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A high quality flow has been established in a low turbulence variable geometry (LTVG) 8' x 8' supersonic wind-tunnel at Princeton. In particular, the facility is being operated at very Iow stagnation pressures (-= 4 psia) giving a large region of laminar flow on a flat plate with laminar boundary layers up to approximately 3mm thick. Mean profiles, amplitude distributions, two wire correlations and spectra have been mcasured in detail through a Mach 3 boundary layer along the centerline of the flat plate. The initial results are for "naturally" occurring instability and transition and they are being followed by measurements of the forced response from a point source (spark) .1.

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Compressible Boundary Layer Receptivity and Instability

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Paper presented at AFOSR Contractor's Meeting
Annapolis, MD
August 18, 1998
Recent Accomplishments
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A high quality flow has been established in a low turbulence variable geometry (LTVG) 8" x 8" supersonic wind-tunnel at Princeton. In particular, the facility is being operated at very low stagnation pressures (≅ 4 psia) giving a large region of laminar flow on a flat plate with laminar boundary layers up to approximately 3mm thick. Mean profiles, amplitude distributions, two wire correlations and spectra have been measured in detail through a Mach 3 boundary layer along the centerline of the flat plate. The initial results are for "naturally" occurring instability and transition and they are being followed by measurements of the forced response from a point source (spark).

Measured mean boundary layer profiles obtained by Pitot measurement are shown in Figure 1. The agreement with the predictions from computations is remarkable. The measured profiles are so close to the predictions that they have been subsequently used to re-calibrate the hot-wire in situ and better define the measured velocity fluctuation amplitude distribution. Measured transitional boundary layer profiles with larger natural forcing at higher pressures are also shown in Figure 1.

The velocity fluctuation energy spectra (Figure 2) reveal the presence of two distinct "humps" in frequency bands corresponding to two distinct modes of fluctuations. A low frequency mode (~1-7Khz) believed to be a high receptivity response to acoustic forcing and a high frequency mode (~8Khz-30Khz) whose peak frequency agrees extremely well with the computed frequency of the most unstable first mode of instability waves (Calculations by Mack and Balakumar).

The two wire correlation measurements show the low frequency mode to have a two dimensional structure characterized by an extremely high correlation coefficient (.8, .9) for wire separation distances up to .8" (Figure 3). The high frequency mode shows a 3D structure (Figure 3) (an analysis in depth is being carried out to determine the characteristic angle of inclination of the wave vector with respect to the free-stream direction in this case). A region of overlap is present in frequency space between the above-mentioned modes of fluctuations; in this region the spanwise correlation coefficient is very low despite the significant contribution to the overall energy content.

The measured energy level of the fluctuations in the boundary layer is affected by the operating conditions of the facility. In particular the intensity of the low frequency mode is dependent on the pressure ratio across the upstream valve and the unit Reynolds number. The low frequency energy content increases as the stagnation pressure and/or the pressure differential across the inlet valve increases; this behavior along with correlation measurements confirms the acoustic nature of the low frequency fluctuations and identifies the upstream valve as the main source of the acoustic noise in the free-stream. At the lowest stagnation pressure with the minimum pressure differential across the upstream valve, the free-stream "turbulence" is very low and of the order of 0.1% (further measurements are being made to characterize accurately the free-stream disturbances).

Amplitude distributions in the boundary layer corresponding to two different unit Reynolds numbers are shown in Figure 4. At the lower stagnation pressure, after approximately 13" downstream of the leading edge, the growth rate of the amplitude of fluctuations in the laminar boundary layer is found to be affected by a disturbance propagating from the corners at the leading edge of the flat plate; measurements have been confined therefore to the region from the leading edge to 12" downstream. Close agreement between the computed eigenfunction (Mack) and the measured narrow band fluctuations was obtained in this region (Figure 5). These are the first reliable and detailed measurements of the eigen function in a compressible boundary layer.

For the higher stagnation pressure, the boundary layer shape is observed to depart from the laminar solution at x = 9.5" - 12", giving a corresponding transition Rex = 6.5 – 9 x 10^6. The somewhat low transition Reynolds number in this case is due to the higher level of fluctuations present in the free stream at these higher unit Reynolds number conditions, confirming again the highly receptive nature of the compressible boundary layer.

