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DNS of Roughened Surfaces

Preliminary Results

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Summary

Introduction:

- Surface Roughness and Jet Engine Intake Flow
- The Classical Prandtl-Schlichting Sand-grain Theory
- What is Direct Numerical Simulation (DNS)?

Direct Numerical Simulation:

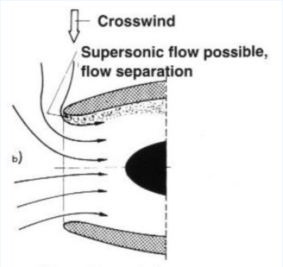
- Smooth Wall (Validation)
- Wavy Wall (Validation)
- Highly Irregular Rough Wall (Applied Study)

Coherent Structures

Why is surface roughness important?

Roughness may cause problems

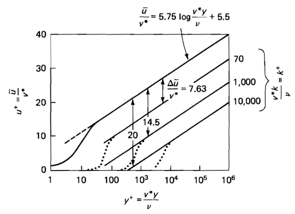
- Real aerodynamic surfaces are subject to roughness due to damages such as corrosion.
- Turbulent flow starts to feel surface roughness at either increased Reynolds number or increased roughness level.
- Increased surface roughness in engine intake may lead to flow distrubances, transition, and distortion. At extreme cases, it might also result in fan blades stalling.



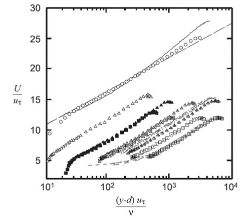
Intake flowfield static plus crosswind (Hunecke 2003)

The classical Prandtl-Schlichting sand-grain theory

- The log-law $U^+(y^+) = \frac{1}{K} ln(y^+ - \Delta y^+) + B - \Delta U^+(k_s^+)$.
- The downward velocity shift $\Delta U^+ \sim \frac{1}{K} ln(1 + 0.3k_s^+)$.
- The equivalent sand-grain roughness height $k_s^+ = \frac{k_s u_\tau}{\nu}$.



Downward shift of log-law (White 1991)



Experimental datum (Birch et al 2011)

What is Direct Numerical Simulation (DNS)?

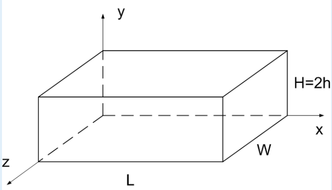
The Navier-Stokes Equations

- Motions of turbulence are encoded mathematically in the Navier-Stokes equations.

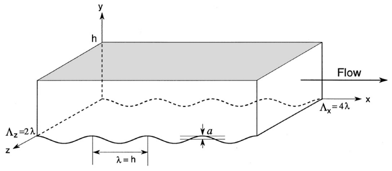
Direct Numerical Simulation

- DNS solves the Navier-Stokes equations directly in space and time.
- Small-scale turbulent motions are supported, rather than modelled, by spatial and temporal resolutions in DNS.
- DNS, as a complementary research tool of experiments, helps to understand flow physics with detailed turbulent motions.
- Small-scale surface roughness elements are directly resolved in DNS mesh.

DNS - Channel Geometry

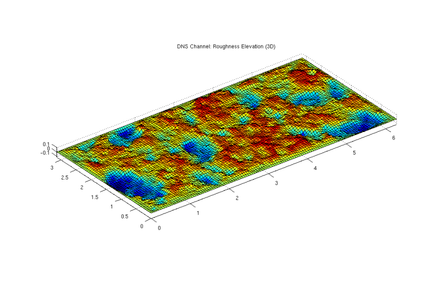


Schematic of symmetric channel geometry (smooth and rough cases)

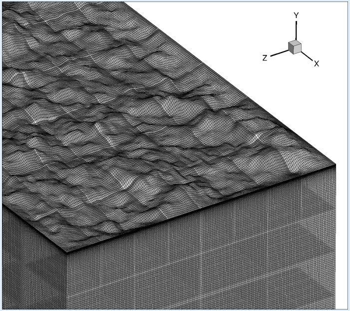


Schematic of asymmetric channel geometry (wavy case $\frac{2a}{\lambda} = 0.1$)

DNS - Roughness sample and CFD mesh



Highly irregular roughness sample from real damaged turbine blade. (Bons et al 2001)



Spatial resolution of DNS mesh over highly irregular roughness surface.

