Effects of Controlled Three-Dimensional Perturbations on Boundary Layer Transition

Thesis by
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In Partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy

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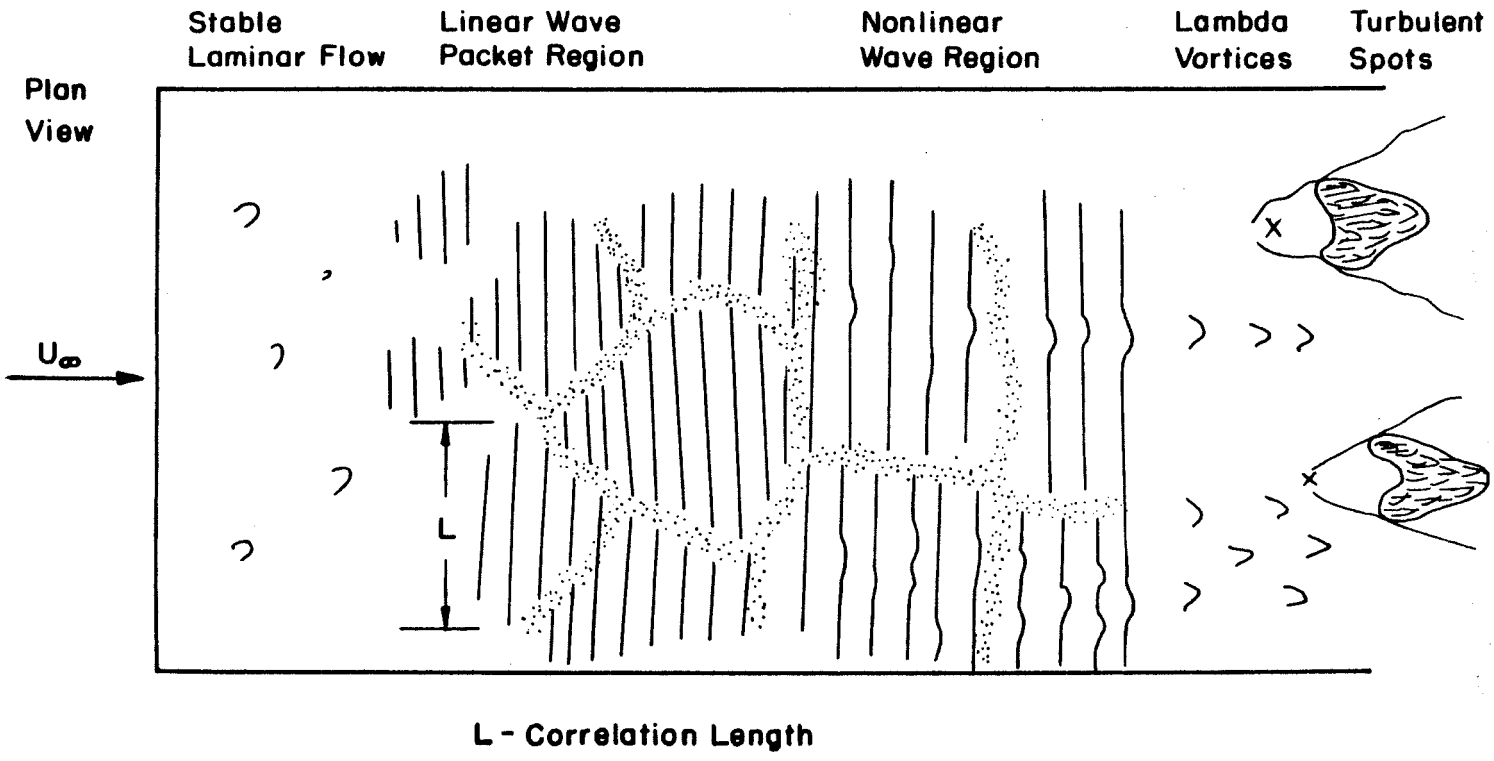


Figure 1.1: Cartoon of Boundary Layer Transition

Photograph of Flat Plate Apparatus in Water Tunnel
Flow from Right to Left

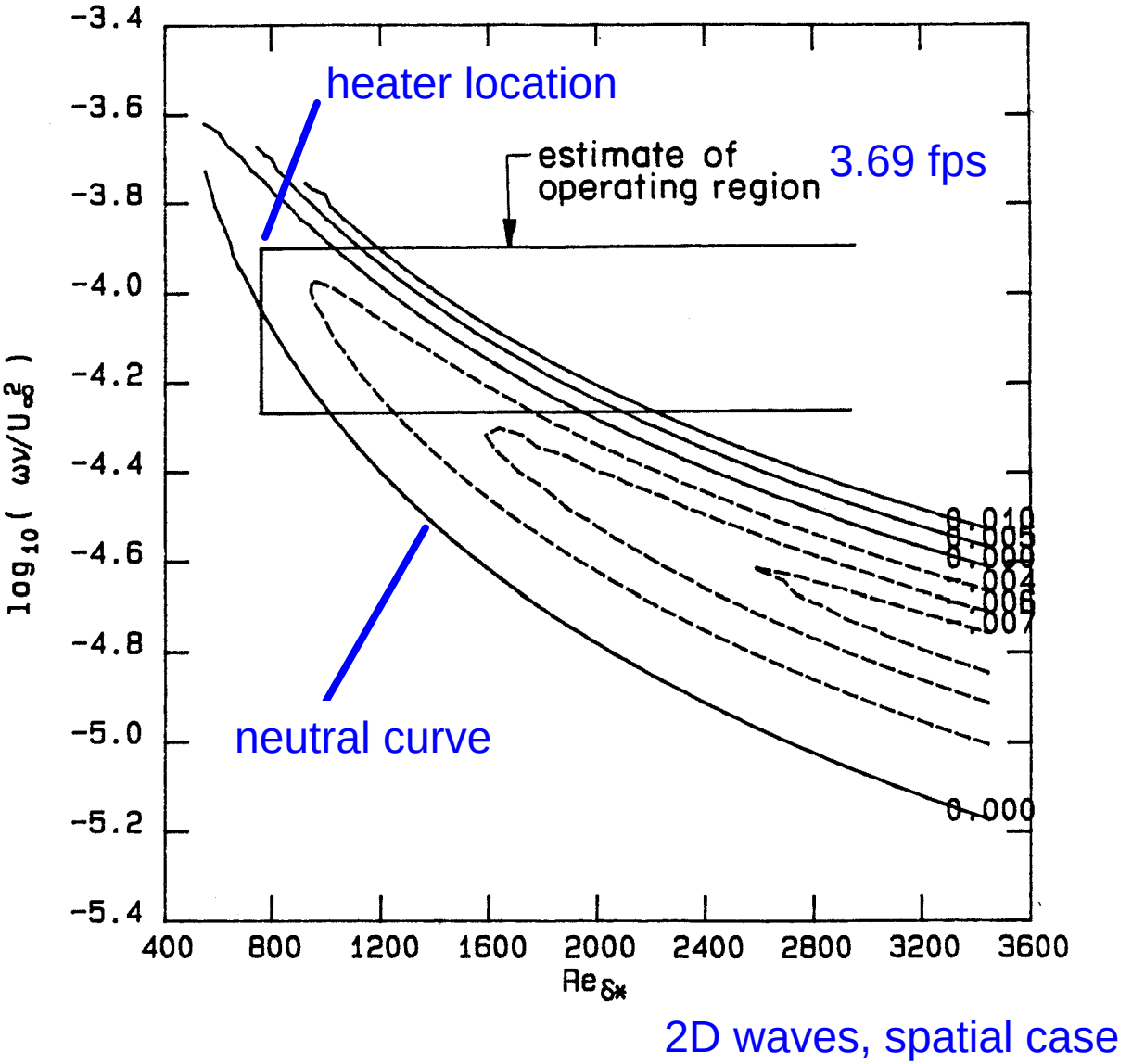
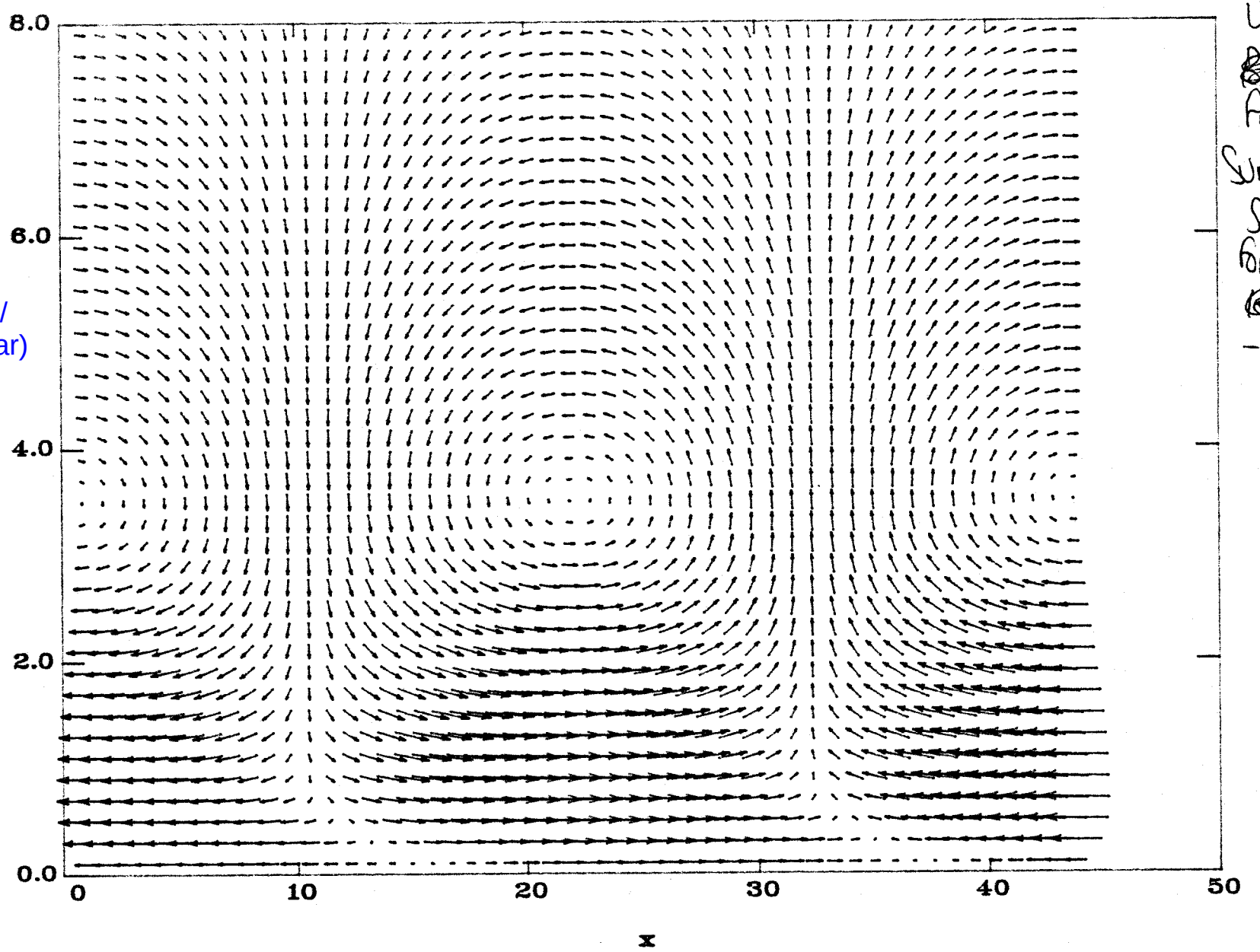


Figure 3.1: Linear Theory Amplification Rate Contours
(α_i contours, provided by L. Mack)

Perturbation velocity vectors for 2D TS wave, one wavelength.
in plane z=0, scaled to size of max. fluctuation. Vertical axis is highly stretched, width is o(40 delta), height is o(delta).

4/2/86
Mock data,
R set #1.
used
& α's
from
Summary
Sheet
for #1
ω .143
-5.6x10^3



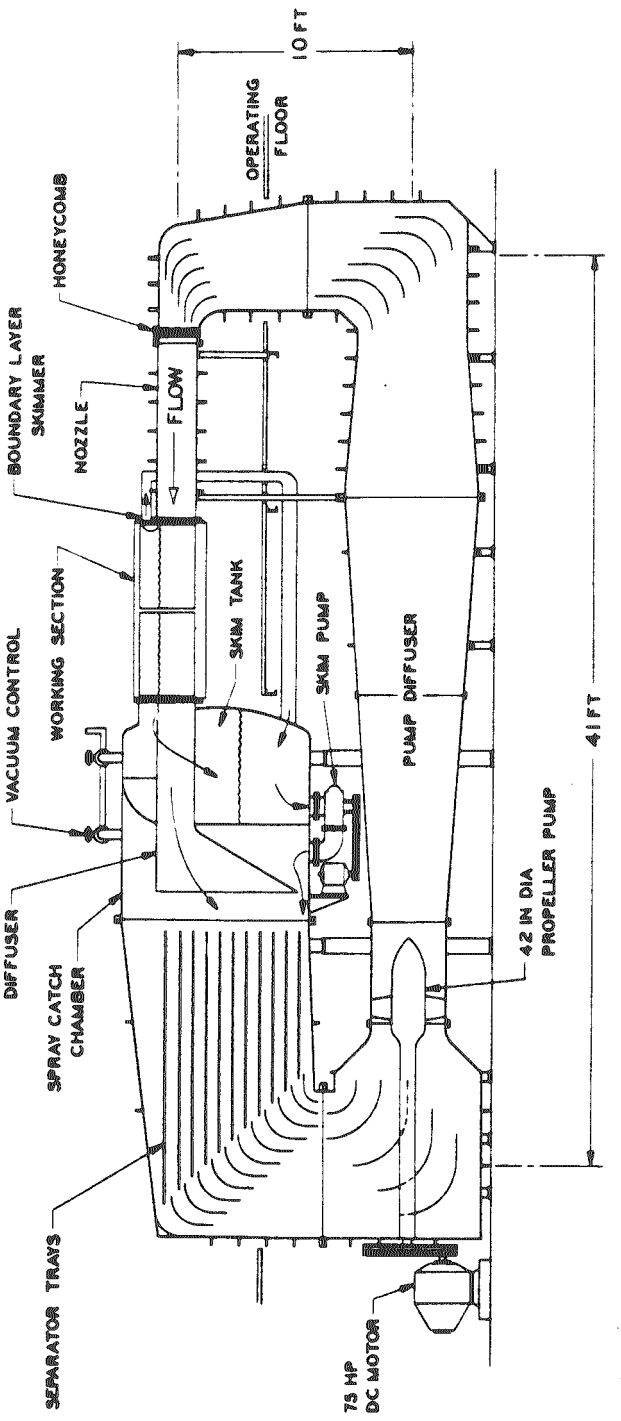


Figure 2.1: Free Surface Water Tunnel Schematic from Ward [46]