In the laminar region of the boundary layer, the time history of the fluctuating voltage shows a relatively uniform ""sinusoidal" behavior at a frequency corresponding approximately to the frequency of the most amplified instability wave (Figure 6). A different pattern emerges as the boundary layer becomes transitional (Figure 7), characteristic spikes not unlike the incompressible counterpart, are evident in the wall region as well as in the outer part of the boundary layer, while the central portion is characterized by bursts of high frequency fluctuations. To help clarify the process of natural transition, correlation measurements have been carried out through the transitional boundary layer, and their analysis is currently being undertaken.

Figure 8 shows a comparison between the measured amplitude distribution in the first-mode band of instability frequencies and the eigen function recently calculated by Balakumar. Further detailed comparisons are being made between growth rates and the detailed instability predictions made for us by Balakumar.

We have begun to examine in detail the forced response of the boundary layer and Figure 9 shows the spectrum of fluctuations measured when the boundary layer is forced by a spark source at a frequency within the instability band. Correlations between two wires separated in the spanwise direction allow us to make detailed comparisons with stability theory predictions of the wave angle (Figure 9). This experimental result gives a wave angle of 60° which we anticipate will be close to stability predictions. Balakumar is providing the corresponding predictions at various locations downstream based on point source forcing at 2" from the leading edge. Figure 10 shows a comparison between the measured amplitude distributions at different forcing amplitudes. The response is clearly in the linear stability regime.

EXPERIMENTS ON STABILITY AND TRANSITION AT MACH 3

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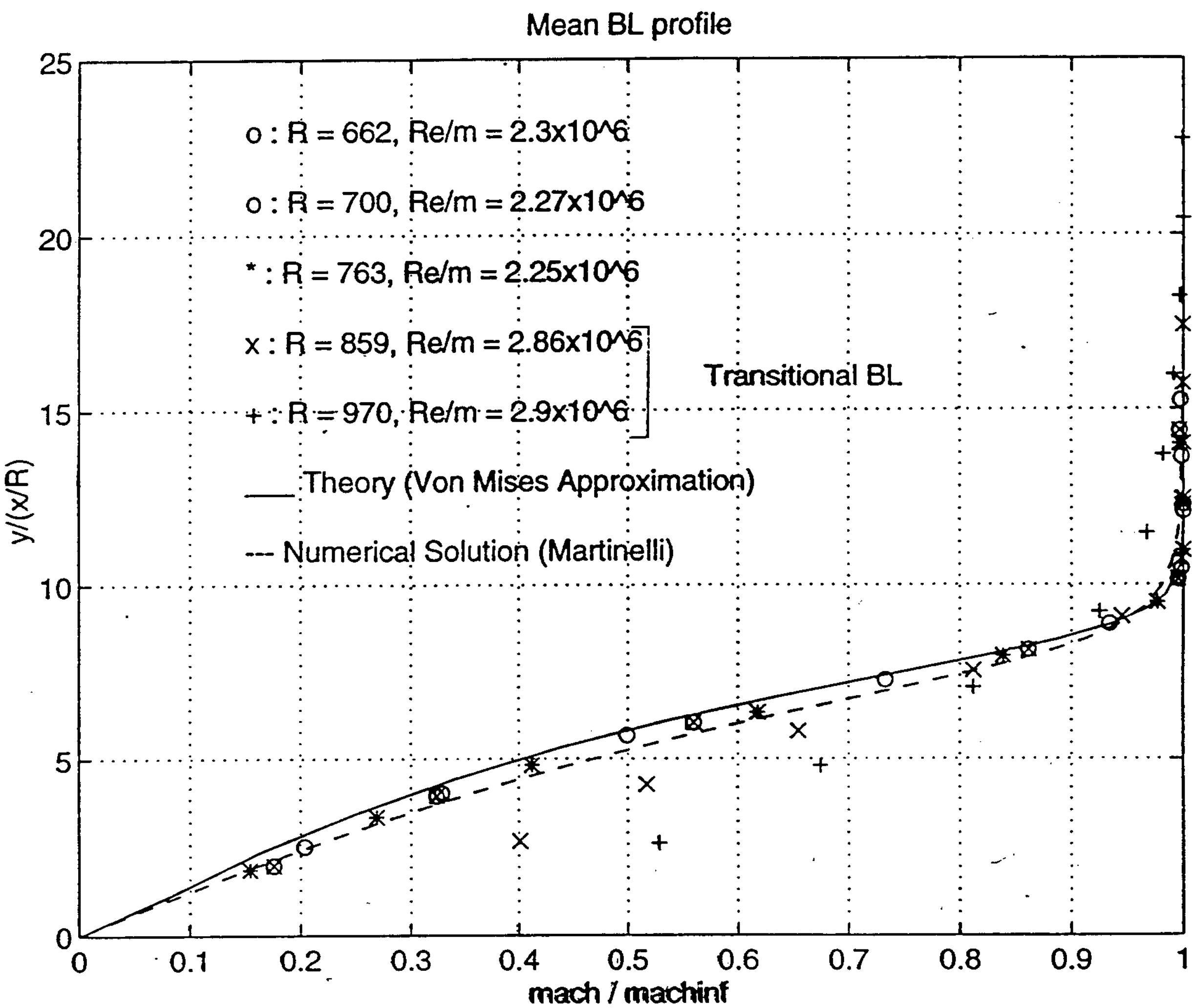
EXPERIMENT

