three groups: Reynolds-Averaged Equation (RANS), Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS).

RANS is average of NS equation over time. Although it has been extensively used in industry to provide flow statistic, it cannot provide any detailed time-dependent information. There are many flow studies over riblets that used averaged equation. For instance, Beibei et al. (2011) modelled triangular riblets with k-ε turbulence model. In addition, two attempts have been made to model the flow over riblets using low Reynolds number K-e turbulence models (Djenidi, 1991; Launder and Li, 1991). They used curvilinear grids acquired by conformal mapping which provide curved grid lines parallel to the riblets surfaces. Launder and Li obtained the results which occurred at riblets sizes 2-3 times larger than the optimum experimental size. The reason for their controversial results is because of the use of both mixing length and low Reynolds number k-e turbulence models related to the critical near wall damping assumptions.

(a)

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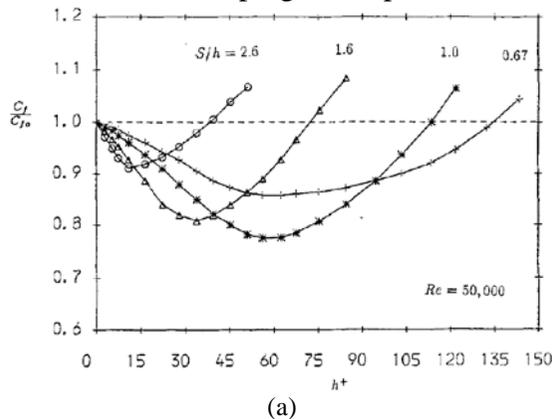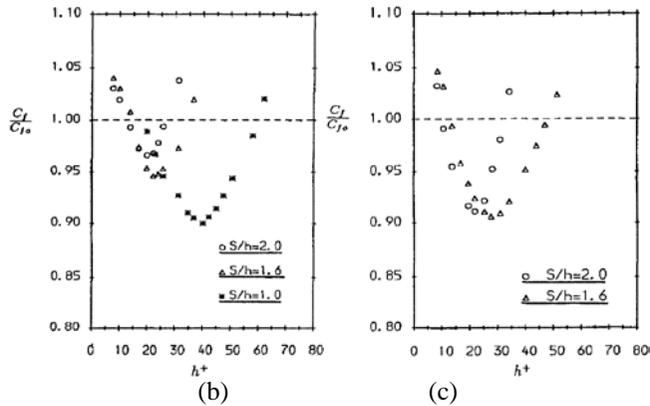
Figure 11: Drag reduction behaviour for (a) L-shaped riblets (b) V-shaped riblets (c) U-shaped riblets (Launder and Li, 1993)

The other type of modelling is LES which separates velocity into large scale and small scale components. This is due to the fact that small scale motions play a less important role in the process of transport of mass, energy and other scalar properties. Therefore, the large eddies are more accurate than the small ones. In this method, the large scale is obtained by filtering, and small scales are represented by sub-filter model. The disadvantage of this modelling is that it does not consider all scales, omitting the very smallest ones. There are few researchers who considered this approach for flow over riblets. For instance, Peet et al. (2010) documented Large Eddy Simulation (LES) study of turbulent flow in a channel, one wall of which is covered with riblets. Another type of eddy driven model is viscous wall region modelling. In this method, only the region between the wall and the outer edge of the viscous wall region has been considered to be simulated (Hanratty et al., 1977; Chapman and Kuhn, 1986; Tullis and Pollard, 1994).

The most advanced method is DNS, which can solve NS equation without any averaging closure and need for a subgrid-scale model. Direct Numerical Simulation can be viewed as a numerical experiment producing a series of non-empirical solutions. Therefore, it is appropriate for addressing basic research questions regarding turbulence physics. The only disadvantage is its computational cost, which prevents DNS from being used as a general-purpose design tool. Also, this drawback leads to a severe limitation on the maximum Reynolds number that can be considered. Many researches, such as Goldstein et al. (1995), Goldstein and Tuan (1998) and El-Samni et al. (2007), have used DNS for modelling flow over riblets.

Khan (1986) performed a direct numerical simulation of a turbulent channel flow. He used a unidirectional algebraic stress model for modelling turbulent flows. His results have been criticized by Djenidi et al. (1990) who

drew attention to the low grid resolution used, and Wilkinson et al. (1987), who doubted the existence of the calculated counter-rotating vortices within the riblets valleys. Another one of the earliest attempts at DNS modelling the flow over riblets was performed by Kim et al. (1987). In 1991, Jimenez and Moin also performed direct numerical simulations of unsteady channel flow at low to moderate Reynolds numbers. In order to reduce the channel size, they could demonstrate that the near wall turbulence statistics and presumable flow mechanisms in the minimal channel are in good agreement with the natural channel. In general, DNS for riblets can be separated into two categories: spectral methods and finite methods.