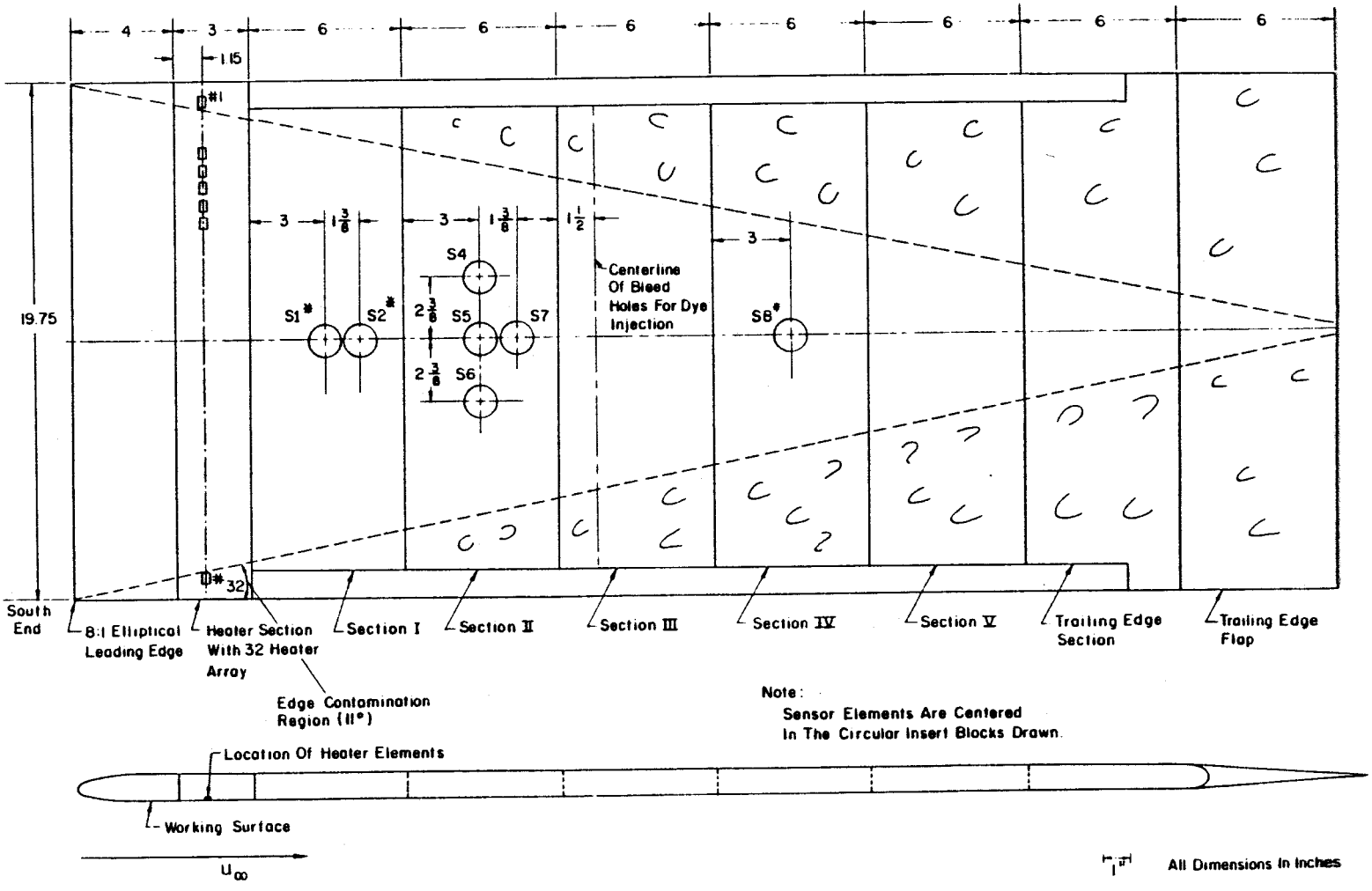


Figure 2.2: Flat Plate Model Schematic: First Configuration asterisks explained in Section 2.4

Typical Shear Trace

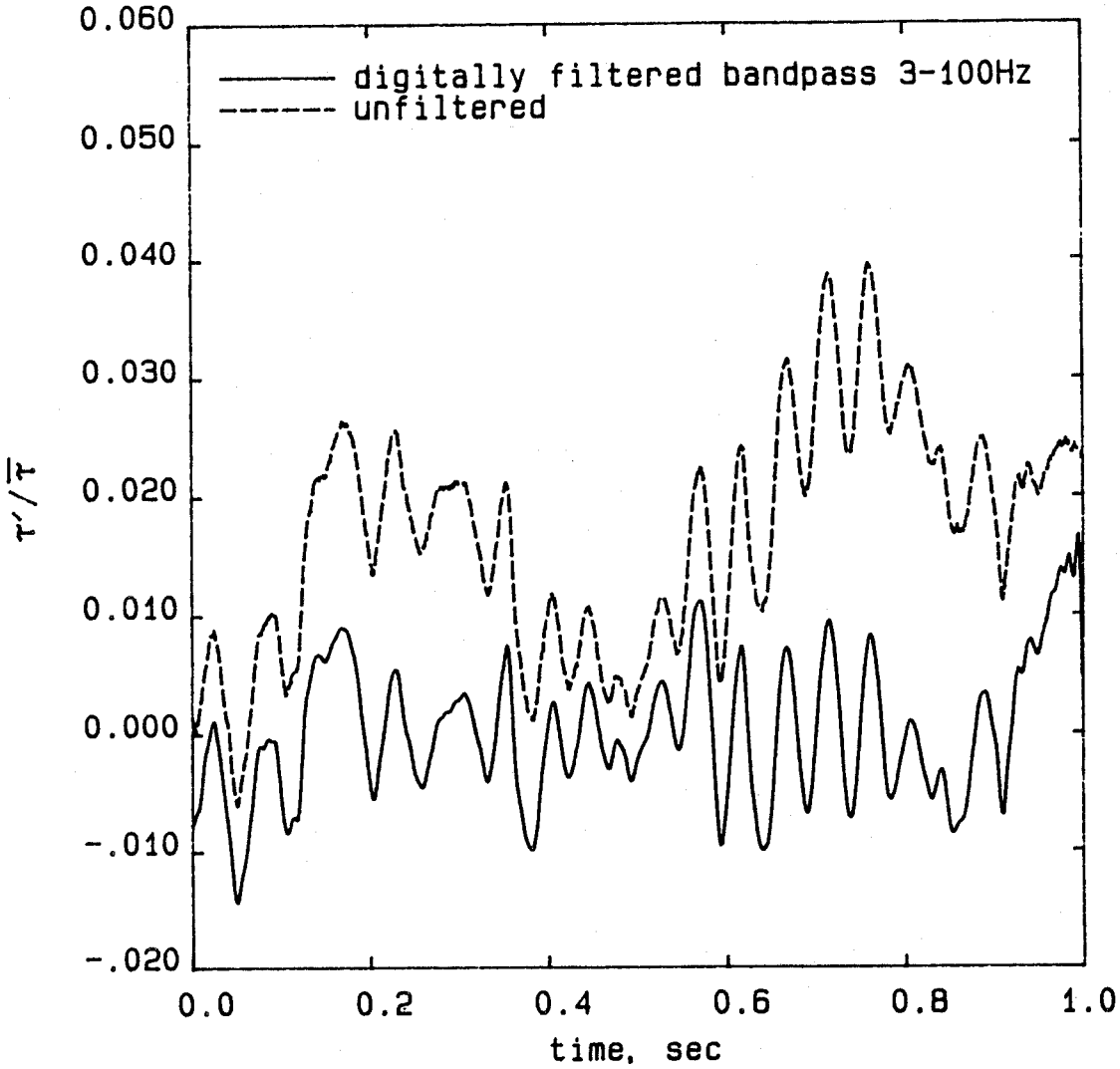


Figure 3.2: Shear Trace of Natural Waves at S7, $Re_{\delta^*} = 1400$
5-5r06, $U_\infty = 3.66$ fps

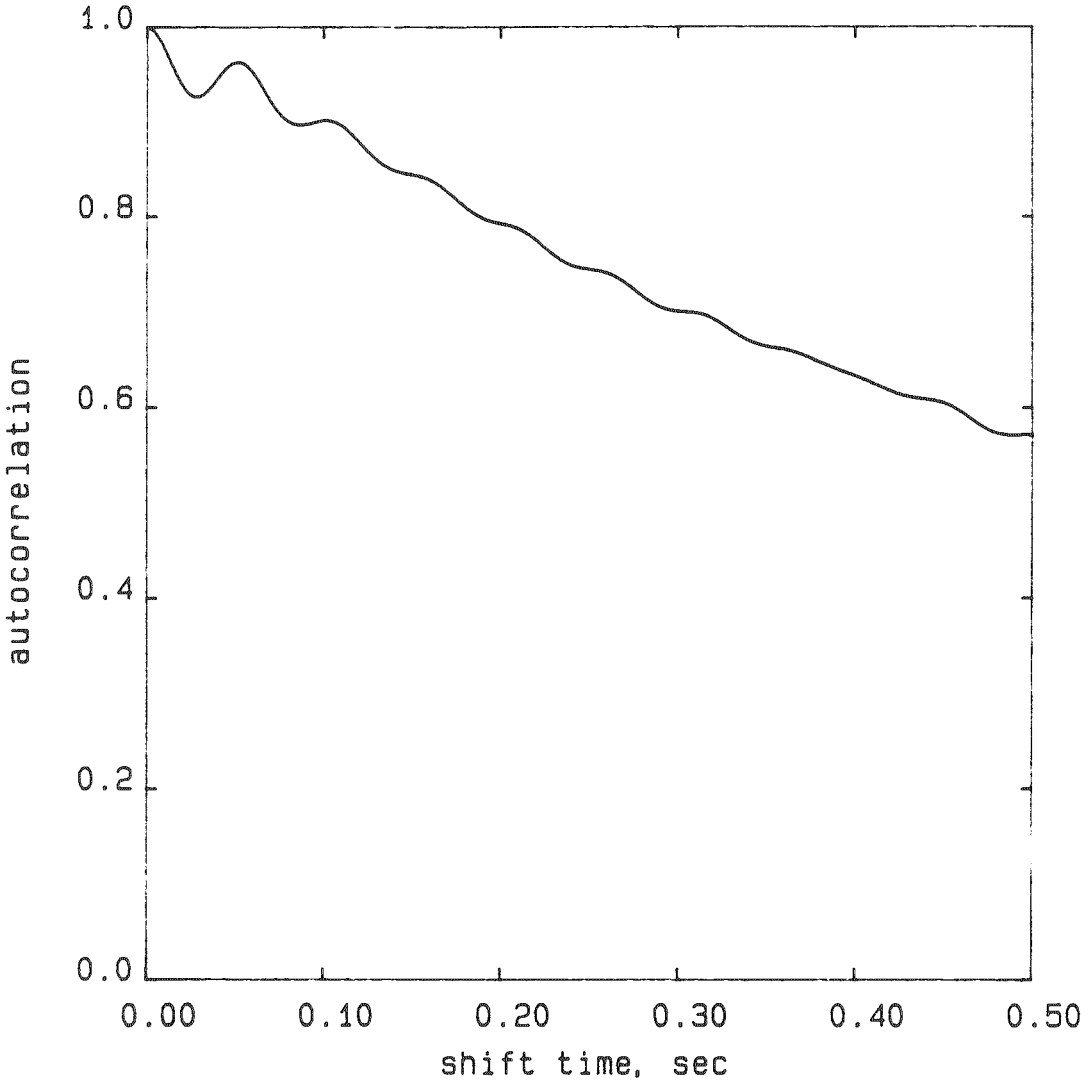


Figure 3.3: Autocorrelation of Natural Instability Waves at S7
($Re_{\delta^\star} = 1400$, 5-5r06.c22, $U_\infty = 3.66$ fps)