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DNS - BOFFS model setup.

Simulation parameters for 3D fully-developed turbulent channel flow:

General parameters

Case	$Re_h(Re_b) \sim$	Method	Domain	Grids
Smooth	7150	high-order FDM	$(2\pi, 2, \pi)$	(257,147,193)
Rough	5362	high-order FDM	$(2\pi, 2, \pi)$	(257,147,193)
Wavy	(3183)	high-order FDM	$(4, 1, 2)$	(297,118,233)
KMM 1999 (Smooth)	—	Spectrum method	$(2\pi, 2, \pi)$	(256,193,192)
Cherukatet et al 1998 (Wavy)	(3460)	Spectral element method	$(4, 1, 2)$	(48,21,64)

Inner-scale parameters

Case	$Re_\tau \sim$	Δy^+_{1st}	Δx^+	Δy^+_c	Δz^+
Smooth	360	0.36	8.8	7.5	5.9
Rough	360	0.36	8.8	7.5	5.9
Wavy	290	0.1	8.0	7.1	5.0
KMM 1999 (Smooth)	395	—	10.0	6.5	6.5
Cherukatet et al 1998 (Wavy)	300	—	—	—	—

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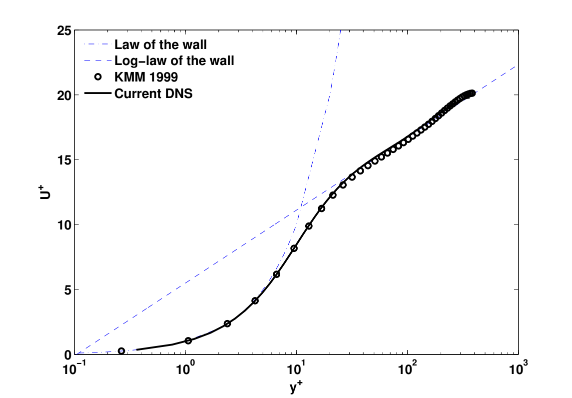
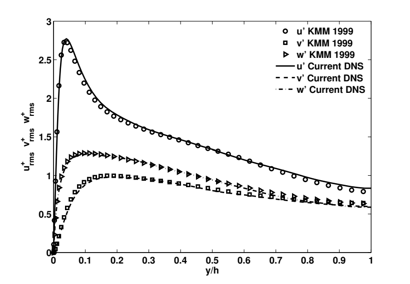
DNS - Smooth wall (Validation)

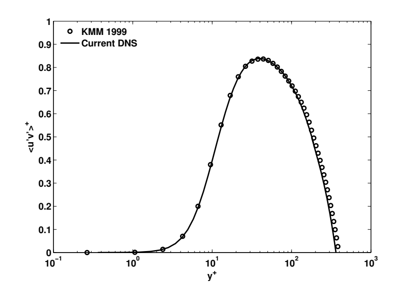


Mean streamwise velocity profiles

DNS - Smooth wall (Validation)

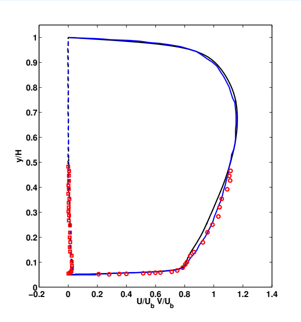


RMS velocity fluctuation profiles

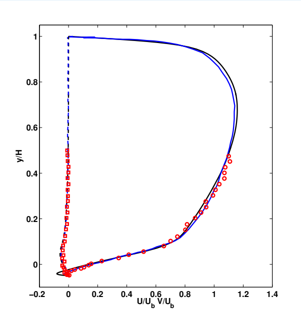


Reynolds shear stress profiles

DNS - Wavy wall (Validation)