Chu and Karnidakis (1993) has modelled three-dimensional incompressible Navier-Stokes equations integrated via a spectral element-Fourier method to compute the flow over riblet. For time discretization of governing equations, a high-order splitting algorithm has been employed based on mixed explicit-implicit stiffly stable schemes (Karniadakis, Israeli and Orszag 1991; Tomboulides, Israeli and Karniadakis 1989; Crawford, 1996). In this algorithm, first the nonlinear terms obtained for each Fourier component are considered. Then, the pressure equation is incorporated, and the incompressibility constraint is enforced. At the end the viscous corrections and the imposition of the boundary conditions included. Periodic conditions were assumed on the upstream and downstream domain boundaries. In addition, for the spectral element discretization, they broke up the computational domain into several quadrilaterals in two dimensions, which are mapped isoparametrically to canonical squares. Karniadakis and his group claimed that turbulence is sustained with as little as 4 Fourier-modes in the stream wise direction, but the full spectrum of scales certainly cannot be resolved with this number of modes. They also paid attention to the resolution requirements around the riblet peaks, although the grid spacing seems a little large in the streamwise direction (Pollard, 1998).

Case	h^+	s^+	Re	Re_τ	$Drag$
A	17.70	20.41	4280	181 (u), 177 (r)	-5%
B	31.01	35.66	3280	148 (u), 155 (r)	+10%
C	18.57	21.42	3280	144 (u), 143 (r)	-2%

(a)

Case	L_{x_1}	L_{x_2}	L_{x_3}	$L_{x_1}^+$	$L_{x_2}^+$	$L_{x_3}^+$
A	5.61	2.05	1.15	1018	372	209
B	5.61	2.1	2.3	830	311	340
C	5.61	2.065	1.5	808	297	216

(b)

Table 1: (a) Reynolds number for the upper channel wall (u) and riblet surface (r), - presents drag reduction and + shows drag increasing (b) computational domain parameters in global and wall units (Crawford, 1996)

Duan and Choudhari (2012) simulated the boundary layer flow over riblets with the compressible Navier-Stokes equations, solved in generalized curvilinear coordinates. The most important advantages of spectral methods is the fact that the magnitude of the expansion coefficients goes to zero when the basis-function variations correctly 'fit' the dependent-variable variations (in terms of smoothness, boundary conditions, and regions of most rapid spatial change); therefore, the error decreases faster and the model converges with exponential or 'infinite-order' accuracy. Another attractive feature of this method, specifically Fourier- and Chebyshev-based methods, is the ability to employ fast transformations when computing and when using the collocation/pseudo-spectral procedure to calculate, both of which must be done at each time step. In addition, when Fourier spectral methods have been employed in directions where the turbulence is statistically homogeneous, this automatically produces conditions whose history and spatial structure fully satisfy the governing equations. As a disadvantage of this method, it is not able to consider complex geometries; and the special treatments required to enforce inflow/outflow boundary conditions. In addition, the need to access the entire domain in each direction and employing global basis functions leads not to perform well on large distributed memory parallel systems (Coleman and Sandberg, 2010).

Finite methods are another type of DNS technique for flow over riblets which include mostly finite volume and finite different methods. Choi et al. (1993) have performed a DNS study on one wall of a plane channel using the finite volume method. The computational box is chosen to be a minimal flow unit (Jimenez and Moin, 1991). A uniform mesh is used in the stream-wise direction and the stream-wise spacing is rather coarse. A non-uniform mesh with hyperbolic tangent distribution is used in the wall normal direction. In span-wise, a non-uniform orthogonal mesh is employed with concentrations of the grid around the riblets peaks. For advancement, a fully implicit method has been used which approximates the spatial derivatives using information at the new time step.
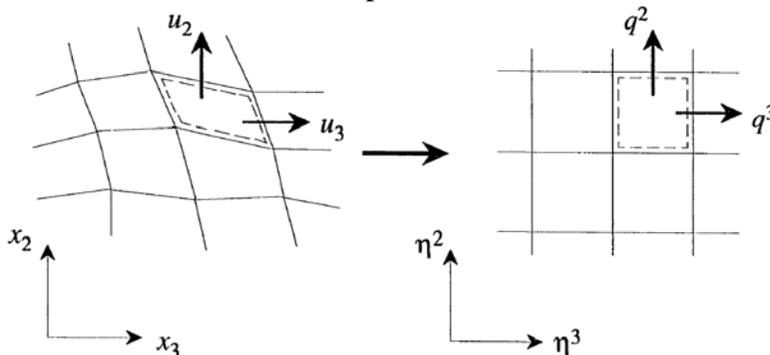
Figure 12: coordinate transformation (Choi et al., 1993)

