Dynamics of Turbulent Flow in the Vicinity of Highly Irregular Surface Roughness

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How do local topographical features alter the spatial and temporal behavior of near-surface turbulence?

STATUS QUO

Most studies involve "idealized" roughness

• Usually single topographical scale • Typically arranged in very ordered manner

Realistic roughness encountered in practical engineering systems

• Highly irregular • Contains a broad range of scales • **Can adversely impact drag and heat transfer at surface: reduced performance**

Challenges

• Insights from "idealized" roughness studies do not entirely translate to the unique cases of realistic roughness • **Detailed studies of realistic roughness are critically important**

NEW INSIGHTS

Laboratory studies of realistic roughness

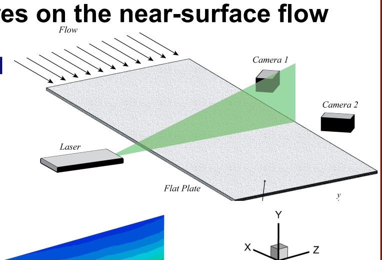
• Profilometry of damaged turbine blades used to build roughness models by rapid prototyping for testing in laboratory wind tunnel • Outer layer of turbulence over such surfaces behaves similarity to smooth wall • **first such observations** • Impact of irregular roughness isolated very close to surface • **Largest topographical features dominate impact, but finer scales can alter flow locally**

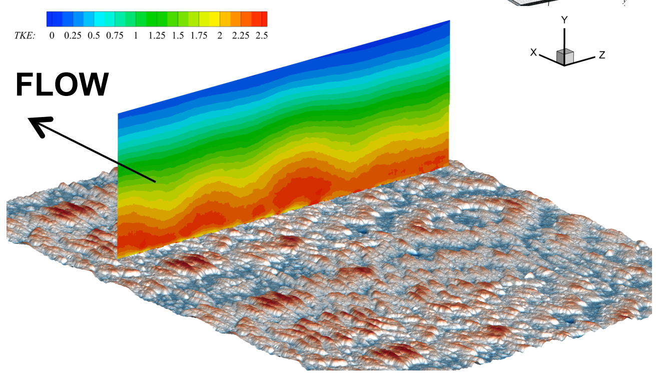
Photos of damaged turbine blades (Bons, 2010)

HOW IT WORKS:

• Model of highly irregular surface tested in wind tunnel • Velocity fields over surface measured by stereo PIV in plane normal to mean flow (below) • **Statistics compared to smooth-wall flow to assess impact of local roughness features on the near-surface flow**

Schematic of experimental arrangement.





Turbulent kinetic energy (TKE) for flow over the rough surface.

MAIN ACHIEVEMENTS:

• Standard stereo PIV measurements completed for flow over smooth and rough surfaces • **Flow near the surface shows strong correlation to local topographical details** • Time-resolved (TR) measurements underway to capture unsteady flow

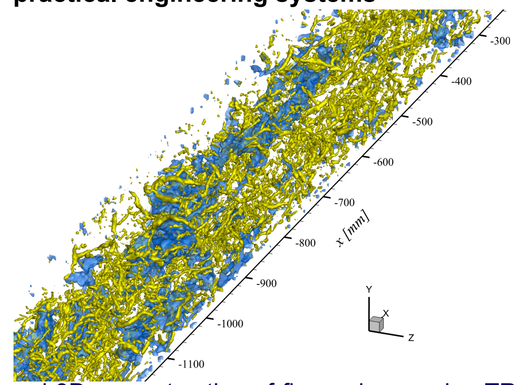
ASSUMPTIONS AND LIMITATIONS:

• Three-dimensional data not captured • **Considering quasi-3D reconstruction from TR data based on Taylor's hypothesis (see right) & tomographic PIV**

QUANTITATIVE IMPACT

Current Impact

• **This effort is first attempt at unraveling the impact of realistic roughness on near-surface turbulence** • Local topographical details found to generate strong near-surface turbulence (left and below) • **Such effects must be captured by turbulence models in order to correctly predict flow behavior in practical engineering systems**



Quasi-3D reconstruction of flow volume using TR data to study 3D vortex organization and TKE generation.

