A Brief Study of the Effect of Rigid Swept Surface Waves on Turbulent Drag

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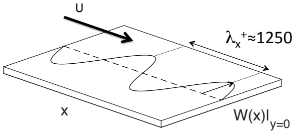
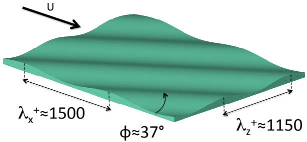
Background

- A reduction of turbulent drag is desirable for energy savings and combustion emission reduction.
- Aside from active flow control and novel aerodynamic designs, passive methods are of interest for low cost and/or backward compatible implementation.
- Riblets and possibly other engineered surface microgeometries are promising candidates for high-Reynolds number applications.
- Surface engineering, durability and maintenance are still a challenge, suggesting exploration of parallel or complementing approaches.

Background

- Viotti [1] studied by Direct Numerical Simulations (DNS) channel flows with steady sinusoidal spanwise velocity forcing at the wall (SSL=Spatial Stokes Layer) at $Re_\tau = 200$.
- The phase-averaged turbulent spanwise flow in the SSL was found to be identical to the laminar solution and correctly predicted by a linear model. He estimated that the net power savings could be over 20% at a forced velocity amplitude $A^+_{SSL} = 6$ with $\lambda^+_x \in [1000, 1500]$.
- Assuming the spanwise shear stress oscillations are the key drag reduction mechanism, Chernyshenko [2] concluded from a linear analysis that a few percent of drag reduction is possible for a passive swept wavy wall sized to match the spanwise shear stress in the SSL.
- At $Re_\tau = 200$ and in the range of optimum SSL wavelength, the optimum wall wave amplitude $h^+_w \in [1, 10]$ with an angle of 37.4°between the wave crests and the freestream.



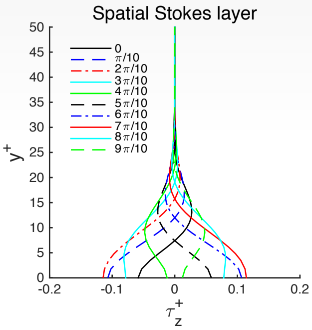


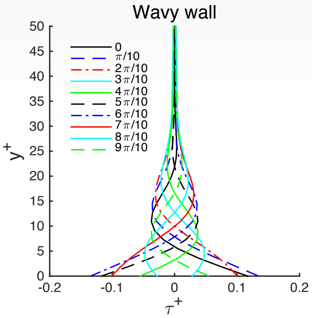
[1] C. Viotti et al, Physics of Fluids 21, 115109 (2009)

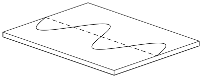
[2] S. Chernyshenko, physics.flu-dyn arXiv:1304.4638v1, April 16 2013

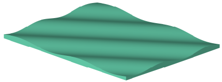
Spanwise shear stress matching

- The wall wave amplitude and crest angle are chosen to minimize the spanwise shear stress difference between the SSL and the wavy wall.









Research Objective

Study the drag over swept, wavy, solid walls sized per the linear theory based on the SSL analogy by

- test plate prototyping and drag measurements in the 7x11 Inch Low-Speed Wind Tunnel at the NASA Langley Research Center (LaRC);
- Direct Numerical Simulations of wavy channels and comparison to flat channels with or without SSL forcing.

Research Objective

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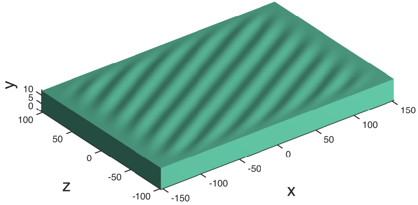
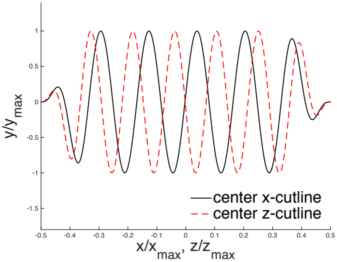
Test plate prototyping

- Aluminum $30 \times 20 \times 1.3cm$ flat and wavy plates were rapid-prototyped using CNC-machining methods by a commercial vendor. The waves are smoothly damped at the edges with zero net volume offset w.r.t. flat plate.
- Wavelengh $\lambda = 26.8mm$, peak-to-valley amplitudes $2h_w = 232$, $1046\mu m$ ($h_w/\lambda = 0.43,\ 1.95\%$), wave crest angle $\phi = 37.4^\circ$ w.r.t. the inflow direction.
- The waves are within 2% of the design value. The surface roughness RMS after polishing is $< 1.5\mu m$.





