# Three dimension structured surfaces – Type 2

# Structures with two orthogonal waves

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## 1_Introduction

**Two dimension structured surfaces** have shown the capability to provide a flow drag reduction of the order of 10 %. This flow drag reduction is lower in the case of riblets with a triangle shape (5 to 6%) and larger in the case of riblets with a knife blade shape (10 to 12%). These performances were calculated with a RANS code and found in line with experiments carried out in the past by numerous workers. See web page on "2D structured surfaces".

**A three dimension structure surface - Type 1** including two flow drag reduction mechanisms has been analysed. These mechanisms are: a 2D structured surface associated with a transverse oscillating flow (wave). The resulting flow drag reduction is of the order of 20% at the optimum condition. These performances were determined with a LES code. See web page on "3D structured surfaces – Type 1".

**A new shape of 3D structured surface (Type 2)** is proposed to provide a greater flow drag reduction. This type 2 **includes two orthogonal oscillating waves**, one parallel to the structured surface (as per type 1) and a new one normal to the structured surface and oriented in the flow direction. As very little calculation has been performed with this type of 3D structured surface, a phenomenological analysis is provided below to explain the mode of operation of the different types of riblets: 2D longitudinal riblets and 3D riblets, types 1 and 2.

## 2_Two dimension structured surfaces

Two dimension structured surfaces have shown a capability to provide a drag reduction of the order of 10 %. It is slightly lower in the case of triangle shape riblets (5 to 6%) and slightly larger in the case a knife blade shape riblets (10 to 12%).

These performance were validated with a Reynolds Average Navier Stokes (RANS) code (equations) modelling the turbulence. The calculation was performed using the turbulence model: ***k - ε* model.** See site web page "2D structured surfaces"

Several validation calculations were performed:

a) The effect of the triangle shape was analysed in four cases of triangle base angle Alpha (see figure 2.1): 10, 45, 60 and 80 degrees showing a maximum drag reduction of, respectively, 0.6, 6.5, 6.2 and 3.5 per cent. These maximum were reached for a dimensionless width ($s^+$) of 18. These calculation results are confirmed by experimental results found in the literature.

b) The effect of the riblet shape was analysed in considering two extreme cases: triangle and knife blade shape riblets finding a maximum drag reduction of 6.2 per cent in the first case (60 degree triangle) and 12.3 per cent in the second case (h/s=0.5). These maxima were reached for a dimensionless width ($s^+$) ranging between 18 and 20. These calculation results are confirmed by experimental results presented in the literature.

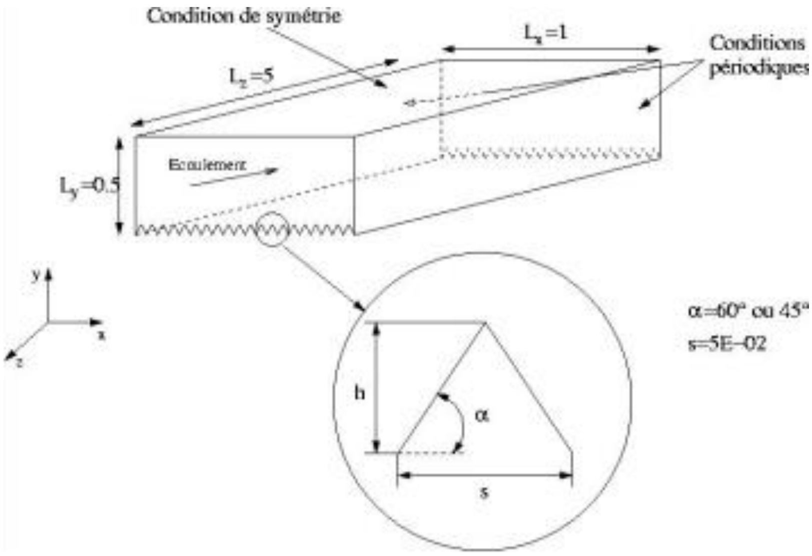


Figure 2.1: definition of the volume analysed with a RANS code.

It has to be pointed out that it was possible to perform calculations of two dimension riblets with a RANS code while it appeared not possible with the three dimension riblets using the transverse flow oscillation mechanism.