END-OF-PHASE GOAL

Research Goals

• Identify key temporal and spatial features of near-surface flow modifications • **Crucial to drag and heat-transfer impact of roughness** • Presently interfacing with modeling and simulation researchers to assist in model development • Improve prediction of such effects for enhanced design of engineering systems

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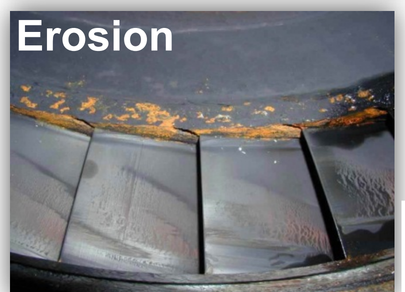
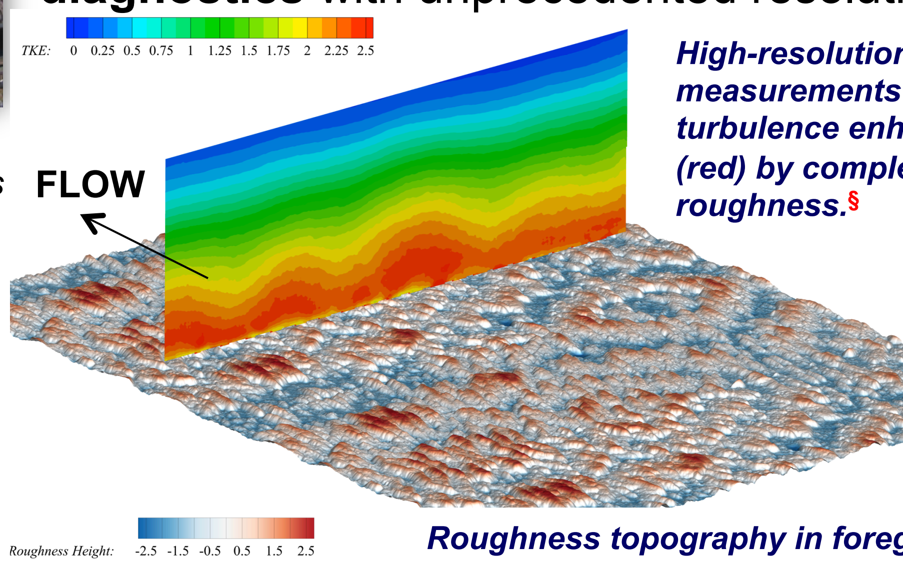
Performance of Engineering Flow Systems Compromised by Surface Damage



Photos of cumulative damage to turbine blades (Bons, 2010).

Harsh operating environments damage flow surfaces (left). Increased drag and thermal loads result, degrading system performance and yielding premature failure. ***Improved predictions of system performance required.***

This effort[*,§] is the **first** to measure flow interactions with surface damage from actual flow systems using **state-of-the-art optical diagnostics** with unprecedented resolution.



High-resolution measurements of turbulence enhancement (red) by complex roughness.[§]

Roughness topography in foreground.

[*]Mejia-Alvarez & Christensen, *Phys. Fluids*, 2010

[§]Mejia-Alvarez, Barros & Christensen, CFS-2 Book Chapter, in press, 2012

Kenneth T. Christensen

Professor & Kritzer Faculty Scholar

- Dean's Award for Excellence in Research, 2012
- Frenkiel Award for Fluid Mechanics (APS-DFD), 2011[*]
- Assoc. Fellow, AIAA
- Beckman Research Award (Illinois), 2011
- Editorial Board, *Meas. Sci. Tech., Exp. Fluids*
- NSF CAREER Award, 2007
- AFOSR YIP, 2006