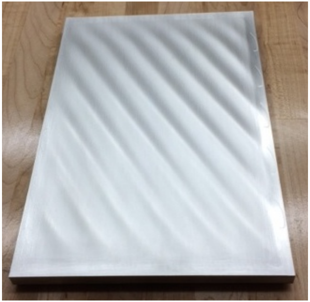
Test plates

The plate with shallow waves (230A, center) came in with tool marks (depth $< 25\mu m$) and was reordered. No difference in drag could be experimentally resolved between the plates with and without defects (next).

$h/\lambda = 0$

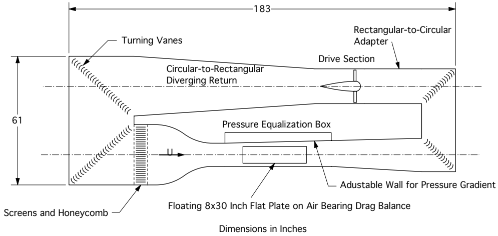
$h/\lambda = 0.43\%$

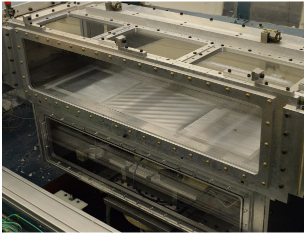
$h/\lambda = 1.95\%$



7"x11" Low Speed Tunnel - Plan view

- Unit Reynolds number $0.5 \times 10^6 < Re/m < 3.3 \times 10^6$.
- Turbulent flow measurements at $7 - 50m/s$ freestream velocity, $750 < Re_\theta < 5200$, $Re_\tau \geq 200$.
- Boundary layer tripped by a 0.91mm diameter rod placed at 0.6m upstream of the test model.

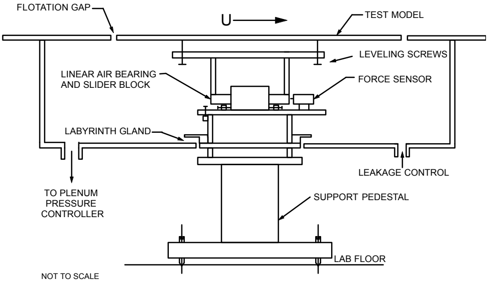




7"x11" Low Speed Tunnel - Floating Drag Balance

Repeatability limitations

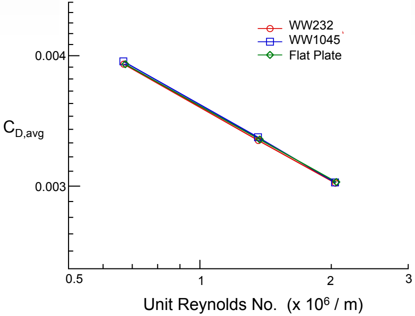
- plate alignment ($\pm 25\mu m$)
- plenum to test section pressure mis-matching (flow through flotation gaps)
- streamwise pressure gradient adjustment (divergent rear tunnel wall)
- force cell and low-pass filter accuracy
- air bearing internal flow characteristics
- balance isolation from tunnel vibrations
- turbulent boundary layer run-to-run repeatability



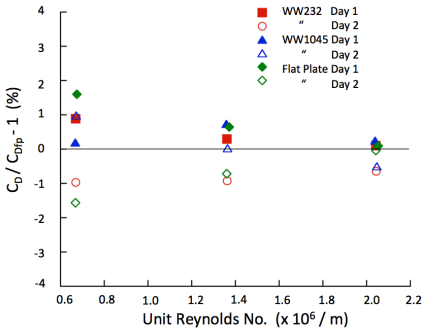
Drag Measurements

- The drag offset from the wavy wall is within the 1-2% test repeatability limit.

