Simulation of Flow over a Roughness Element

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Applications

Understanding how surface roughness can inhibit free stream velocity allows for:

- Aerodynamic improvement
- Turbulence mitigation
- Higher energy efficiency

Examples of surface perturbation prevention include the use of:

- Flush mounted rivets on aircraft
- Winglets on aircraft wing tips
- Smooth transitions between perpendicular surfaces

Industries benefited from roughness element perturbations:

- Aviation/Aerospace
- Automotive
- Construction

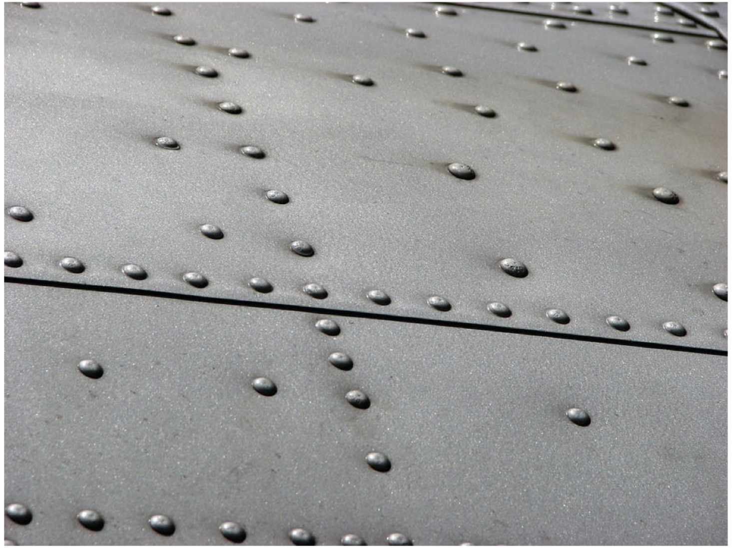

Figure 1 - Surface inconsistencies caused by protruding rivets (*ref 4*)

Experimental Setup using TSP

- Temperature sensitive paint (TSP) is the industries choice for temperature visualization of fluid flow
- TSP creates color gradients based on relative surface temperatures, using LEDs and camera technology to collect data
- Free stream velocity, U∞, is a defined fluid velocity upstream from the roughness element/cylinder
- Water was chosen as the operating fluid due to its predictable interactions
- Beneath the TSP layer, a heating plate was applied to create temperature gradients
- Experimentation geometry:
  - 117 cm x 30 cm x 7 cm

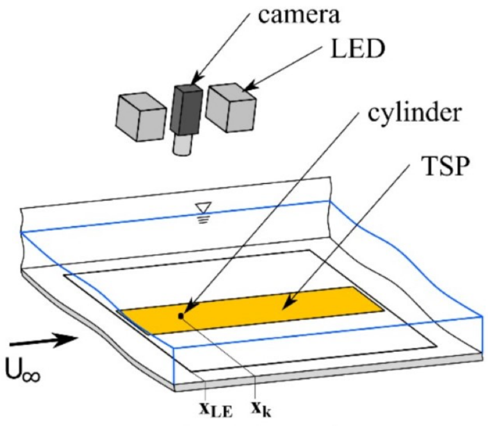

Figure 2 - Section of the experimental setup (*ref 9*)

Theory

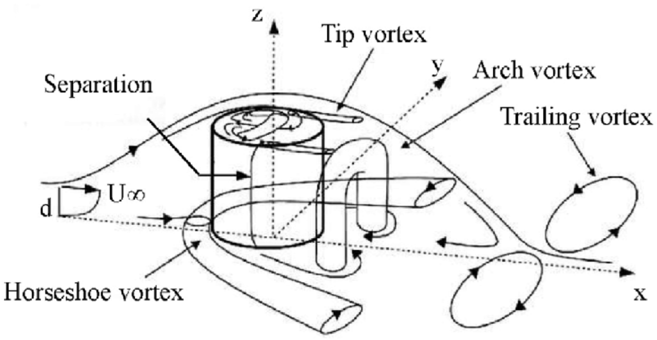

Figure 3 - Horseshoe vortex structure around a cylindrical roughness element (*ref 5*)

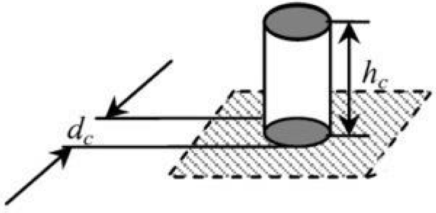

Figure 4 - Example of a roughness element (*ref 6*)

Horseshoe Vortex: a vortex that is formed when a fluid flows around an object in the shape of a horseshoe

