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This grant supported the purchase of state-of-the-art particle-image velocimetry (PIV) equipment, necessary modifications to an existing boundary-layer wind tunnel and construction of roughness panels in support of an AFOSR core grant (FA9550-05-1-0043). The equipment proposed was meant to significantly improve the PIV spatial dynamic range achievable in the PI's lab as well as broaden the range of Reynolds numbers that could feasibly be studied to meet the goals of the PI's current and future research efforts with AFOSR. In addition, significant modifications to an existing boundary-layer wind tunnel and construction of various roughness topologies were proposed to enhance the PI's capabilities to study the influence of highly-irregular surface roughness on the character of wall-bounded turbulence. The PI is also utilizing the new PIV cameras procured with this DURIP funding to advance his development of microscale temperature-measurement methods in support of an AFOSR MURI grant (FA9550-05-1-0346) on which he is a co-PI.

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Final Report for AFOSR DURIP Grant FA9550-05-1-0246

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Federally-Funded Grants Impacted by this Funding

1. **AFOSR Core Grant FA9550-05-1-0043:** *Studies of Real Roughness Effects for Improved Modeling and Control of Practical Wall-Bounded Turbulent Flows* (K. T. Christensen, PI; Dr. Rhett Jeffries, Program Manager)
2. **AFOSR MURI Grant FA9550-05-1-0346:** *Microvascular Autonomic Composites* (S. White, PI; K. T. Christensen and others, co-PI; Dr. Les Lee, Program Manager)

Project Summary

This grant supported the purchase of state-of-the-art particle-image velocimetry (PIV) equipment, necessary modifications to an existing boundary-layer wind tunnel and construction of roughness panels in support of an AFOSR core grant (FA9550-05-1-0043). The equipment proposed was meant to significantly improve the PIV spatial dynamic range achievable in the PI's lab as well as broaden the range of Reynolds numbers that could feasibly be studied to meet the goals of the PI's current and future research efforts with AFOSR. In addition, significant modifications to an existing boundary-layer wind tunnel and construction of various roughness topologies were proposed to enhance the PI's capabilities to study the influence of highly-irregular surface roughness on the character of wall-bounded turbulence. The PI is also utilizing the new PIV cameras procured with this DURIP funding to advance his development of microscale temperature-measurement methods in support of an AFOSR MURI grant (FA9550-05-1-0346) on which he is a co-PI.

Fund Usage

The original proposal requested funds for the following equipment and tasks:

1. Two 2k × 2k 12-bit frame-straddle CCD cameras from TSI, Inc.
2. One 200 mJ, double-pulse Nd:YAG laser from TSI, Inc.
3. One PC workstation with significant storage capacity for PIV image acquisition and analysis.
4. Modifications to an existing boundary-layer wind tunnel and construction of roughness surfaces in support of the PI's core grant (FA9550-05-1-0043).

The new CCD cameras were requested as a means of achieving a greater spatial dynamic range as compared to the existing 1k × 1k CCD cameras in the PI's lab. Resolving a greater range of spatial scales is of crucial importance to the PI's core effort on the impact of highly-irregular surface roughness on the character of wall turbulence. However, during the time between submission of the original proposal and awarding of this grant TSI, Inc. introduced a new state-of-the-art PIV camera with a 4.1k × 2.7k 12-bit CCD array. This new camera architecture currently represents the true state-of-the-art in PIV imaging because it offers both the broadest spatial dynamic range available as well as extremely low levels of image noise. The PI therefore purchased a pair of these newer cameras