Case	s/δ	s^+	h^+	α	$N_{x_1} \times N_{x_2} \times N_{x_3}^\dagger$	Δx_3^+
A	0.2270	40	20.0	45°	$16 \times 129 \times 128$	1.28
B	0.2270	40	34.6	60°	$16 \times 129 \times 128$	1.28
C	0.1135	20	10.0	45°	$16 \times 129 \times 256$	0.64
D	0.1135	20	17.3	60°	$16 \times 129 \times 256$	0.64

Table 2: Parameters for the simulation over sawtooth riblets, 6 % drag reduction is achieved by Case D (Choi et al., 1993)

The finite methods are generally suitable to parallelization, easy to implement with high-order accuracy; and their high-order finite nature can provide an excellent compromise between accuracy and flexibility for flows involving realistic geometries, such as riblets. Moreover, curvilinear coordinates and grid stretching is routinely used to obtain accurate results with less computational cost (Coleman and Sandberg, 2010). Recently, Garcıa-Mayoral and Jimenez (2012) have modelled riblets with direct numerical simulations at Reτ ≈ 550. They found that the Immersed boundary method can be considered as another accurate method for simulating flows over riblets and micro-textures.
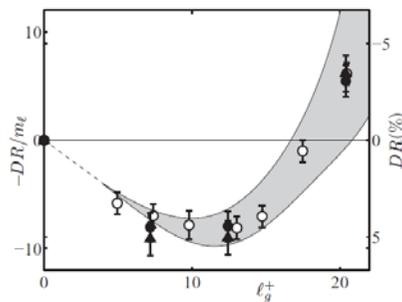
Figure 13: Friction-reduction for DNSs of channels with rectangular riblets at Reτ ≈ 180 and 550. O, *DR* and *DR*/m_ℓ at Reτ≈ 180; ●, *DR* at Reτ ≈ 550; ▲, *DR*/m_ℓ at Reτ ≈ 550. Error bars have been estimated from the time-history of C_f. The shaded area envelopes results for several experimental riblets (Garcıa-Mayoral and Jimenez, 2012)

Conclusion

Non-random-roughness technologies have been used in diverse engineering and industrial applications. In many engineering applications (e.g. heat exchangers, turbine blades, ship and submarine hulls, high performance aircraft, and piping systems) surface roughness can significantly affect the skin friction and heat transfer characteristics (Hosni et al., 1993). Usually, a large portion of the total drag on long objects with relatively flat sides comes from turbulence at the wall, so riblets will have an appreciable effect. In addition, understanding the extent of the roughness effect arising from a variety of textured types would improve predictive capabilities for drag reduction. The recommendations and suggestions for future work are indicated as follow:

- The review of controlling near-wall turbulence by riblets demonstrated that the reason why riblets give only about 10% reduction in skin friction is due to the geometry optimization. Therefore, surface texturing may be a solution as a passive method due to its variety in sizes and shapes. In addition, some researchers have tried to simulate the flow over three-dimensional riblets experimentally in order to understand why this structure leads to the reduction of viscous drag in turbulent flow. The difficulty of such research has become clear due to the variety of variables and the complexity of the accompanying three-dimensional flow. Consequently, most of the CFD research is performed on a two-dimensional representation of the riblets, thereby decreasing the complexity of the problem. In many cases, the preparation of the surface mesh is the most time-consuming phase. Also, this phase often requires trimming or approximation of tiny parts difficult to resolve with the mesh. For this reason and the fact that the textures are three dimensional despite of the riblets, the need for three dimensional modelling arises.
- For all type of turbulence flow with different Reynolds number as long as it is continuously turbulent the instability problem exists in the buffer layer. Therefore, it is acceptable to assume that in this sub-layer the damping action of the viscosity is equally large with the effect of three dimensional perturbations; and these disturbances are intensified and are sufficiently large inside log low layer that is totally turbulence.
- At the present time the study of effect of riblets focuses on riblets' sizes and shapes. Since the density of the riblets on the surface is almost linearly proportional to the amount of coverage with riblets over the body surface, the effect of riblets density has not been considered. However, this might not be economical and beneficial for all case studies. Therefore, apart from investigating the geometrical properties of the riblets (or textures), the statical properties of their finite densities (configuration) will be specifically interested.

Acknowledgments

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