PECASE: Multiscale Experiments & Modeling in Wall Turbulence

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Manipulation of turbulent boundary layer structure using a morphing surface

STATUS QUO

Potential fuel efficiency increase and savings associated with control of skin friction associated with wall turbulence are immense

- Area of intense research interest, but physics and multiscale nature of flow confound control attempts, particularly at high Reynolds numbers of interest to AFOSR

Need for a low order understanding of structures that contribute to vortical motion and statistics, and maintain mean velocity profile

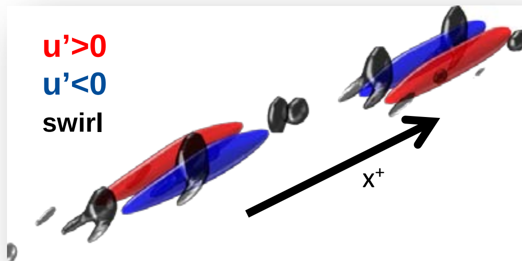
NEW INSIGHTS

Critical layer model identifies propagating wave-like motions responsible for observed vortical motions and structure

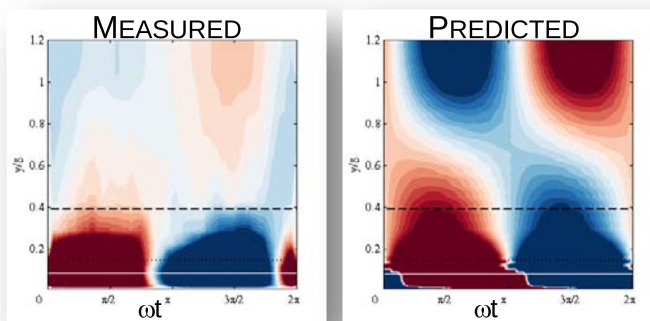
- Modal formulation permits connection between model output and experimentally observed spectral features
- Hairpin vortex packet development shown to be a consequence of (linear) superposition of modes and the nonlinear nature of the swirl operator
- "Modulating packet" also captures velocity skewness and large-scale amplitude modulation of small scales
- Represents a new kernel of turbulence – a dynamically important, studiable sub-unit
- Strong evidence that model can be used to guide control efforts (connection to previous grant on the use of dynamic roughness to manipulate turbulent boundary layer)

MAIN ACHIEVEMENTS:

- Model captures the generation of hairpin vortex packets



- Dynamic roughness can be used to manipulate turbulence properties, model predicts its effect.



Plots of the measured and predicted streamwise velocity over one period of oscillation of dynamic roughness at the wall

HOW IT WORKS:

- Nature of swirl diagnostic (nonlinear function of linear superposition of velocity modes) requires that hairpins form in packets and straddle dominant velocity modes.
- Model can be used to predict coupling of dynamic roughness at the wall to amplified velocity modes.

QUANTITATIVE IMPACT

ASSUMPTIONS AND LIMITATIONS:

- Need to understand distribution of modes and forcing required to sustain the mean velocity profile in order to alter flow structure deterministically (not by trial & error)

Current Impact

- Model permits predictive understanding of spectral and structural features that will be observed in wall turbulence with increasing Reynolds number
- Allows prediction of the effect of dynamic roughness
- Turbulence can be manipulated by design

Planned Impact

- Extension of modeling framework to manipulate additional properties of the turbulent boundary layer
- Identification of new potential strategies to control near-wall turbulence using morphing surfaces

END-OF-PHASE GOAL

Research Goals

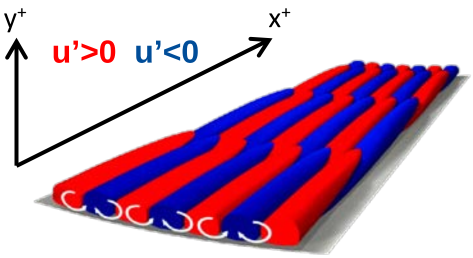
- Complete low order model of wall turbulence using forced propagating modes and extend to and implement control strategies capable of reducing skin friction

“Turbulence by design”

Joint experimental and modeling campaign reveals tunable skeleton of wall turbulence

Understanding of mechanisms of wall turbulence remains limited. Current approaches include direct numerical simulation (limited to low Reynolds number by resolution constraints), point and planar experimental measurements.