Boundary Layer: thin layer of fluid near the surface where are the velocity changes from zero to the free stream velocity

Roughness element: a small objects within the flow of a fluid that causes the flow to change

Ansys CFD

A computational fluid dynamics (CFD) program that simulates complex fluid flow

Uses Navier–Stokes and continuity equations to solve fluid systems

Verification and validation

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=\rho g_x-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=\rho g_y-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\rho g_z-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Figure 5 - Navier–Stokes equations

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0$$

Figure 6 - Continuity equations

Boundary Layer Simulation and Effects on Roughness Element Downstream Wake

The Blasius boundary layer simulation was naturally formed over a non-slip condition surface, with a free stream velocity of 0.04 m/s.

$$\eta = y\sqrt{\frac{U}{x\nu}}, \quad f'(\eta) = \frac{u}{U},$$

$$ff'' + 2f''' = 0$$
$$f(0) = f'(0) = 0$$
$$f'(\infty) = 1$$

Figure 7 - The Blasius Boundary Layer Solution equations (*ref 3*)

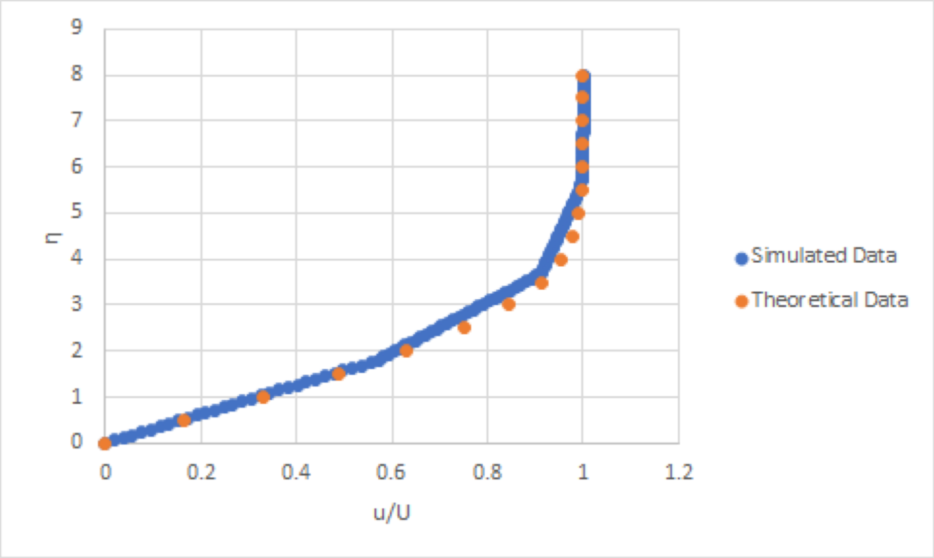

Figure 8 - Theoretical Blasius solution compared with simulated Blasius solution obtained through CFD

Methods

Geometry:

- Inlet simulation
  - 42 cm x 30 cm x 7 cm channel
- Simulation with roughness element
  - 75 cm x 30 cm x 7 cm
  - Roughness element: 15 cm diameter and 1 cm height

Mesh:

- Standard linear mesh

Initial conditions:

- Initial velocity = 0.04 m/s
- Reynolds number = 380

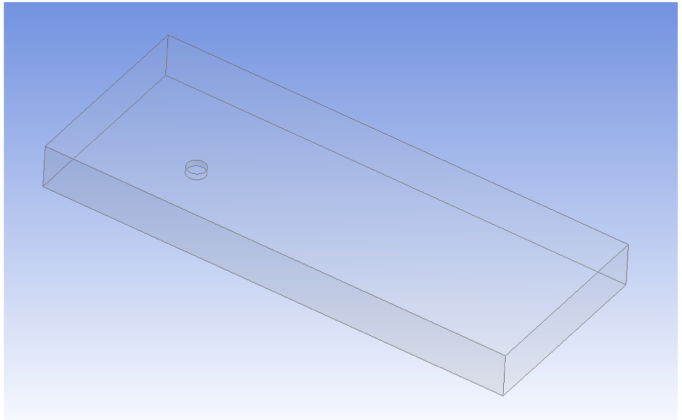

Figure 9 - 3-D model with roughness element

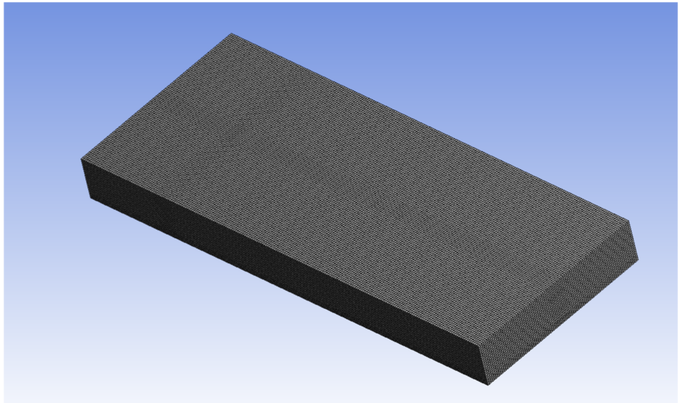

Figure 10 - Standard linear mesh with roughness element

Detail View of Computational Mesh

