ON THE EVOLUTION OF LOCALIZED DISTURBANCES AND THEIR SPANWISE INTERACTIONS LEADING TO BREAKDOWN

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ABSTRACT

Localized Disturbances in a laminar boundary layers represent a more realistic model of transition than the extensively studied, two or quasy three-dimensional perturbations regardless of the fact if they evolve in a linear manner or not. Localized disturbances can originate by surface imperfections, insects or dust. The disturbances can be Harmonic (i.e. containing a single frequency and a complete set of spanwise wave numbers) or Pulsed (i.e containing a band of streamwise and spanwise wave numbers).

At sufficiently low amplitudes localized disturbances behave according to a linear stability model. It is highly probable that in a natural transition process such localized disturbances will overlap and interact. These interactions could either delay transition because of a partial wave cancellation resulting in an attenuation of the disturbance, or adversely enhance it by promoting non linear interactions. The non linearity could be simply amplitude dependent or cause a triad resonance. Non linear processes in a wave packet lead to breakdown and to the formation of turbulent spots. When the amplitude of the harmonic disturbance saturates, non linear prcesses widen the band of the lower amplified frequencies adjacent to the frequency of excitation.

Experimental results describing the spanwise interactions of harmonic and pulsed localized disturbances leading to breakdown will be presented and discussed. A comparison to the evolution and breakdown of a single localized disturbance will be provided.

1)

On the Evolution of Localized Disturbances and their Spanwise Interactions Leading to Breakdown

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Acknowledgments: Y. Mitnik, B. Margaliot.

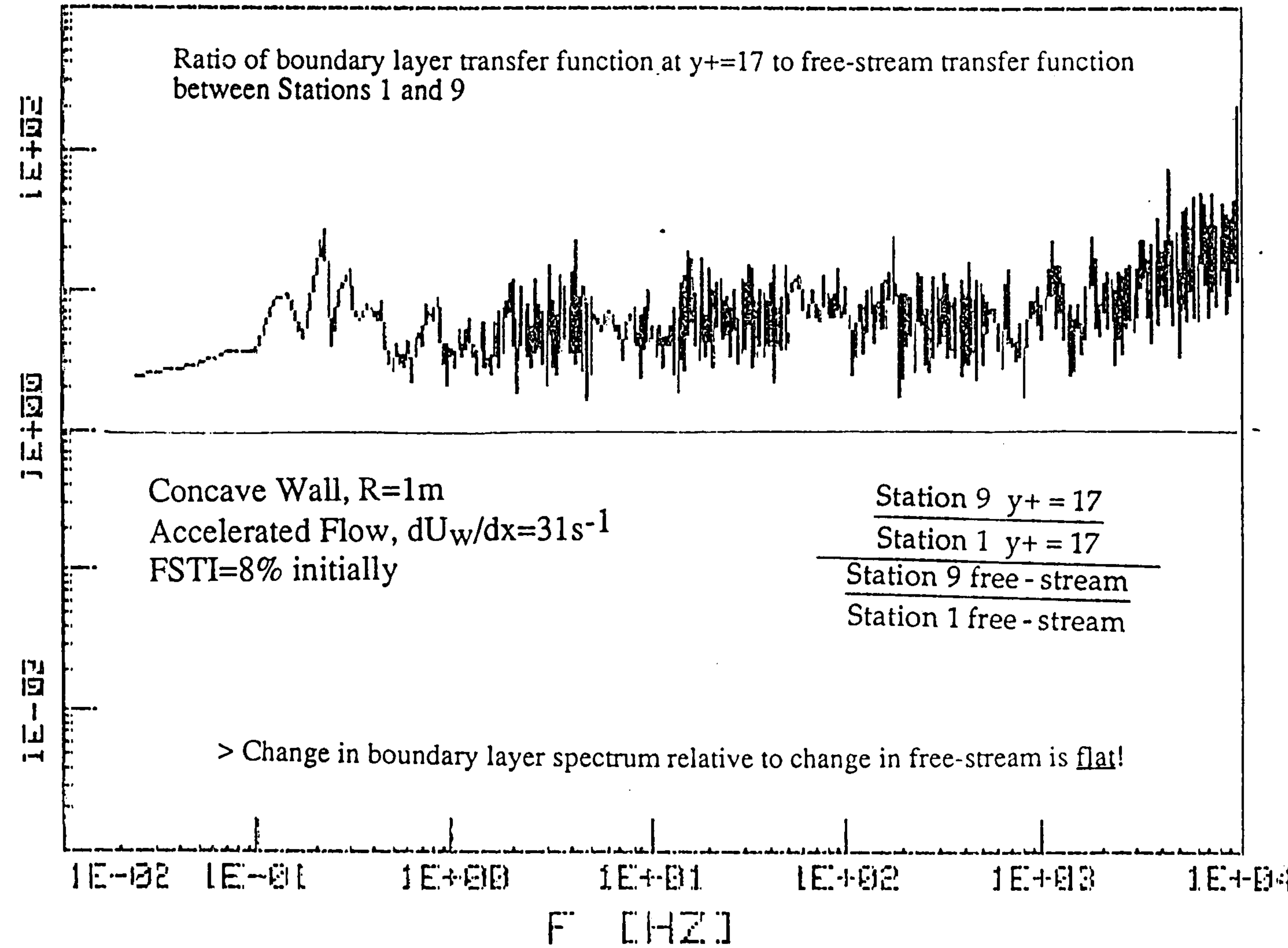
OBJECTIVES

DOES SPANWISE INTERACTION OF LOCALIZED DISTURBANCES PROMOTES TRANSITION ?

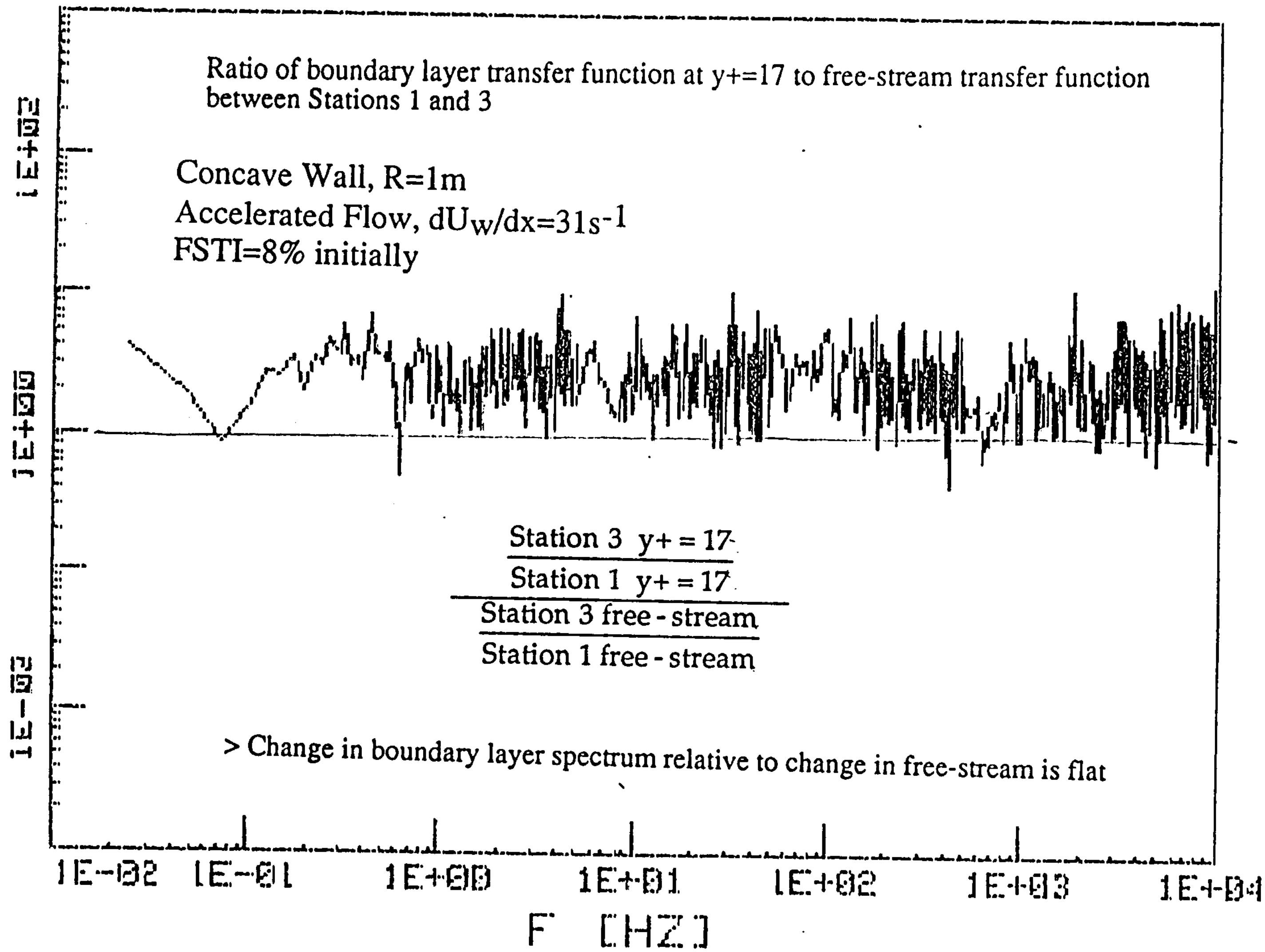
Comments about NATURE of TRANSITION
due to an ISOLATED:
Harmonic Point Source and Wave Packet

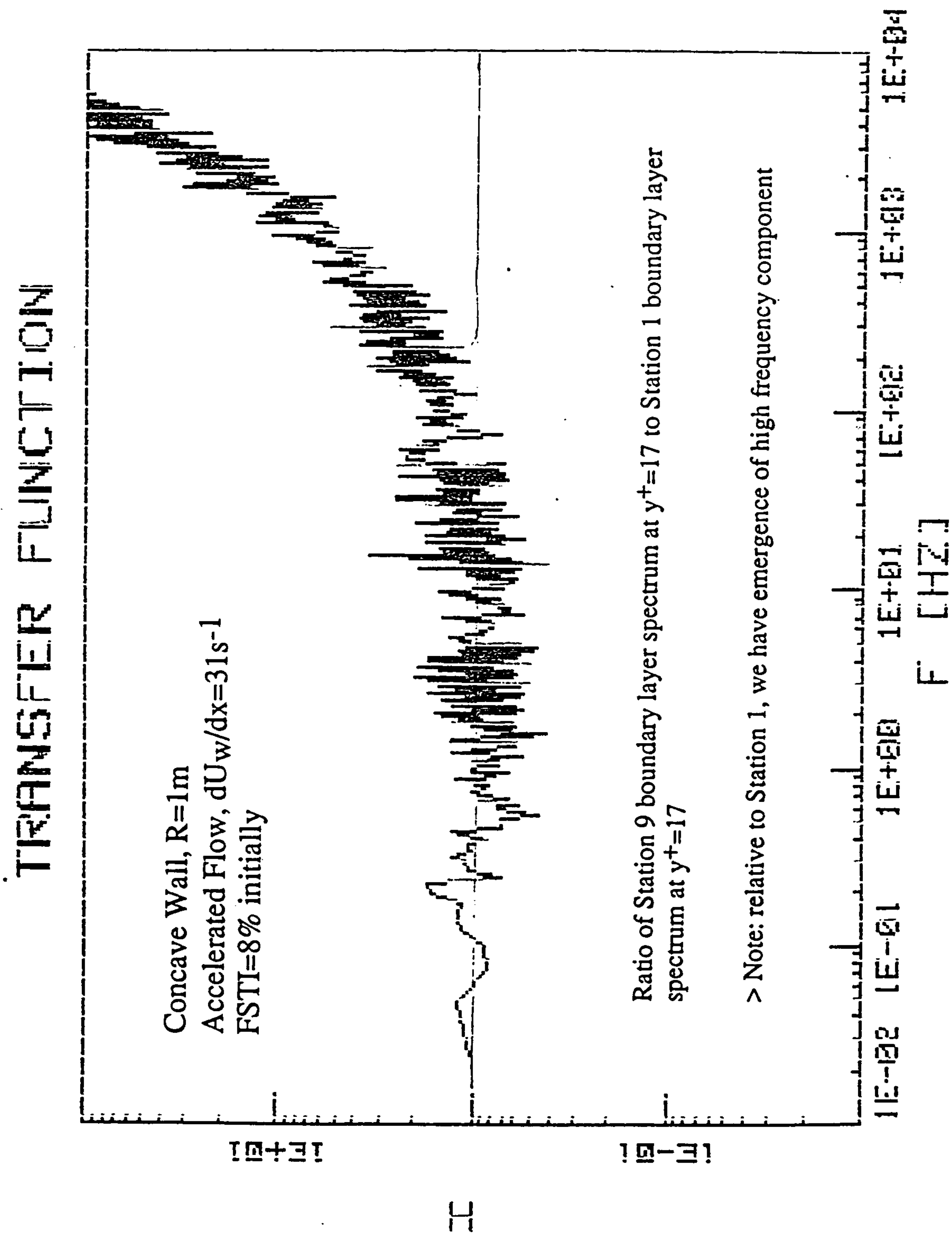
Relevance / Difference between TRANSITION
due to TWO HPS INTERACTION and TWO WP INTERACTION
(leading to breakdown)