A possible explanation may be the following:

1) *In the case of a flat surface*, the low speed streaks sweep the smooth surface generating relatively large viscous losses (figure 2.3 (a)) before bursting into the flow core.

2) *In the case of triangle shape riblets with optimised dimensions*, the low speed streaks are lifted to the top of the triangle sweeping the top part of the triangle with some viscous losses but less than in the previous case (figures 2.2 and 2.3 (b)). It has also to be mentioned than the riblets limit the transverse displacement of the low speed streaks.

3) *In the case of a triangle shape riblets with too large dimensions* (mostly the width), the low speed streaks enter partly or entirely into the grooves (between riblets) increasing the viscous losses compared to the previous case (figure 2.3 (c)). It has also to be mentioned that when the low speed streaks are fully embedded into the structures the flow drag may be greater to the one corresponding to the smooth surface case. This was observed during code simulation and experiments (flow above twice the optimum flow)

4) *In the case of knife blade riblets with optimised dimensions*, the low speed streaks float at the top of the knife blades strongly limiting the viscous losses providing therefore the maximum flow drag reduction (figure and 2.3 (d)).

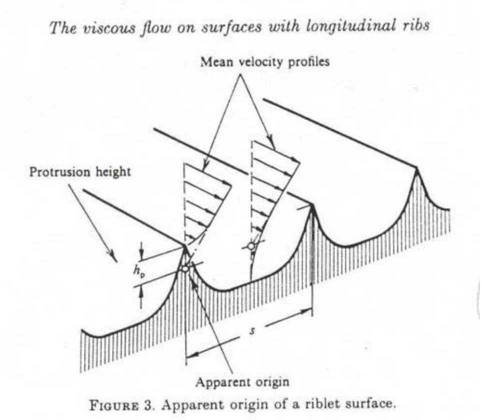


*Figure 2.2 – Two dimension structures (riblets) aligned in the flow direction.*
*Diagram by D.Bechert (1989)*

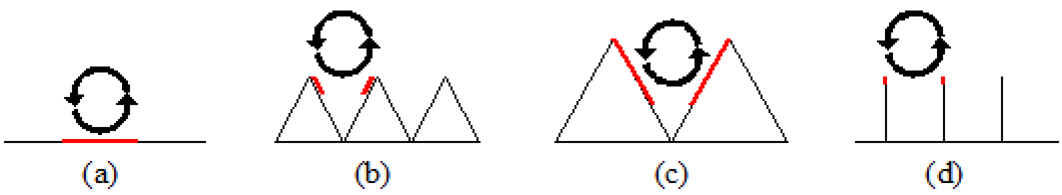


*Figure 2.3 – Principle of operation of 2D structures. A turbulent structure (stream wise vortex) over: a) a smooth surface, b) triangular riblets with adapted dimensions, c) triangular riblets with too large dimensions, d) knife blade riblets with adapted shape and dimensions.*

**In the case of 2D riblets, a RANS code is suitable to perform an aerodynamic analysis of longitudinal grooves (riblets) considering the unchanged nature of the low speed streaks** (same for figures 2.3 - a to d)**. In particular, the average diameter and length of the low speed streaks are practically unchanged with the average length approximately equal to 50 times the average diameter.**

# 3_Three dimension structured surfaces – Type 1

A three dimension structure surface including two flow drag reduction mechanisms has been analysed. These two mechanisms are: a two dimension structured surface associated with a transverse oscillating flow.

The capability to reduce the flow drag with a transverse oscillating excitation has been demonstrated in numerous works: W.J. Jung et al. (1992); F. Laadhari et al. (1994), K.S. Choi et al. (1997), C. Kannepalli (2000), S.M. Trujillo et al. (1997), J.H. Choi (2002), Quadrio and Ricco (2003). See web page on “3D structured surfaces – Type 1”. These works have generally concluded that an optimum drag reduction is obtained for a dimensionless period ($T^+$) of excitation of the order of 100. They have shown also that the flow drag reduction increases with the amplitude of the oscillation but there was little energy consideration between the input oscillating energy and the degree of flow drag reduction.

The oscillating flow excitation obtained in these works with an oscillating plate has been transposed in the present study by curving (sinusoidal shape), in the transversal direction, the two dimension structures (Riblets - Figure 3.1).