- LTVG Mach 3 supersonic wind tunnel with ejector system operated at P0 ~ 4 and 5 Psia

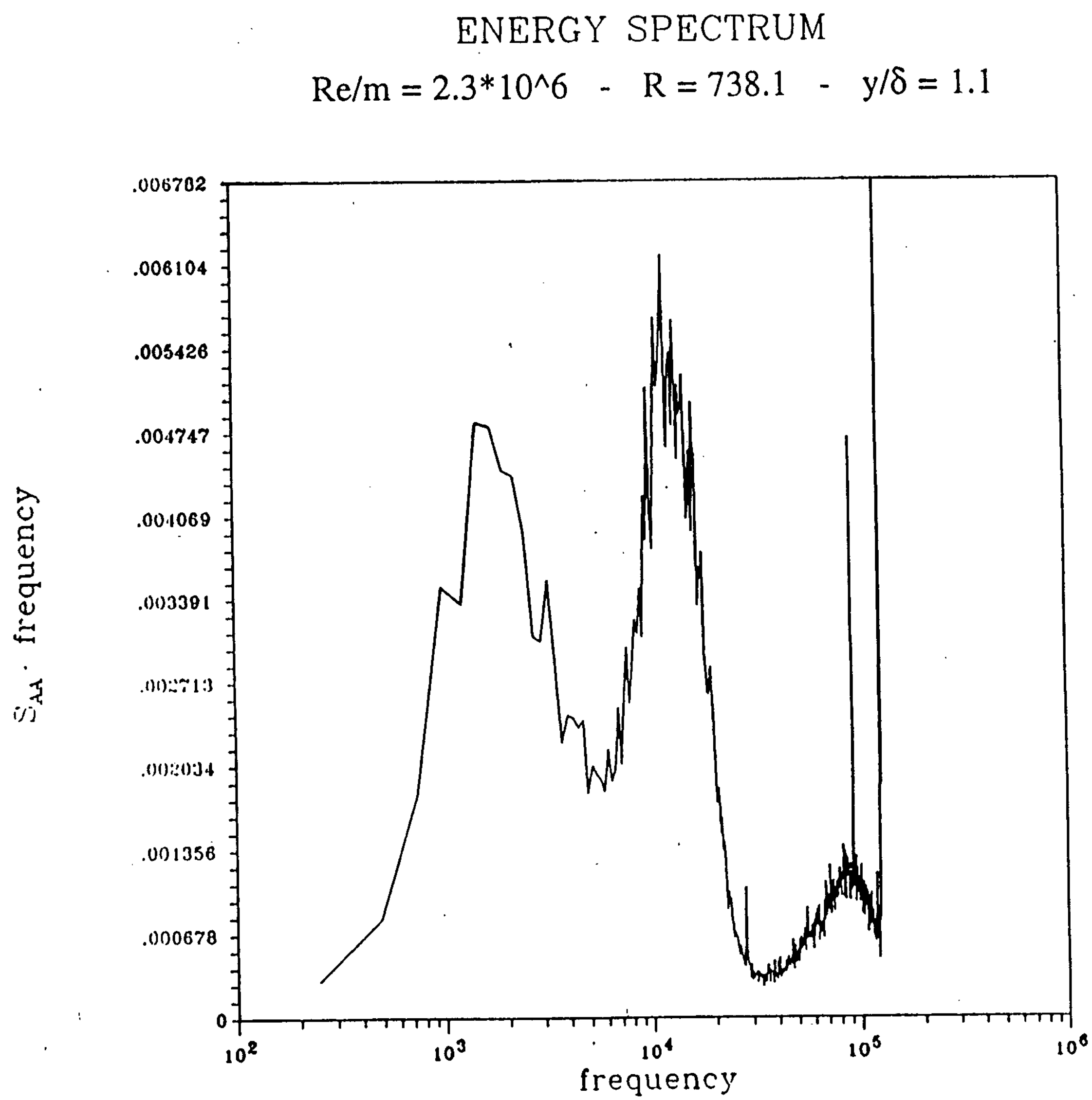
- 8" x 8" Test section

- Flat plate BL (Re/m = 2.4x10^6 and 2.8x10^6)



Mean BL profile
o : R = 662, Re/m = 2.3x10^6
o : R = 700, Re/m = 2.27x10^6
* : R = 763, Re/m = 2.25x10^6
x : R = 859, Re/m = 2.86x10^6
+ : R = 970, Re/m = 2.9x10^6
Transitional BL