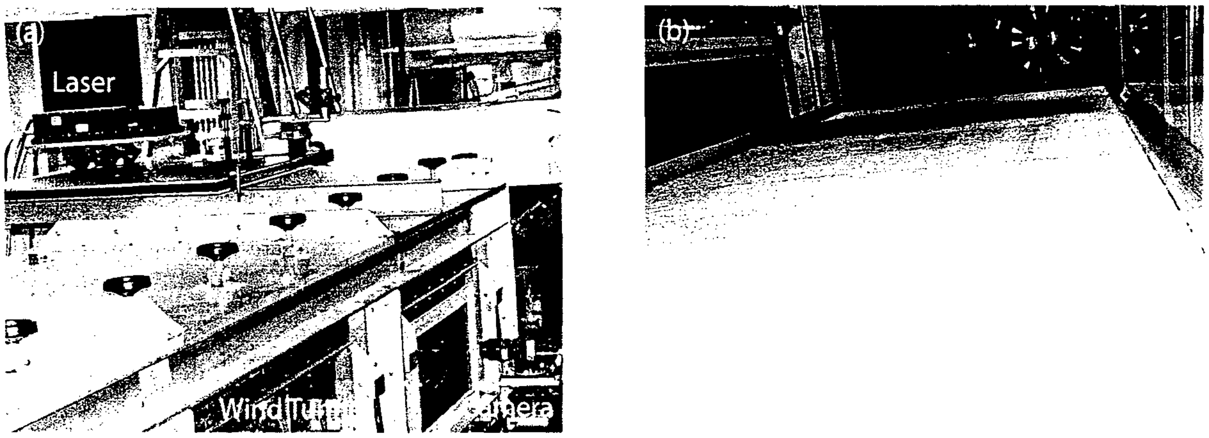

Figure 1: (a) Photo of new PIV equipment installed in the boundary-layer wind tunnel facility. (b) Photo of replicated surface roughness installed along the floor of the wind tunnel.

instead of those originally listed in the proposal (The PI's group is actually the first in the world to purchase and implement these cameras in a PIV experiment). In addition, the laser and workstation (dual processor; $\sim$ 9 terabytes of storage) were purchased as specified in the original proposal. Finally, due to a generous educational discount provided by TSI, Inc. on the laser and PIV cameras, the PI was also able to purchase a new timing synchronizer with 1 ns resolution (compared to the existing timing units in the PI's lab that have 200 ns resolution). Figure 1(a) presents a photo of the new laser and one of the new PIV cameras installed in the existing wind-tunnel facility. **It should be noted that the estimated lifetime of this new PIV equipment is at least 10 years meaning it will have an extremely positive impact not only on the research discussed herein but also on the PI's research endeavors for at least the next decade.**

As noted in the listing above, funds were also requested to modify an existing boundary-layer wind tunnel and construct roughness plates in support of the PI's core grant. The wind-tunnel modifications included removing the opaque ceiling above the measurement station to allow optical access both for imaging of wall-parallel planes in the flow as well as introduction of wall-normal lightsheets into the flow (Wall-normal lightsheets and viewing of wall-parallel planes were previously achieved from below through the transparent flat plate). In addition, the existing 6 m-long smooth boundary-layer flat plate was separated into two pieces, with the downstream half lowered relative to the upstream half to allow roughness inserts to be placed along the downstream 3 m of the flat plate. Two roughness cases were replicated from a surface scan of a damaged turbine blade (graciously provided to the PI by Prof. J. Bons of BYU from one of his previous efforts in this area (Bons, 2002)) to fill the downstream half of the wind tunnel (the same topology was replicated in both cases but with different scalings to achieve $\delta/k = 28$ and $\delta/k = 50$, an important parameter in rough-wall turbulence). A public-access 3D powder-deposition printer housed in the Beckman Institute at the University of Illinois was utilized by the PI's Ph.D. student to build replicas of the digitized surface topology. Each of the roughness cases consists of nearly one-hundred 7" × 7.5" individual roughness panels. These panels were then mounted on cast aluminum base plates and laid along the downstream 3 m of the flat plate which was precisely lowered to align the mean elevation of the surface roughness with the upstream smooth-wall fetch. **It should be noted that the roughness inserts were designed specifically to be removable, so these surfaces can be re-used in future research efforts.** Figure 1(b) provides a view toward the downstream-end of the tunnel with the $\delta/k = 28$ roughness installed. Measurements are made 2.5 m downstream of the smooth-to-rough transition and the roughness is painted black in this region to minimize unwanted reflections of the incident laser light (see figure 1(b)).