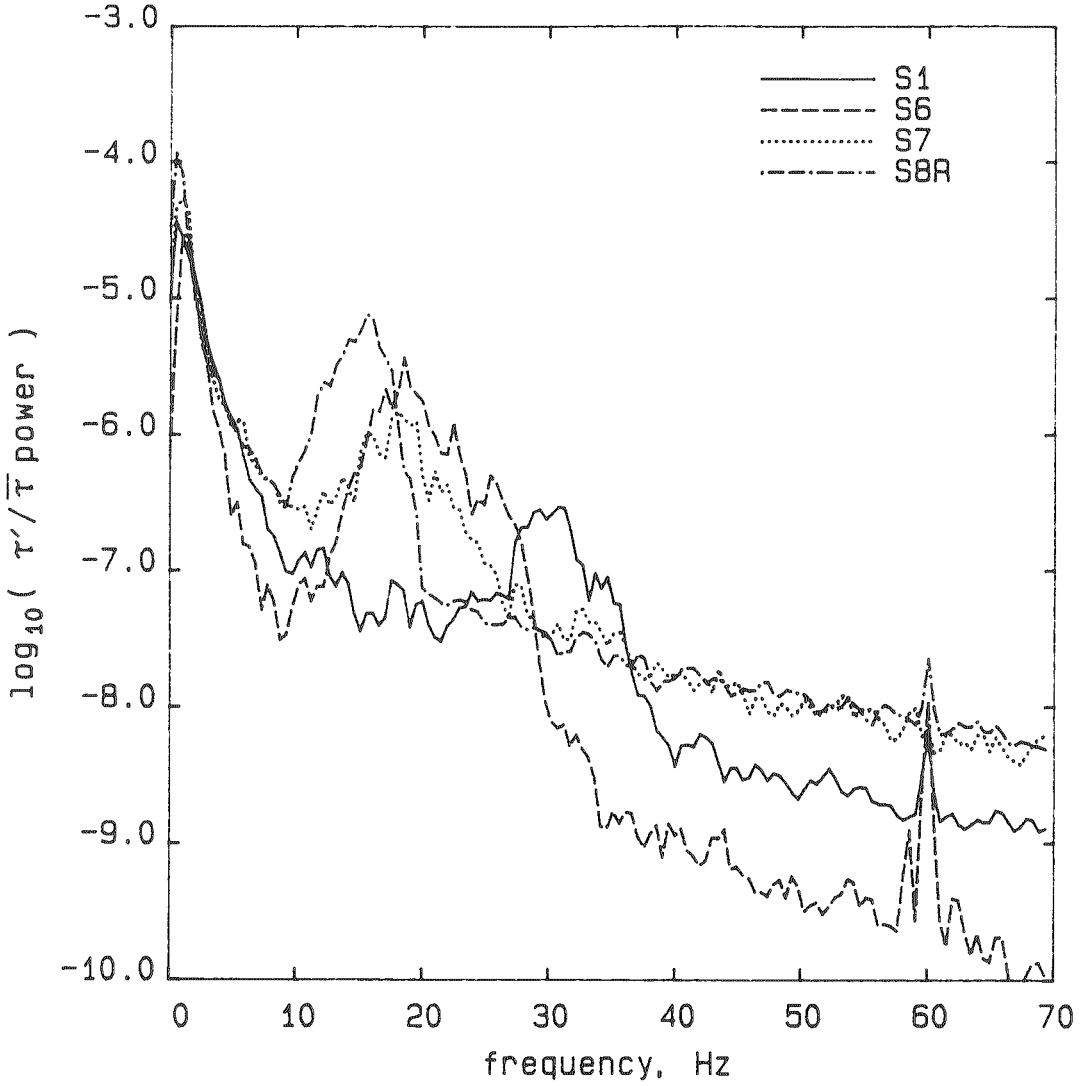


Figure 3.4: Spectra of Instability Waves at Four Streamwise Locations ($Re_{\delta^*} = 1100, 1350, 1400, 1750$, 5-5r06, $U_\infty = 3.66$ fps)

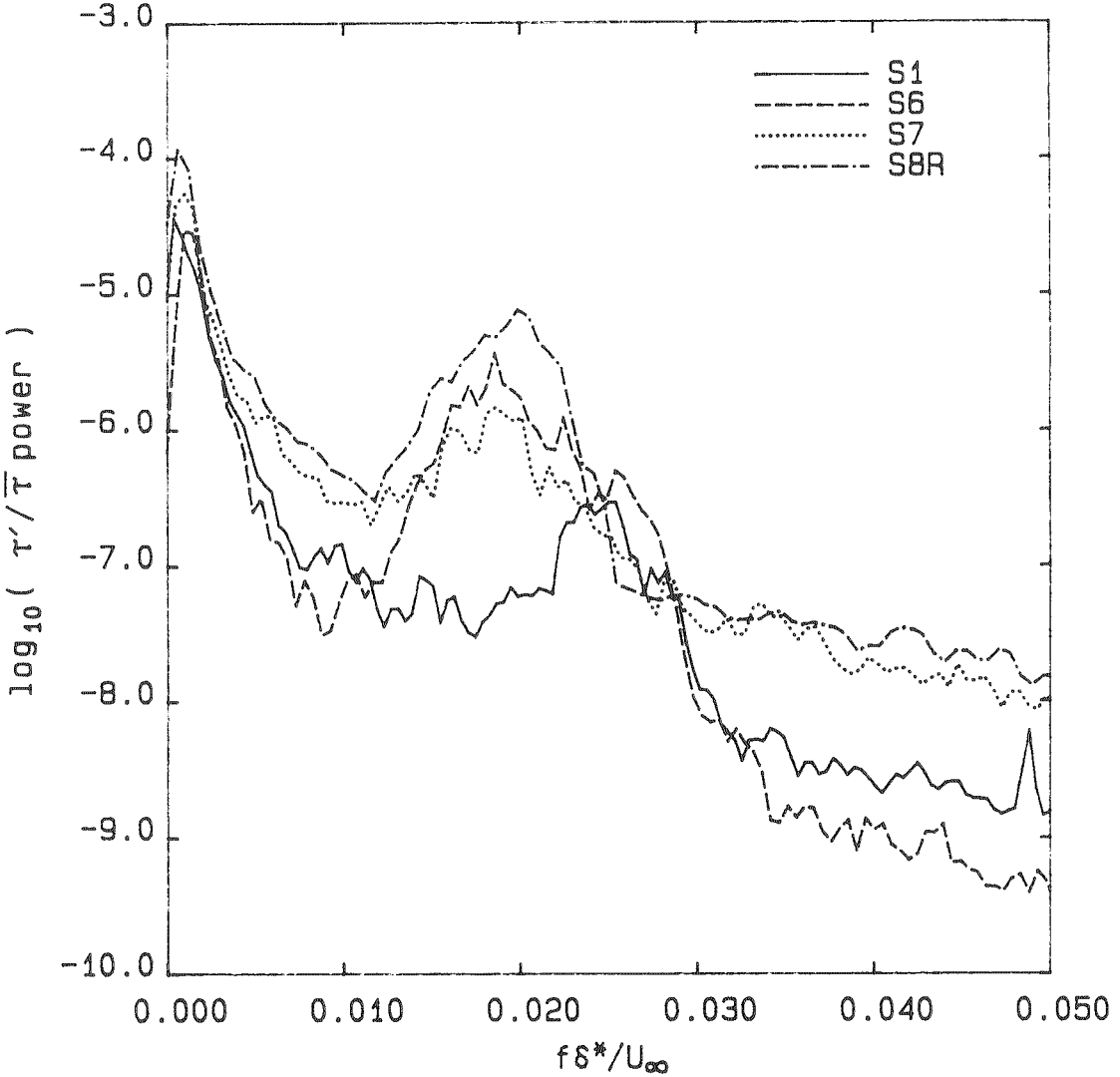


Figure 3.5: Reduced Spectra of Natural Instability Waves
(same conditions as in previous figure)

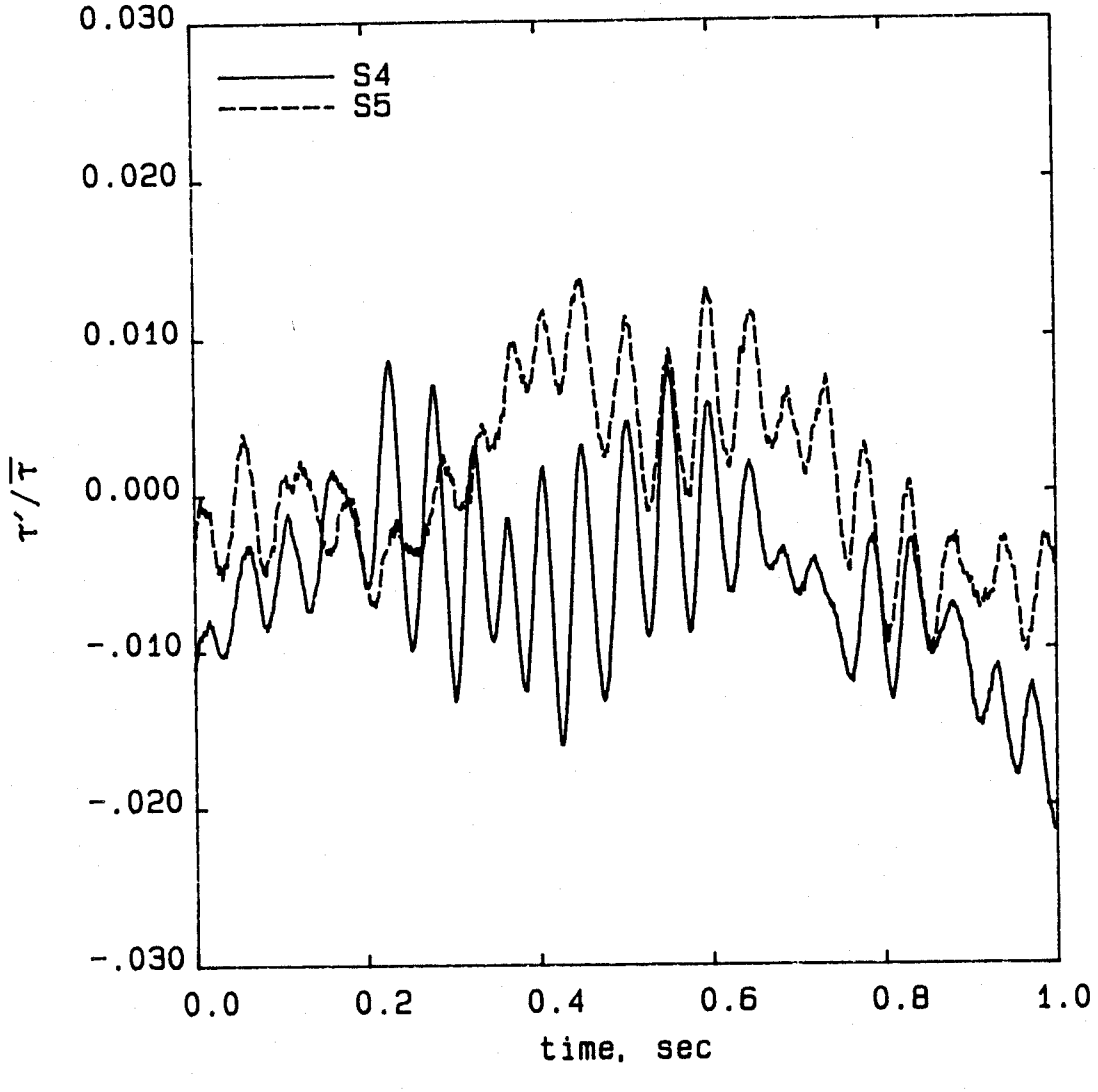


Figure 3.6: Naturally Occurring Waves at Two Spanwise Locations
($Re_{\delta^*} = 1300$, 4-13mr01, $U_\infty = 3.50$ fps)

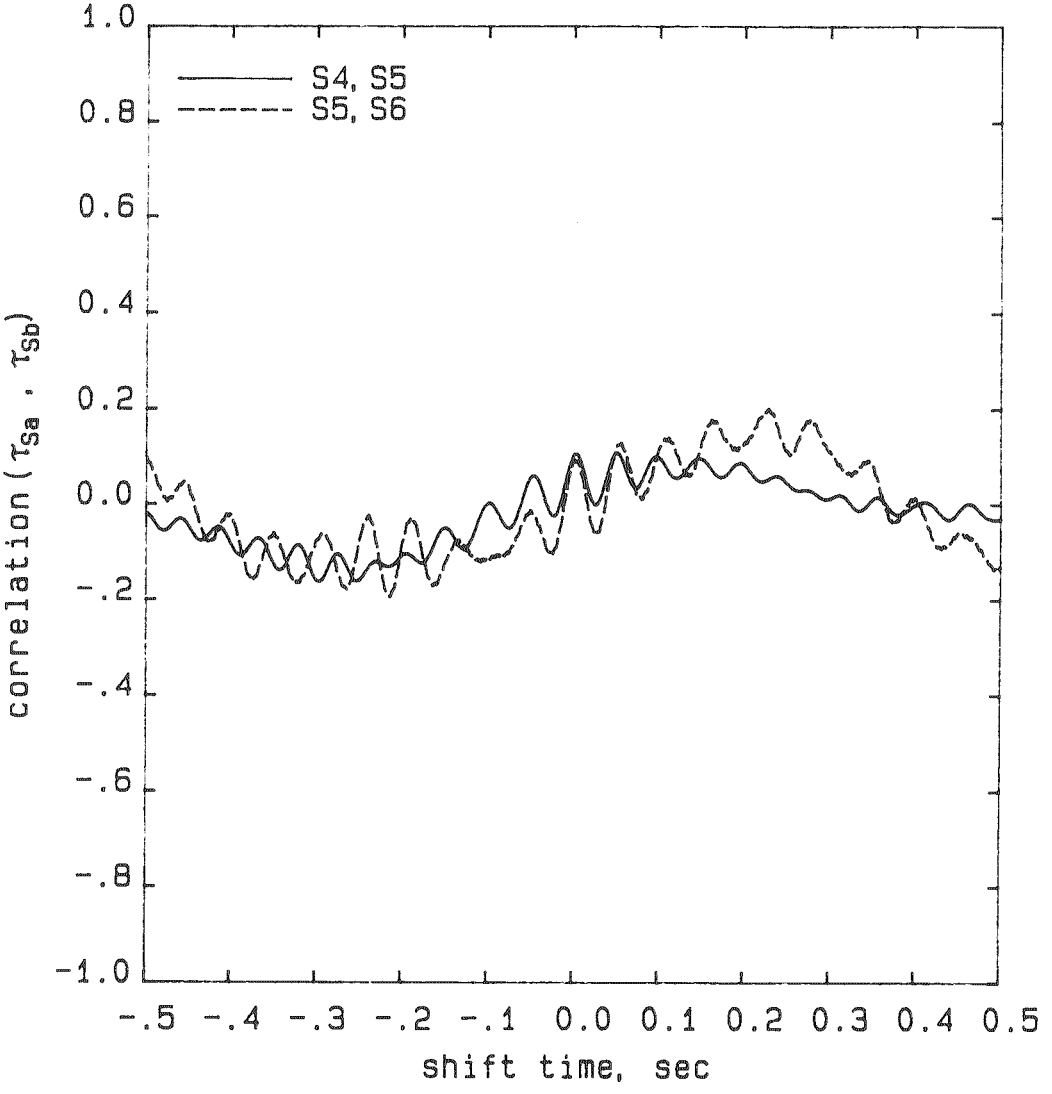


Figure 3.7: Cross-Correlation of Shear at Three Spanwise Locations ($Re_{\delta^*} = 1300$, 4-13mr01, $U_\infty = 3.50$ fps)