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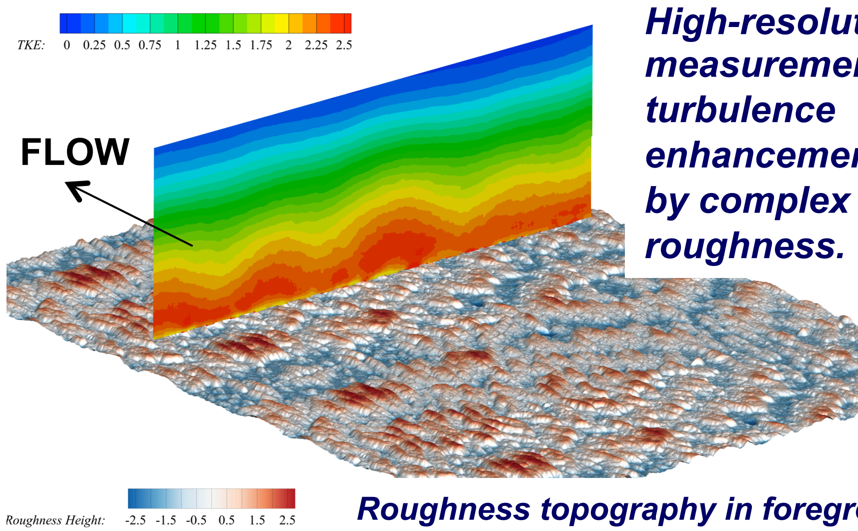
High-Resolution Measurements Reveal Turbulence Enhancement Due to Complex Surface Damage

K. T. Christensen / U. Illinois

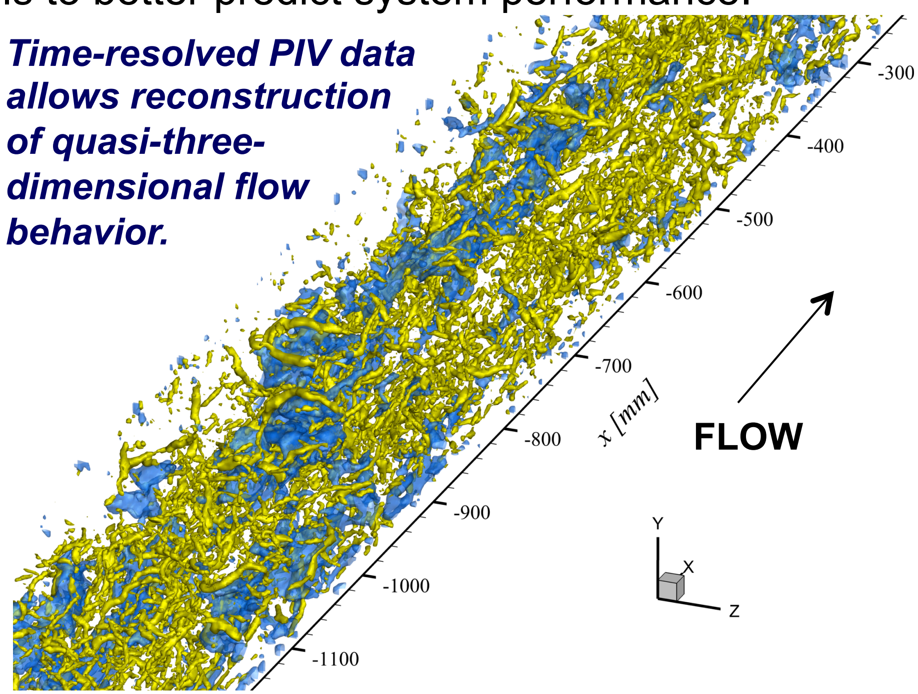
Surface damage to turbine blades is complex and adversely impacts system performance (increased drag and thermal loads)

- Surface damage typically modeled with simple elements (sand, hemispheres, etc.).
- **Current approach is <u>first</u> to replicate actual, complex surface damage (left) and measure its impact on flow using state-of-the-art diagnostics.**
- Largest features of surface damage generate turbulence enhancement (left below).
- Extensive datasets acquired have provided unique <u>collaborative</u> opportunities for improving numerical models to better predict system performance.



High-resolution measurements of turbulence enhancement (red) by complex roughness.

Roughness topography in foreground.



Time-resolved PIV data allows reconstruction of quasi-three-dimensional flow behavior.