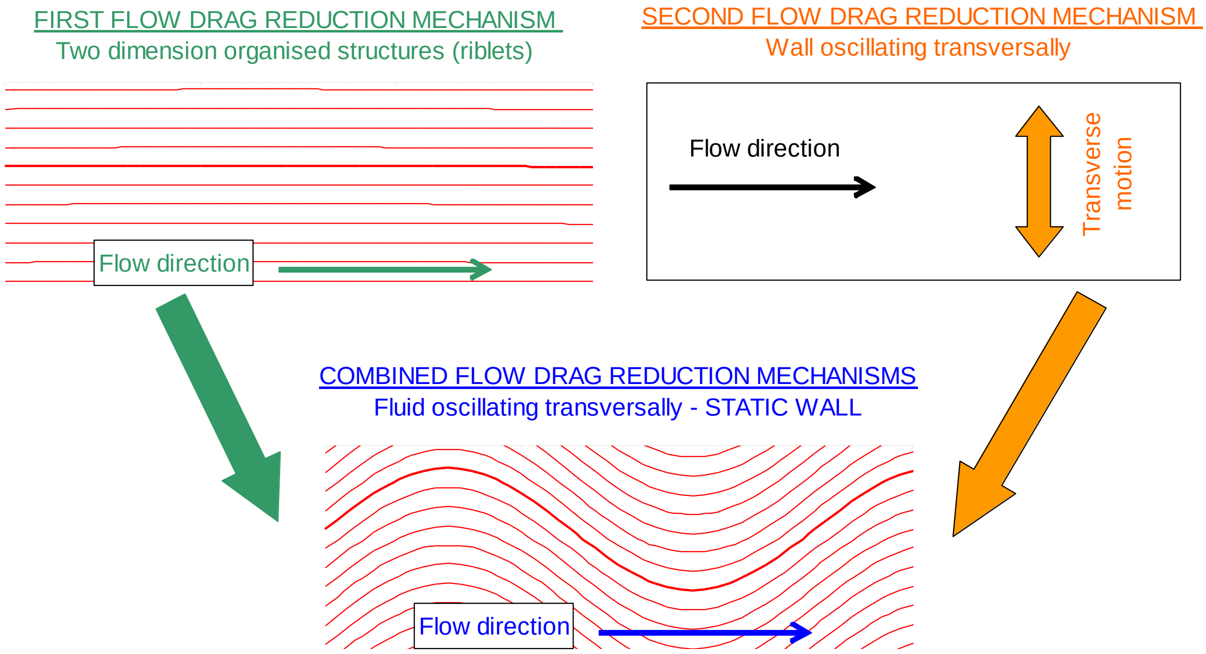


*Figure 3.1 – Design of a three dimension structured surface combining the benefits of two flow drag reduction mechanisms: a two dimension structured surface and the transverse motion of an oscillating plate.*

The resulting flow drag reduction is of the order of 20% at the optimum condition of the transverse oscillation (length or period and amplitude) and using the optimised 2D riblet parameters (knife blade type). These performances were obtained by using a Large Eddy Simulation (LES) code.

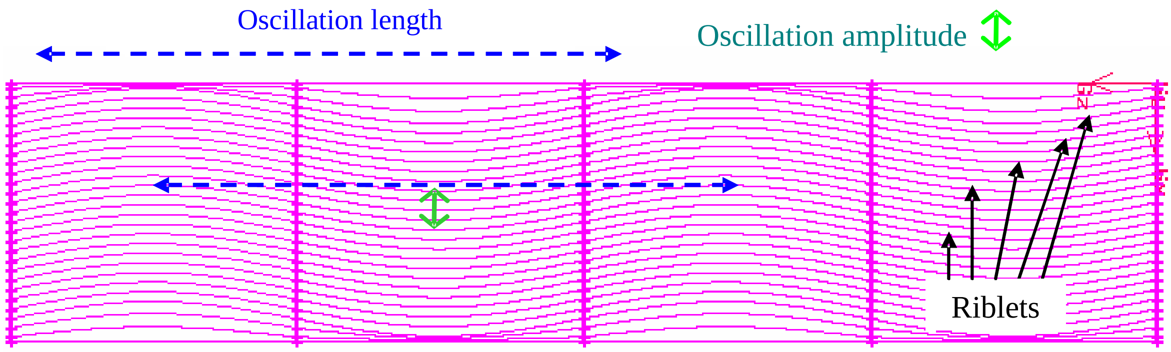


*Figure 3.2 – A three dimension structured surface presenting a sine wave shape with oscillation length and amplitude.*