Impact on Current and Future Research

The new equipment has greatly improved the PIV capabilities of the PI's lab, most notably for the PI's AFOSR-funded effort on the impact of highly-irregular surface roughness on the character of wall turbulence. Upon receipt of the new PIV equipment and completion of the wind-tunnel modifications, the PI's student performed a series of experiments in the presence of a smooth wall. The increased spatial dynamic range of the new PIV cameras allowed us to acquire data at a Reynolds number nearly twice as high as had been previously reported in the literature. A subset of these measurements was utilized to study the population trends of spanwise vortices in smooth-wall turbulence and a manuscript on this topic is currently under review for publication in *Journal of Fluid Mechanics* (Wu and Christensen, 2005). This smooth-wall data will be vital for uncovering the exact impact of highly-irregular roughness on wall-bounded turbulence.

The wind-tunnel modifications and roughness replication constituted a six-month effort with the latter only recently completed. PIV measurements in the streamwise–wall-normal plane in the presence of surface roughness have now been undertaken for the case of $\delta/k = 28$ at three different Reynolds numbers ($\mathrm{Re}_\theta = 3900$, 8300 and 11000). A typical PIV realization from the $\mathrm{Re}_\theta = 8300$ case is presented in figure 2(a). This result highlights the unique capabilities of the new PIV equipment: the acquired field of view is $1.4\delta \times \delta$ ($\delta = 120\,\mathrm{mm}$) in the streamwise–wall-normal plane (although only half of the wall-normal field of view is presented) and the spatial resolution (twice the vector grid spacing) is $680\,\mu\mathrm{m}$, yielding a dynamic spatial range of 250:1. For reference, if this experiment were performed with one of the PI's existing 1k × 1k PIV cameras over the same field of view, the spatial resolution would be approximately 2.7 mm (yielding a dynamic spatial range of 62:1), a factor of nearly four coarser than that achieved with the new PIV imaging equipment. While measurements with the older 1k × 1k camera have not been taken in the same rough-wall flow, one can illustrate the stark differences that would be achieved compared to the new technology by re-plotting only every fourth vector for the field in figure 2(a) which would yield an effective spatial resolution of 2.7 mm. Figure 2(b) presents this result and it is clear that even the largest swirling motions (vortices) in figure 2(b) are only marginally resolved. Hence, the new PIV imaging equipment represents a *drastic* improvement over the PI's existing equipment. However, these enhanced capabilities are not without a cost. Each instantaneous PIV field acquired with the new imaging equipment requires approximately 55 MB of storage (50 MB per image pair and 5 MB for each vector field) which represents more than an order of magnitude increase compared to the older equipment (3 MB per field). Therefore, the extremely large storage capacity of the new workstation ($\sim$9 terabytes) is crucial for the acquisition of several thousand statistically-independent velocity realizations at each flow condition (i.e., each Reynolds number and roughness condition).

These extensive datasets are being used to study the impact of highly-irregular surface roughness on the underlying statistical and structural character of wall turbulence. For example, two-point spatial correlations of velocity represent fundamentally-important quantities in the study of turbulence because they often reflect the average spatial characteristics of the underlying instantaneous structure of the flow (Townsend, 1976). Figure 3 presents two-point velocity correlation coefficients computed at $\mathrm{Re}_\theta = 8300$ for smooth and rough-wall ($\delta/k = 28$; $k^+ = 124$) turbulence at $y_{\mathrm{ref}} = 0.15\delta$. The two-point correlation coefficient of streamwise velocity, ρ_{uu}, is typically elongated in the streamwise direction and inclined slightly away from the wall in smooth-wall turbulence (the solid-line contours in figure 3(a)). The surface roughness considered herein shortens the streamwise extent of ρ_{uu} appreciably (almost 20%), indicating that the roughness may inhibit the growth of larger-scale structures in wall turbulence. In contrast, ρ_{vv} (figure 3(b)) and ρ_{uv} (figure 3(c)) grow slightly in streamwise extent.