Power law log-linear plot



Percent difference from flat plate

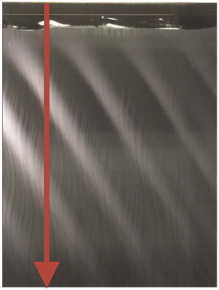


Characterization of flow drift

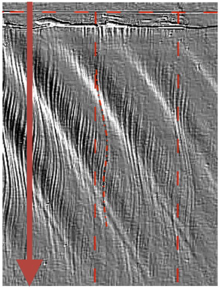
- Oil vapor flow tests on the plate with $h_w/\lambda = 1.95\%$ suggest a slight deviation of the mean flow within $2.5^{\pm}1.5^{\circ}$ of the inflow direction (indicated by a red arrow).
- The mean flow over the plate with $h_w/\lambda = 0.43\%$ seems unaffected.

$h/\lambda = 0.43\%$

$h/\lambda = 1.95\%$



$h/\lambda = 1.95\%(enhanced)$

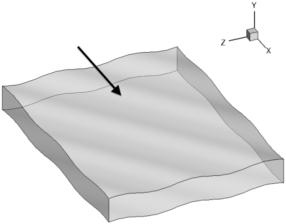


Direct Numerical Simulations

- 3D Direct Numerical Simulations (DNS) were conducted using a fifth order Weighted Essentially Non-Oscillatory (WENO) code for spatial discretization with third order Total-Variation-Diminishing (TVD) scheme for temporal integration, written by P. Balakumar and H. L. Atkins [3].
- Number of grid points in the x, y, and z directions = 1224 $\times$ 257 $\times$ 416. At the flat wall, $\Delta x^+ < 2.8$, $\Delta y^+ < 0.18$, and $\Delta z^+ < 5.8$. At the channel center, $\Delta y^+ < 3.5$.
- MPI simulations with 192 processors.
- Periodic boundary conditions used in stream- and span-wise directions. The flow is maintained by applying a body force in the streamwise direction, determined at every time step by requiring that the average mass-flux remains constant.

DNS Channel Geometries and Flow Parameters

1. Reference: flat channel
2. Spatial Stokes layer $W^+ = A^+_{SSL} sin(k_x x)$
   note:
   $A^+_{SSL} = 2,\ 6 \rightarrow w(y=0) \approx 0.1, 0.3u_\infty$!
3. Swept waves
   $p_w = 0.898 A^+_{WW} k_x/k_z/(k_x/Re_\tau)^{1/3}$ [a]



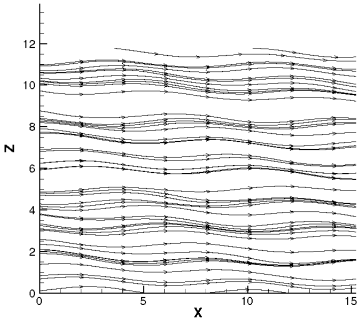
Parameter	Value
$Re(h)$	3200
Re_τ	200
M	0.3
$u_{\tau,ref}$	0.062
λ_x/h	7.6
k_x/k_z	0.7657
$L_x/\lambda_x,\ L_z/\lambda_z$	2.0
$A_{SSL}/u_{\tau,ref}$	2, 6
$A_{WW}/u_{\tau,ref}$	1.5, 6.8
h_w/λ	0.5, 2.25%

[a] S. Chernyshenko, physics.flu-dyn arXiv:1304.4638v1

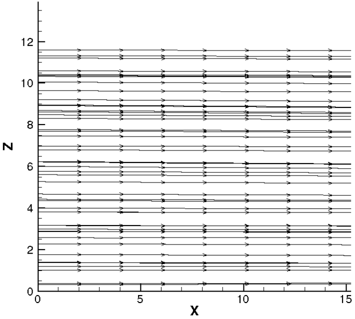
Streamlines over the Shallow Waves ($h/\lambda = 0.5\%$)

At the channel center, the mean streamline direction deviates by less than 0.1° from the inflow.