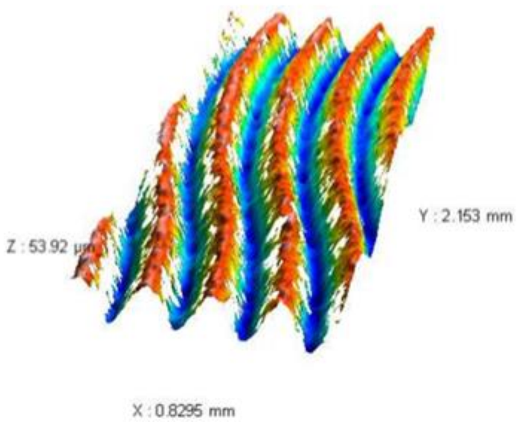


*Figure 3.3 – Perspective view of a three dimension structured surface with sine waves.*

This LES code was validated in two very different flow cases:

1) *An oscillating plate*. The same order of magnitude of the dimensionless period (between 50 and 100) was found during the LES calculation confirming the results found experimentally earlier by other workers with an oscillating plate.
2) *Two dimension structures of the knife blade type*. The same order of magnitude was found as shown in a previous report. See site web page "Two dimension structured surfaces".

These calculations could not be performed with a RANS code due to a major change in the boundary layer. According to DNS calculations made by some workers with an oscillating plate, the oscillation movement tends to reduce the diameter and extend the length of the low speed streaks. They quoted in some cases a ratio of 200 between the length and the diameter of the low speed streaks. See figures 3.4 and 3.5.

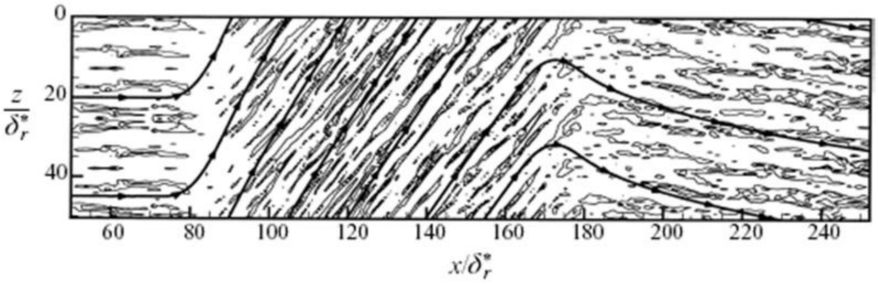


*Figure 3.4-Contours of negative streamline velocity fluctuations (from C. Kannepalli–2000)*

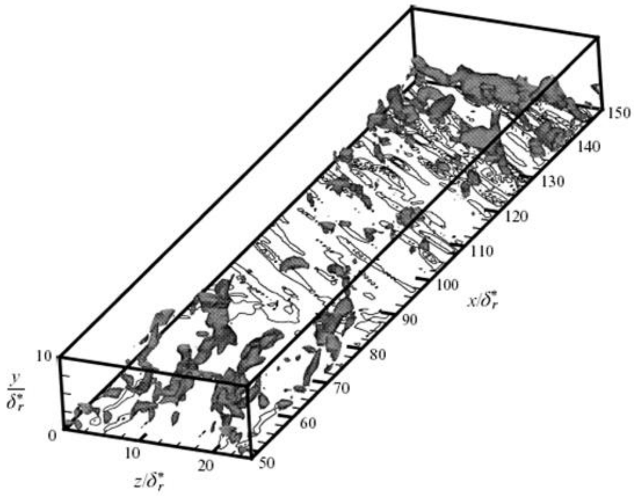


*Figure 3.5 - Low pressure of iso surfaces superimposed on contours of wall enstrophy (from C. Kannepalli – 2000)*

**The very significant change in the boundary layer of a 3D structured surface is the reason why an aerodynamic analysis could not be carried out with a RANS code** (turbulence modeling) contrary to 2D structured surfaces. **The use of a LES code was therefore required for studying 3D structured surfaces.**

# 4_Three dimension structured surfaces – Type 2

Despite the 3D structured surface (type 1) provides a considerable flow drag reduction, of the order of 20%, it is though that other features could be brought to the type 1 mechanism to provide a greater flow drag reduction.