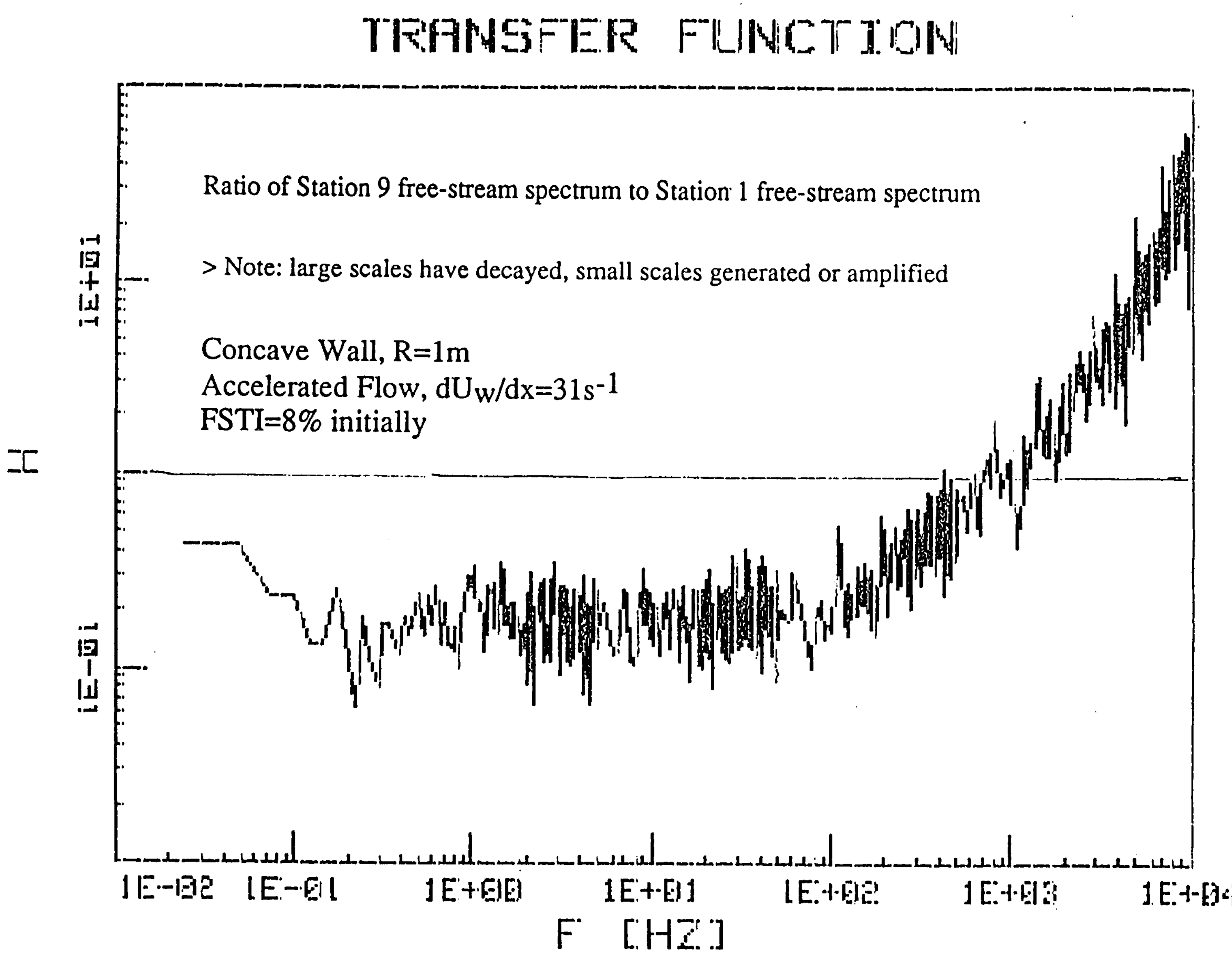
SPECTRA RATIO

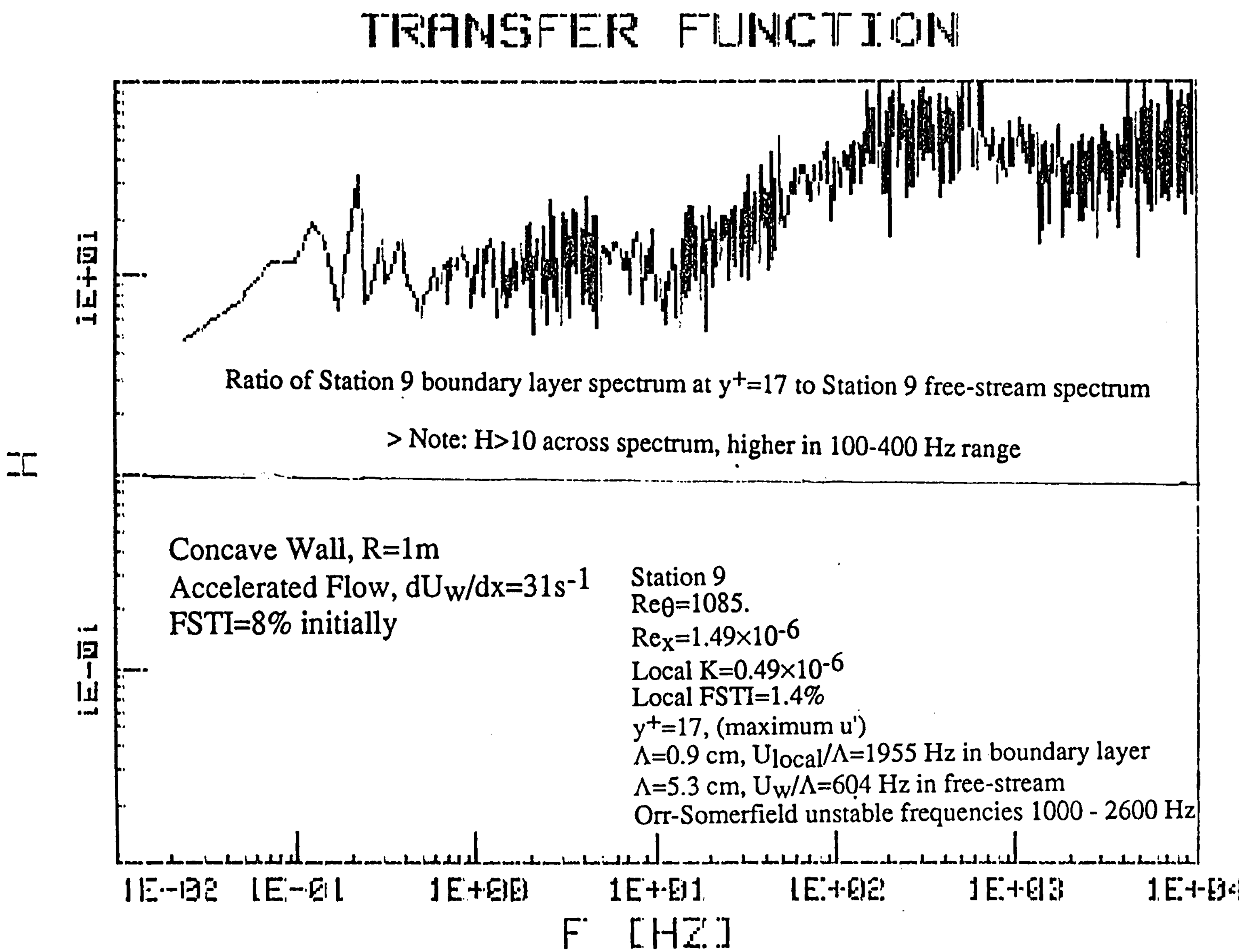


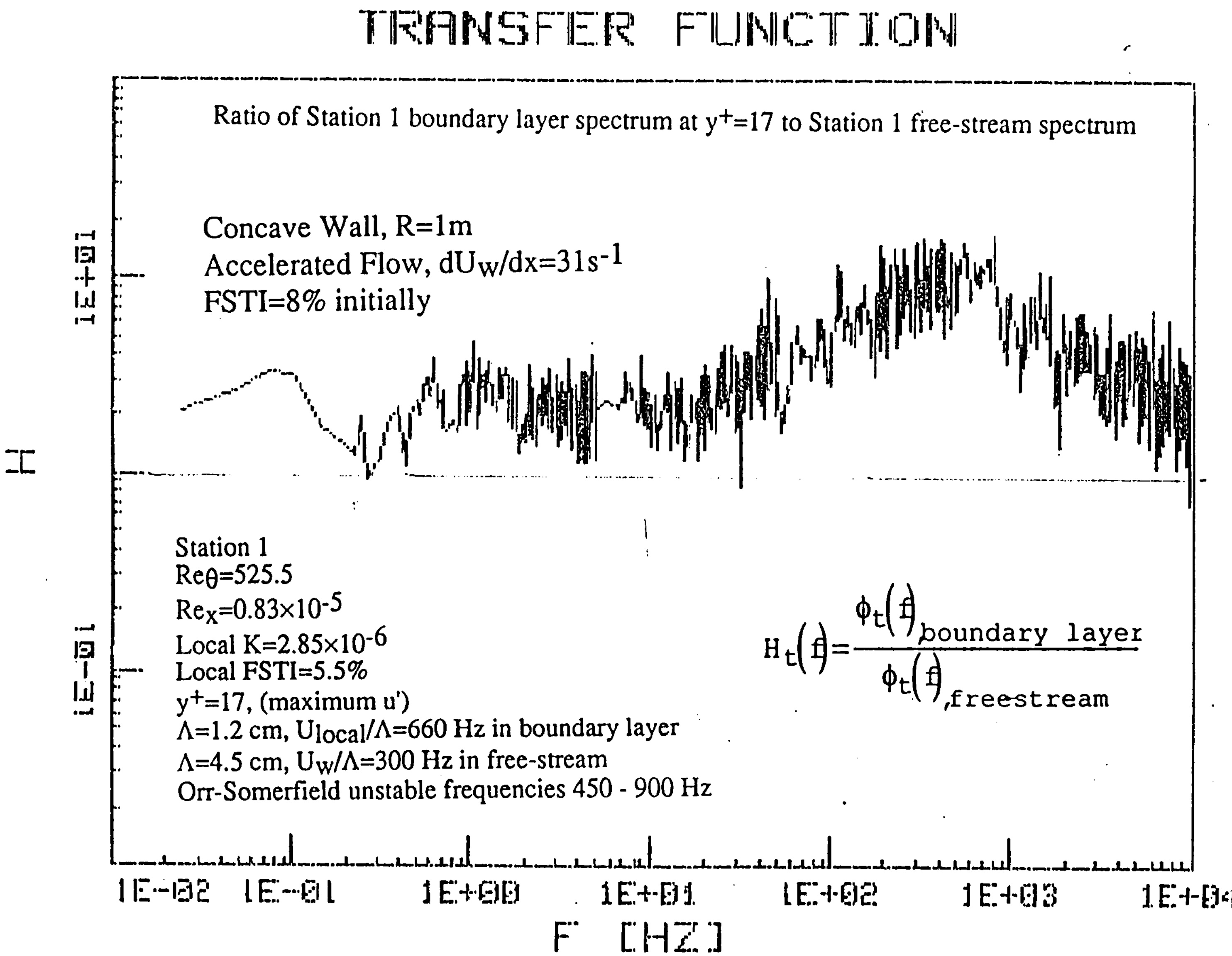
SPECTRA RATIO



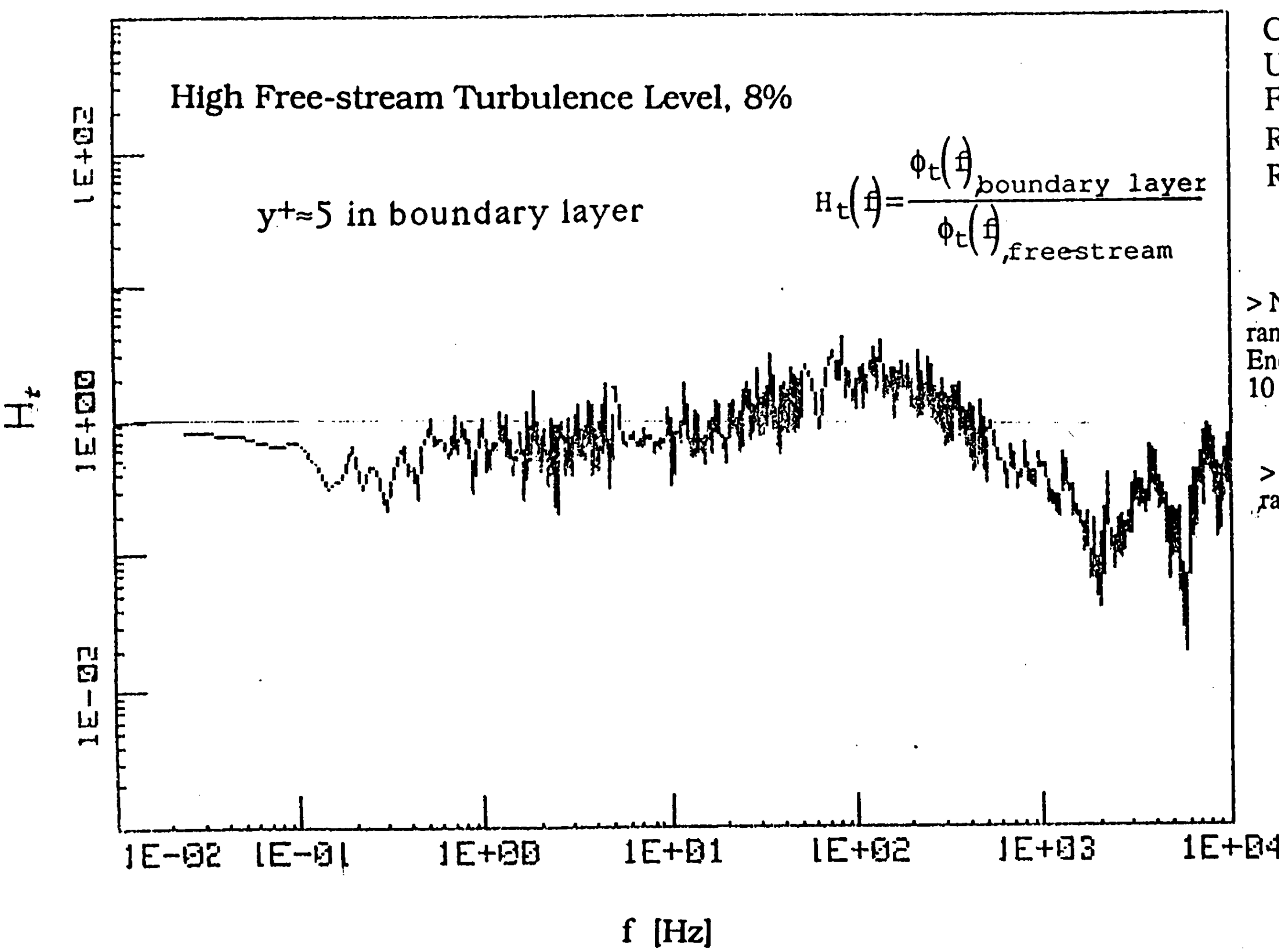

TRANSFER FUNCTION
Concave Wall, R=1m
Accelerated Flow, dUw/dx=31s-1
FSTI=8% initially
Ratio of Station 9 boundary layer spectrum at y+=17 to Station 1 boundary layer spectrum at y+=17
> Note: relative to Station 1, we have emergence of high frequency component
1E-02
1E-01
1E+00
1E+01
1E+02
1E+03
1E+04
F [HZ]
1E+01
1E-01
H