At the wall



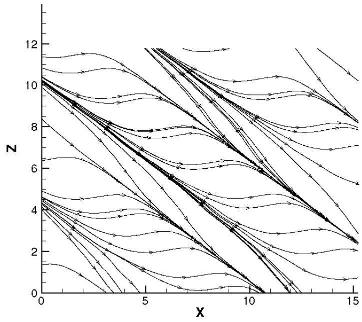
At the channel center



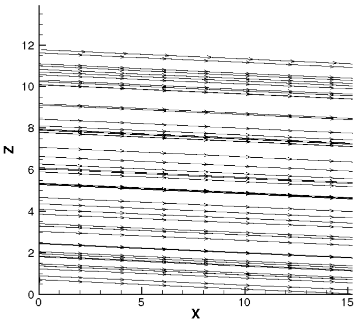
Streamlines over the Deep Waves ($h/\lambda = 2.25\%$)

- The spanwise mean flow at the channel center is oriented at an angle of 2.5° from the inflow direction (similar to the oil vapor flow results).

At the wall

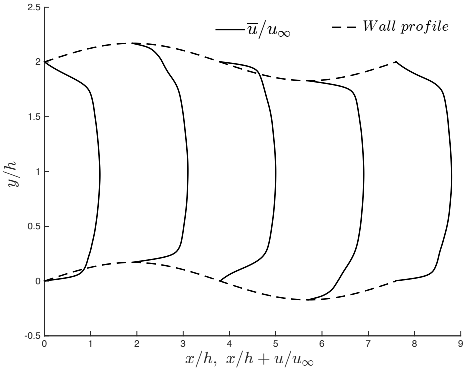


At the channel center



Spanwise velocity profile ($h/\lambda = 2.25\%,\ z = 0$)

- Note $h_w/h = 17\%$ for the channel with deep waves

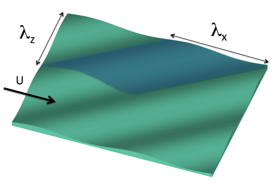


Drag simulation results

- The friction coefficient for the flat plate is 7.4×10^{-3}, in reasonable agreement with prior DNS and experimental results. Below data are normalized by the flat channel data.
- The SSL drag reduction is consistent with the results obtained by Viotti (32% DR at $\lambda_x^+ = 1250$).
- The drag is increased by 1.7% in the case of the shallow waves.
- The drag obtained for the channel with deep waves is very different from the plate measurements.

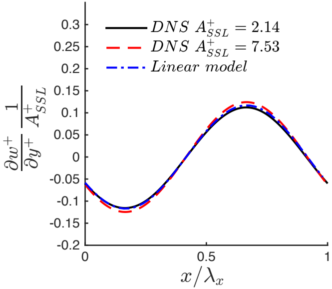
Drag component	$A_{SSL}^+ = 7.53$	$A_{SSL}^+ = 2.14$	$h_w/\lambda = 0.5\%$	$h_w/\lambda = 2.25\%$
c_f	4.89×10^{-3}	6.72×10^{-3}	7.44×10^{-3}	7.73×10^{-3}
% Friction drag	66.1	91.0	100.6	104.6
% Pressure drag	-	-	1.1	28.0
% Total drag reduction	33.9	9.1	-1.7	-32.6

DNS vs. Linear Model

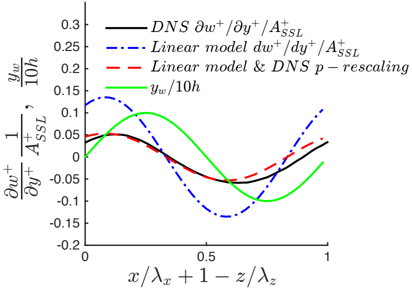


- The linear model works well for the SSL (within 1.5% for $A^+_{SSL} = 2.14$ and 7% for $A^+_{SSL} = 7.53$).
- The model used to size the waves overestimates the spanwise shear stress by a factor of up to two, mostly due to an overestimate of the wall pressure.

SSL



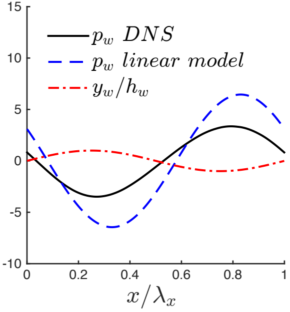
Wavy wall ($h_W/\lambda = 0.5\%$)



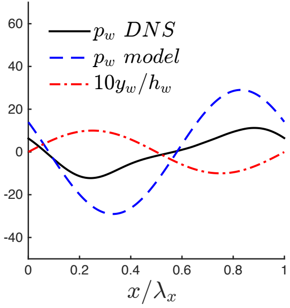
Pressure phase and amplitude

- The simulated pressure phase offset w.r.t. the inviscid case is 12° for the shallow waves and 28° for the deep waves. The observation is consistent with the larger pressure wave observed over the deep waves.
- Analysis of the vertical pressure profile shows that the approximation $\frac{\partial p}{\partial y} = 0$ used in the linear model is not valid in the channel, the pressure perturbation amplitude is strongly damped between wall and channel center.