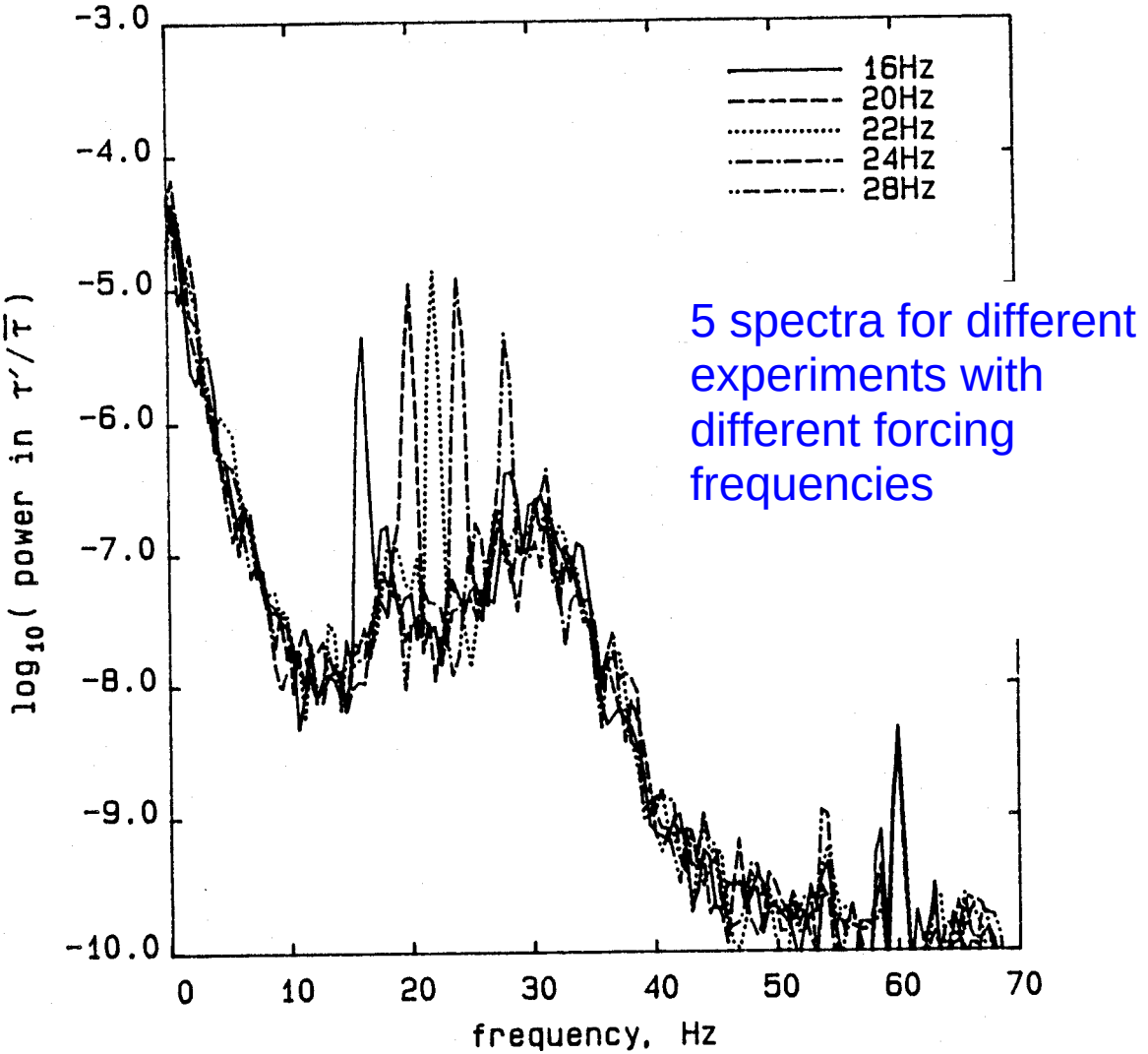


Figure 3.8: Wall Shear Spectra in Linear Region at $Re_{\delta^*} = 1100$
Five Spectra for Different Heat Frequencies
(83 watts total power, S1, 2D forcing, 4-22, $U_\infty = 3.68$ fps)

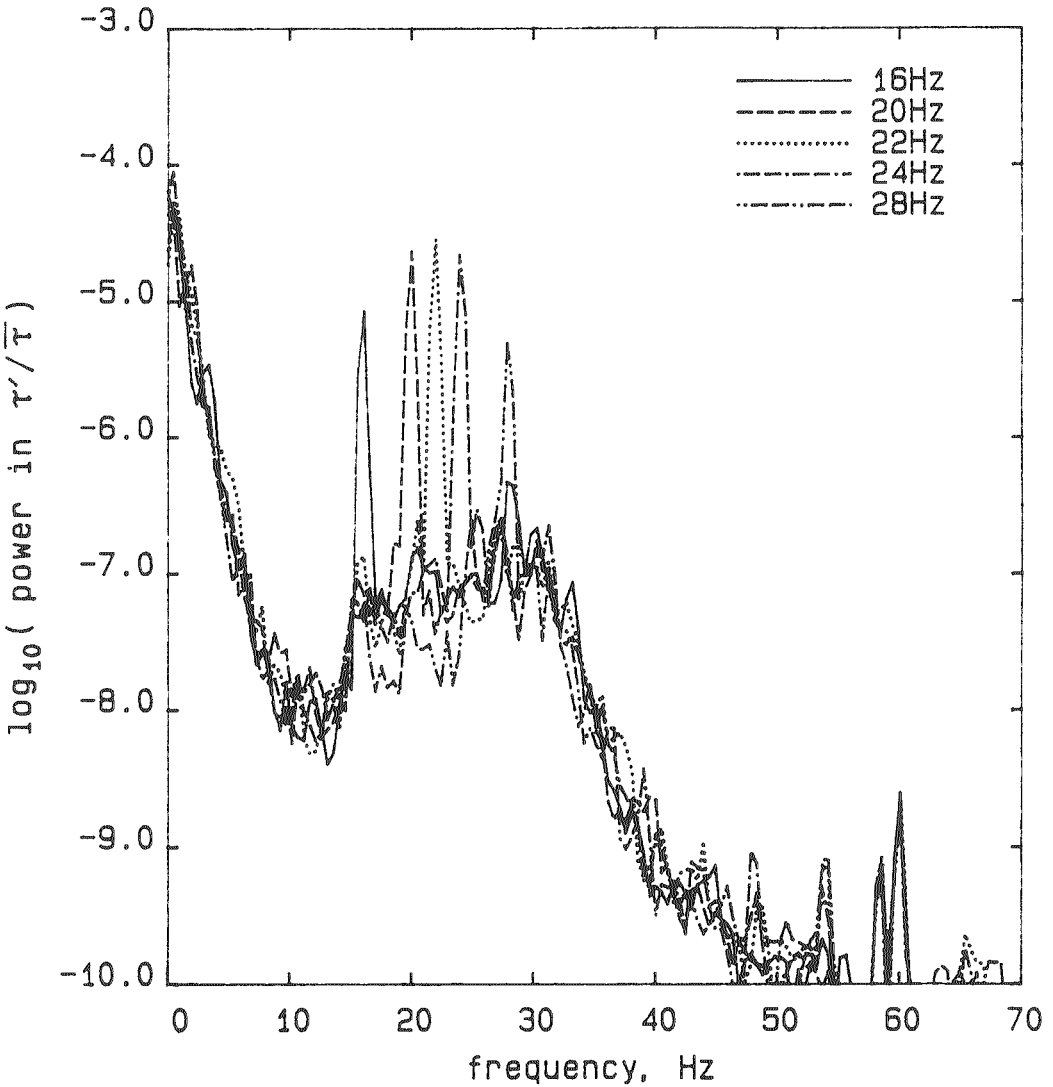


Figure 3.12: Wall Shear Spectra at $Re_{\delta^*} = 1150$
for five different heating frequencies
2D forcing, 83 watts, S2F, 4-22, $U_\infty = 3.68$ fps

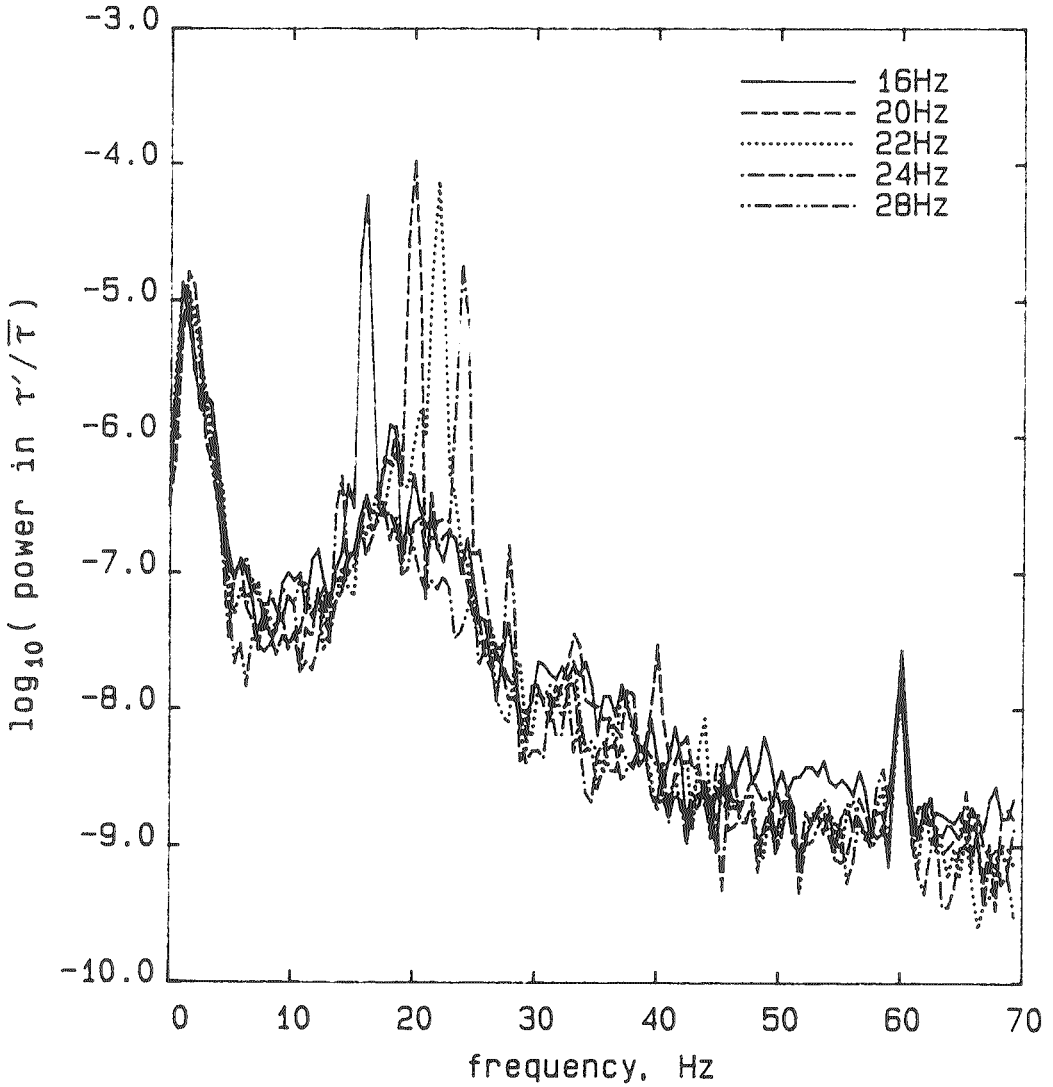


Figure 3.13: Wall Shear Spectra at $Re_{\delta^*} = 1350$
for five different heating frequencies
2D forcing, 83 watts, S5, 4-22, $U_\infty = 3.68$ fps

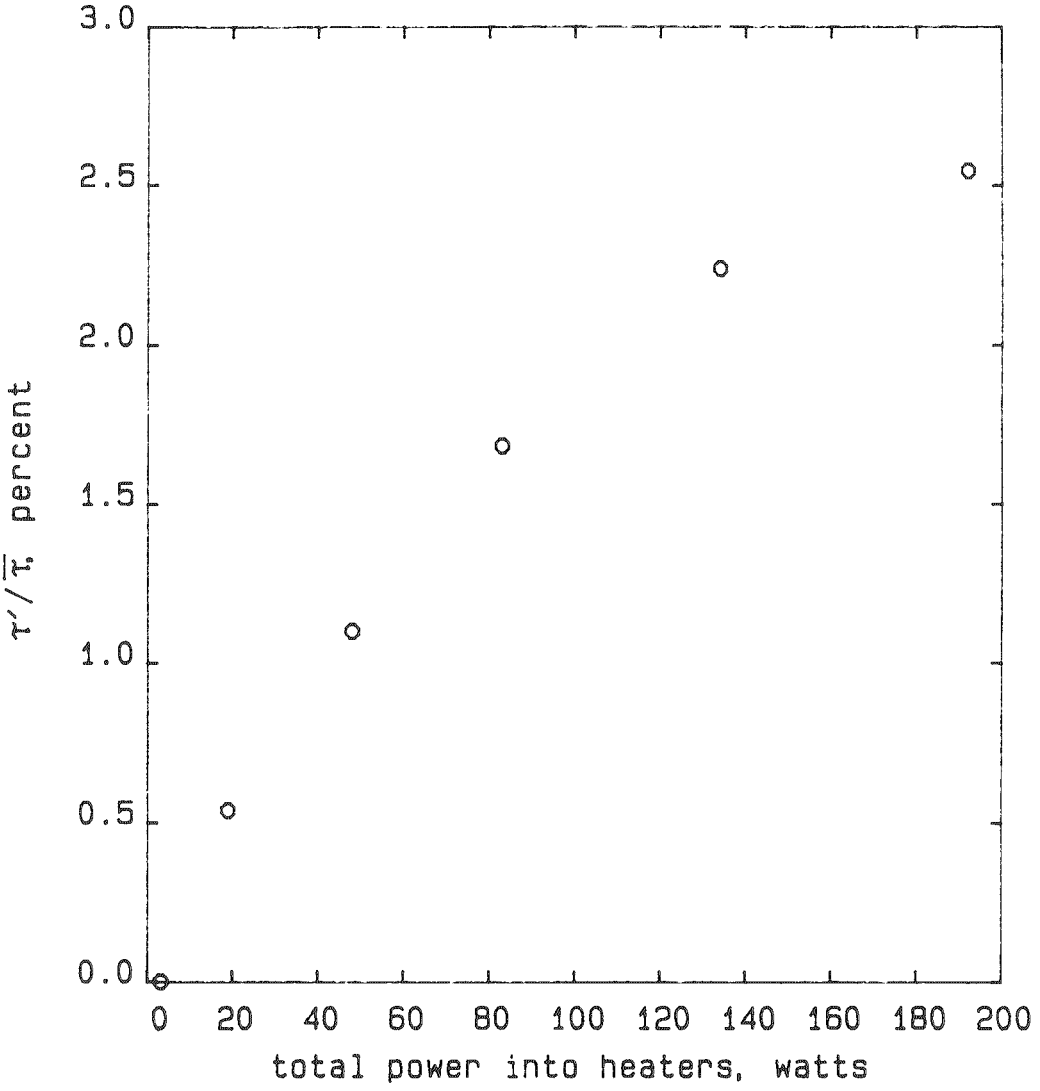


Figure 3.14: Primary Response Amplitude vs. Forcing Power
10Hz 2D forcing S6, 4-13mII, $Re_{\delta^*} = 1300$