TRANSFER FUNCTION
Ratio of Station 9 free-stream spectrum to Station 1 free-stream spectrum
> Note: large scales have decayed, small scales generated or amplified
Concave Wall, R=1m
Accelerated Flow, $dU_w/dx=31s^{-1}$
FSTI=8% initially
1E+01
1E-01
H
1E-02
1E-01
1E+00
1E+01
1E+02
1E+03
1E+04
F [HZ]


TRANSFER FUNCTION
H
1E+01
1E-01
Ratio of Station 9 boundary layer spectrum at y+=17 to Station 9 free-stream spectrum
> Note: H>10 across spectrum, higher in 100-400 Hz range
Concave Wall, R=1m
Accelerated Flow, dUw/dx=31s-1
FSTI=8% initially
Station 9
Reθ=1085.
Rex=1.49×10-6
Local K=0.49×10-6
Local FSTI=1.4%
y+=17, (maximum u')
Λ=0.9 cm, Ulocal/Λ=1955 Hz in boundary layer
Λ=5.3 cm, Uw/Λ=604 Hz in free-stream
Orr-Somerfield unstable frequencies 1000 - 2600 Hz
1E-02
1E-01
1E+00
1E+01
1E+02
1E+03
1E+04
F [HZ]


TRANSFER FUNCTION
Ratio of Station 1 boundary layer spectrum at y+=17 to Station 1 free-stream spectrum
Concave Wall, R=1m
Accelerated Flow, dUw/dx=31s-1
FSTI=8% initially
Station 1
Reθ=525.5
Rex=0.83×10-5
Local K=2.85×10-6
Local FSTI=5.5%
y+=17, (maximum u')
Λ=1.2 cm, Ulocal/Λ=660 Hz in boundary layer
Λ=4.5 cm, Uw/Λ=300 Hz in free-stream
Orr-Somerfield unstable frequencies 450 - 900 Hz
Ht(f)= φt(f)boundary layer / φt(f)freestream
H
1E+01
1E-01
1E-02
1E-01
1E+00
1E+01
1E+02
1E+03
1E+04
F [HZ]

TRANSFER FUNCTION

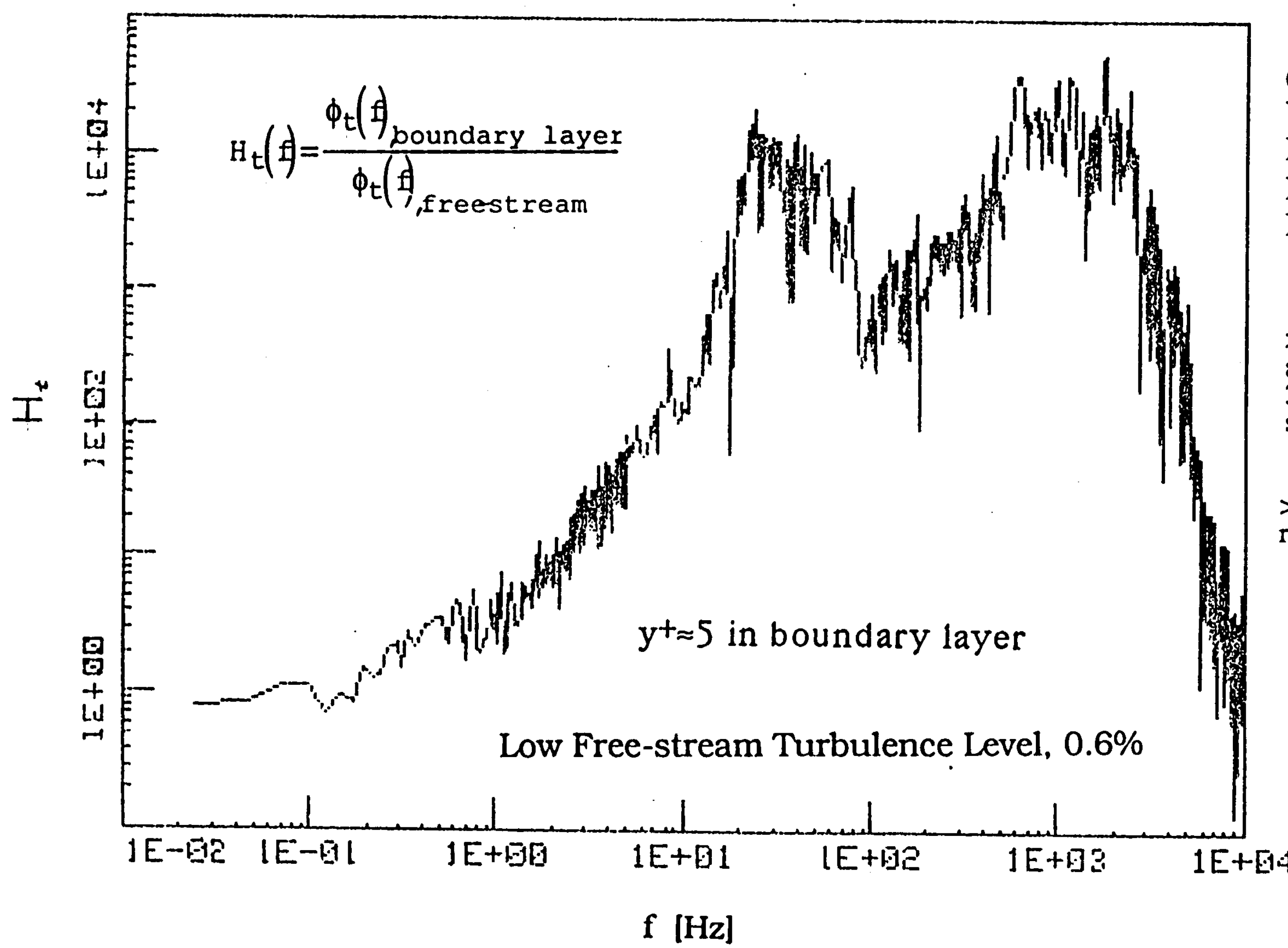


Concave Wall, R=1m
Unaccelerated Flow
FSTI=8%
$Re_x=1.12\times10^5$
$Re_\theta=366$

> Note, H≈2 in the 50 - 300 Hz range. Damped above 300 Hz. Energy in free-stream disributed over 10 - 2000 Hz.

> Orr-Somerfield unstable frequency range, 1200 - 1900 Hz.

TRANSFER FUNCTION

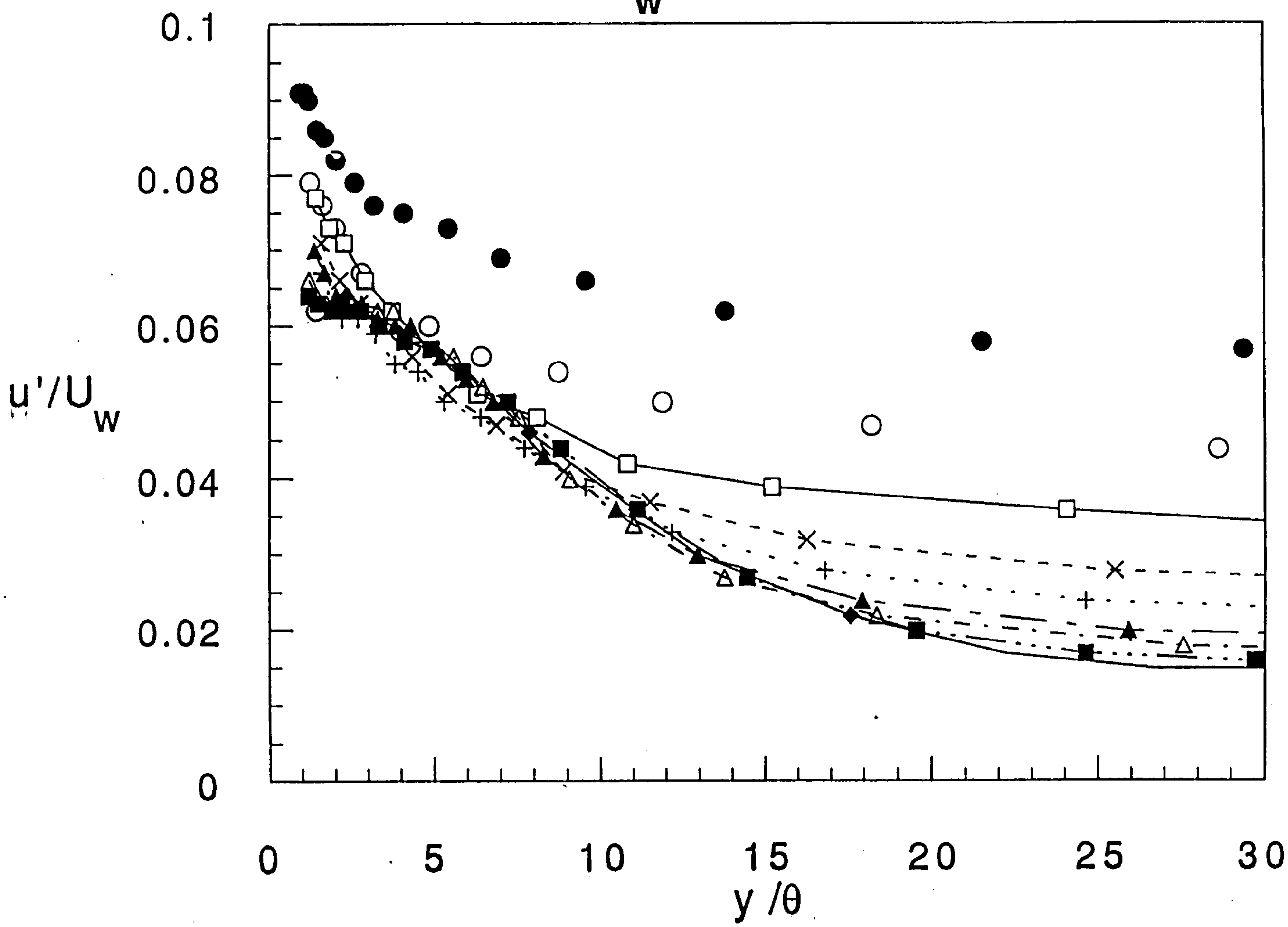


Concave Wall, R=1m
Unaccelerated Flow
FSTI=0.6%
$Re_x=3.6\times10^5$
$Re_\theta=560$

> Note, high ratios in the approximate ranges 20 - 60 Hz and 300 - 3000 Hz. Energy in the free-stream in range 0 - 20 Hz.

> Orr-Somerfield unstable frequency range, 310 - 840 Hz.

Normal Stress Profiles, Concave Wall, R=1m
Accelerated, $dU_w/dx = 31\ s^{-1}$, FSTI=8%

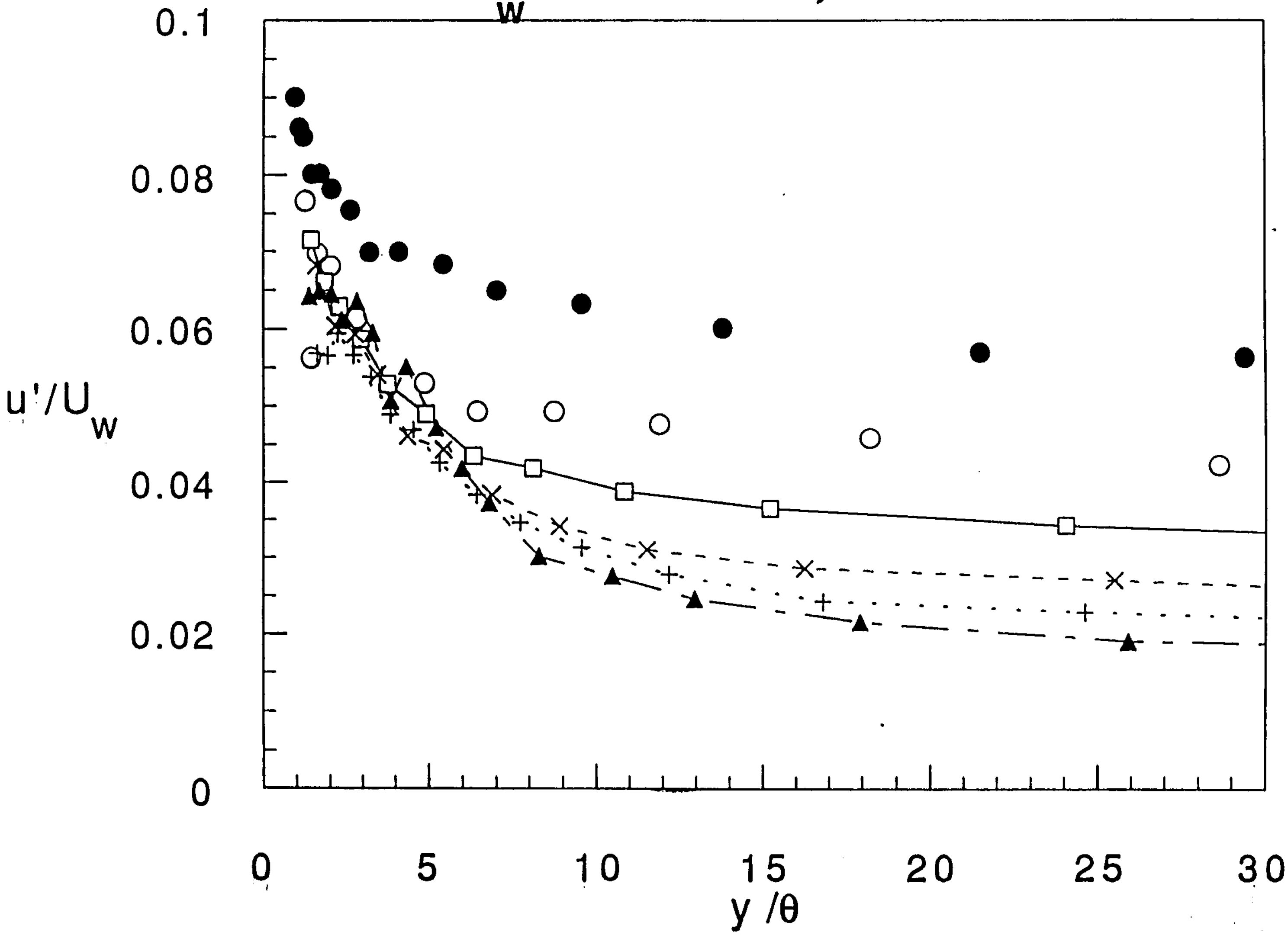


> For comparison to the next figure.