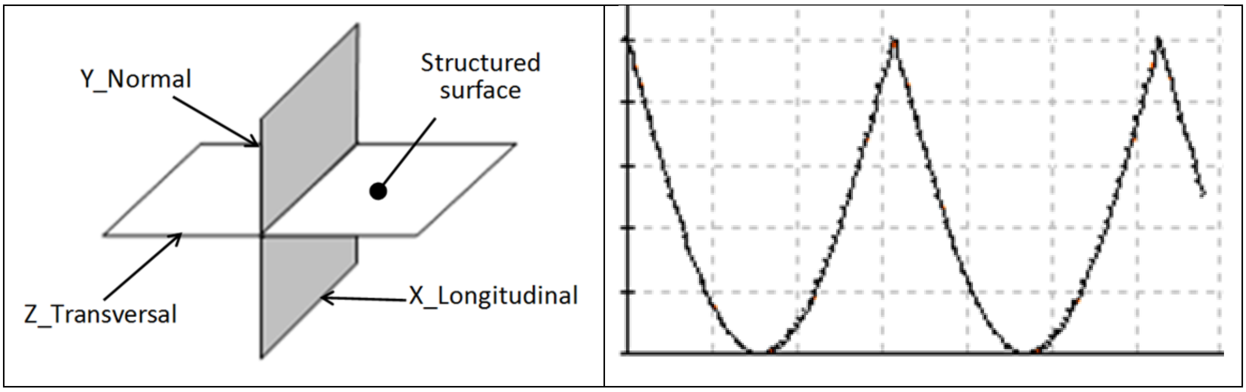


*Figure 4.1 – Left: coordinates X, Y and Z. Right: 2D Riblet shape (ellipsoid) in plane YZ*

A least two actions are foreseen.

**The first action concerns the riblet width**. In the case of 2D riblets, the optimum dimensionless width $S^+$ falls in the range of 18 - 20 (knife blade type) corresponding to low speed streaks with a length / diameter ratio (L/D) of 50. It is more likely that in presence of an oscillating flow where the low speed streaks are considerably stretched (L/D of the order of 200), an optimum width $S^+$ would be significantly smaller than the values quoted above.

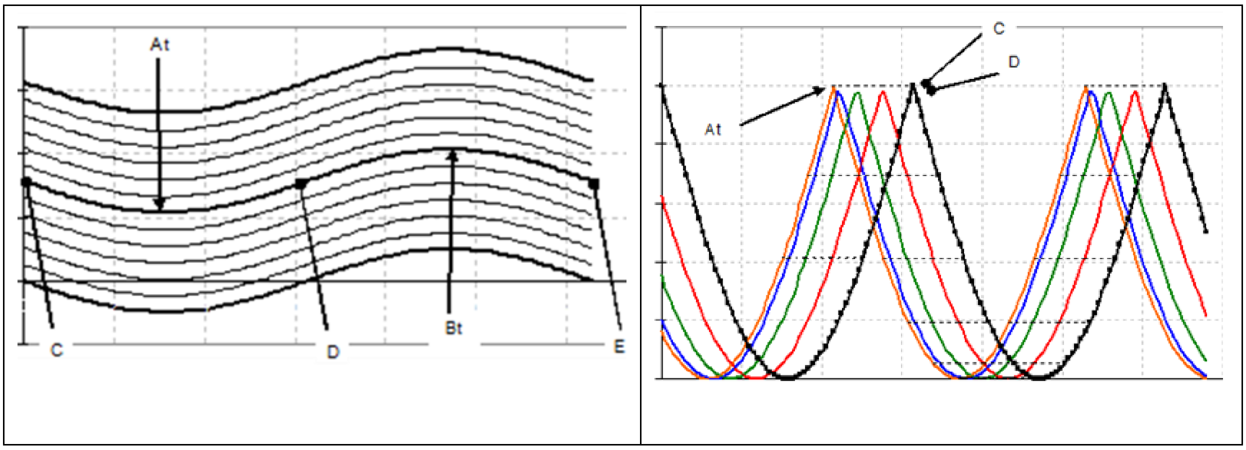


*Figure 4.2 – 3D structured surface – Type 1, a single oscillating wave. Left: Representation in plane XZ. Right: Representation in YZ planes (different X values).*