Theory (Von Mises Approximation)
--- Numerical Solution (Martinelli)
y/(x/R)
mach / machinf
0
5
10
15
20
25
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Fig. 1



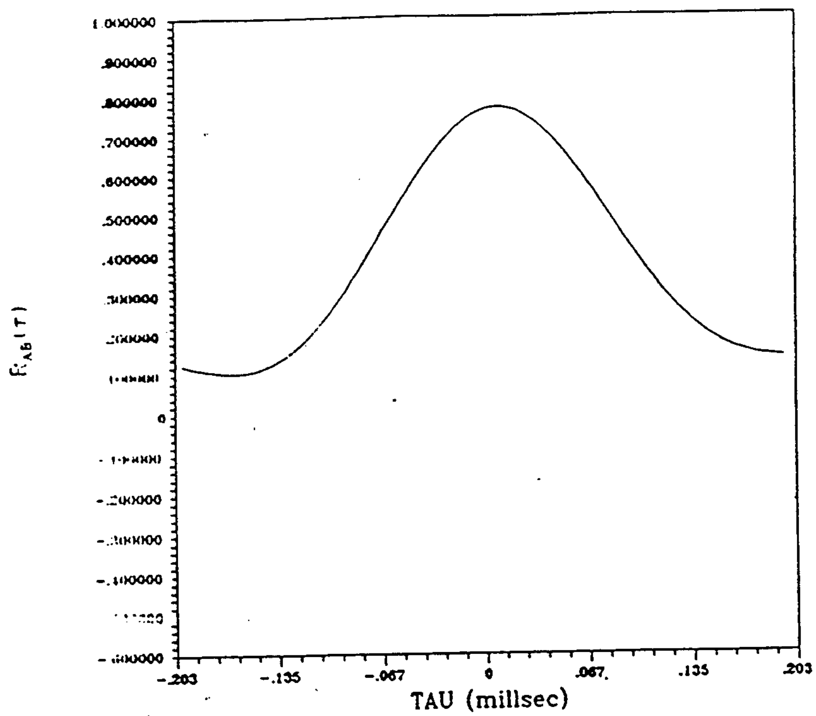
ENERGY SPECTRUM
Re/m = 2.3*10^6 - R = 738.1 - y/δ = 1.1
.006782
.006104
.005426
.004747
.004069
.003391
.002713
.002034
.001356
.000678
0
S_AA · frequency
10^2
10^3
10^4
10^5
10^6
frequency