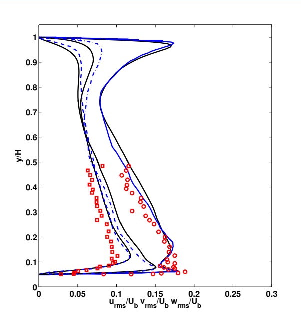
Mean streamwise velocity profiles at crest



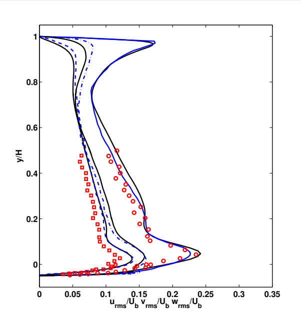
Mean streamwise velocity profiles at trough

(Black: Current DNS, Blue: DNS of Cherukat 1998, Red: Exp of Hudson 1993)

DNS - Wavy wall (Validation)



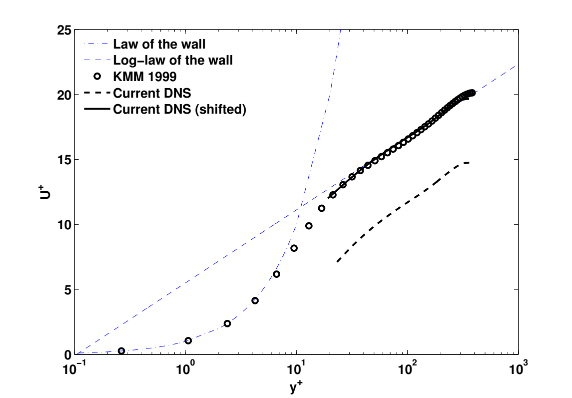
RMS velocity fluctuation profiles at wave crest



RMS velocity fluctuation profiles at wave trough

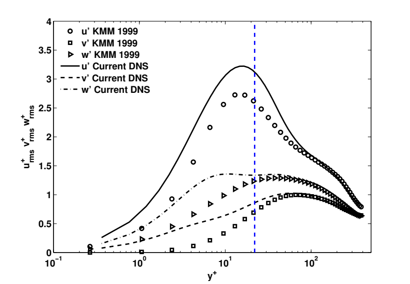
(Black: Current DNS, Blue: DNS of Cherukat 1998, Red: Exp of Hudson 1993)

DNS - Highly irregular rough wall (Applied study)

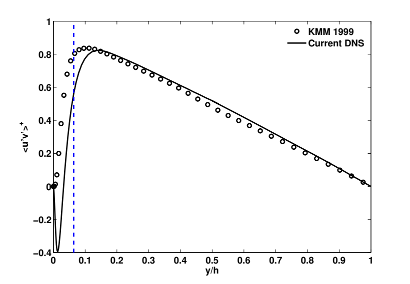


Mean streamwise velocity profiles ($\Delta U^+ = 4.9$, $\Delta y^+ = 4$ and $k_s^+ \sim 22$)

DNS - Highly irregular rough wall (Applied study)

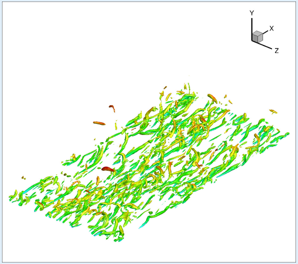


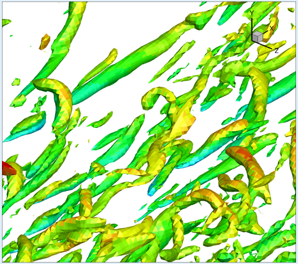
RMS velocity fluctuation profiles



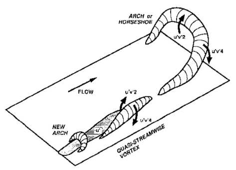
Reynolds shear stress profiles

Coherent structures over smooth wall





Quasi-streamwise vortices over smooth wall.