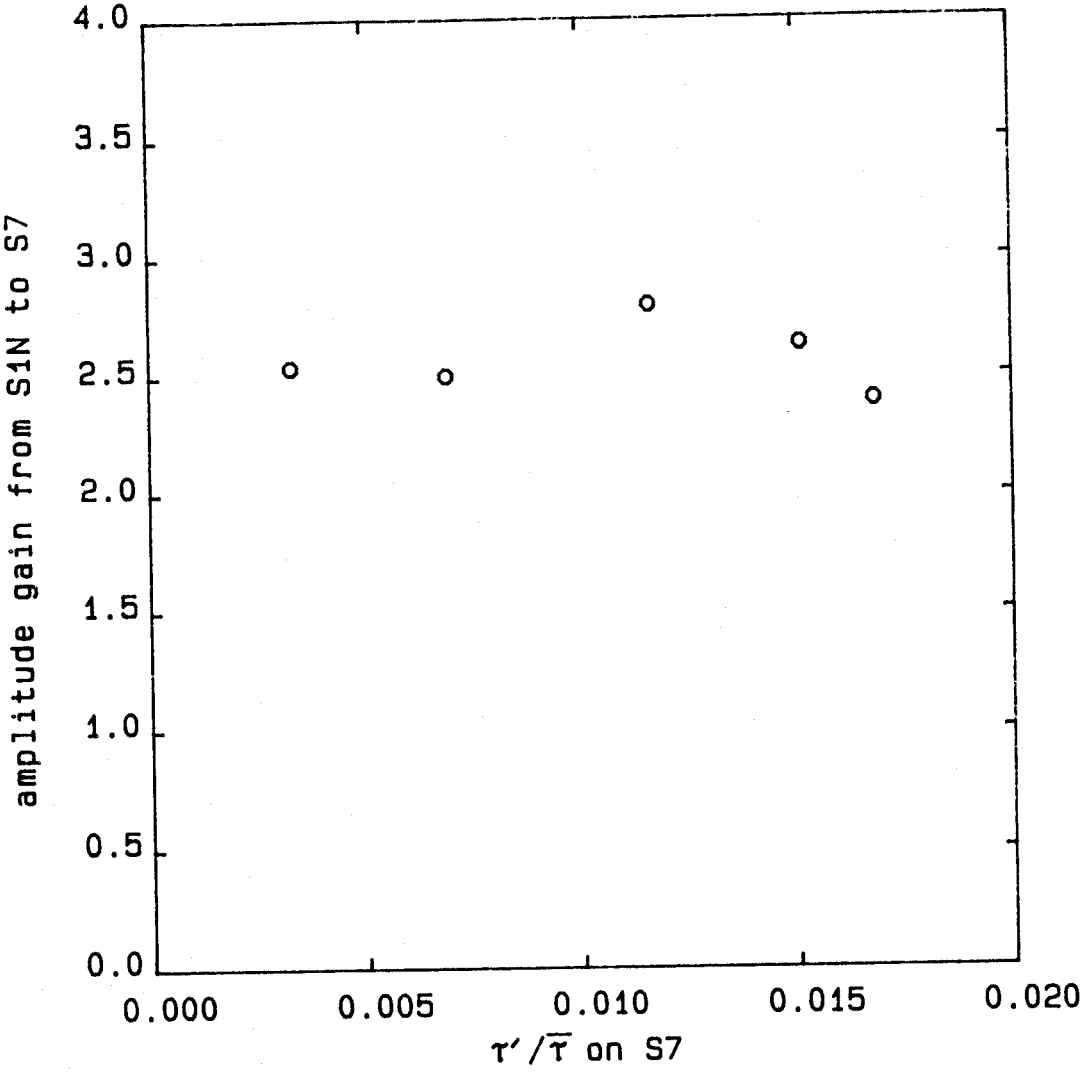


Figure 3.15: Growth Rate of Primary Response vs. Wave Amplitude
$U_\infty = 3.50$ fps, 20Hz, 4-13mII
$Re_{\delta^*}(S1N) = 1050$, $Re_{\delta^*}(S7) = 1350$

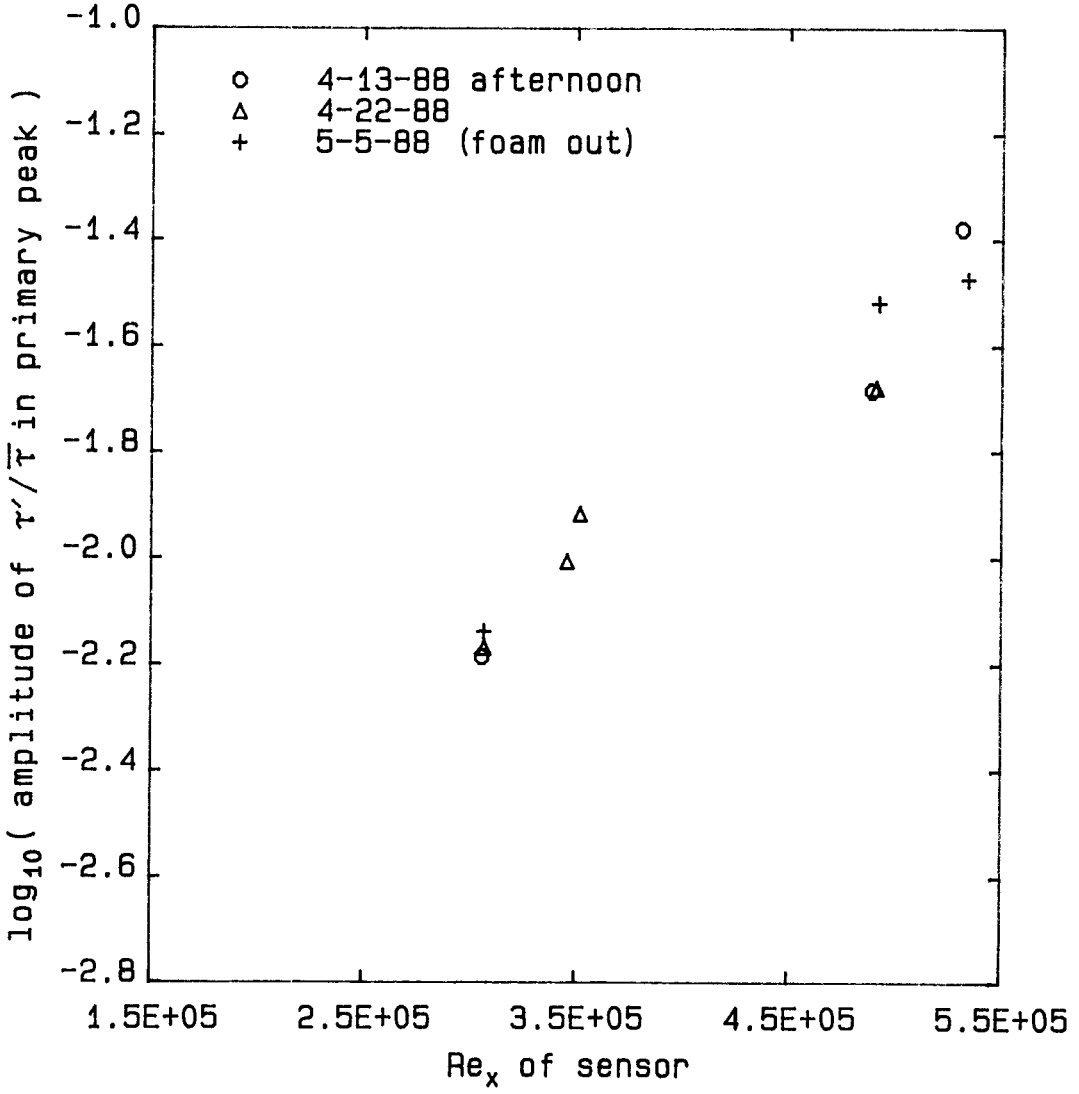


Figure 3.16: Growth Rate of Waves Created with Same Forcing on Different Days
192 watts, $U_\infty = 3.68$ fps, 2D 20Hz,
heater at $Re_x = 1.5 \times 10^5$

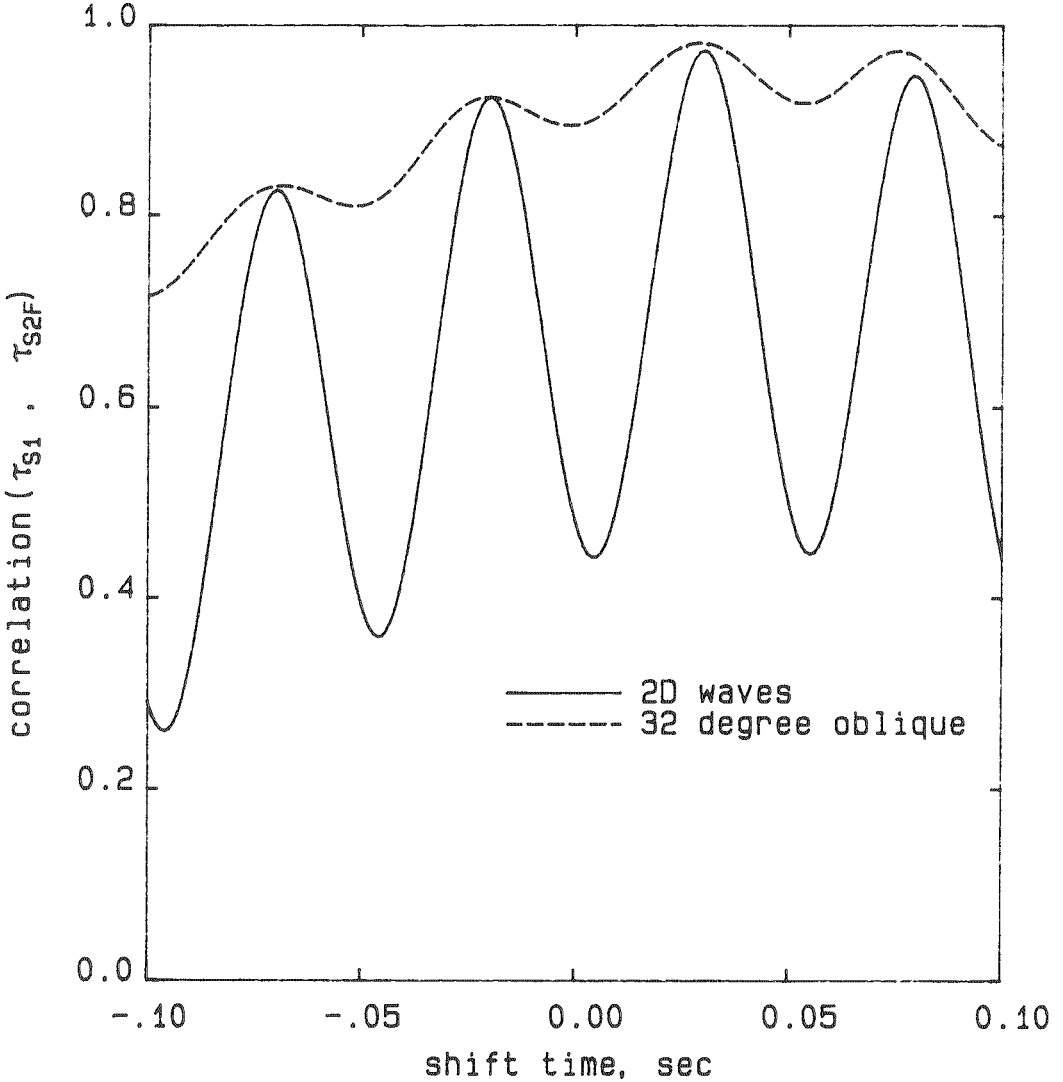


Figure 3.17: Cross-Correlation of Low Reynolds Number Phase Speed Data
20Hz 192 watt forcing, S1 and S2F, 4-22
$Re_{\delta^*}(S1) = 1100$, $Re_{\delta^*}(S2F) = 1150$, $U_\infty = 3.68$ fps