**The second action concerns the riblet height**. With the 3D structure type 1, the riblet height is the same whatever the location is on the sine wave that is disregarding the lateral flow acceleration. This lateral acceleration is maximum at the sine wave crests (successively oriented to the left and to the right) and nil at the inflexion points. Where the lateral acceleration is maximum, the height should be reinforced to maintain the low speed streaks within the riblets while where the lateral acceleration is minimum (nil), the height could be reduced to decrease the viscous losses generated by the low speed streaks. In between these two positions, the riblet height should vary continuously.

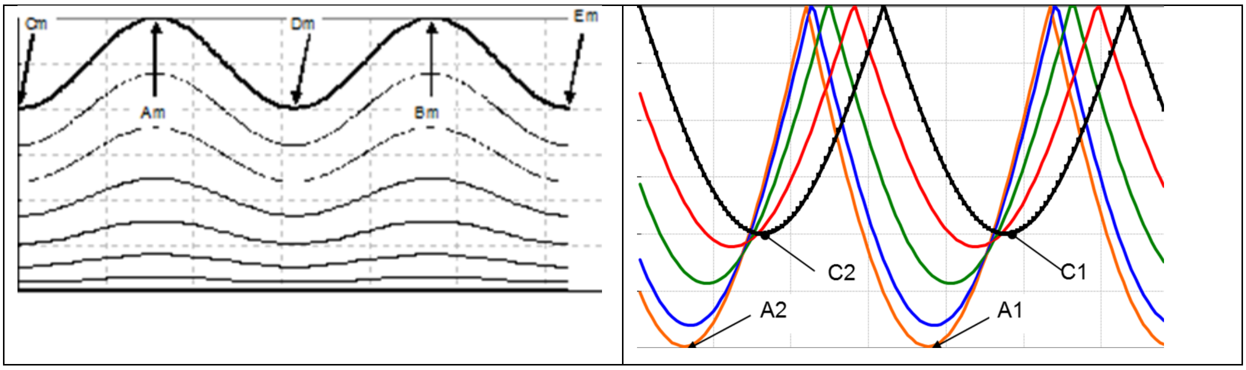


*Figure 4.3 – Three dimension structured surface – Type 2-Two orthogonal oscillating waves. Left: Representation in a XY plane of the surface undulation (coating thickness). Right: Representation in several YZ planes in the flow direction (different X values).*

Following this comment, assuming a flat surface for the bottom of the grooves, the riblet height could be increased and decreased sinusoidally as represented on figure 4.3 (left) and figures 4.4 where points A and B correspond:

- to the maximum displacement (left and right) in the transverse plane (half a period) – Figure 4.2
- to the maximum displacement in the normal plane (one period) – Figure 4.2

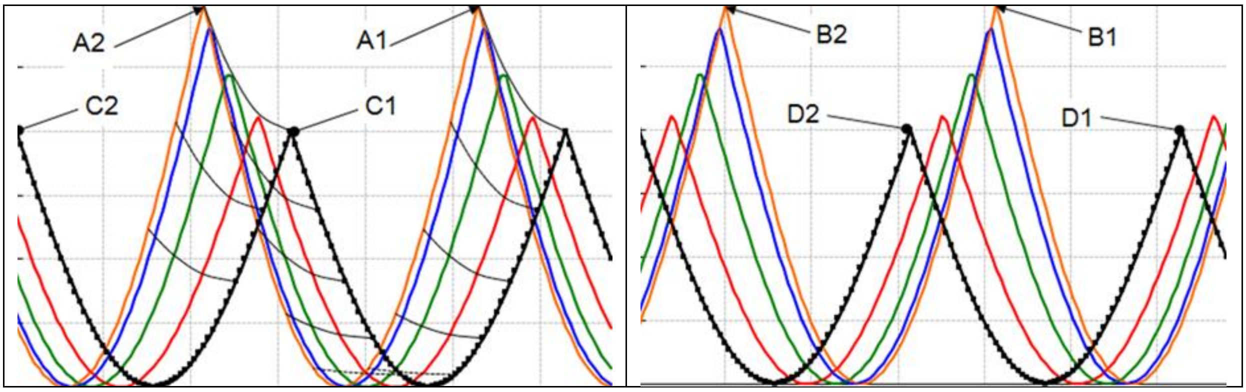


*Figure 4.4 – Three dimension structured surface – Type 2-Two orthogonal oscillating waves. Left: Representation in several YZ planes in the flow direction of points A to C (different X values) - Right: Same as left figure but for points B to D.*