$h_W/\lambda = 0.5\%$



$h_W/\lambda = 2.25\%$



Linear Models for Turbulent Drag Reduction Calculations

Cartesian model used here

- Incompressible boundary layer equations linearized around a linear profile $U^+ = y^+$

$$\begin{cases} \dfrac{\partial u}{\partial x} + \dfrac{\partial v}{\partial y} + \dfrac{\partial w}{\partial z} = 0 \\ \dfrac{\partial p}{\partial y} = 0 \\ y\dfrac{\partial u}{\partial x} + v = -\dfrac{\partial p}{\partial x} + \dfrac{\partial^2 u}{\partial y^2} \\ y\dfrac{\partial w}{\partial x} = -\dfrac{\partial p}{\partial z} + \dfrac{\partial^2 w}{\partial y^2} \end{cases}$$

- Wavy wall forcing emulated by pressure oscillation at the BL edge: $p = \hat{p}(y)e^{i(k_x x + k_z z)}$

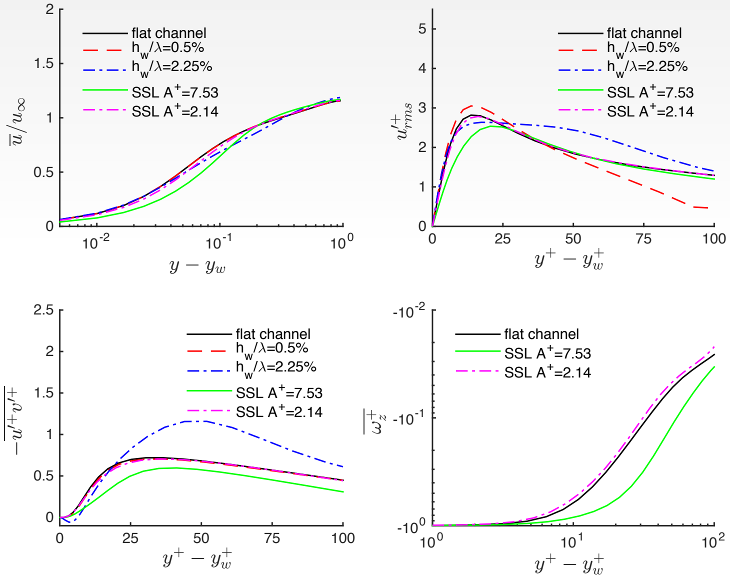
Curvilinear model per [a]

- $(x, y, z) \rightarrow (S, N, T)$
- $Q(S, N, T, t) = \overline{Q}(S, N)$ $+q'(S, N, T, t) + h_w \hat{q}(N)$
- $\hat{q} = \left\{\hat{v_S}, \hat{v_N}, \hat{v_T}, \hat{p}\right\}$
- 2D mean flow $Q_m = \left\{\overline{u_x v_y}\right\}$
- Loyd's model for the Reynolds stress R_s, with phase and amplitude functions of the distance to the wall
- Wave induced stress $W_s = f(\hat{q})$

$$\begin{cases} \dfrac{d\hat{q}}{dN} = A(\overline{Q}, R_s)\hat{q} + B(\overline{Q}, R_s) \\ \mathcal{L}(Q_m) = -\dfrac{\partial(R_s + W_s)}{\partial y} \end{cases}$$

[a] Sengupta & Lekoudis, PoF **29**, 4, 1986

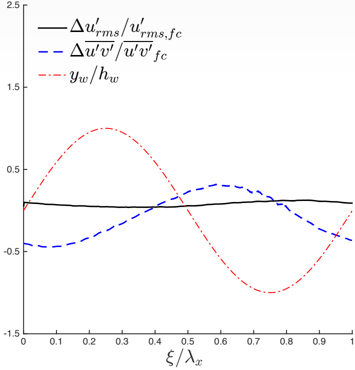
Phase-Averaged Profiles



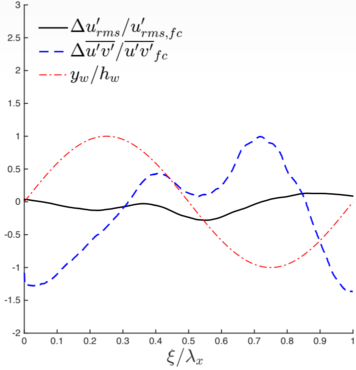
Phase-Averaged Profiles

- The Reynolds stress is maximum on the downhill slope.
- u'_{rms} is maximum on the uphill slope.