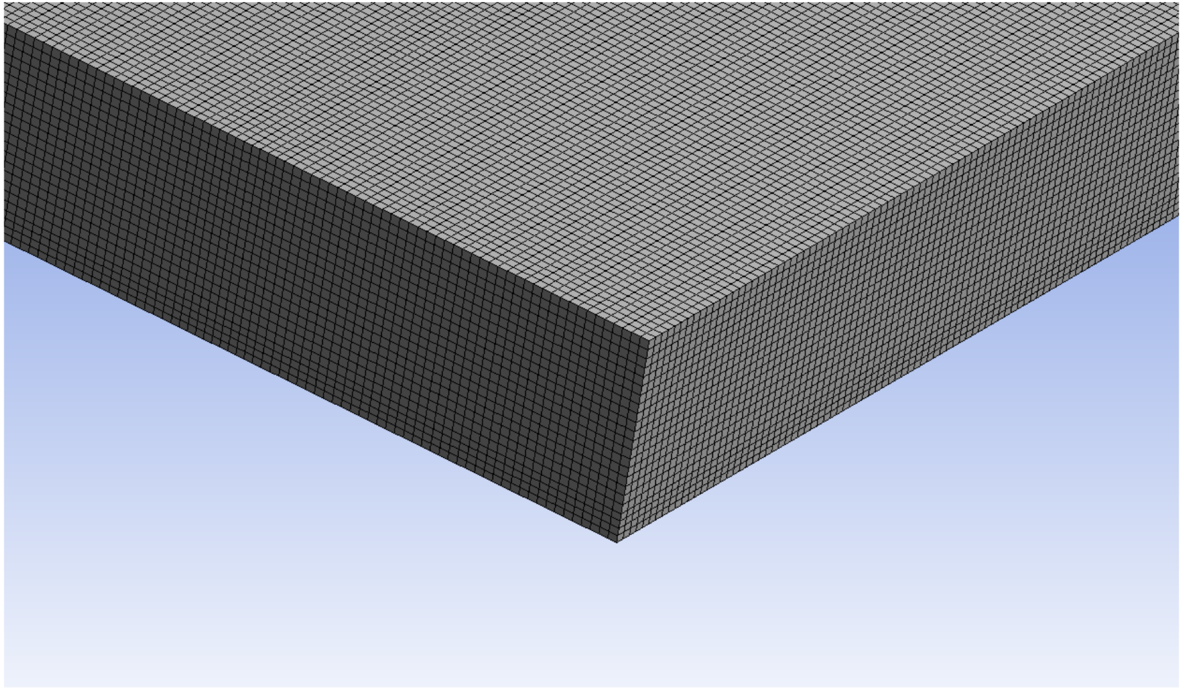

Figure 11 - Enlarged image of
standard linear mesh

Results

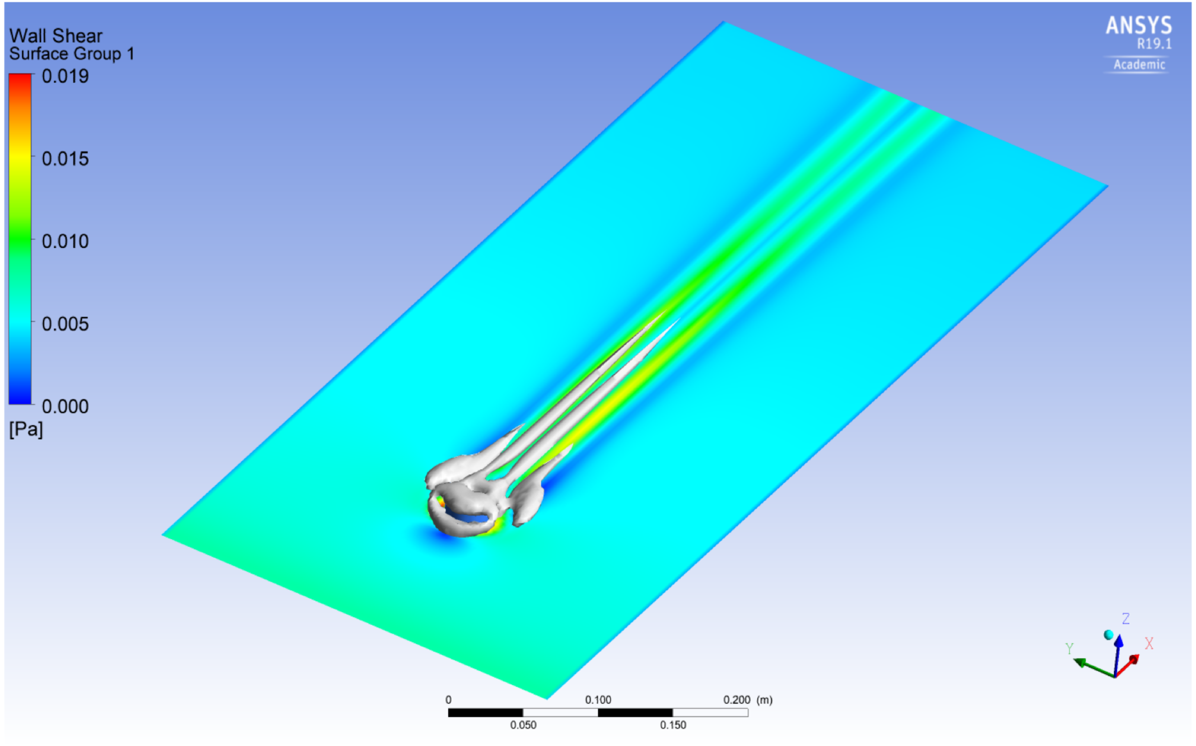

Figure 12 - Q criterion vorticity around roughness element, emphasized over the surface wall shear

Results (cont.)