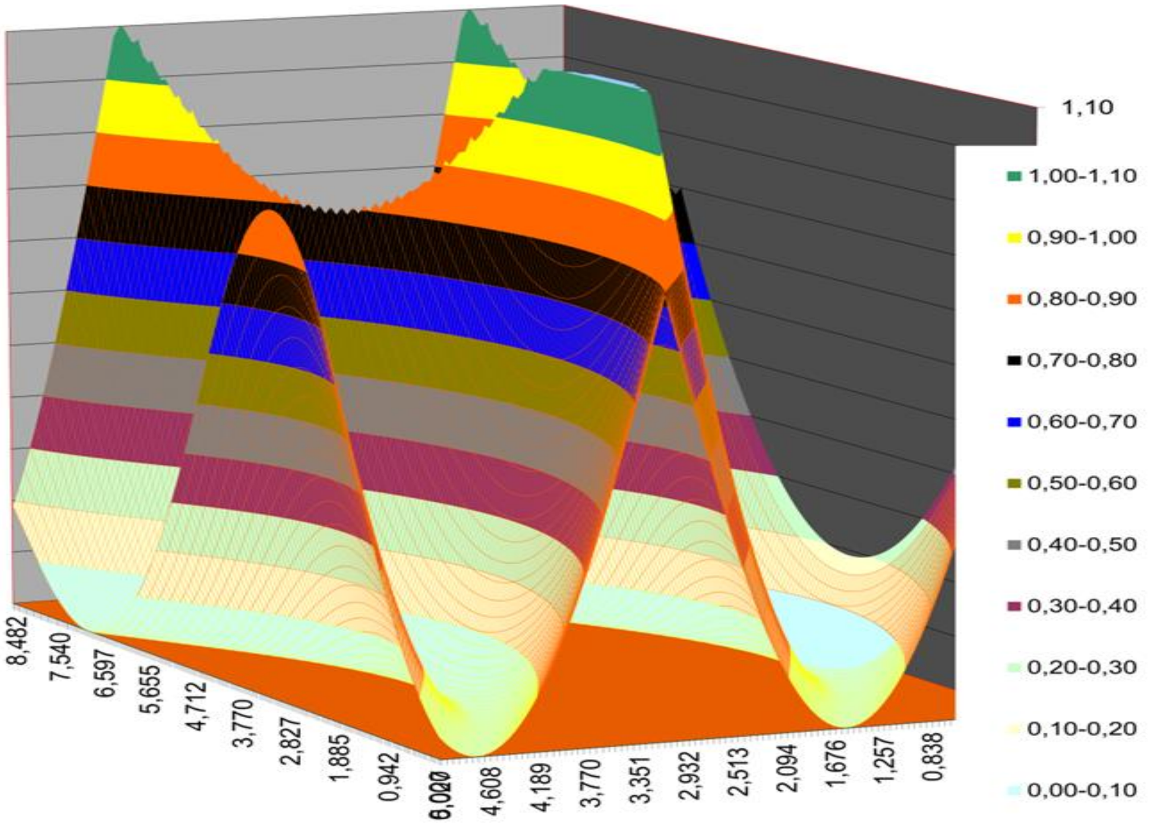


*Figure 4.5 – Three dimension structured surface – Type 2 - Perspective view – Case where the bottom surface is flat, top surface varies with the wave amplitude acting in the XY plane.*

As a consequence, the two waves are orthogonal with two different periods: T for the transverse wave and T/2 for the normal wave.

The normal oscillating waves may be acting in two ways:

- The bottom of the grooves lay on a flat surface providing crest and valley on the top of the structured surface in direction of the flow (Figures 4.3 left; figures 4.4 left and right and also figure 4.5).
- The top of the riblets lay on a flat surface providing crest and valley at the bottom of the grooves in direction of the flow (Figure 4.3 right and figure 4.6).