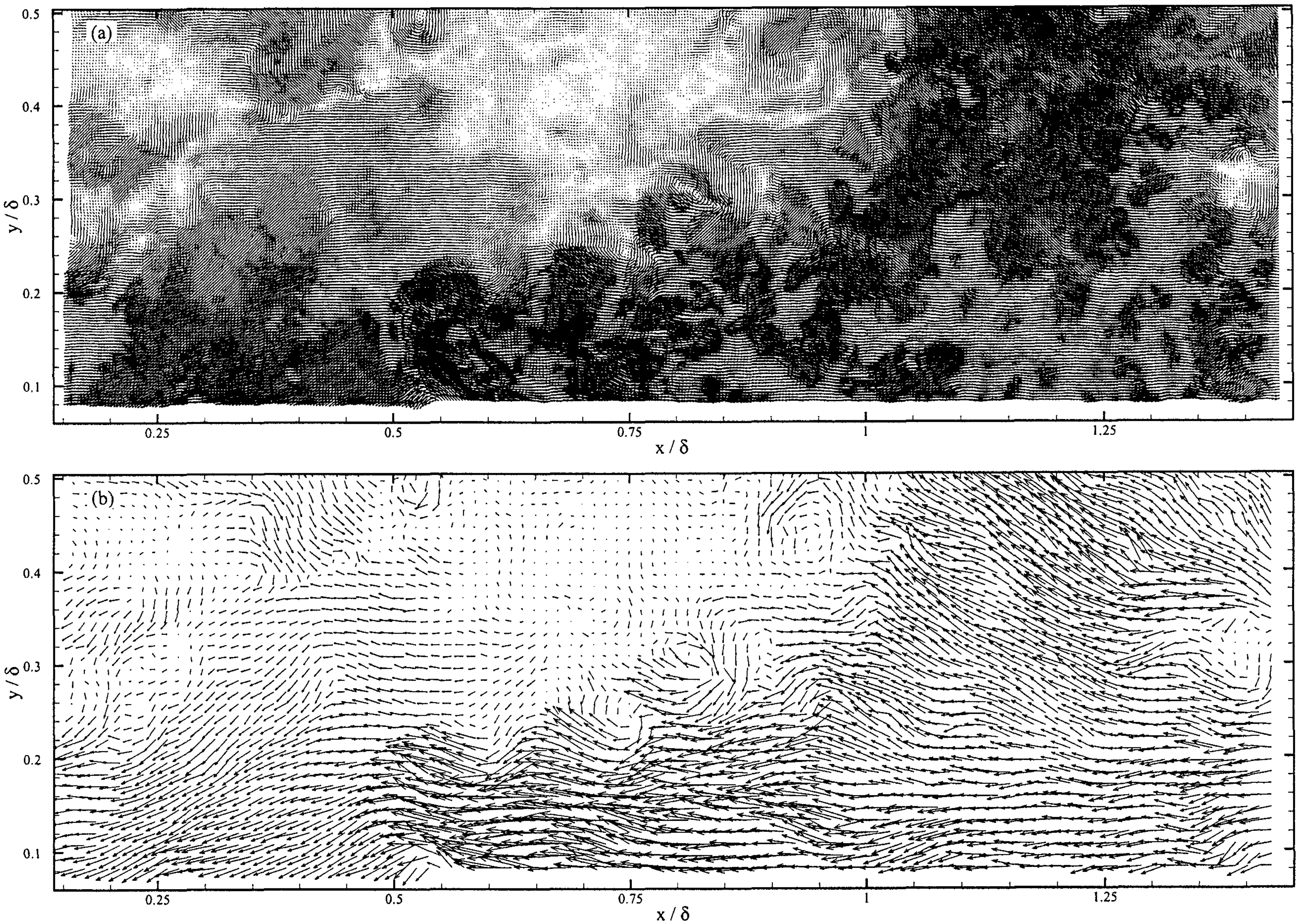

Figure 2: (a) Representative instantaneous velocity field in the streamwise–wal-normal plane of a turbulent boundary layer in the presence of real roughness measured with one of the new PIV camera. (b) As in (a) but with only every fourth vector plotted to simulate the result that would have been achieved with existing PIV equipment.