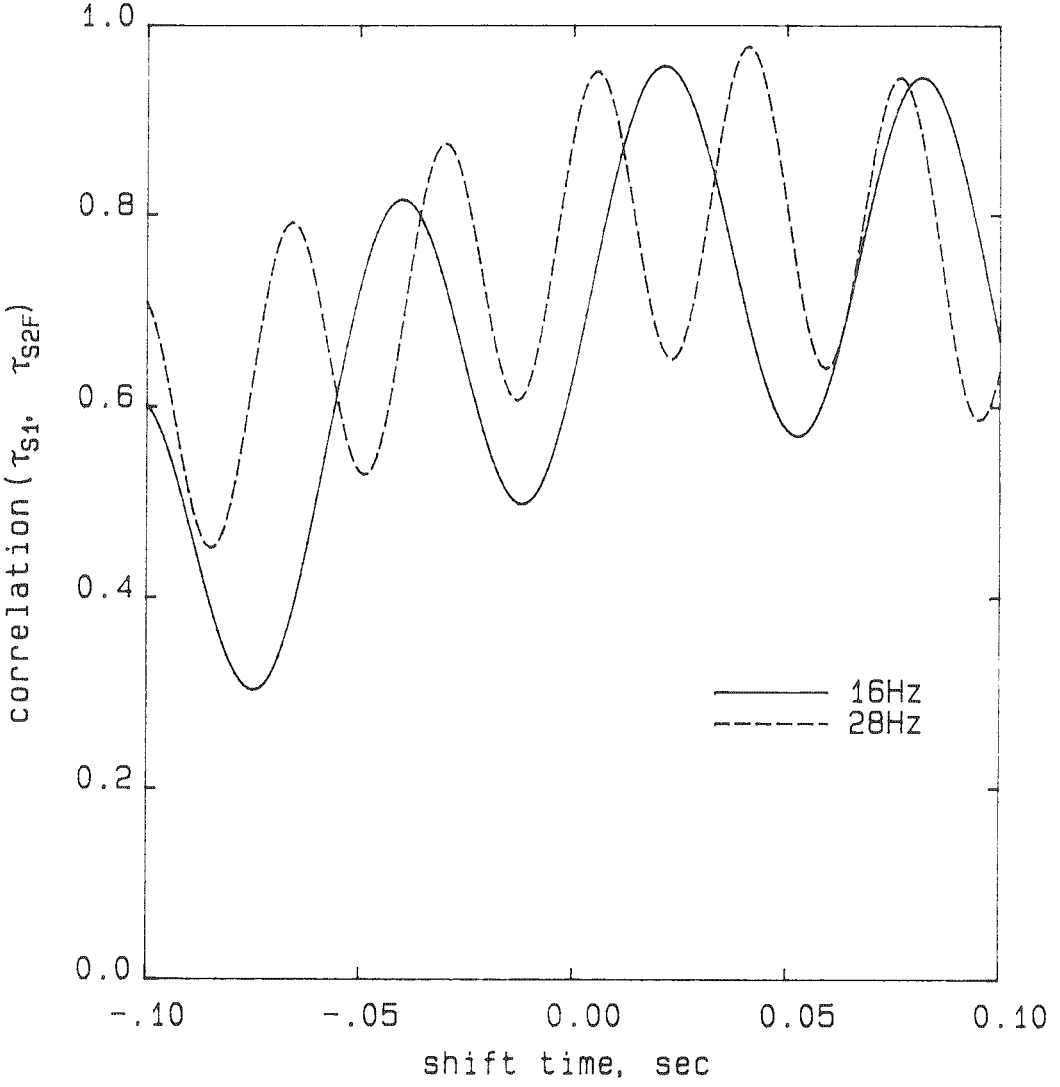


Figure 3.18: Cross-Correlations for Extreme Frequency Data
192 watt 2D forcing, S1 to S2F, 4-22
$Re_{\delta^*}(S1) = 1100$, $Re_{\delta^*}(S2F) = 1150$

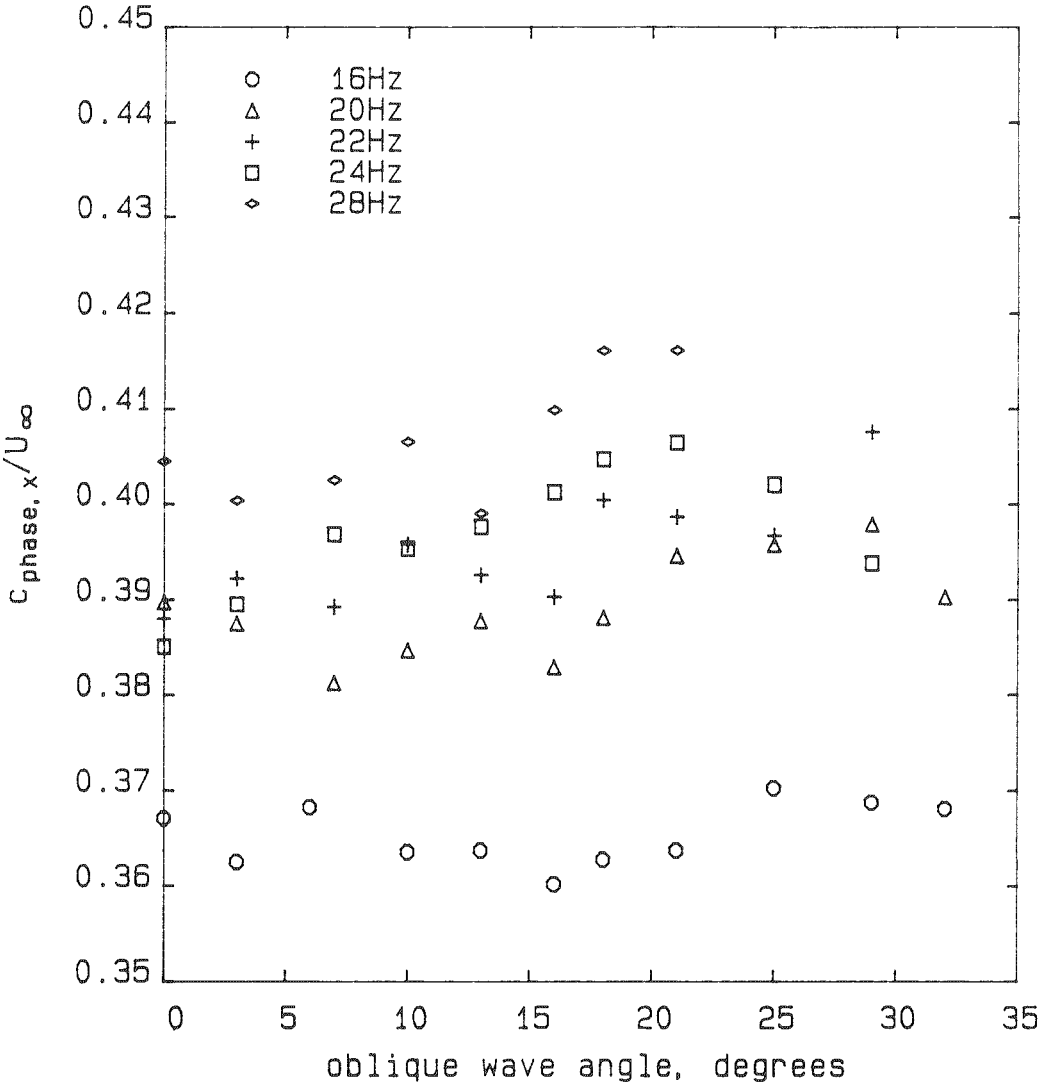


Figure 3.19: Phase Speeds for Oblique Waves at $Re_{\delta^*} = 1100$
at five heating frequencies, from S1 to S2F
192 watts, 4-22, $Re_{\delta^*}(S1) = 1100$, $Re_{\delta^*}(S2F) = 1150$

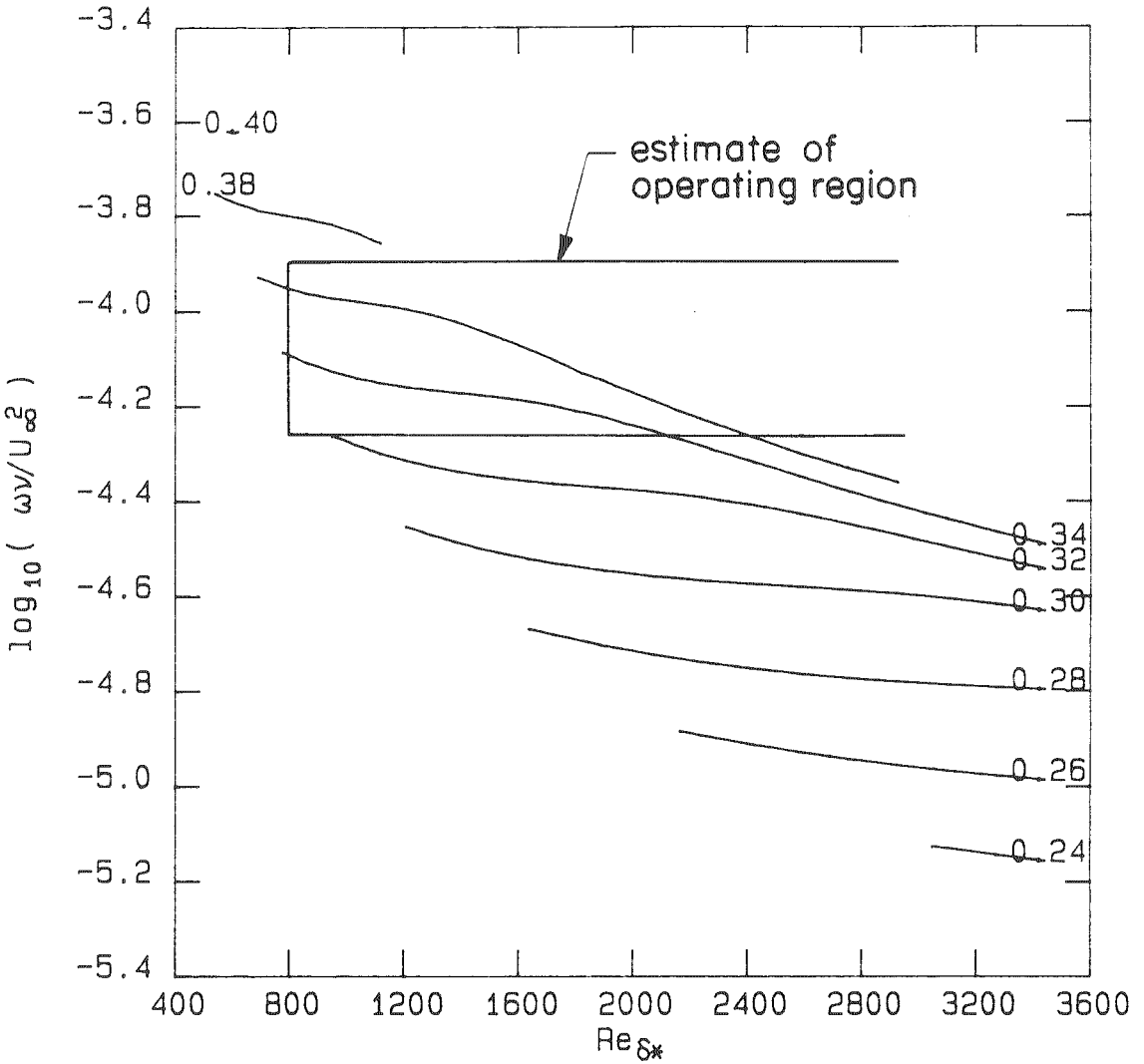


Figure 3.20: Linear Theory Results for Streamwise Phase Speeds
contours of $c_{phase,x}/U_\infty$ at 0.02 intervals
2D linear theory results from L. Mack
see Section 3.2 for operating region estimate

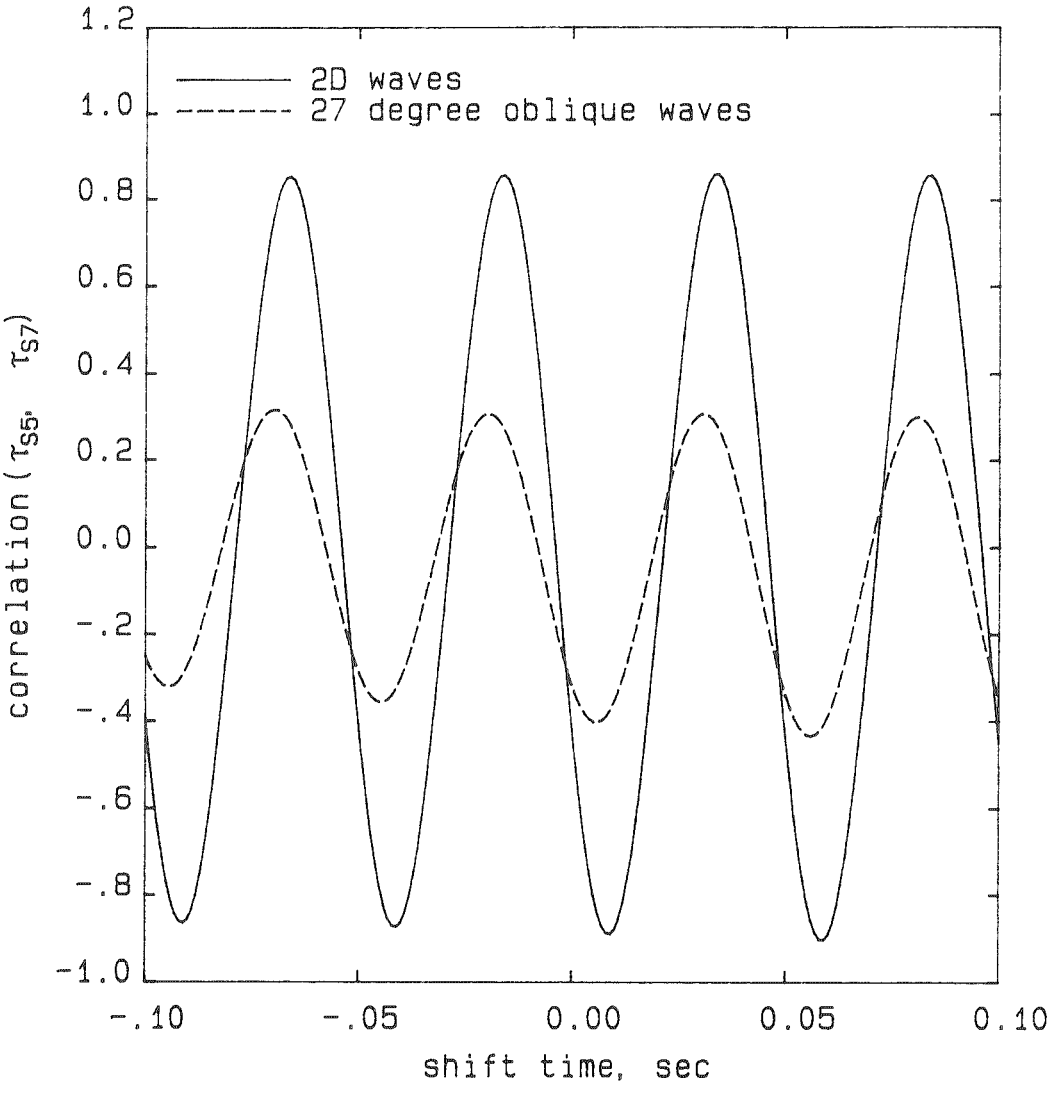


Figure 3.21: Cross-Correlation for High Reynolds Number Phase Speed Data
20Hz 192 watt forcing, S5 to S7, 4-13a, $U_\infty = 3.68$ fps,
$Re_{\delta^*}(S5) = 1350$, $Re_{\delta^*}(S7) = 1400$