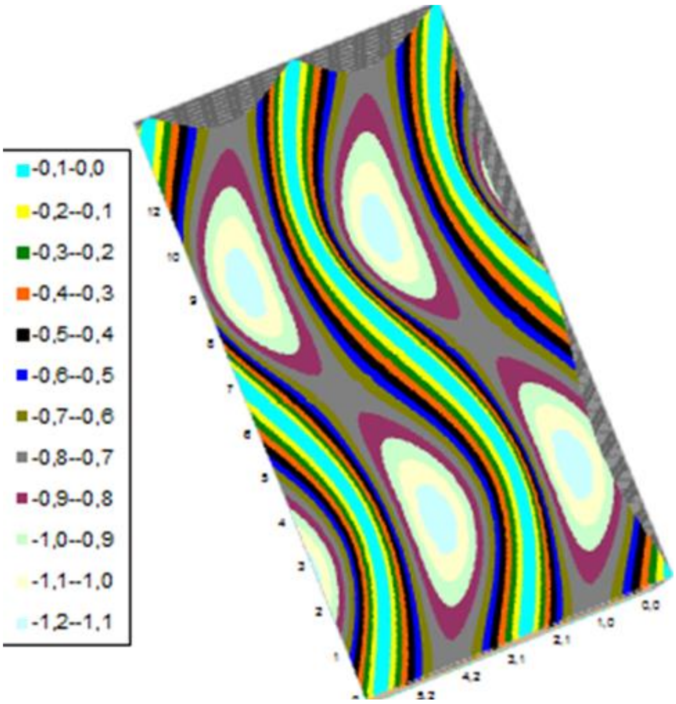


*Figure 4.6 – Three dimension structured surface – Type 2 - Top view – Case where the top surface is flat, bottom surface varies with the wave amplitude acting in the XY plane.*

Studying, with a LES code, a 3D structured surface – Type 2 in order to determine the optimum condition would be very complex as it will require determining at least five parameters:

- The optimum width and height of the basic riblets
- The length and amplitude of the transverse oscillating wave
- The amplitude of the normal oscillating wave considering that its length is half the length of the transverse one.

It has to be noted that the normal oscillating wave is beneficial in two ways:

- It improves the operation of the transverse wave (more efficient at wave crests and less viscous losses at the inflexion points).
- It provides a second flow oscillation excitation which could reinforce the stabilisation and stretching of low speed streaks.

The optimisation work being carried out **one could expect a flow drag reduction exceeding significantly 25 per cent.**

# 5_Conclusion

A LES Code could establish the mechanism of drag reduction provided by a plate oscillating transversely to the main flow direction. The maximum flow drag reduction was obtained for a dimensionless period of 100. In this specific case, the drag reduction tends to increase with the amplitude of the oscillation, disregarding the energy required to move the plate.

2D riblets of the knife blade type provide a maximum drag reduction of the order of 10 %. The same result was found with RANS and LES codes (see corresponding Web site pages).

3D structured surfaces (Type 1) combining the above two flow drag reduction mechanisms (2D riblets and transposed transverse flow oscillation) provide a drag reduction of the order of 20 % according to the LES code validated with the oscillating plate and 2D riblets. The maximum drag reduction was achieved for a dimensionless period of 100 and a maximum angle of the transverse oscillation of the order of 10 degrees.

It is anticipated that further drag reduction could be obtained by adding a second oscillating wave oriented in the flow direction and orthogonal to the transverse wave. This second wave (normal wave) could be of a sine wave type with a frequency equal to twice the transverse wave frequency. This normal wave would provide a riblet height increase at the crests of the transverse wave and a riblet height decrease at the inflexion points of the transverse wave. This should provide several advantages:

- A better control of the low speed streaks at the transverse wave crests
- Less viscous losses at the inflexion points of the transverse wave
- An additional parietal oscillating effect provided by the normal wave.

This optimum dimension values ($h^+$ and $S^+$) obtained during the 2D riblet calculations (flow simulation with RANS code) should be reviewed in relation with 3D riblets whatever they are of type 1 (A single oscillating wave) or type 2 (Two oscillating waves).

Once a complete optimisation study has been carried out, it is expected to get a flow drag reduction significantly greater than 25 per cent.