Conceptual model of the kinematical relationships between ejection/sweep and coherent motions at low Reynolds number. (Robinson 1990, Panton 2001)

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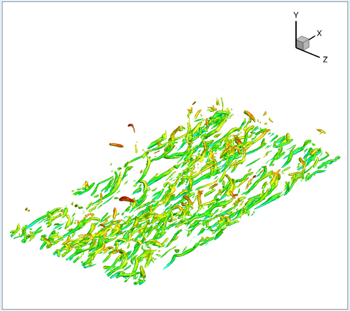
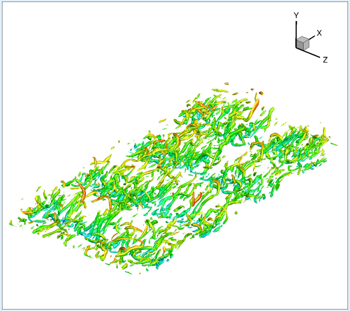
Coherent structures over smooth and wavy walls



Smooth wall



Wavy wall

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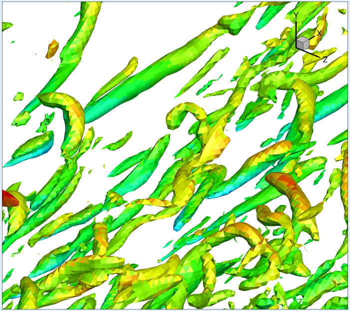
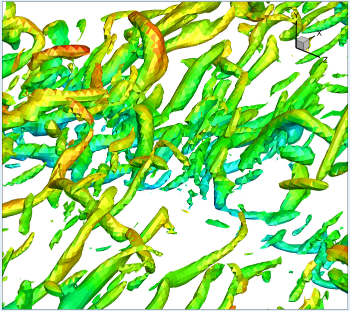
Coherent structures over smooth and wavy walls (zoomin)



Smooth wall



Wavy wall

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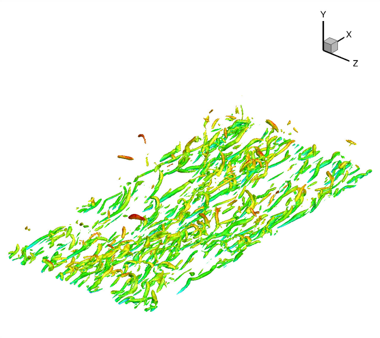
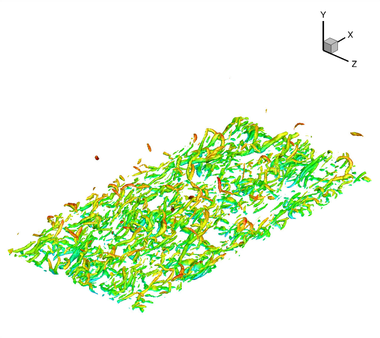
Coherent structures over smooth and highly irregular rough walls



Smooth wall.



Real rough wall.

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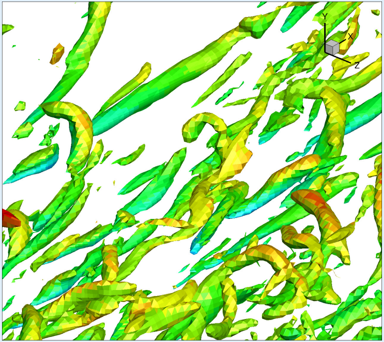
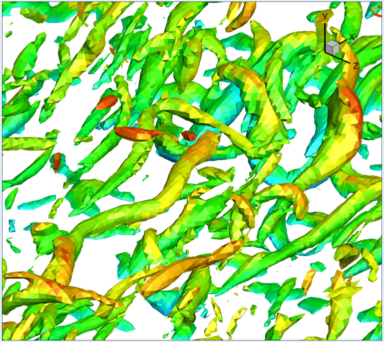
Coherent structures over smooth and highly irregular rough walls (zoomin)



Smooth wall.



Real rough wall.

Conclusion

- Real irregular roughness, in contrast to sand-grain roughness, increases turbulence intensity in the near-wall region, and its effect may extend up to flow region three times higher.
- Near-wall coherent structures over the rough surface have distinctly different characters with respect to those over a smooth wall.
- Next stage to further contrast flow physics between smooth and rough wall turbulence.