Fig. 2

CROSS CORRELATION

250Hz ≤ freq ≤ 5000Hz

Naturally occurring instability



CROSS CORRELATION

11000Hz ≤ freq ≤ 20000Hz

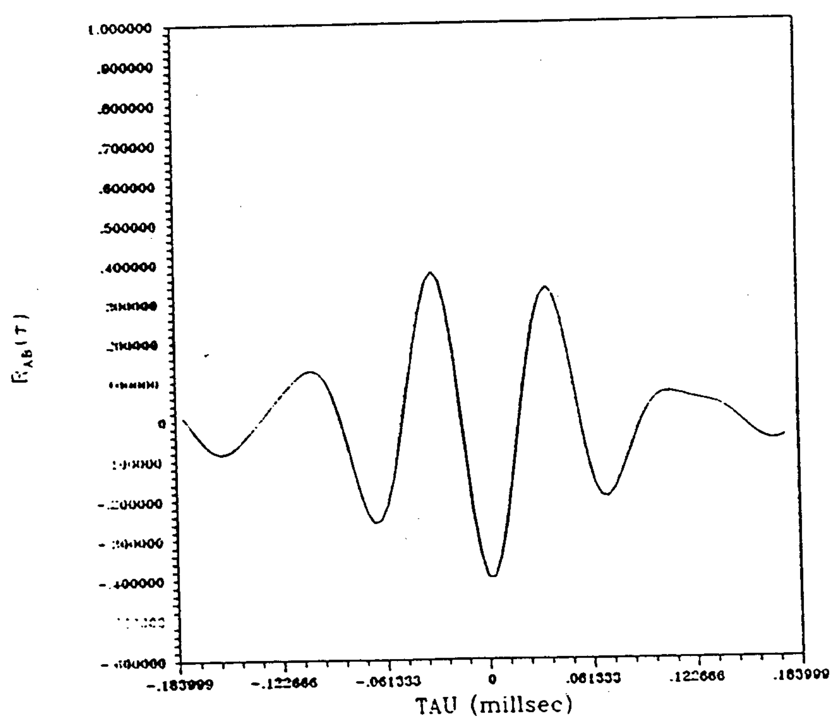
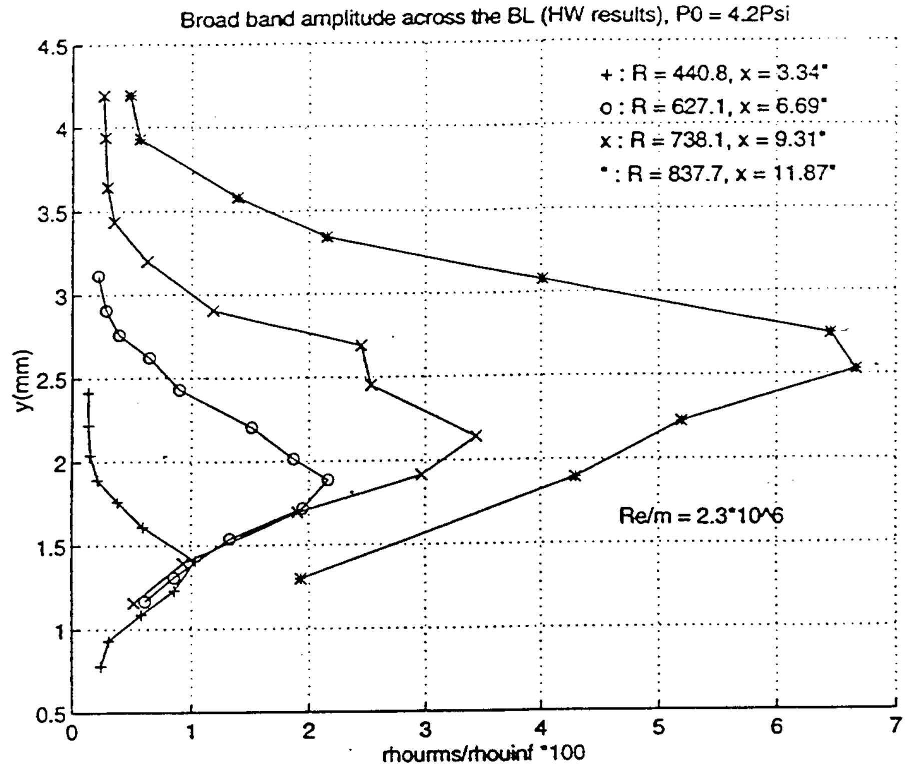


