



RESNICKINSTITUTE
science + energy + sustainability

RESEARCH HIGHLIGHTS

From the Resnick Sustainability Institute
Graduate Research Fellows at the
California Institute of Technology

A Fresh Approach to Flow Turbulence Towards Reduction of Skin-friction Drag

Subrahmanyam Duvvuri

*Research advised by Prof. Beverley McKeon with funding from
the Air Force Office of Scientific Research*

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Global Significance

"Turbulence is the most important unsolved problem of classical physics."

- Richard Feynman (1964)

Transport by land, sea and air is the biggest energy expenditure sector, accounting for 30% of global consumption. Consequently, this sector is also a major contributor to carbon emissions. Ever-growing strain on the global oil supply chain and stringent emission standards set by the world's regulating agencies demand more efficient transport machines.



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Goals to this end can be met to a significant extent by exploring novel methods for vehicular drag reduction. In addition, attractive economic benefits can be derived from such pursuits, making them all the more relevant. Consider the case of the airline industry: annual oil consumption is expected to hit the 3 billion barrels mark by the year 2030. A mere 1% reduction in drag on modern commercial aircrafts roughly translates to a cut of 24 million barrels in oil consumption and 9 million tonnes in CO₂ emissions annually as per current projections.

Similar estimates for the shipping industry are equally impressive. Such numbers make a strong case for exploration of promising drag reduction strategies. **This research project targets a long-term reduction in turbulent skin friction drag of up to 20%—a threefold increase over current state-of-the-art control schemes** that give up to 7% reduction in a laboratory setting over a restricted range of flow parameters. Advances in drag reduction technology nicely complement ongoing efforts to develop and promote alternative energy sources, and are in tune with the Resnick Sustainability Institute's energy mission.



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Project Summary

Fluid turbulence is the primary cause for high skin-friction drag experienced by fast moving bodies like airplanes. The physics of flow around such bodies is mostly contained in the boundary layer—a thin region of fluid in the immediate vicinity of the body surface.

In this project we explore the concept of using a spatially localized dynamic roughness actuator on the surface (wall) to manipulate large portions of downstream flow field inside a turbulent boundary layer. Amplitudes of roughness perturbations are only a small fraction of the boundary layer thickness, in essence, *tickling* the flow to produce a large amplification of input. Measurements investigating the downstream response of the boundary layer flow will aid in the development of a scalable transfer function model. This would potentially enable us to develop a closed-loop control mechanism for drag reduction in the long-term.

Potential Impact

This project helps us better understand the complex science behind turbulent flows and design next-generation strategies for mitigation of skin-friction drag. Our expectation is that this work lays the foundation for control schemes that exploit the non-linear coupling between flow scales in turbulence to manipulate small-scale energetic turbulence in boundary layers through practical large-scale dynamic inputs. Or in other words, this study potentially enables the design of roughness actuators and also the actuation algorithm for drag reduction. An effective and practical scheme would lead to direct environmental and economic benefits of significant proportions.



Image showing the test section of the Merrill wind tunnel at Caltech where experiments on perturbed turbulent boundary layers are carried out.

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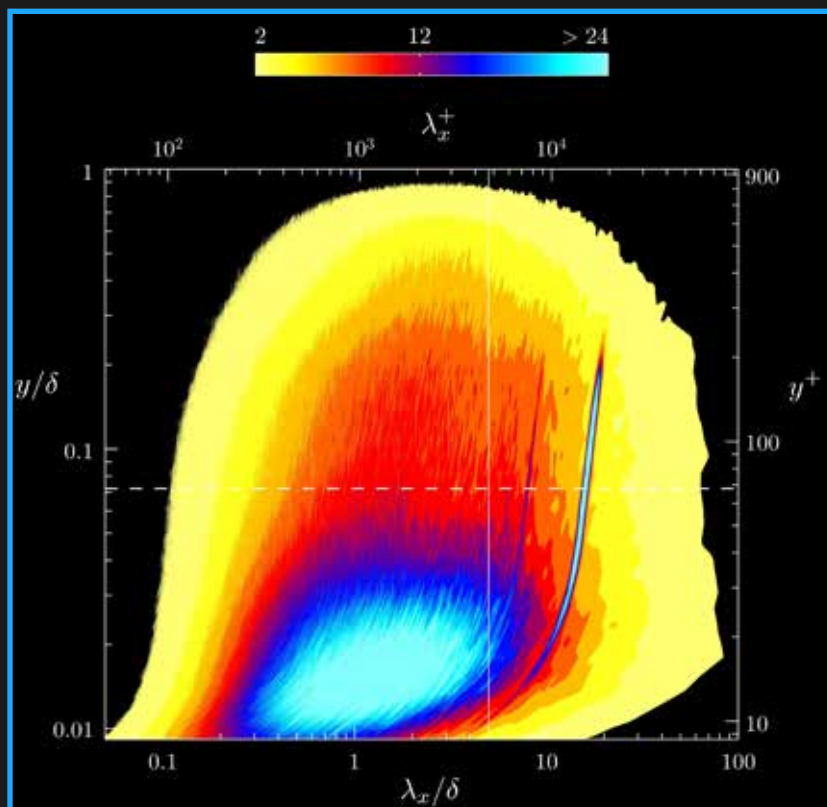
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The Science

Fluid turbulence poses great scientific and engineering challenges due to its multi-scale (spatial and temporal) nature with a large separation and non-linear coupling between scales. The key to successful design of a flow manipulation or control scheme is to understand and exploit the scale coupling in a favorable way.