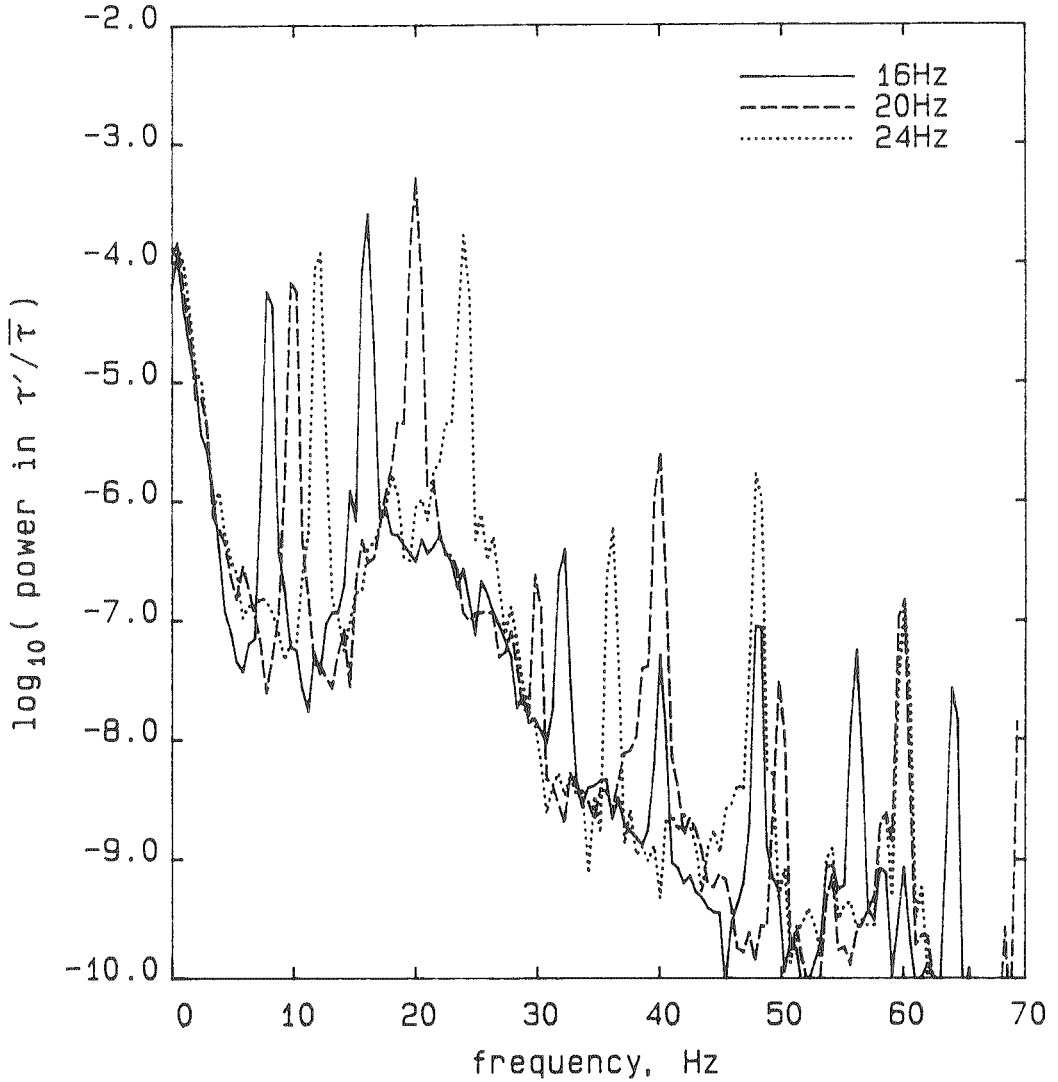


Figure 3.27: Wall Shear Spectra for Highly Nonlinear Waves
S4, $Re_{\delta^*} = 1300$, $U_\infty = 3.50$ fps, 4-13mII
192 watts

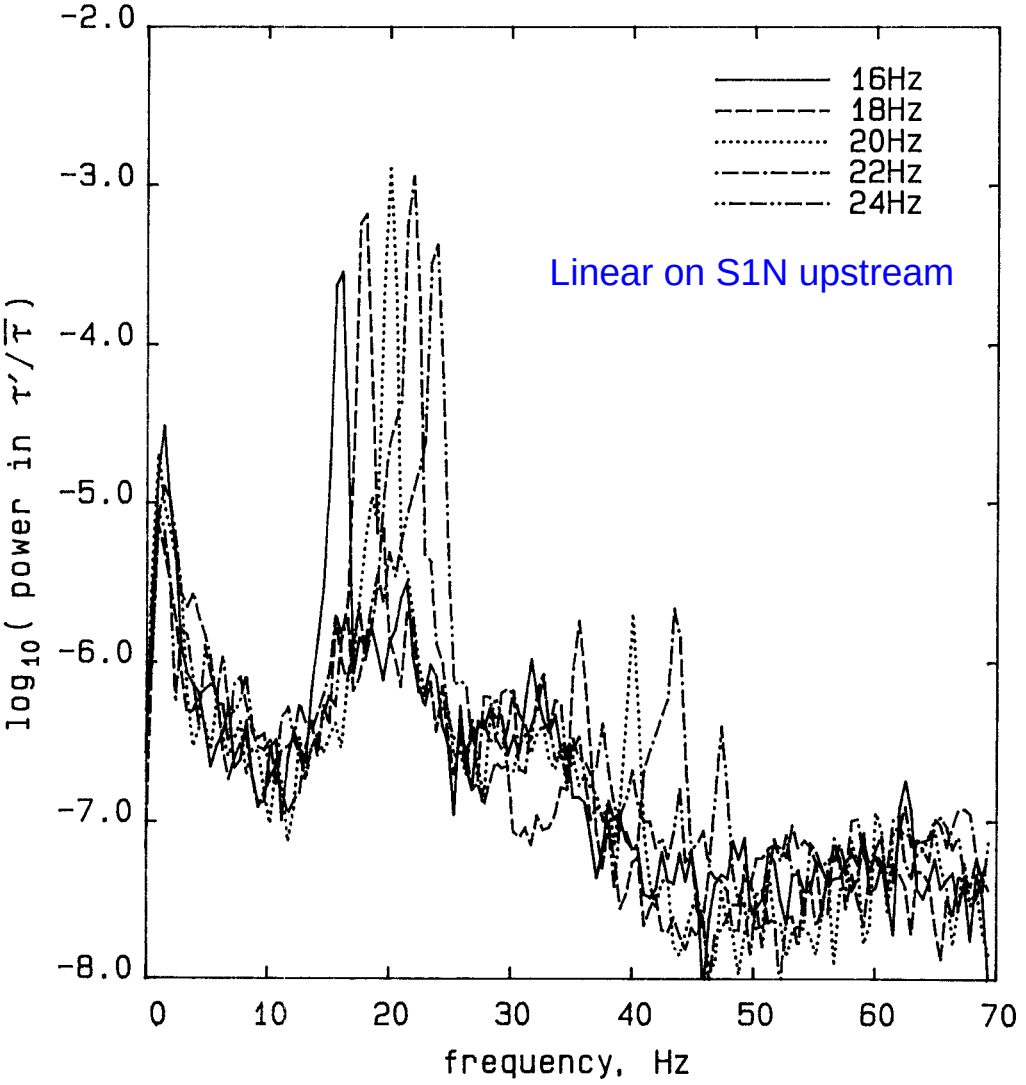


Figure 3.28: Wall Shear Spectra Showing Second Harmonics S7, $Re_{\delta^\star} = 1400$, 192 watts, ~~2D waves~~, 4-13a

caption calling them 2D waves inconsistent with text.

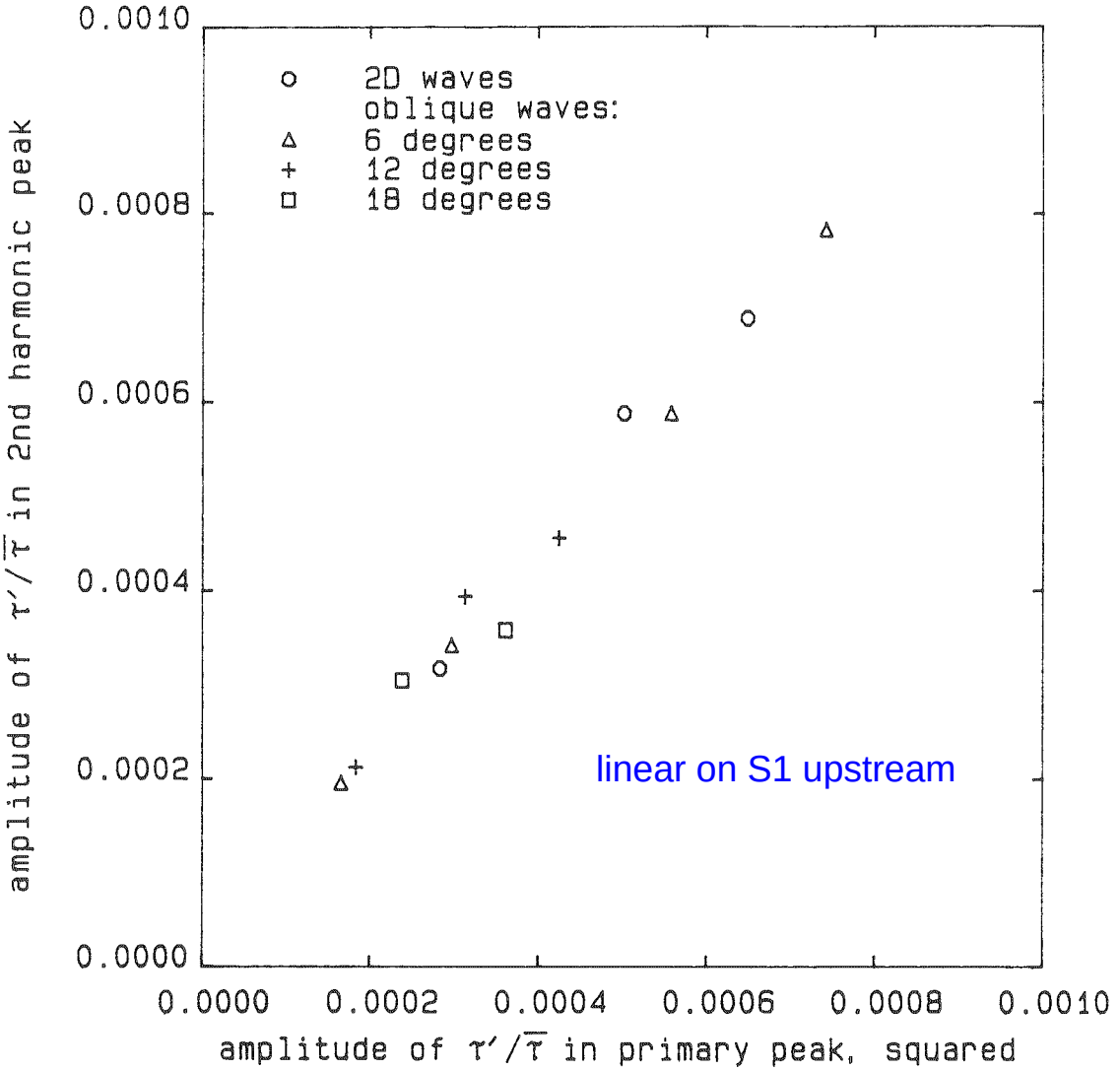


Figure 3.29: Amplitude of Second Harmonics vs. Primary
20Hz, S6, $Re_{\delta^*} = 1300$, 4-13mII, varied heater power