	Reθ	Rex×10⁻⁵
●	525.5	0.83
○	462.4	1.85
□	467.9	2.93
×	488.6	4.49
+	549.2	6.23
▲	689.1	7.96
△	839.4	9.86
■	920.9	12.4
◆	1085.	14.9

Normal Stress Profiles, Non-Turbulent Zone Concave Wall, R=1m, Accelerated

$dU_w/dx = 31\ s^{-1}$, FSTI=8%



> Note the very large contribution from the non-turbulent zone.

	Re_θ	$Re_x \times 10^5$
●	525.5	0.83
○	462.4	1.85
□	467.9	2.93
×	488.6	4.49
+	549.2	6.23
▲	689.1	7.96

> u' laminar -- values computed from measurements taken only when flow is identified to be non-turbulent -- based upon the u' signal.

Development of Velocity and Temperature Profile Correlations for Accelerated Flow

- Start with boundary layer equation

  Assume constant properties

$$\rho u\frac{\partial u}{\partial x}+\rho v\frac{\partial u}{\partial y}-\frac{\partial \tau}{\partial y}+\frac{dP}{dx}=0$$

- Do not make Couette flow assumptions
- Do not set dP/dx term to zero
- Eliminate v using continuity equation
- Intergrate from zero to y
- Convert to wall coordinates

  For convection terms,

$$\int(a)dy=\int(b)dy^+ +\int(c)dx$$

  Assume history independent and set last integral to zero

- Resulting equation

$$\frac{\tau}{\tau_o}=1+p^+y^+ +\left(\frac{K}{\sqrt{\frac{c_f}{2}}}+\frac{\nu}{U_\infty\frac{c_f}{2}}\frac{d\sqrt{\frac{c_f}{2}}}{dx}\right)\int_0^{y^+}u^{+2}dy^+$$

- Apply mixing length model with vanDriest damping

$$\frac{\tau}{\tau_o}=\left(1+\kappa^2y^{+2}\left(1-e^{-y^+/A^+}\right)^2\frac{du^+}{dy^+}\right)\frac{du^+}{dy^+}$$

  k=0.41

  Variable A^+ as a function of p^+

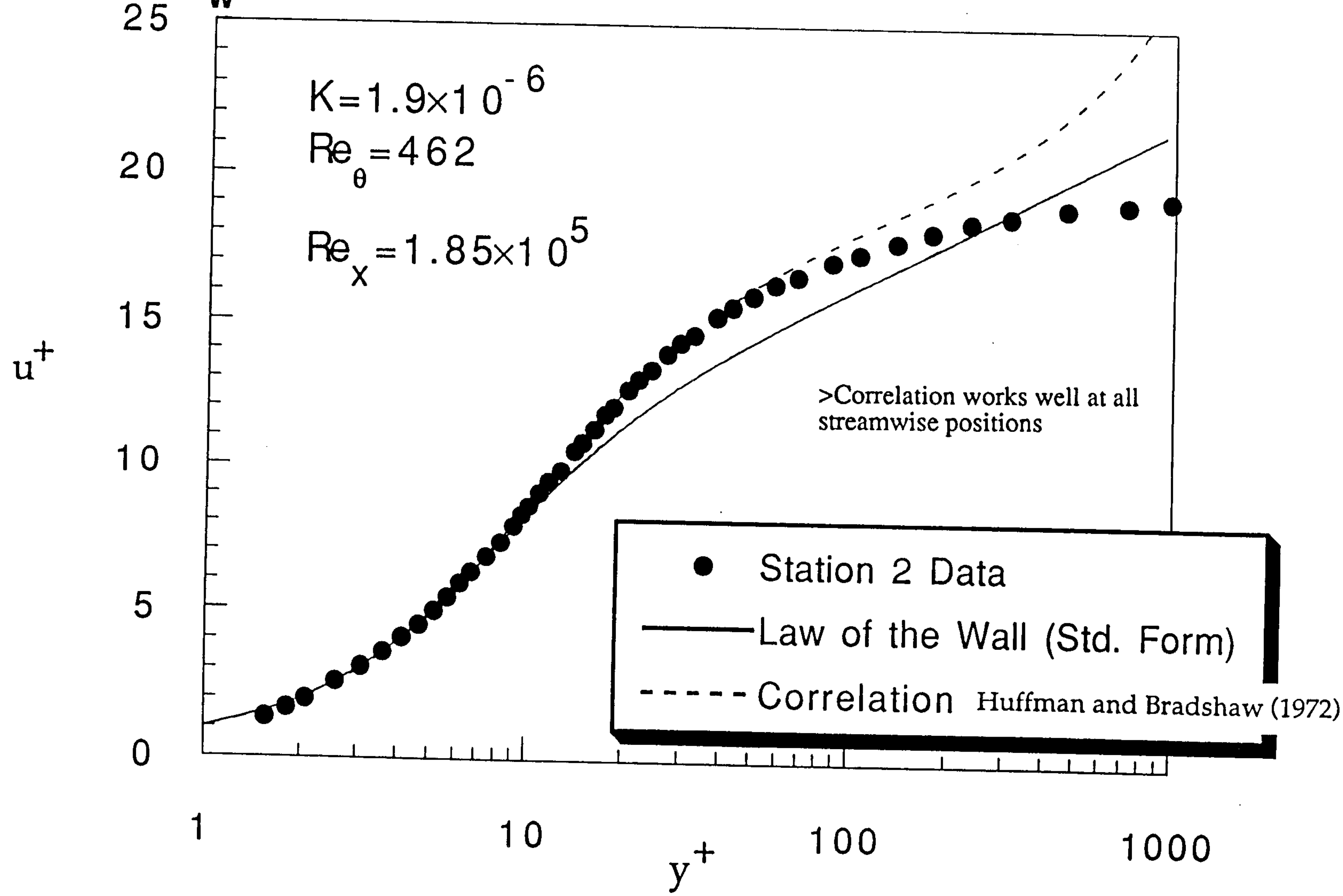
- Solve for du^+/dy^+ and integrate

$$u^+=\int_0^{y^+}\left[\frac{-1+\sqrt{1+4\left(1+p^+y^+ +\left(\frac{K}{\sqrt{\frac{c_f}{2}}}+\frac{\nu}{U_\infty\frac{c_f}{2}}\frac{d\sqrt{\frac{c_f}{2}}}{dx}\right)\int_0^{y^+}u^{+2}dy^+\right)\left(\kappa^2y^{+2}\left(1-e^{-y^+/A^+}\right)^2\right)}}{2\left(\kappa^2y^{+2}\left(1-e^{-y^+/A^+}\right)^2\right)}\right]dy^+$$

- Similar derivation for temperature profile. For constant heat flux b.c.:

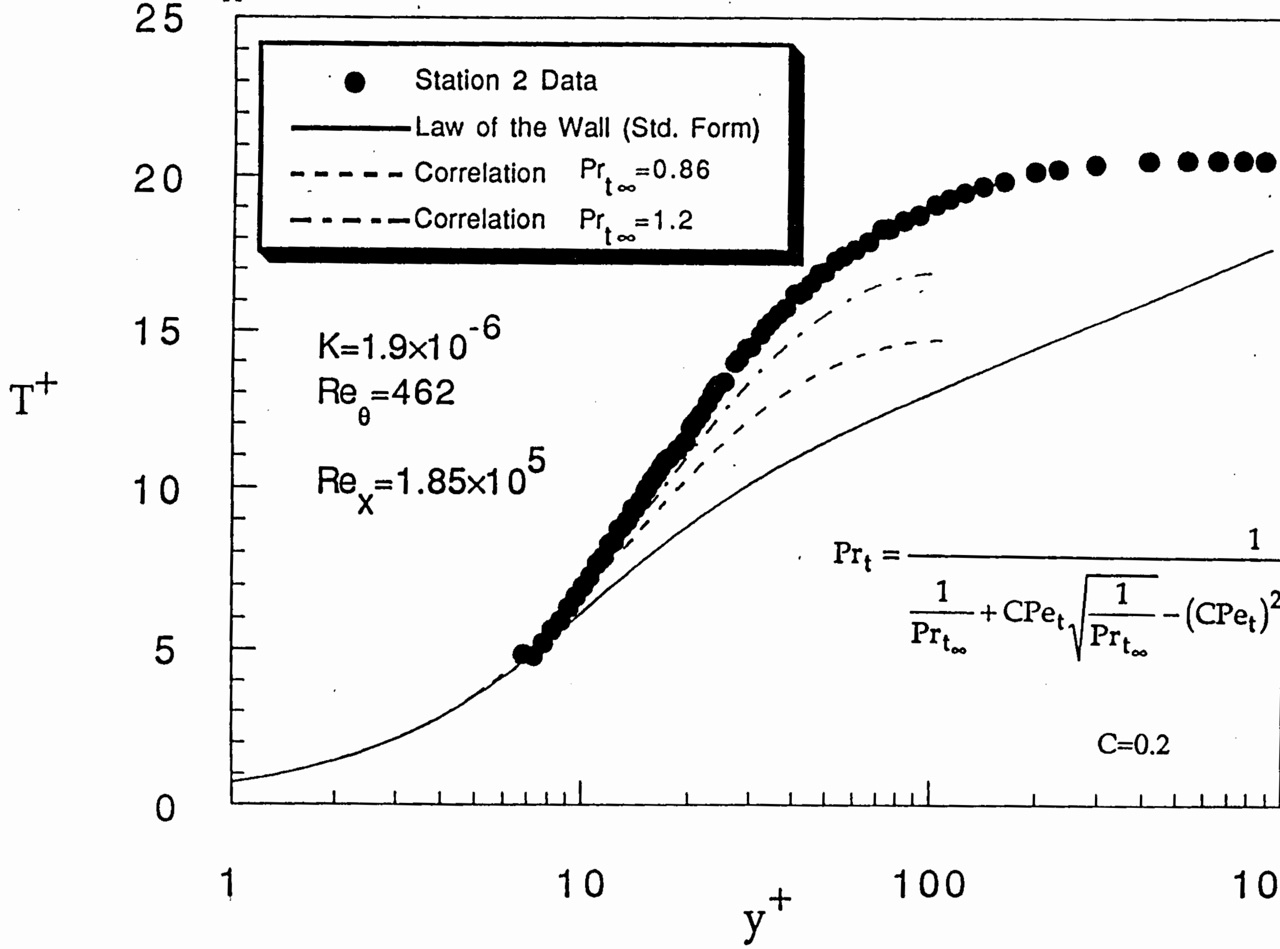
$$t^+=\int_0^{y^+}\left[\frac{1+\left(\frac{t_\infty^{+2}\nu}{U_\infty\frac{c_f}{2}}\frac{dSt}{dx}+\frac{Kt_\infty^+}{\sqrt{\frac{c_f}{2}}}\right)\int_0^{y^+}u^+dy^+ -\left(\frac{K}{\sqrt{\frac{c_f}{2}}}+\frac{\nu}{U_\infty\frac{c_f}{2}}\frac{d\sqrt{\frac{c_f}{2}}}{dx}\right)\int_0^{y^+}u^+t^+dy^+}{\frac{1}{Pr}+\frac{\kappa^2y^{+2^+}\left(1-e^{-y^+/A^+}\right)^2}{Pr_t}\frac{du^+}{dy^+}}\right]dy^+$$

Velocity Profile, Accelerated Flow $dU_w/dx = 31\,s^{-1}$, Transitional Station



Temperature Profile, Accelerated Flow

$dU_w/dx = 31\,s^{-1}$, Transitional Station



$Pr_{t\infty}=0.86$ as recommended by Kays and Crawford (1980)

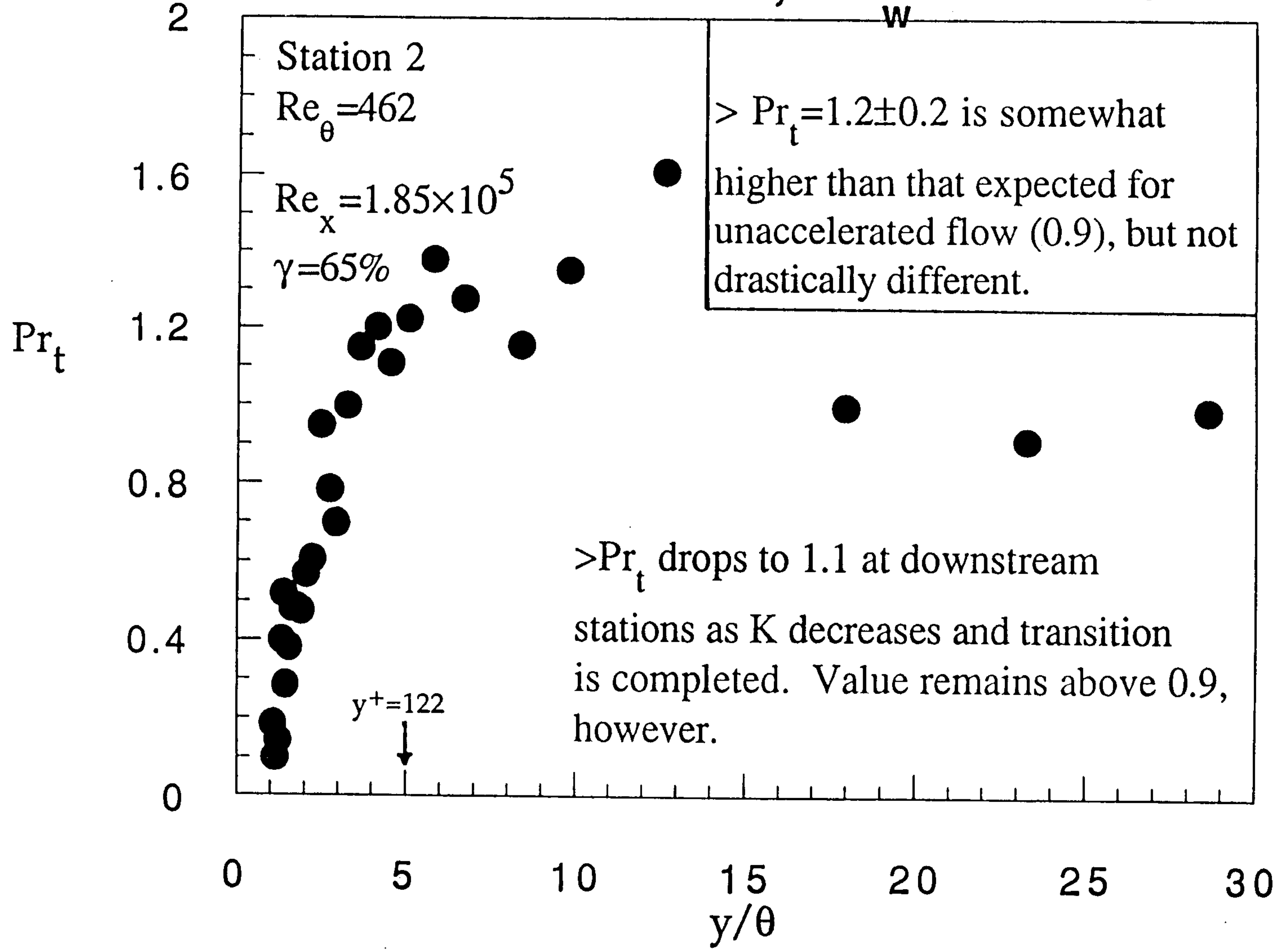
$Pr_{t\infty}=1.2$ from measurements (as shown in next figure)