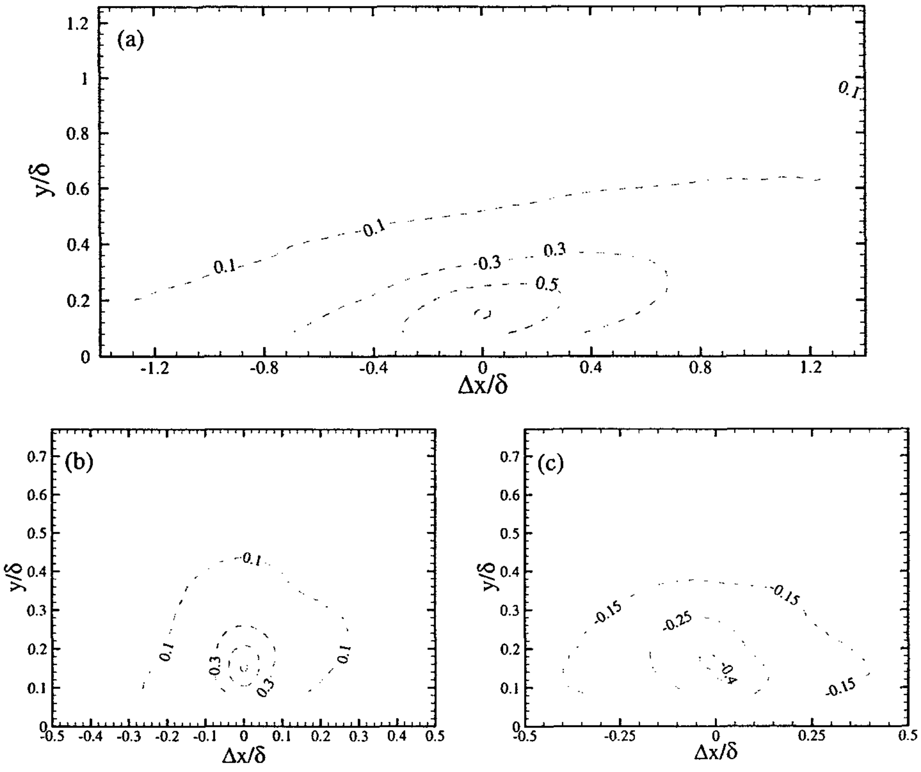

Figure 3: Two-point spatial correlations of velocity. (a) ρ_{uu}; (b) ρ_{vv}; (c) ρ_{uv}. —: smooth; – –: rough.

The reduction in ρ_{uu} coupled with the slight growth of ρ_{vv} and ρ_{uv} in the presence of roughness is consistent with the notion that surface roughness reduces the anisotropy of the flow. This behavior is consistent with the observations of Krogstad and Antonia (1994) who noted a similar trend toward isotropy in the multi-point correlations for flow over wire mesh.

In the near-term, the PIV equipment and roughness panels will be utilized further in the context of the PI's current core grant as originally proposed. In particular, stereo PIV measurements will be made in wall-parallel planes to uncover the spanwise impact of surface roughness. In addition, wall-normal and wall-parallel PIV measurements will be made in the presence of the second roughness case ($\delta/k = 50$). As noted above, the PI is also utilizing the high-resolution PIV cameras in a MURI effort funded by AFOSR entitled "Microvascular Autonomic Composites" (Dr. Les Lee, Program Manager). An optical methodology for measuring instantaneous temperature fields at the microscale is being developed as part of this project and the new PIV cameras procured with this DURIP funding offer such a high spatial dynamic range and low noise level that they are playing a pivotal role in achieving 0.1°C resolution which represents the accuracy goal of this instrumentation development.

In the long-term, the PI will certainly utilize the equipment and roughness panels made possible by this DURIP grant in future efforts to be proposed to AFOSR and other federal funding agencies. One such study to be proposed in the next 12 months to AFOSR will involve the coupled influence of highly-irregular surface roughness and non-zero streamwise pressure gradients in wall turbulence. Both of these non-canonical influences appear in a variety of practical applications of interest to AFOSR, including the flow over damaged turbine blades, for example.

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