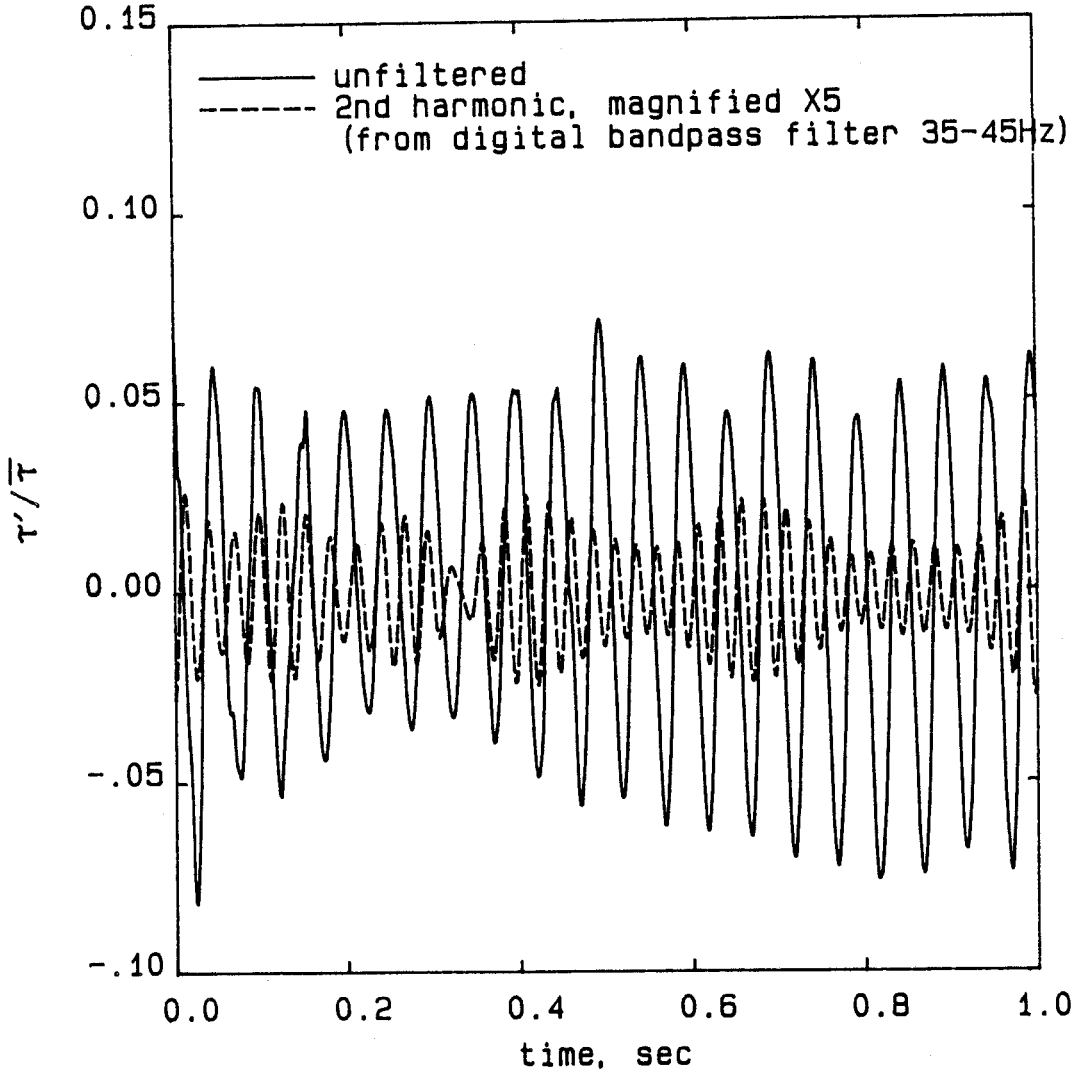
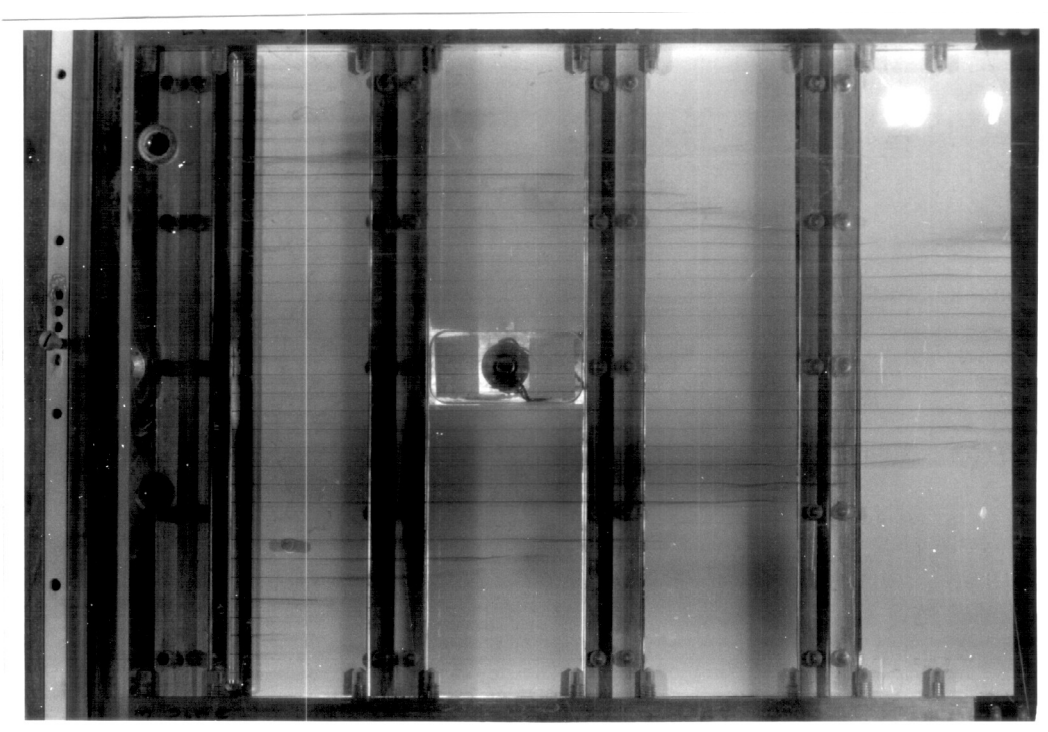
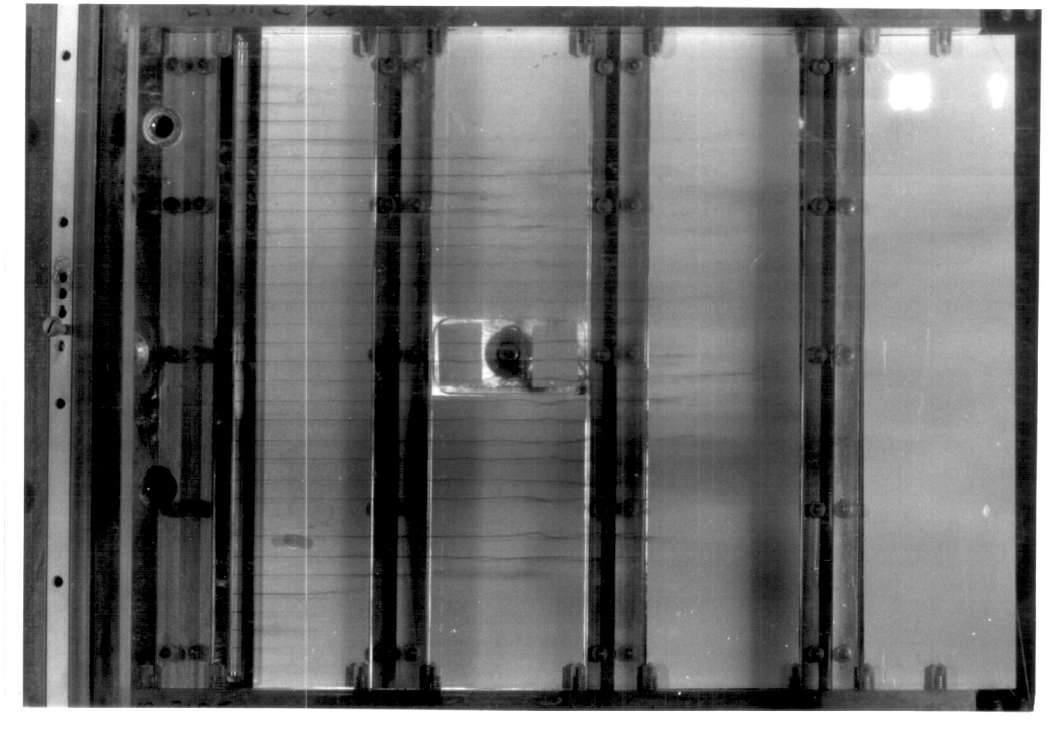


Figure 3.31: Time Trace of Nonlinear 2D Wave Showing Second Harmonic S7, $Re_{\delta^*} = 1400$, $U_\infty = 3.68$ fps, 20Hz 2D, 4-13a

Photographs of Dye Streaks Showing Transition. Flow from left to right, 3.50 ft/sec. Upper photo unforced. Lower photo forced at 8Hz, 190W, 12-deg. angle.





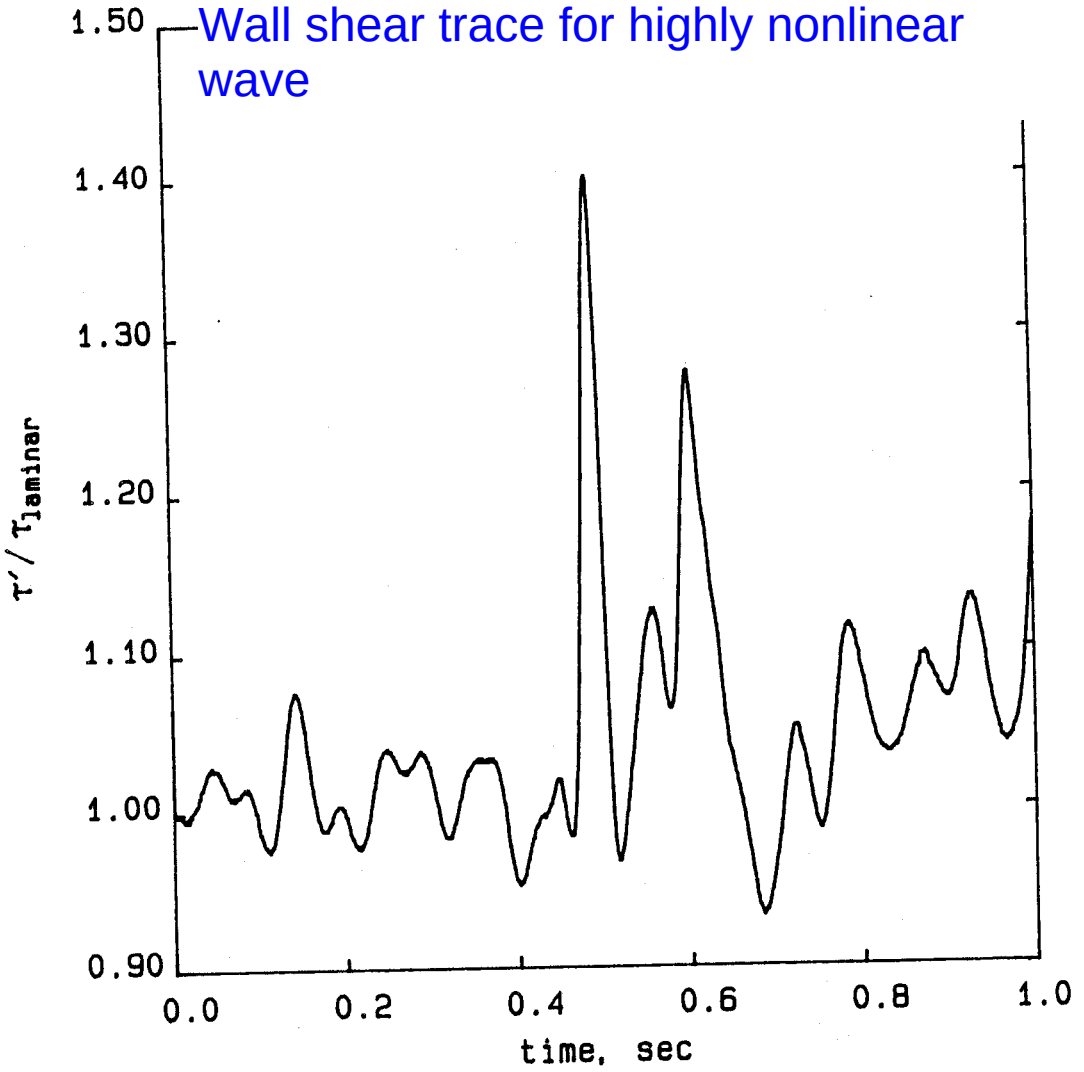


Figure 3.36: Time Trace of Wall Shear for Late Nonlinear Wave
2D 20Hz waves, 192 watt forcing, S8, $Re_{\delta^*} = 1750$, 4-13a

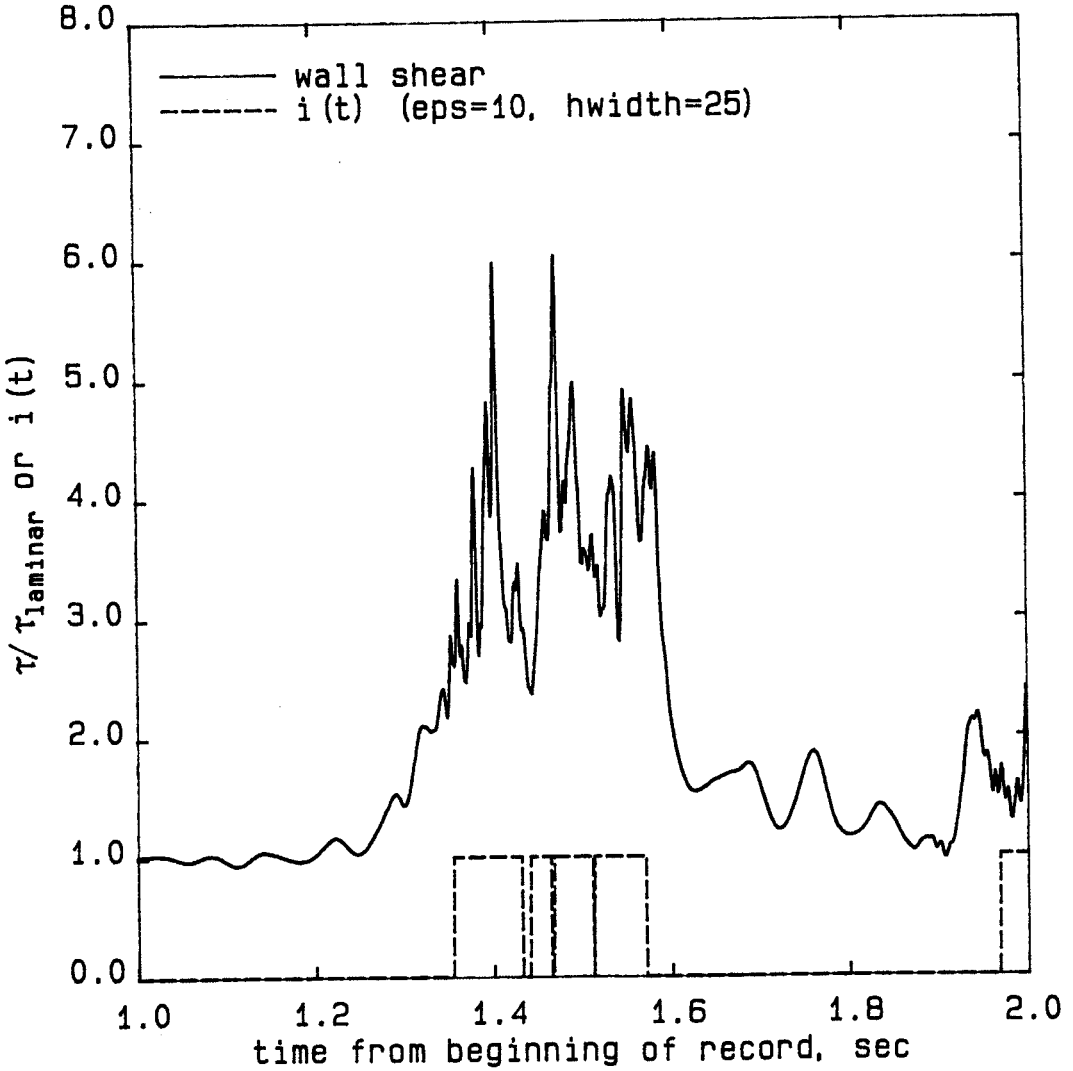


Figure C.5: Comparison of Intermittency Computation Procedures
20Hz 3 degree oblique waves, 192 watts, 4-13a
S8, $Re_{\delta^*} = 1750$
'eps' and 'hwidth' are cutoff and smoothing parameters