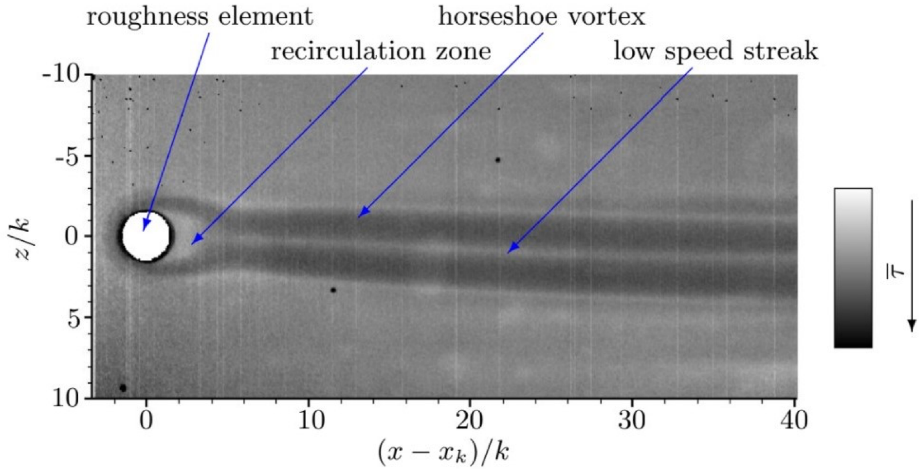

Figure 13 - Cylindrical roughness element at 0.04 m/s

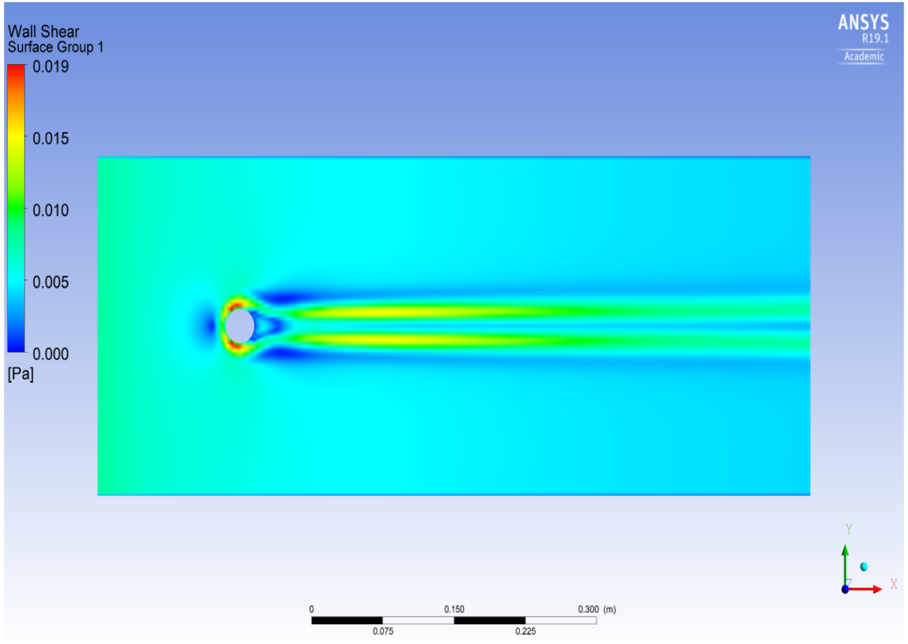

Figure 14 - Surface wall shear along the bottom plate

Results (cont.)

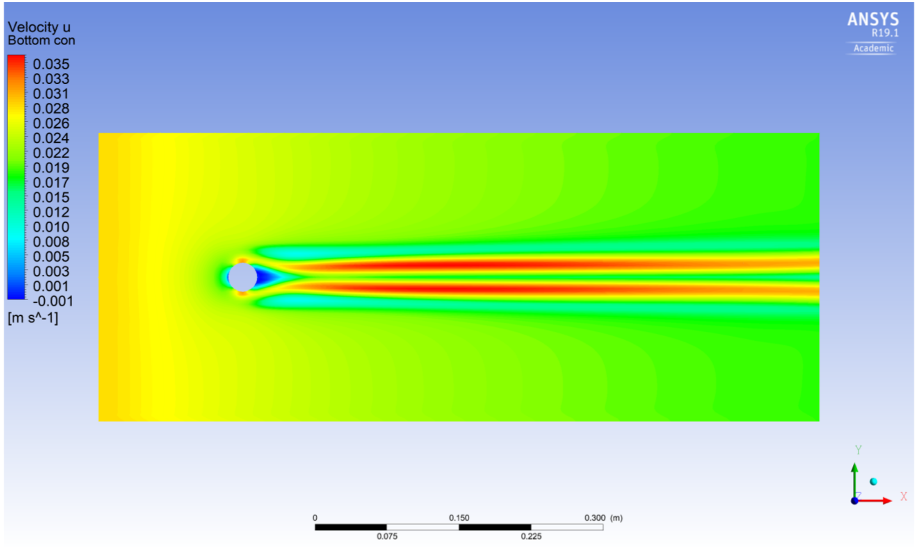

Figure 15 - Contour of velocity in the x direction

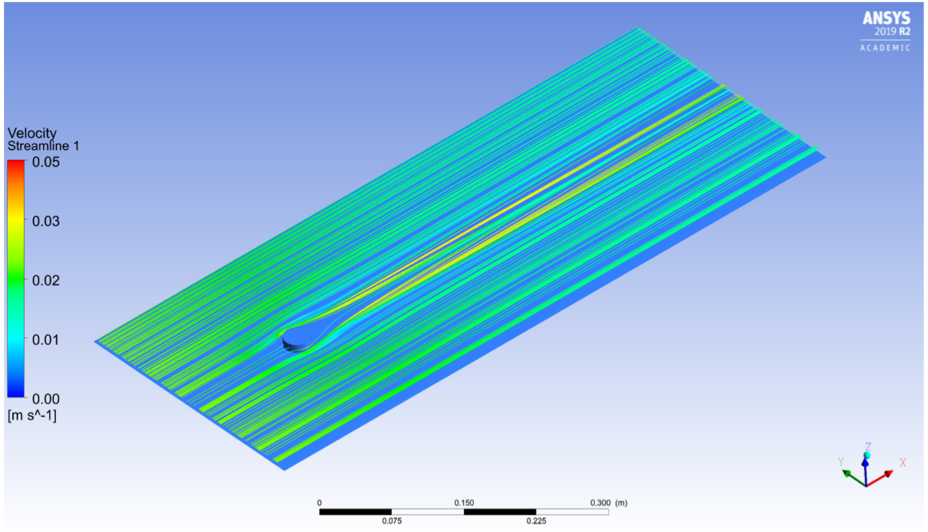

Figure 16 - Velocity streamline contour near the bottom plate

Summary

The interaction of a boundary layer with a roughness element is studied using a simulation approach.

The simulation results show the formation of a horseshoe vortex, which wraps around the front of the roughness element and extends into the wake region past the element.

The wall shear stress signature of the horseshoe vortex compares well with the structure observed in experiments using temperature sensitive paint over a heated surface performed by the German Aerospace Center.

Next steps include the simulation of a heated plate and a variation of the Reynolds number of the flow.

Sources

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