New kernel of turbulence characterized: dynamically important, tractable sub-unit



Sample mode shape

- *Three response modes from critical layer model linearly superposed*
- *Relative phases and amplitudes informed by experimental results*
- *Can be manipulated using dynamic roughness*

“Turbulence by design”

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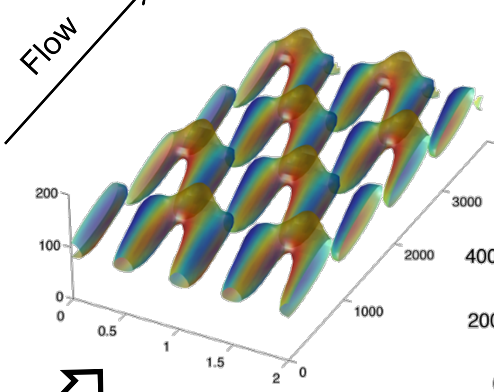
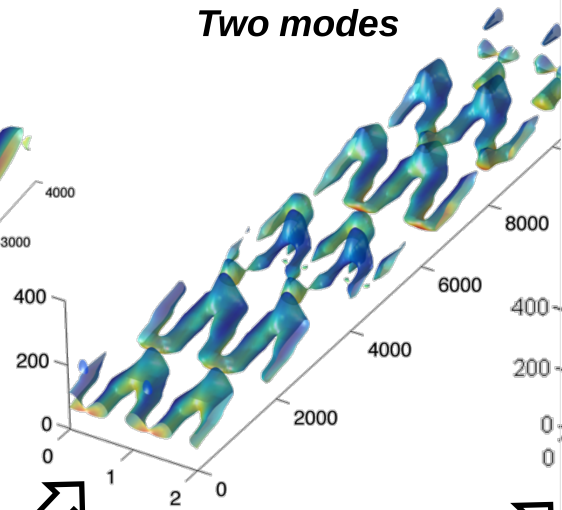
- 2009 PECASE recipient
- 2008 NSF CAREER award winner
- Tenured faculty at Caltech (2011)
- APS-DFD 2011 invited lecturer

Linear superposition of sets of just three modes predicted by model give unified explanation for statistical and structural observations of wall turbulence.
Such modes can be artificially excited : promise of “turbulence by design”

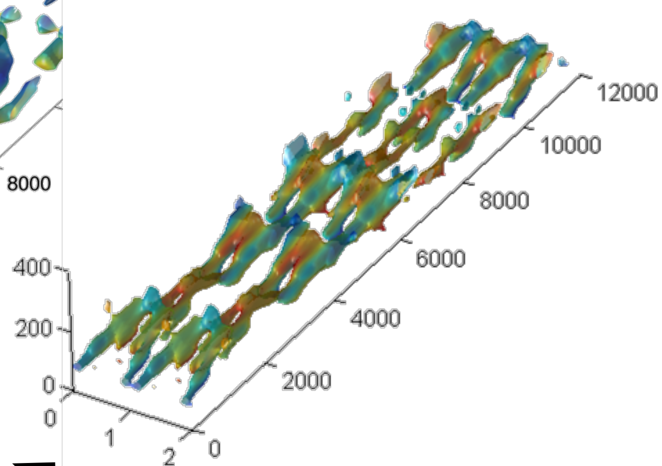
One mode



Two modes



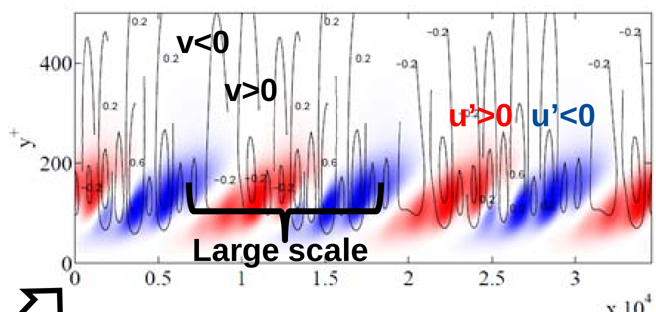
Three modes



Swirl field from one mode reveals periodic array of hairpin vortices

Superposition of two suitably chosen modes leads to formation of hairpin packets

Superposition of three modes leads to “<u>modulating packet</u>” that dictates velocity skewness profile and <u>apparent amplitude modulation of small scales</u>



u and v “modulated by large scale