$h_w/\lambda = 0.5\%$



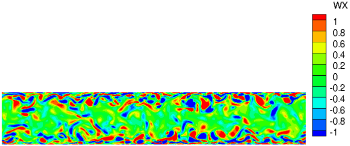
$h_w/\lambda = 2.25\%$



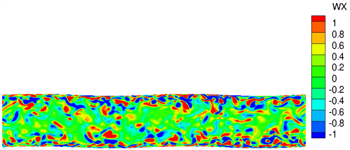
Instantaneous stream-wise vorticity (ZY plane)

- Reduced turbulence in the SSL layer.
- Increased vorticity fluctuations in the channel with deep waves.

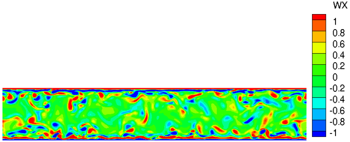
Flat Channel



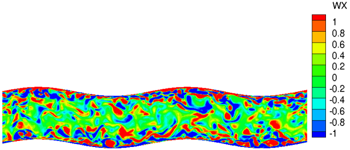
$h/\lambda = 0.5\%$



SSL

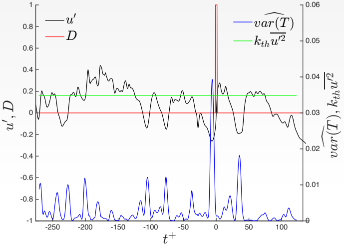


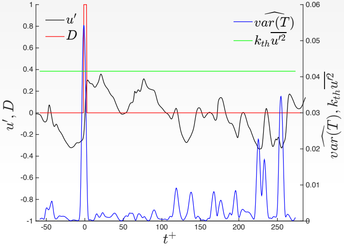
$h/\lambda = 2.25\%$

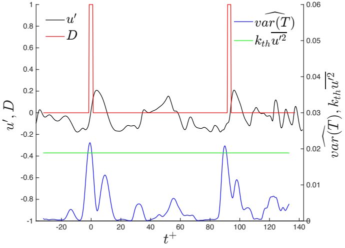


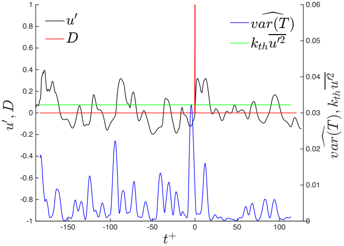
Localized Variance at $y^+_{max.u'_{rms}}$, $z = \lambda_z/4$

$$\widehat{var}(\mathbf{x}, t, T) = \frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} u^2(\mathbf{x}, s)ds - \left(\frac{1}{T}\int_{t-\frac{T}{2}}^{t+\frac{T}{2}} u(\mathbf{x}, s)ds\right)^2 > k_{th}u'^2_{rms} \Rightarrow D(t) = 1$$





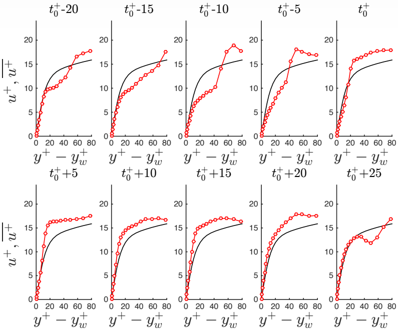




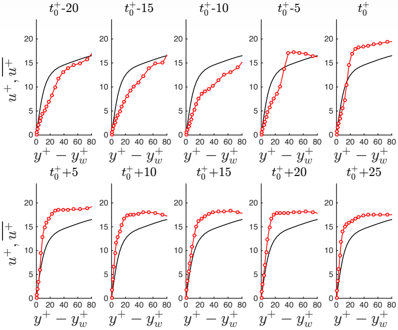
Instantaneous Streamwise Velocity about max. $\widehat{var}$

- t_0^+ is the time of maximum localized variance in the prior plots.
- Detected events correspond to an inflectional transition from a streamwise momentum defect to a momentum excess, followed by an increase of the wall shear stress and recovery toward the average velocity profile.