>Correlations works best at upstream stations

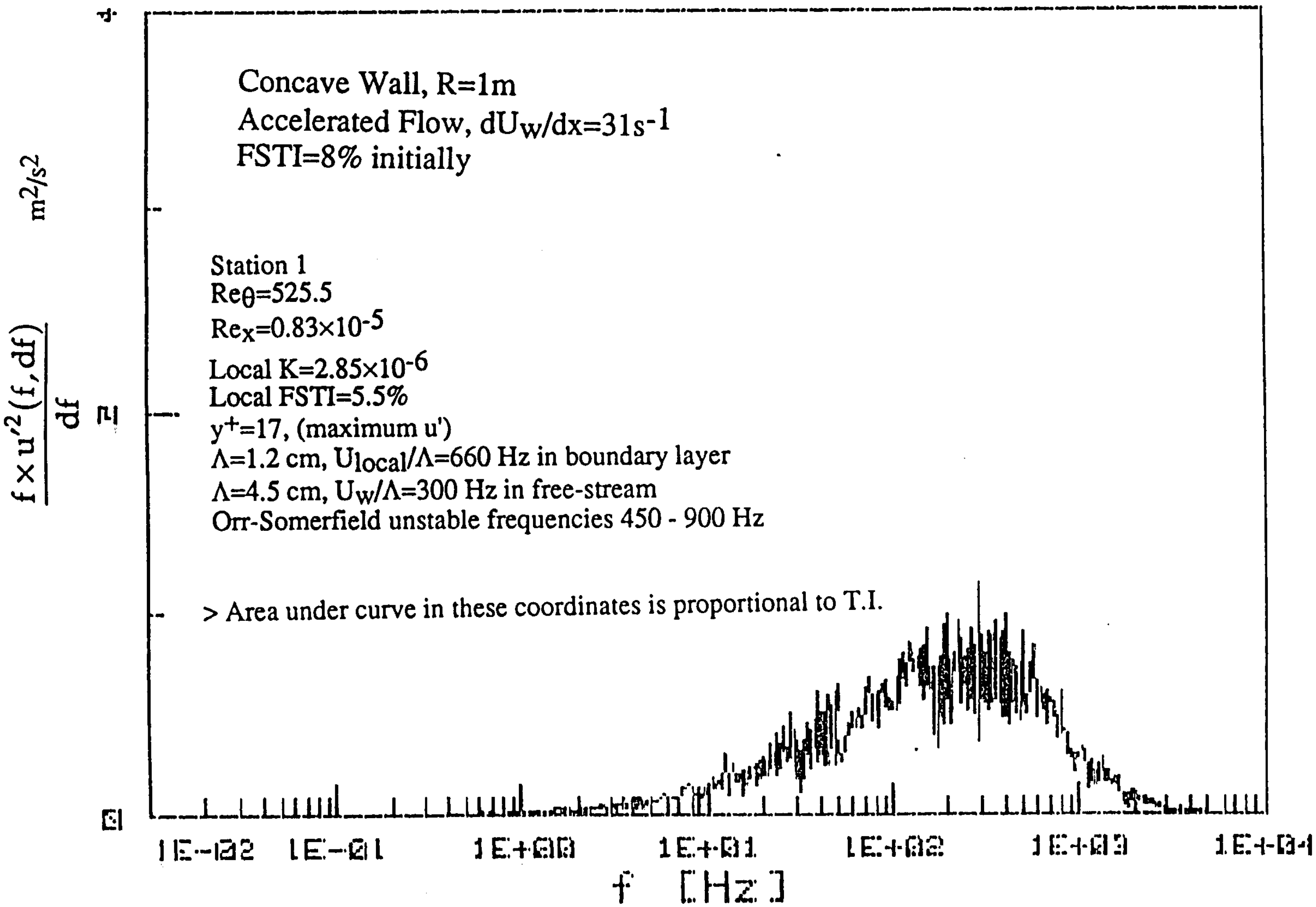
$$Pr_t = \frac{1}{\frac{1}{Pr_{t\infty}} + CPe_t\sqrt{\frac{1}{Pr_{t\infty}}} - (CPe_t)^2\left[1-\exp\left(-\frac{1}{CPe_t\sqrt{Pr_{t\infty}}}\right)\right]}$$

C=0.2

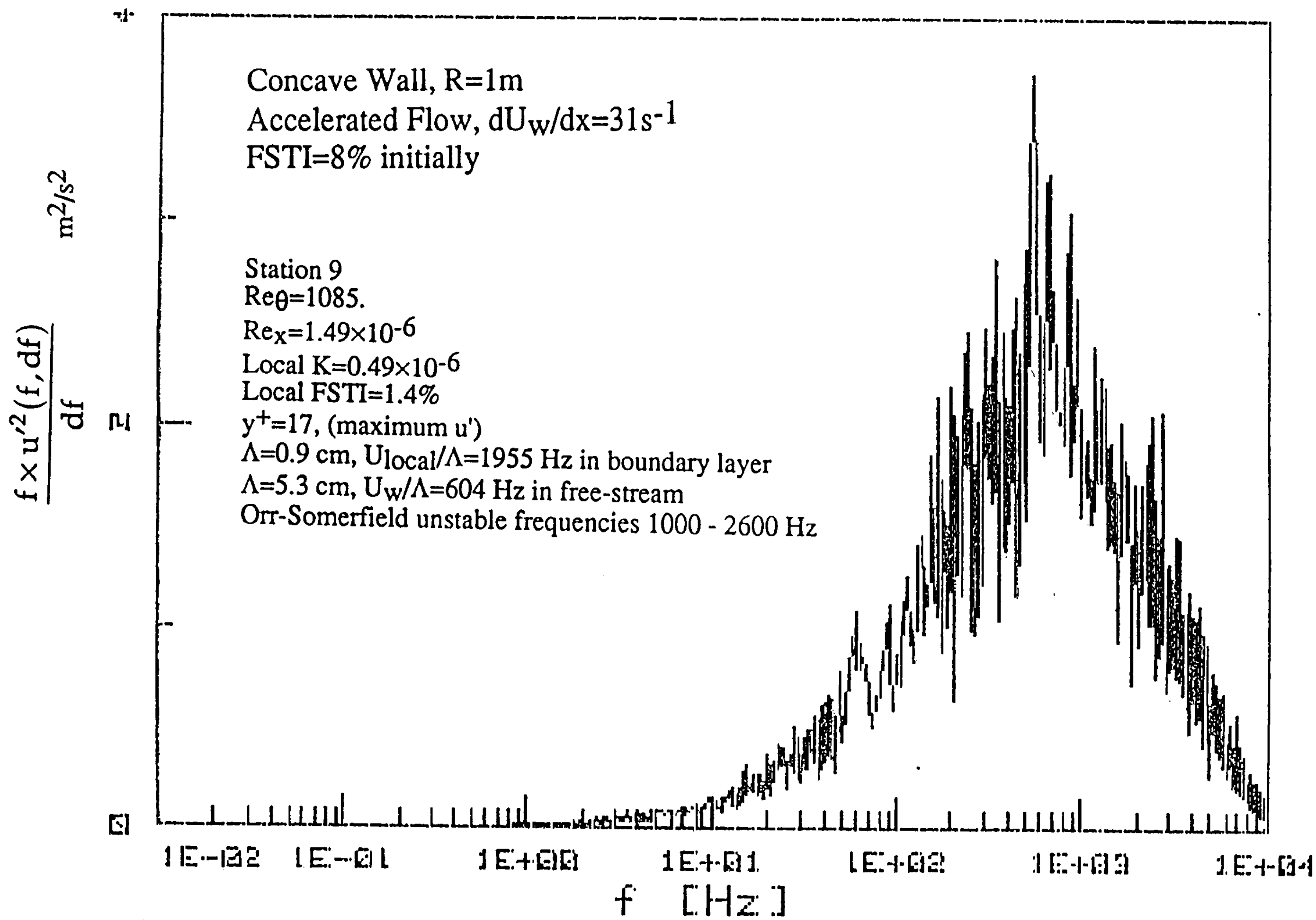
Turbulent Prandtl Number
Concave Wall, R=1m
Accelerated Flow, $dU_w/dx = 31\,s^{-1}$



BOUNDARY LAYER SPECTRA



BOUNDARY LAYER SPECTRA



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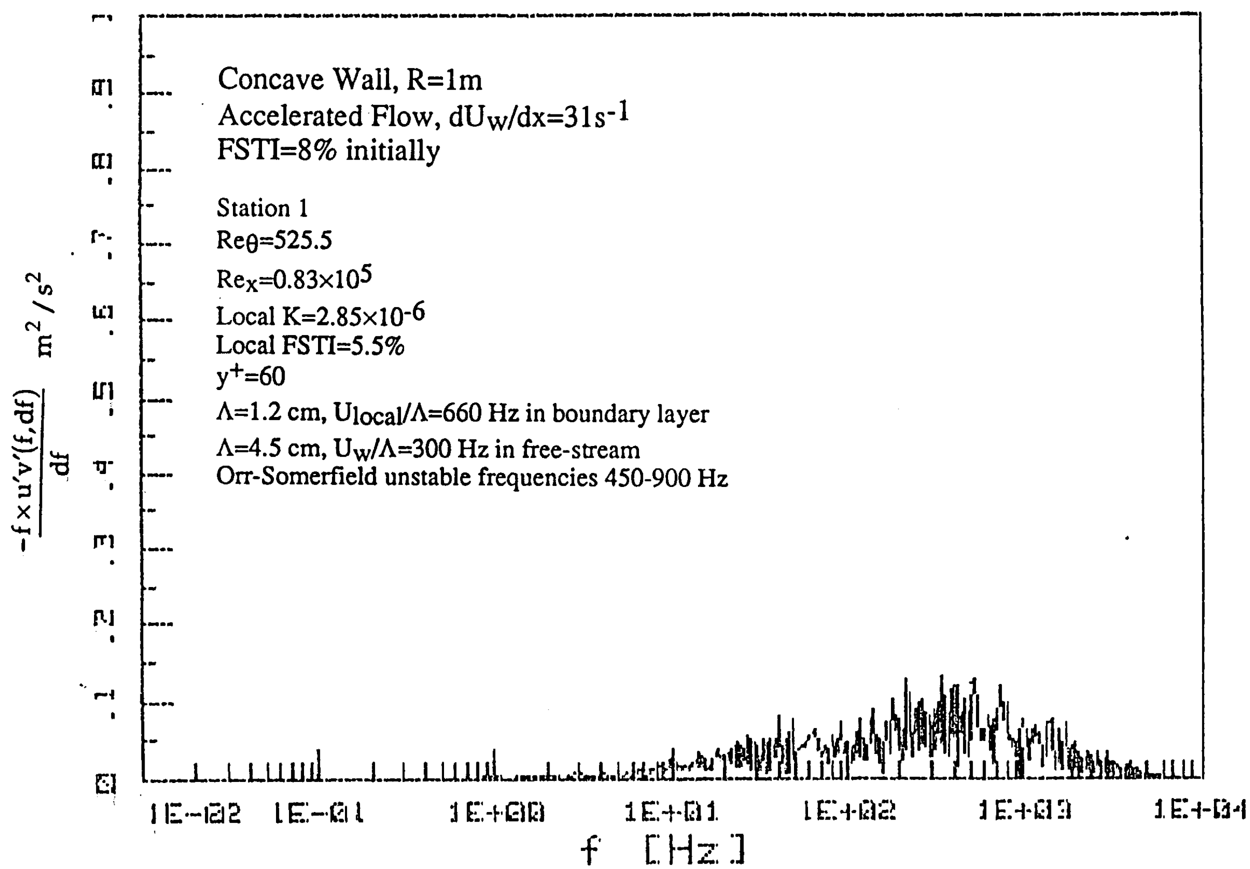
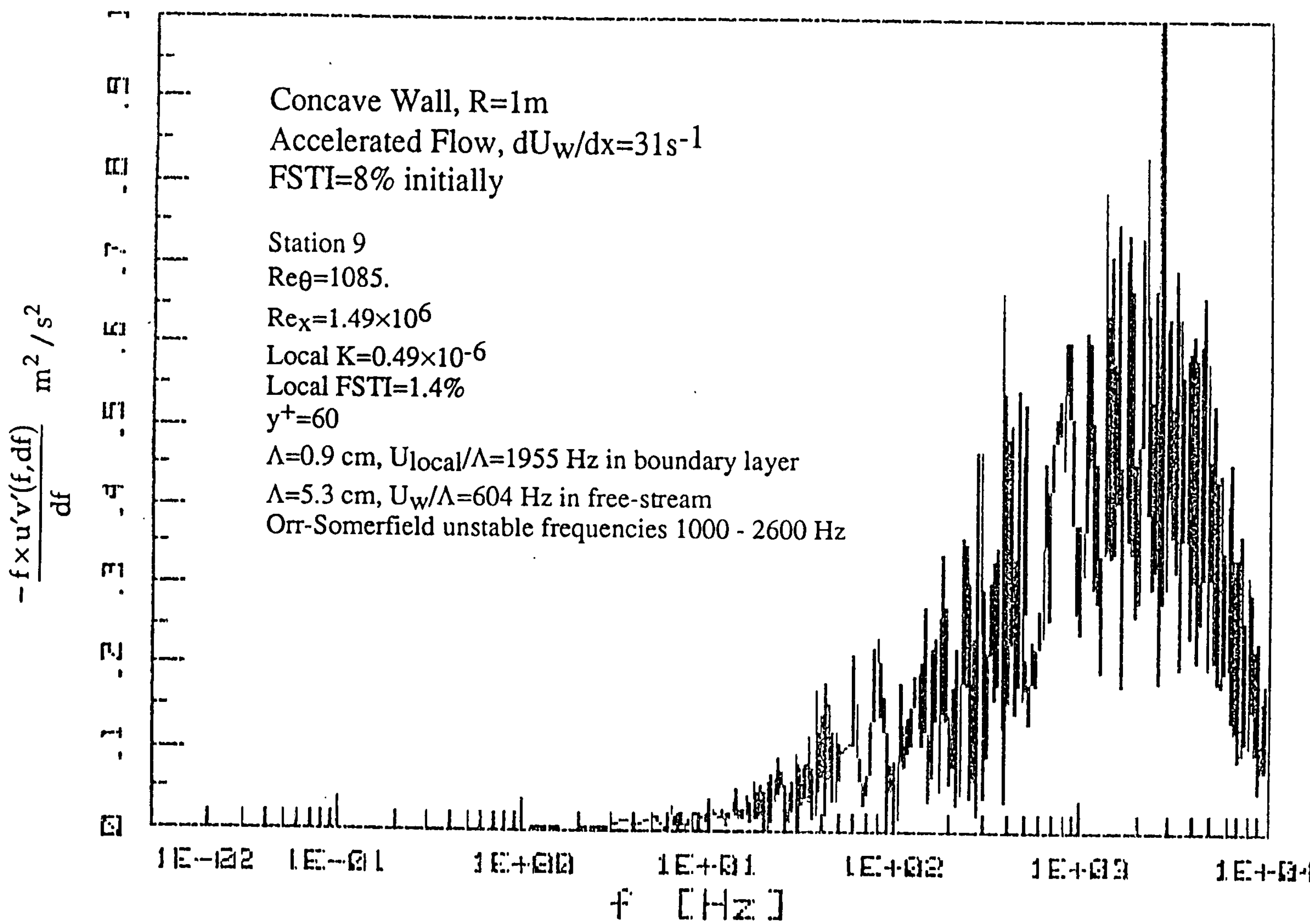
BOUNDARY LAYER SHEAR STRESS SPECTRA

