Effect of an Isolated Roughness Element in a Flat Plate Boundary Layer

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Importance of Surface Roughness

Drag on a vehicle increases with surface roughness.

The aerodynamic properties of an aerostructure are influenced by surface roughness.

Surface roughness on an aircraft wing directly affects fuel consumption and aircraft performance.

Roughness causes the transition to turbulence, which is crucial to study in the field of aerospace.

Past and Present Studies

Instability mechanism governing the 3D laminar turbulent transition over a flat plate with 2D surface imperfections has been studied previously [1].

A backward-facing step (BFS), forward-facing step (FFS), and roughness cavity were analyzed.

The present study examines an isolated roughness element placed on a flat plate, using direct numerical simulation.

The objective of the work is to investigate the effect of the roughness height within the boundary layer displacement thickness range.

Methodology

Governing Equations:
Incompressible Navier-Stokes equations

$$\mathbf{u}_t + \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p = \nu \nabla^2 \mathbf{u}$$

$$\nabla \cdot \mathbf{u} = 0$$

These were solved using Nek5000 [2].

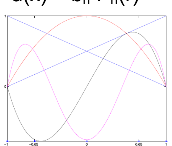
Solver

Nek5000 is an open-source spectral element-based solver.

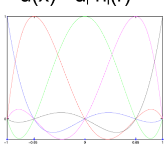
High–order method with high accuracy and good parallel efficiency.

Spectral Element Methods (SEM)

$u(x) = b_n P_n(r)$ $\quad$ $u(x) = u_i h_i(r)$

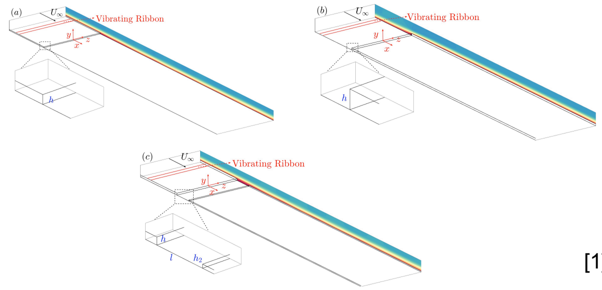


Legendre polynomials $P_n(r)$



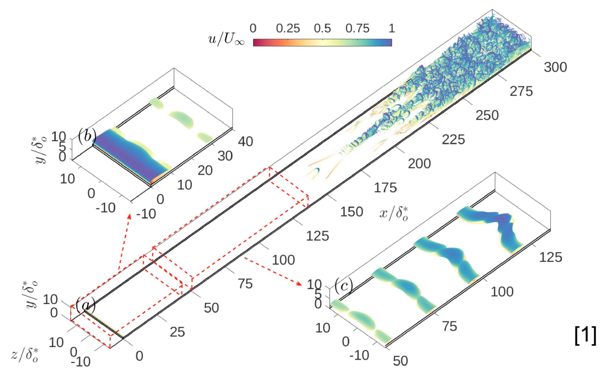
Lagrangian interpolants $h_i(r)$ of Legendre polynomials

Flow Setup and Previous Results



[1]

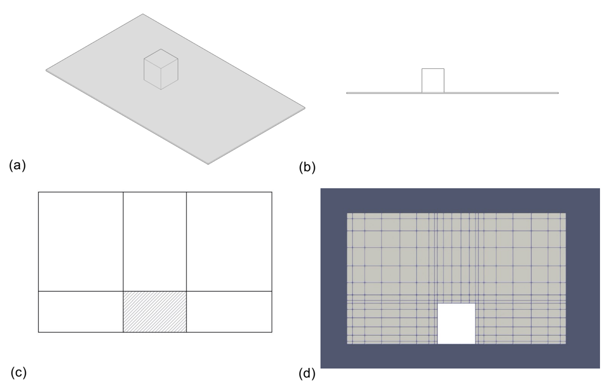
Geometries used in the previous study, a) backward-facing step, b) forward-facing step, c) step cavity



[1]

Flow over forward-facing step, $Re_{\delta^*} = 1000$

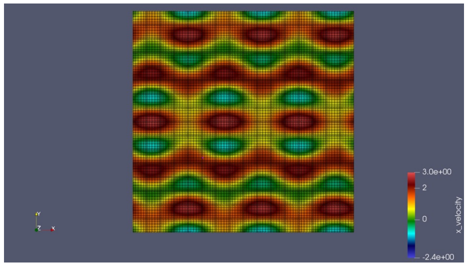
Present Work



Sketch of geometry a) Isometric view, b) Side view, c) Box pre-mesh, d) Grid close-up

Next Steps

- Familiarization with Nek5000:
  Eddy_uv test case, Re = 40



- Computational setup:
  Introduce vibrating ribbon

$$v(x,t) = \begin{cases} A_{2D} f(x) \sin(\omega_{2D} t) & \text{in 2D} \\ A_{2D} f(x) \sin(\omega_{2D} t) + A_{3D} f(x) g(z) \sin(\omega_{3D} t) & \text{in 3D.} \end{cases}$$

$$f(x) = 15.1875\xi^5 - 35.4375\xi^4 + 20.25\xi^3; \quad g(z) = \cos(2\pi z/\lambda_z)$$

$$\xi = \frac{x - x_{R1}}{x_c - x_{R1}} \text{ for } x_{R1} < x < x_c, \text{ and}$$

$$\xi = \frac{x_{R2} - x}{x_{R2} - x_c} \text{ for } x_c < x < x_{R2}.$$

[3]

- Grid convergence study
- Analysis of the instability mechanism

References

[1] Ming Teng "Laminar - Turbulent Transition Over A Flat Plate With Surface Imperfections", Ph. D. thesis, Queen's University, (2022).

[2] P. F. Fischer, J. W. Lottes, and S. G. Kerkemeier, NEK5000, https://nek5000.mcs.anl.gov (2008).

[3] H. F. Fasel and U. Konzelmann, Journal of Fluid Mechanics 221, 311 (1990).

Acknowledgements

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