Flat Channel



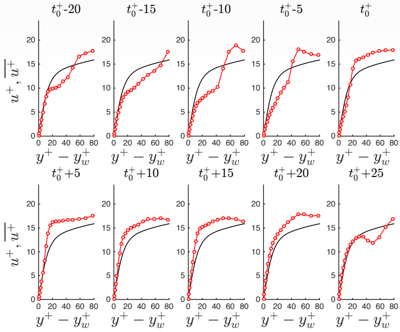
$h/\lambda = 0.5\%$



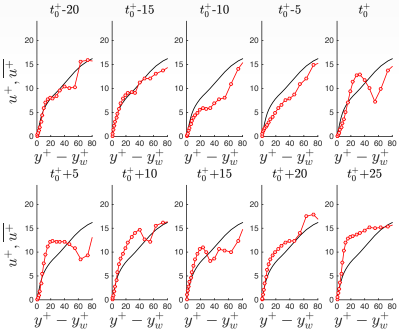
Instantaneous Streamwise Velocity about max. $\widehat{var}$

- The local fluctuations of near wall velocity are largest for the deep waves.

Flat Channel



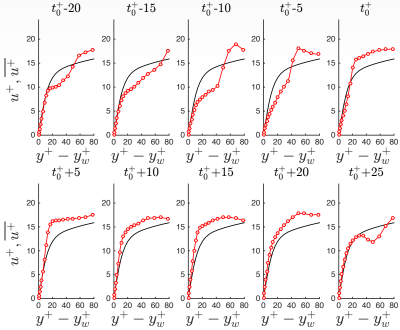
$h/\lambda = 2.25\%$



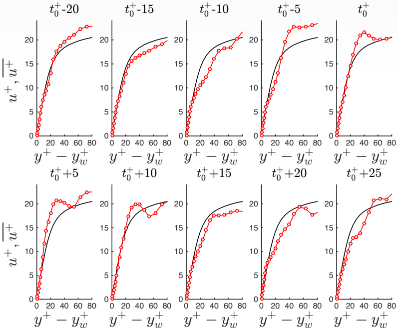
Instantaneous Streamwise Velocity about max. $\widehat{var}$

- The SSL displaces velocity fluctuations away from the wall (by $\approx \Delta y^+ = 5$)

Flat Channel



SSL $A_{SSL}^+ = 7.65$



Streaks: Isocontours for $u'^{+} = -2.0$, $z \leq \lambda_z$

The circle indicates the position of localized variance sampling. An event (red circle) accompanies the passage of a strong streak.

Flat Channel

SSL

Wavy wall $h/\lambda = 0.5\%$

Wavy wall $h/\lambda = 2.25\%$

Conclusions

- Swept wavy surfaces with $h_w/\lambda \approx 0.5\%$ and 2% and a wave crest angle of 37° w.r.t. inflow direction were prototyped and tested in the NASA LaRC 7"x11" Low-Speed Wind Tunnel at $Re_\tau \geq 200$.
- No drag improvement or degradation could be determined within the 1-2% measurement accuracy of the set-up.
- DNS of a channel with $h/\lambda = 0.5\%$ at $Re_\tau = 200$ shows 1.7% drag increase.
- Oil vapor flow measurements over the deep waves showed a mean flow deviation of 2.5° from the inflow direction, consistent with DNS.
- There is a large discrepancy in pressure drag between the wavy plate measurements and the channel DNS.
- No turbulent drag reducing mechanism was identified from the phase averaged and instantaneous flow characteristics over the wavy wall.
- For the SSL, the drag reduction and turbulence characteristics from DNS, as well as the linear model predictions are as expected.
- The model used to size the wavy surface failed to predict the spanwise shear stress and the wall pressure perturbation. Alternative linear models accounting for the wave induced shear stress could be validated by DNS and used for net drag and power calculations vs. geometry and Reynolds number.

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