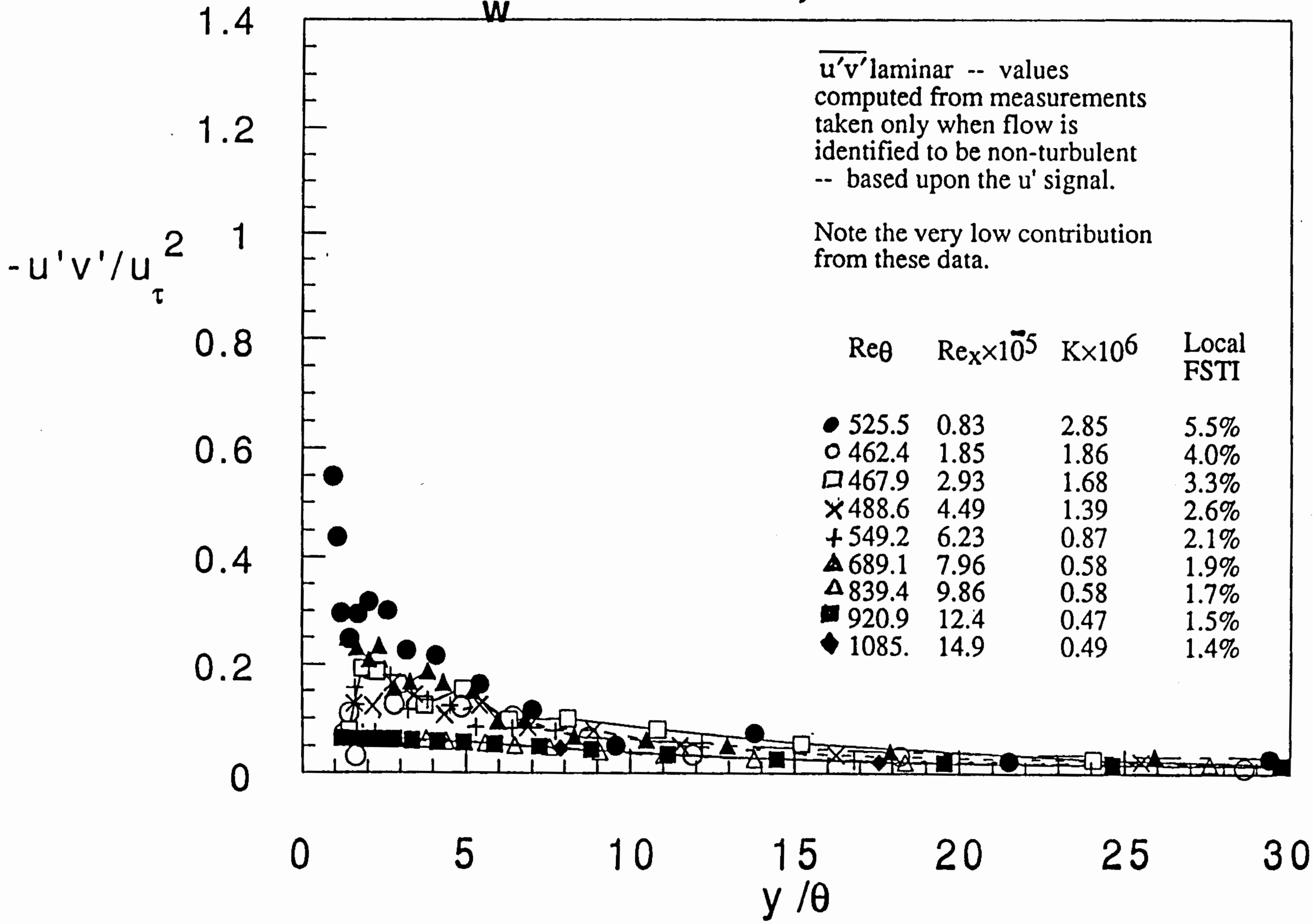


BOUNDARY LAYER SHEAR STRESS SPECTRA



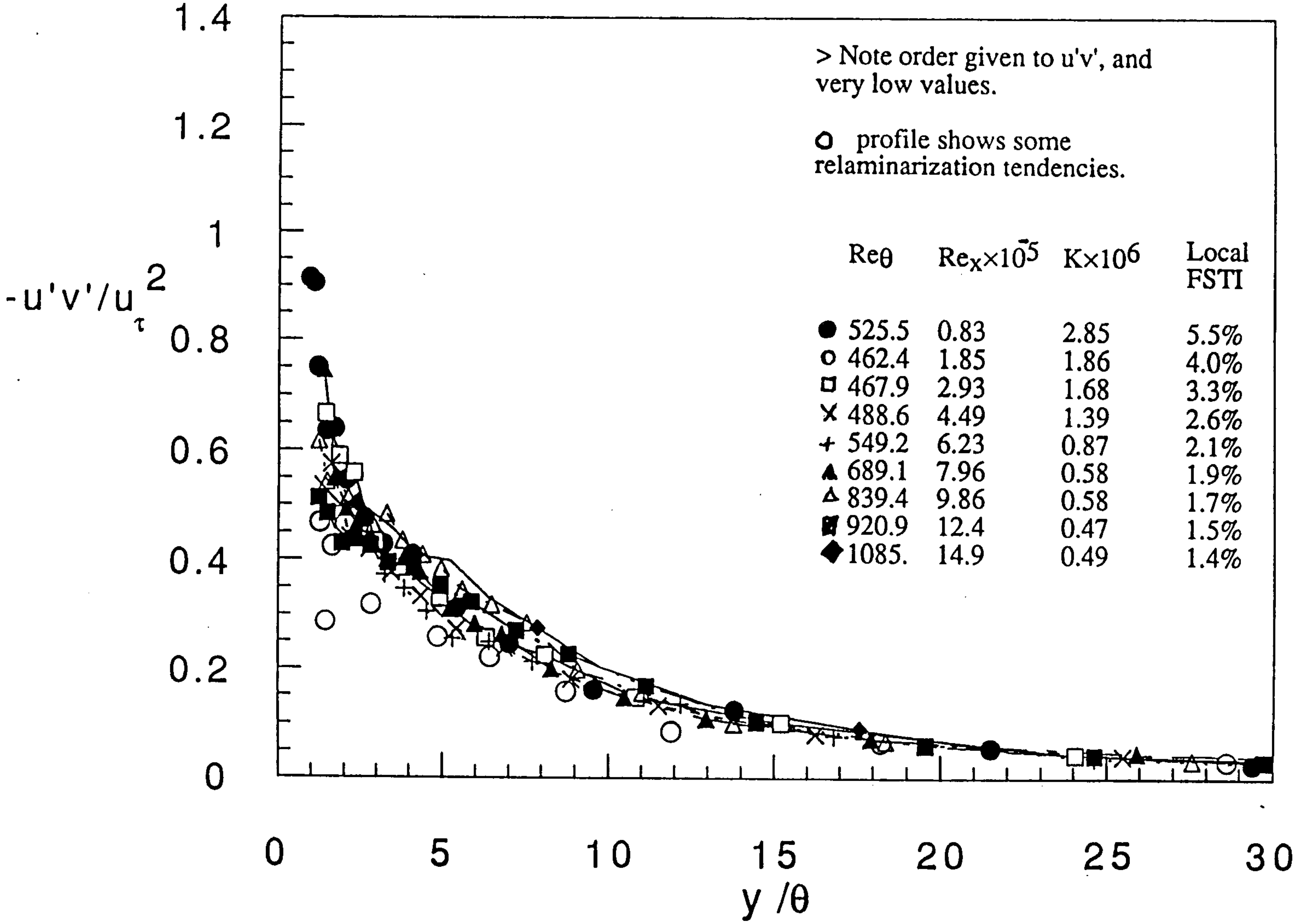
Shear Stress Profiles, Non-Turbulent Zone Concave Wall, R=1m, Accelerated