In boundary layers, much of the turbulent energy in the near-wall region responsible for high skin-friction drag resides at small-scales; direct actuation at those scales is highly impractical. In the present experiments, a synthetic spanwise-constant spatio-temporal mode is forced (or excited) in a canonical flat plate boundary layer flow using a spatially-impulsive patch of dynamic wall roughness. The streamwise length scale of the synthetic mode is chosen to approximately match that of Very Large-Scale Motions (VLSMs) found in canonical wall-bounded turbulent flows at high Reynolds numbers. Flow downstream of the perturbation is investigated through time-resolved hot wire measurements of turbulent velocity fluctuations. Data from these experiments gives us new insights into the coupling between the synthetic large-scale and the energetic small-scales in the flow.

A thorough understanding of the influence of a single synthetic scale on the system allows for design of experiments with multiple scale actuation. With an appropriate phase relationship set through modeling and real-time flow sensing inputs, actuation of a select few large-scales could potentially have a significant desirable effect on near-wall turbulence.



This contour map shows the power spectrum of streamwise turbulent velocity fluctuations. Abscissa and ordinate represent non-dimensional streamwise wavelength (λ_x) and height (y) from the wall. The presence of the synthetic large-scale is clearly evidenced by the thin energetic streak running across the boundary layer height. The dashed horizontal line is the critical layer location (see Duvvuri and McKeon, AIAA 2014-2883 for more details).

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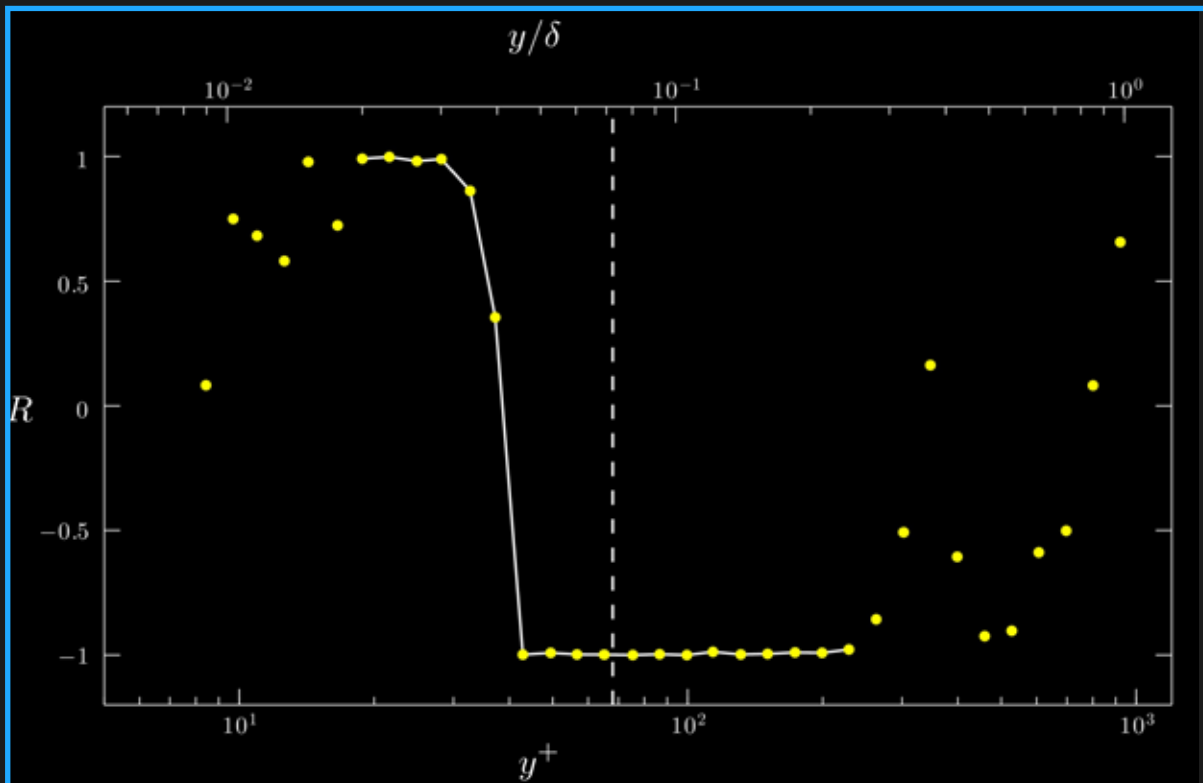
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Key Results

A clear phase organization effect is noticed on the small-scale envelope of turbulence in presence of a synthetic spanwise-constant large-scale. This effect can be seen on all small-scales in the flow, but is strikingly visible among those small-scales that are directly coupled to the synthetic large-scale through non-linear interactions of the triadic form (the significance of triadic interactions arises from the quadratic nature of nonlinearity in the governing Navier-Stokes equations).

Future Steps

The next set of experiments will involve simultaneous forcing of multiple large-scale modes with non-zero spanwise wavenumbers. The aspect ratio (streamwise to spanwise wavelength) of these modes will be approximately set to 10:1, matching naturally occurring VLSM structures. Results from those experiments would take us a step closer towards devising a practical and robust control law for turbulent skin-friction drag reduction.



This plot shows the correlation coefficient between the synthetic large-scale and the envelope of directly coupled small-scales as a function of the non-dimensional height (y) from the wall. Correlation coefficient is a measure of phase between the two quantities; they are in phase very close to the wall, and out of phase away from it. A phase jump of π radians happens close to the critical layer location (marked by the dotted vertical line) of the synthetic mode (see Duvvuri and McKeon, AIAA 2014-2883 for more details).

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Publications

- Duvvuri, S. and McKeon, B. (2014) Phase relationships in presence of a synthetic large-scale in a turbulent boundary layer. AIAA 2014-2883.
- Duvvuri, S. and McKeon, B. (2014) Triadic Scale Interactions in Presence of a Synthetic Large-Scale in a Turbulent Boundary Layer (in preparation).

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