$dU_w/dx = 31\, s^{-1}$, FSTI=8%

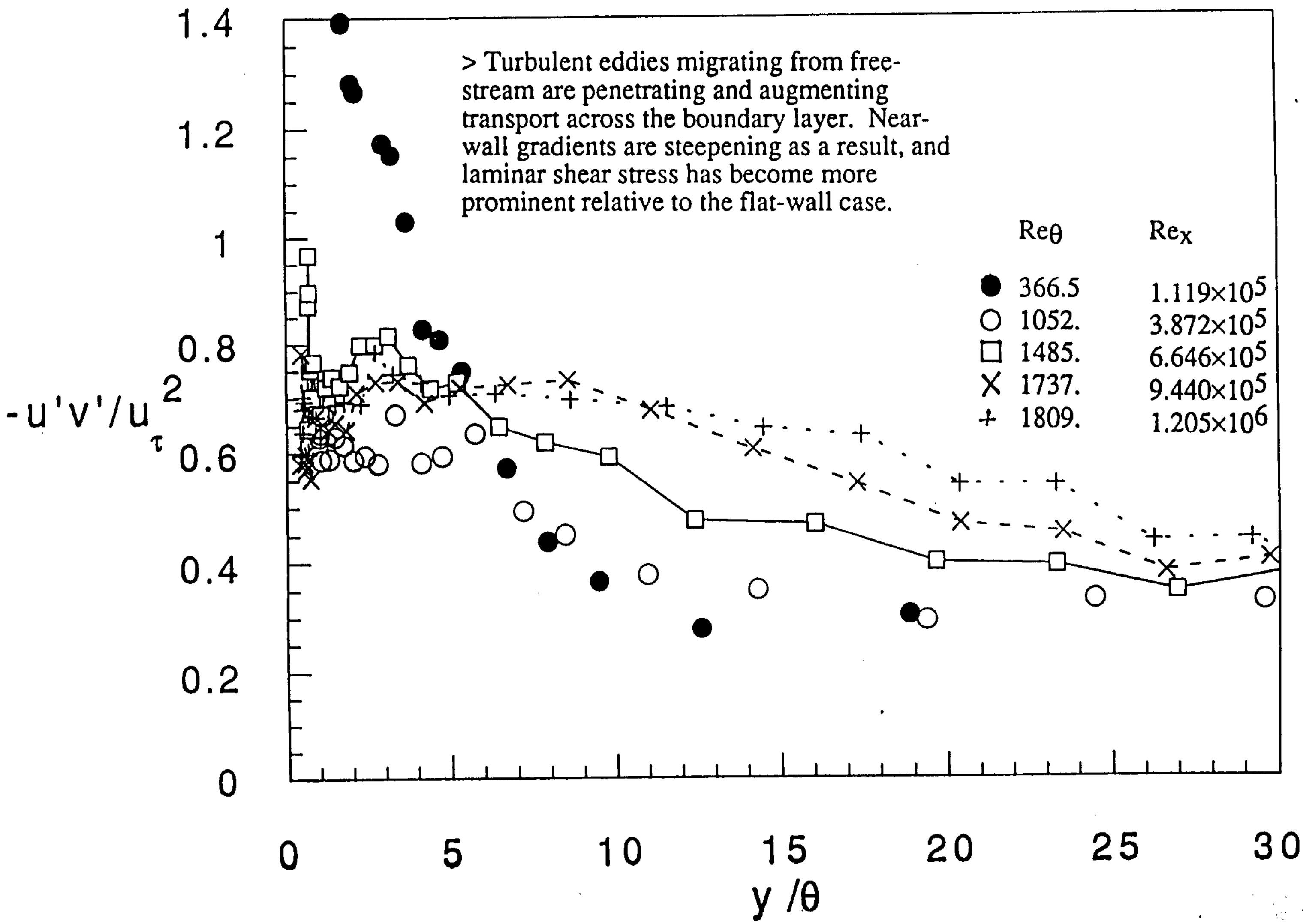


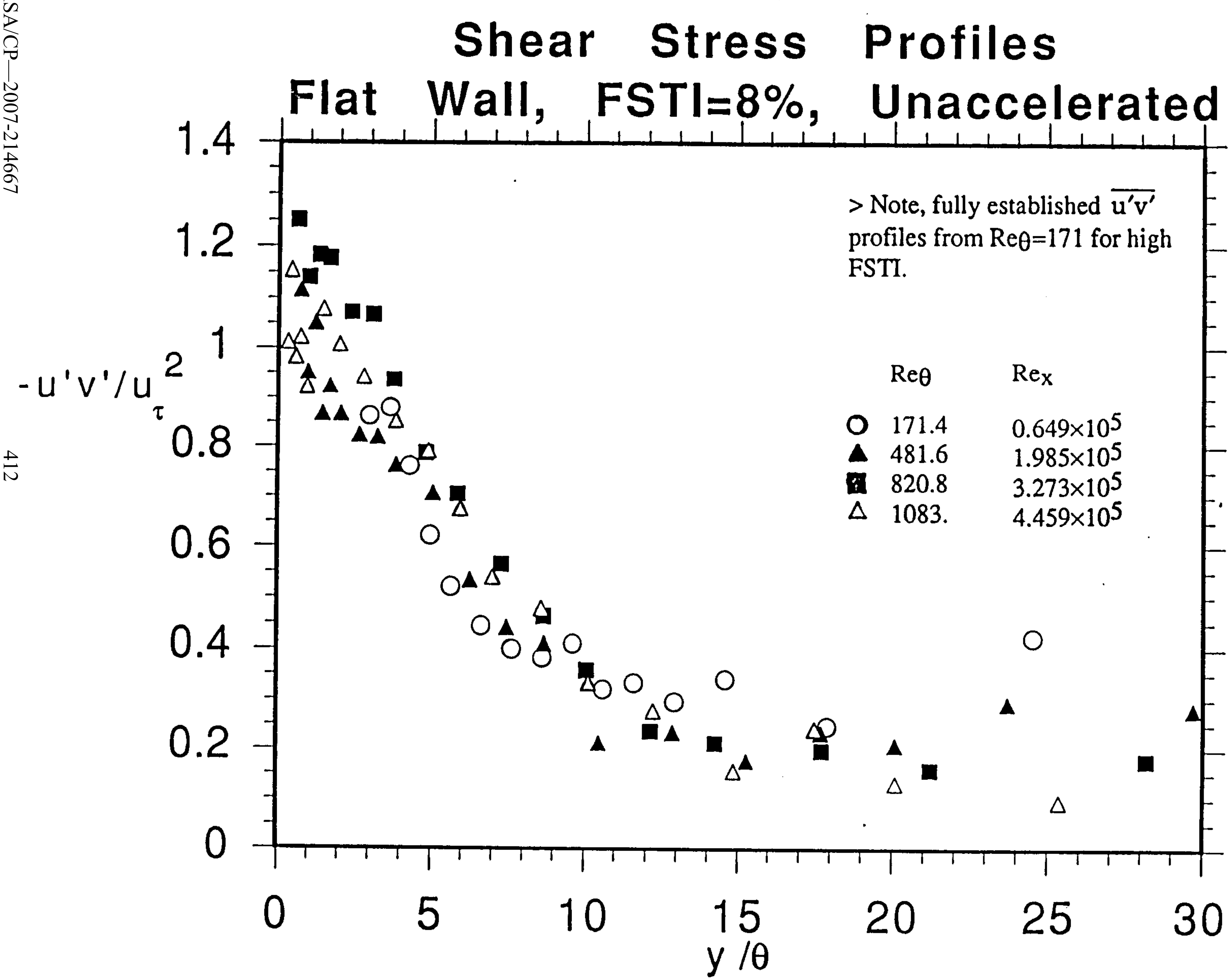
Shear Stress Profiles, Concave Wall, R=1m

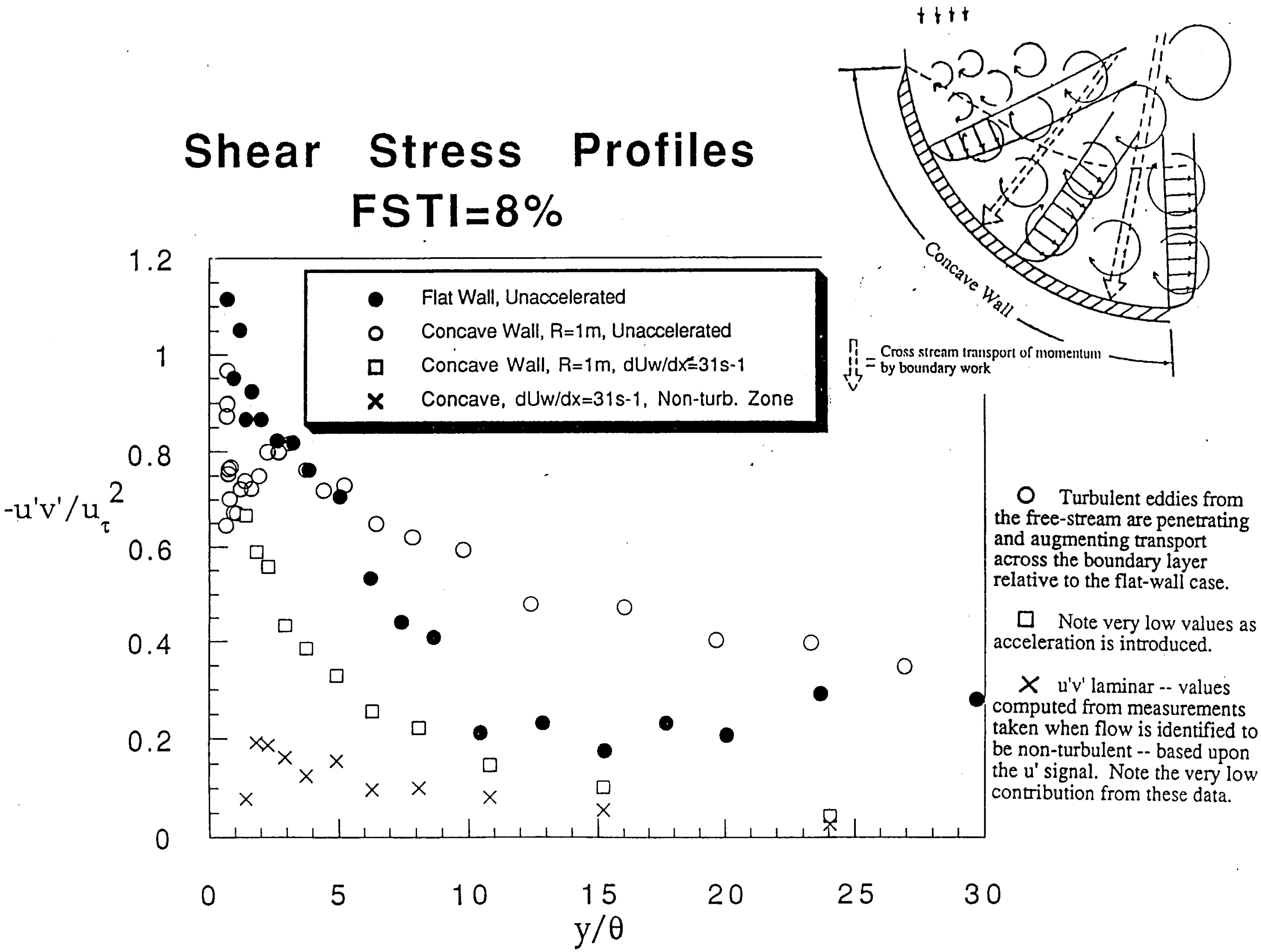
Accelerated, $dU_w/dx = 31\,s^{-1}$, FSTI=8%



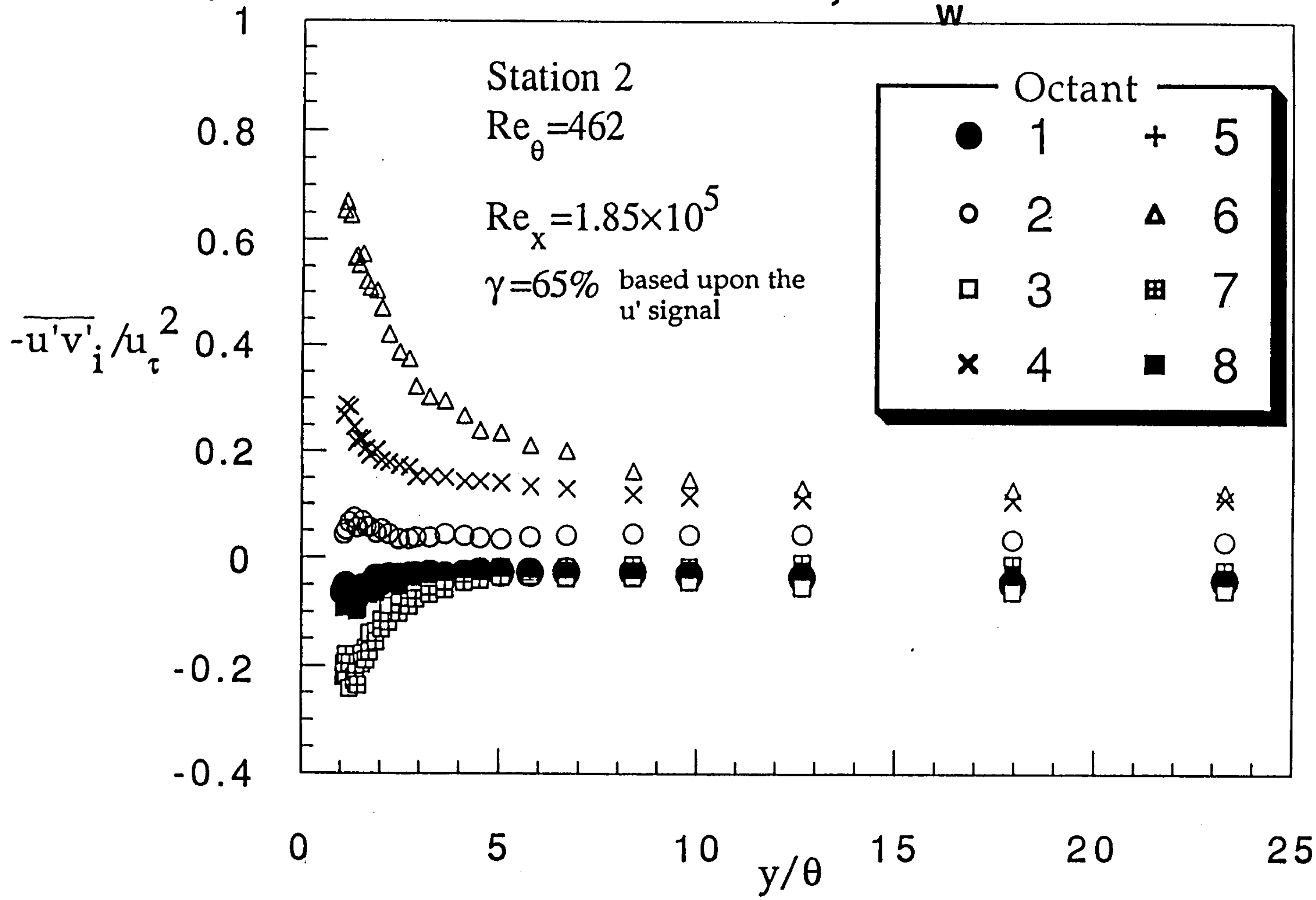
Shear Stress Profiles, Concave Wall R=1m, Unaccelerated, FSTI=8%



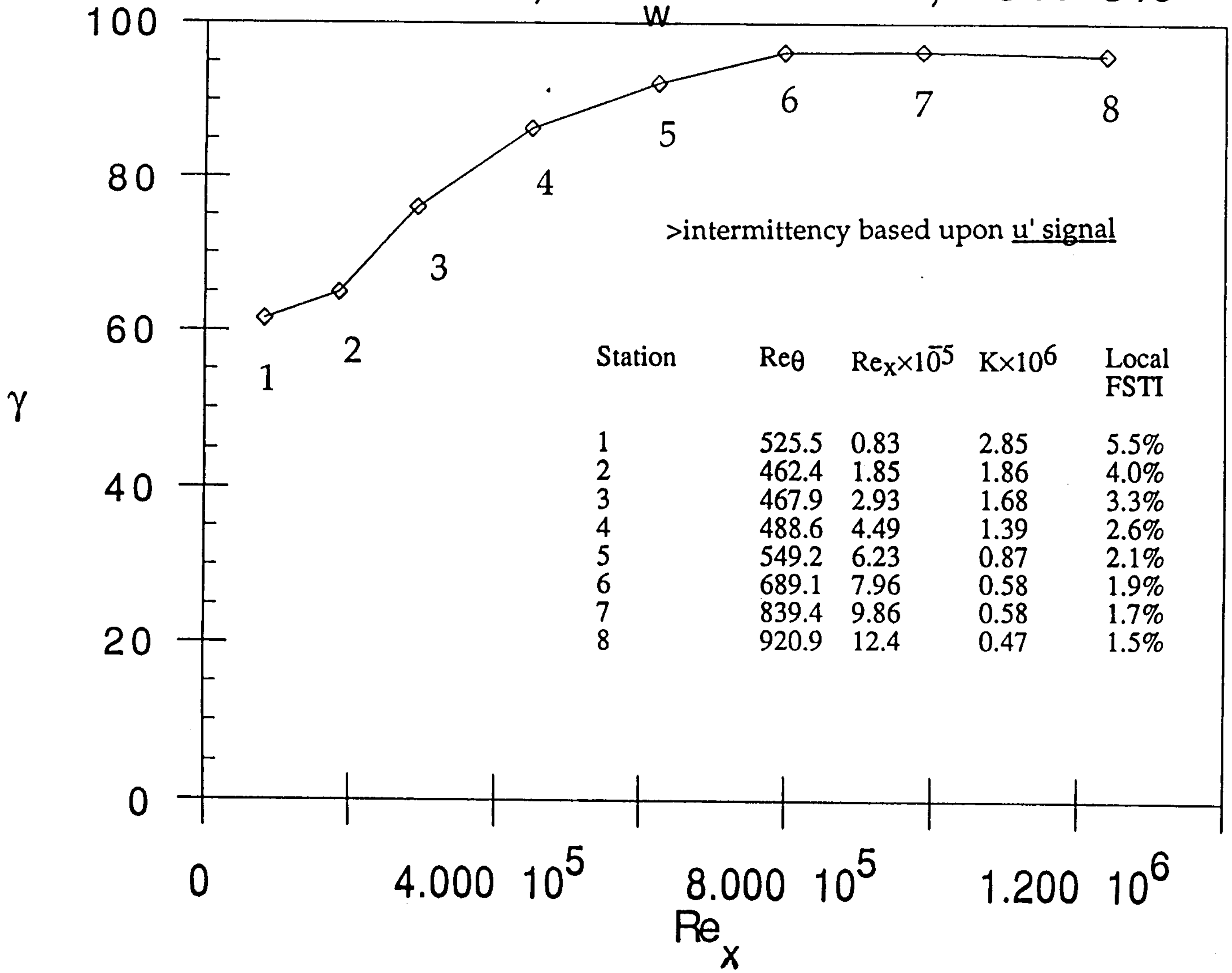

Shear Stress Profiles
Flat Wall, FSTI=8%, Unaccelerated
> Note, fully established $\overline{u'v'}$ profiles from Reθ=171 for high FSTI.
Reθ Rex
171.4 0.649×10^5
481.6 1.985×10^5
820.8 3.273×10^5
1083. 4.459×10^5
$-u'v'/u_\tau^2$
y /θ
0 5 10 15 20 25 30
0 0.2 0.4 0.6 0.8 1 1.2 1.4


Shear Stress Profiles
FSTI=8%
Flat Wall, Unaccelerated
Concave Wall, R=1m, Unaccelerated
Concave Wall, R=1m, dUw/dx=31s-1
Concave, dUw/dx=31s-1, Non-turb. Zone
-u'v'/u_τ^2
y/θ
1.2
1
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
Concave Wall
Cross stream transport of momentum by boundary work
○ Turbulent eddies from the free-stream are penetrating and augmenting transport across the boundary layer relative to the flat-wall case.
□ Note very low values as acceleration is introduced.
× u'v' laminar -- values computed from measurements taken when flow is identified to be non-turbulent -- based upon the u' signal. Note the very low contribution from these data.

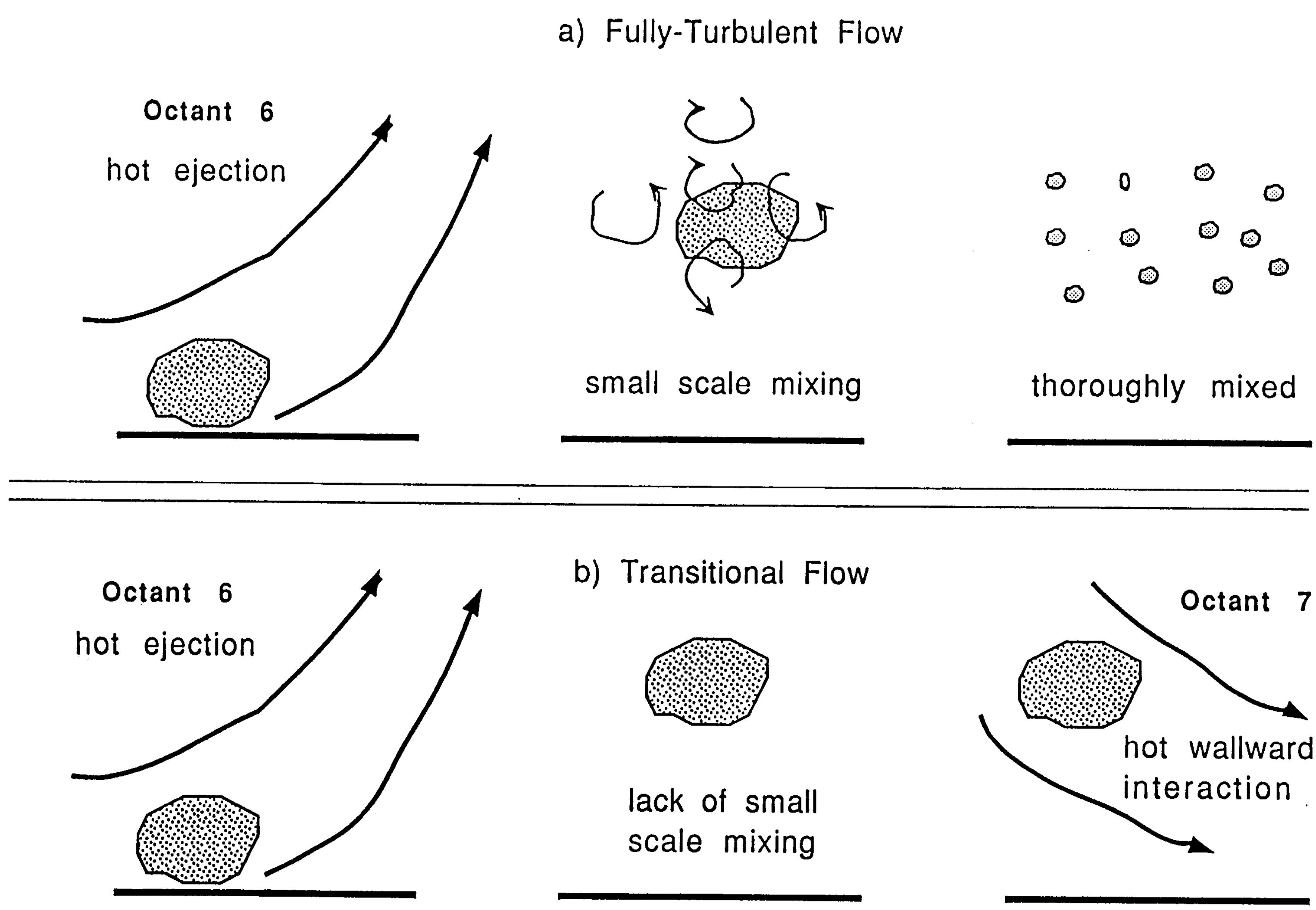
Turbulent Shear Stress Profiles Concave Wall, R=1m, FSTI=8 % Accelerated Flow, $dU_w/dx = 31\,s^{-1}$



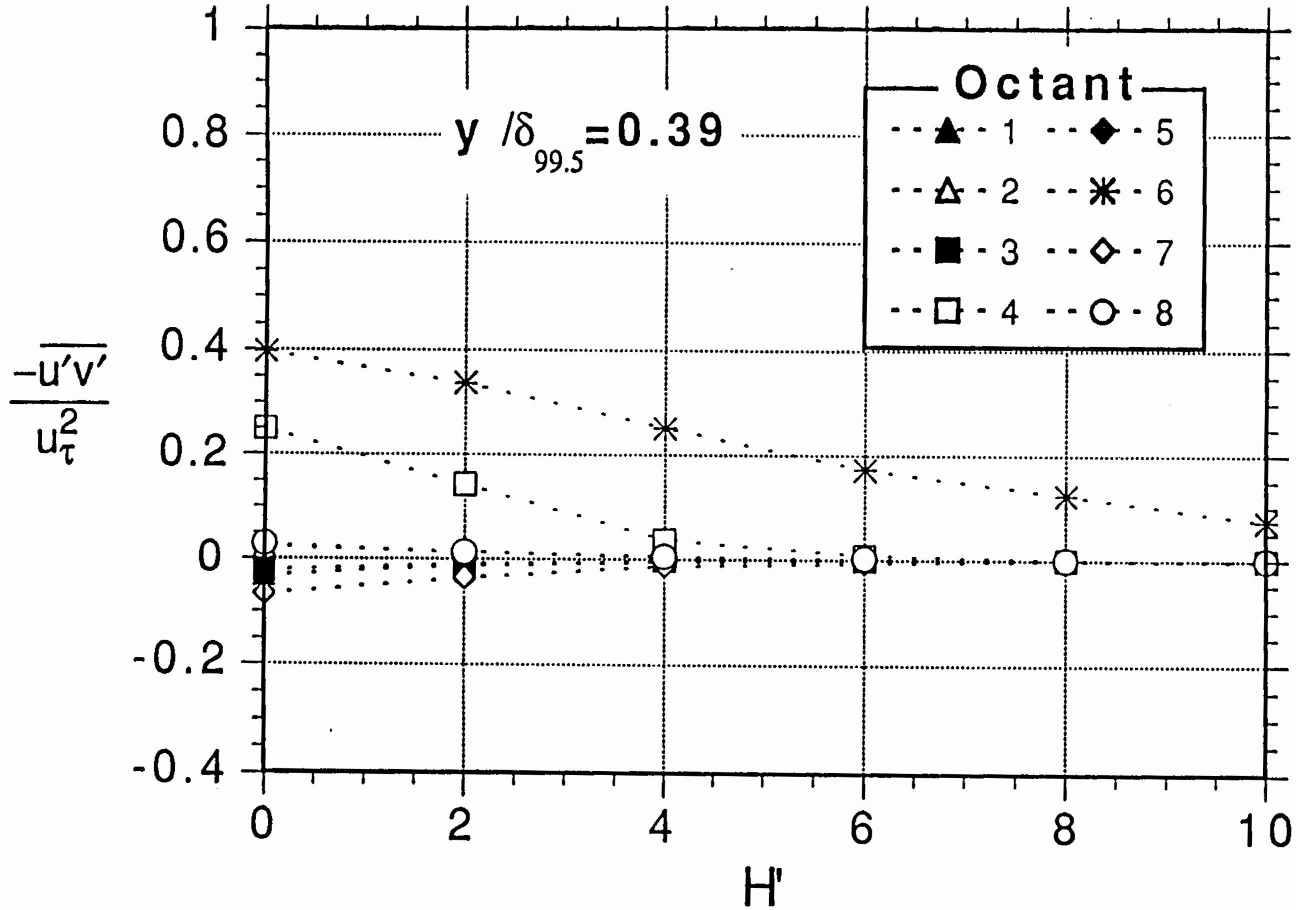
Maximum Intermittency in Profile
Concave Wall, R=1 m
Accelerated, $dU_w/dx=31\,s^{-1}$, FSTI=8%



Station	Re_θ	$Re_x \times 10^{-5}$	$K \times 10^6$	Local FSTI
1	525.5	0.83	2.85	5.5%
2	462.4	1.85	1.86	4.0%
3	467.9	2.93	1.68	3.3%
4	488.6	4.49	1.39	2.6%
5	549.2	6.23	0.87	2.1%
6	689.1	7.96	0.58	1.9%
7	839.4	9.86	0.58	1.7%
8	920.9	12.4	0.47	1.5%



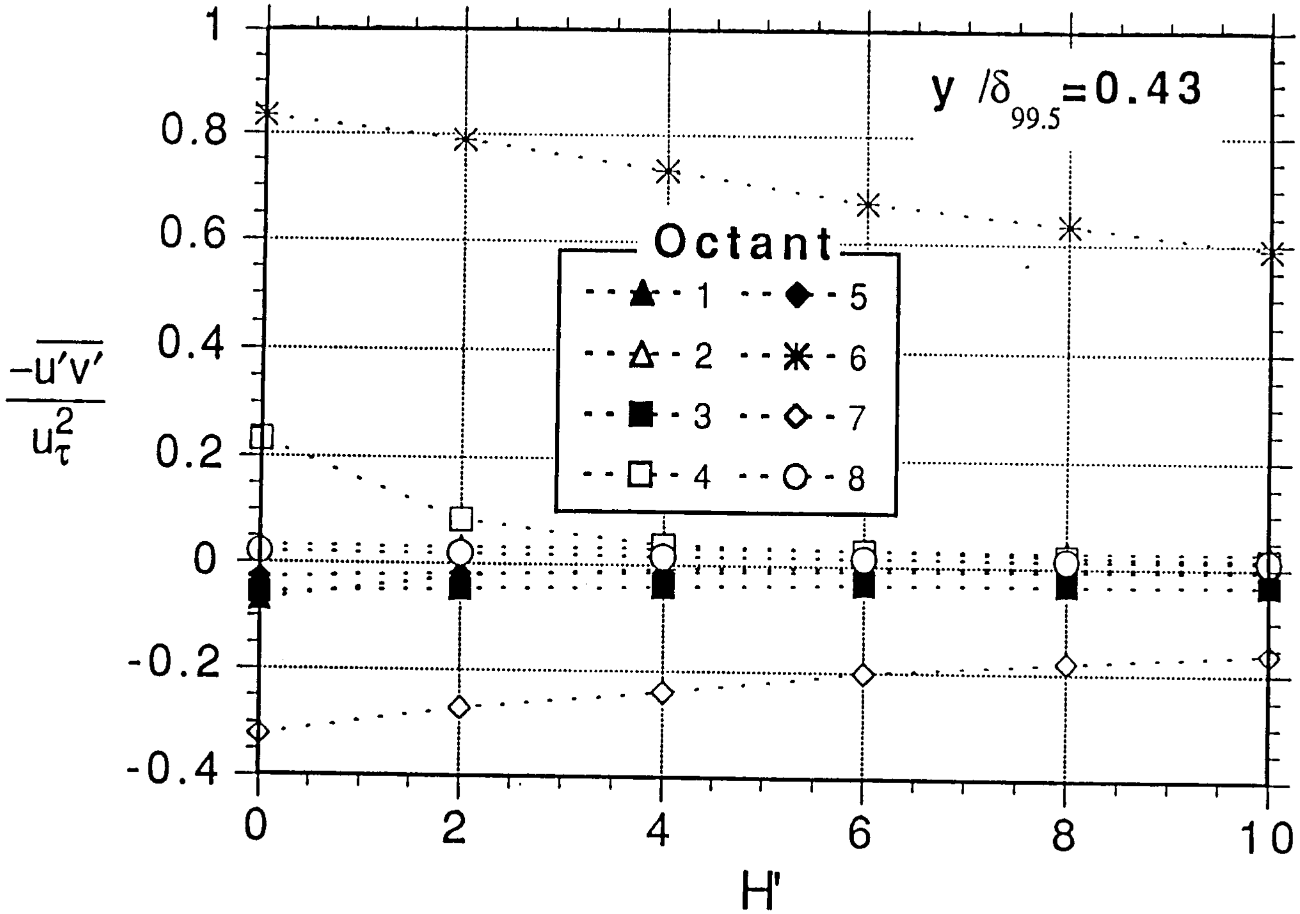
Proposed differences between fully-turbulent and transitional flow structures



Turbulent shear stress vs hole size at $y/\delta_{99.5}=0.39$, 1.5% FSTI flat-wall case, fully-turbulent flow

$Re_\theta=1587$, $Re_x=1.062\times10^6$

> Note that in contrast to transitional flows, the contribution becomes small at large H' values.



Turbulent shear stress vs hole size at $y/\delta_{99.5}$=0.43, 1.5% FSTI flat-wall case, transitional flow

Re_θ=379, Re_x=0.3442×10^6, γ=5%

> When H'≠0, smaller values of u'v' are not used in processing $\overline{u'v'}$ octants. As H' increases, the filter threshold on u'v' grows. Thus, if values are large when H' is large, they come about due to strong events. Note that octants 6 and 7 remain large at large H' values.

CONCLUSIONS

SPANWISE INTERACTION OF LOCALIZED DISTURBANCES PROMOTES TRANSITION

- Increased Amplitude
- Different Spanwise Wavenumbers

THPS transition marked by Gradual Amplification of the Lower than Fundamental frequencies

TWP Transition marked by distinct lower band of Frequencies