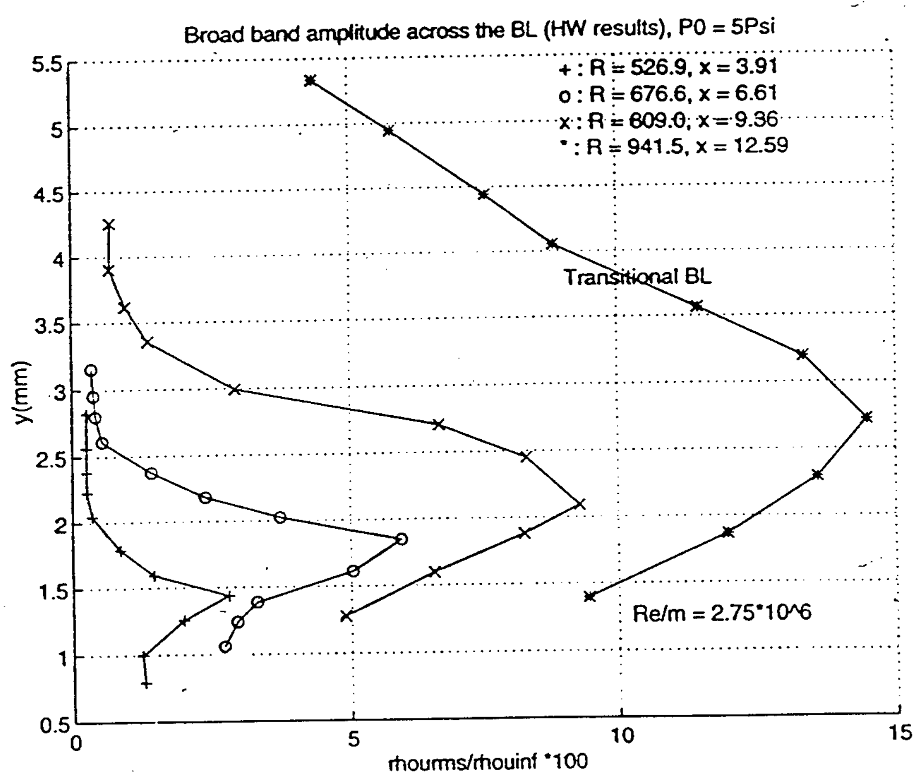
Fig. 3

$\Delta z = .38''$ - $\Delta x = 0''$

$Re/m = 2.14*10^6$ - $R = 723.5$ - $y/\delta = .75$

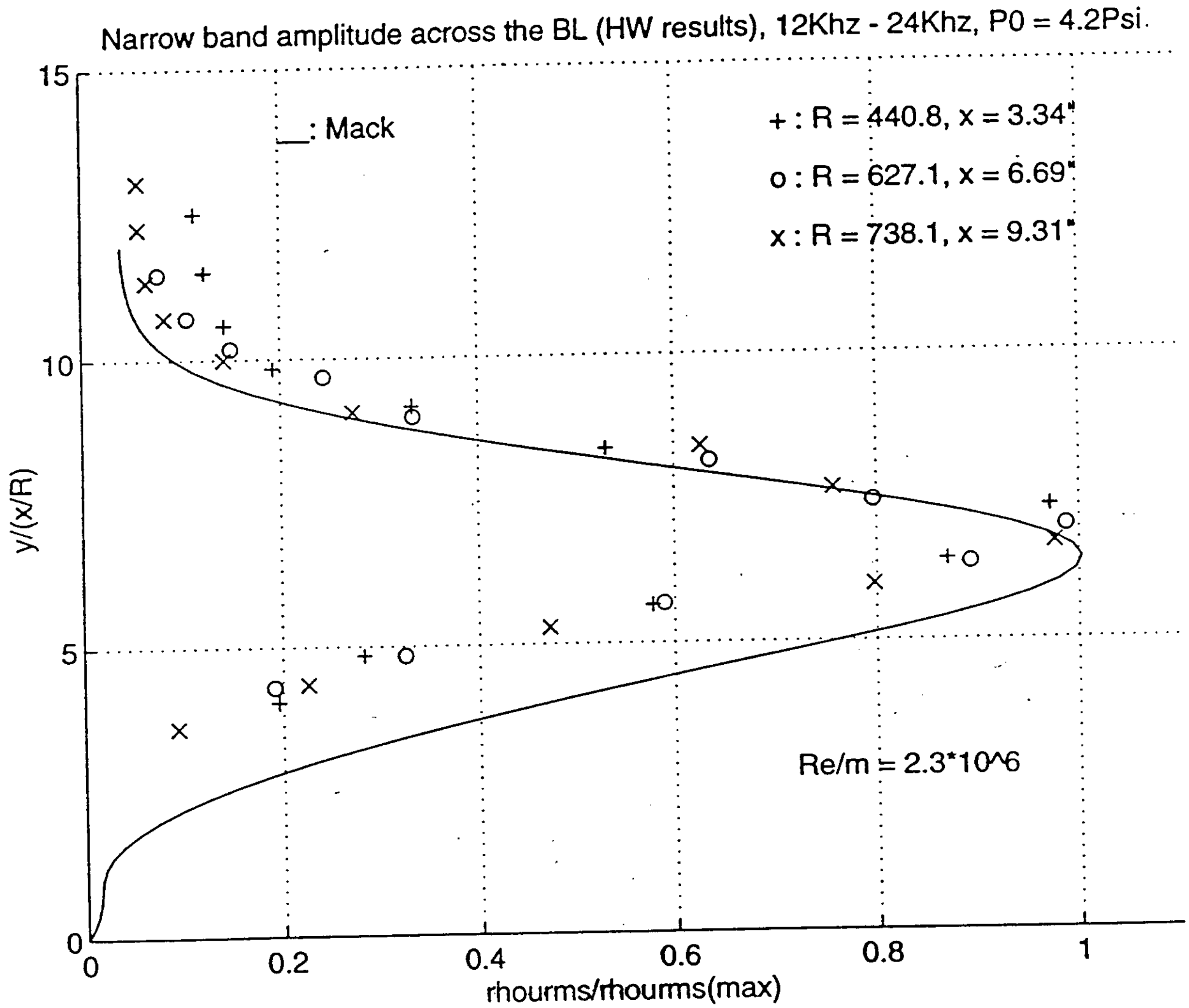


Broad band amplitude across the BL (HW results), P0 = 4.2Psi
+ : R = 440.8, x = 3.34"
o : R = 627.1, x = 6.69"
x : R = 738.1, x = 9.31"
* : R = 837.7, x = 11.87"
Re/m = 2.3*10^6
y(mm)
rhourms/rhouinf *100



Broad band amplitude across the BL (HW results), P0 = 5Psi
+ : R = 526.9, x = 3.91
o : R = 676.6, x = 6.61
x : R = 809.0, x = 9.36
* : R = 941.5, x = 12.59
Transitional BL
Re/m = 2.75*10^6
y(mm)
rhourms/rhouinf *100

Fig. 4



Narrow band amplitude across the BL (HW results), 12Khz - 24Khz, P0 = 4.2Psi.
__: Mack
+ : R = 440.8, x = 3.34"
o : R = 627.1, x = 6.69"
x : R = 738.1, x = 9.31"
Re/m = 2.3*10^6
y/(x/R)
rhourms/rhourms(max)
15
10
5
0
0
0.2
0.4
0.6
0.8
1

Fig. 5

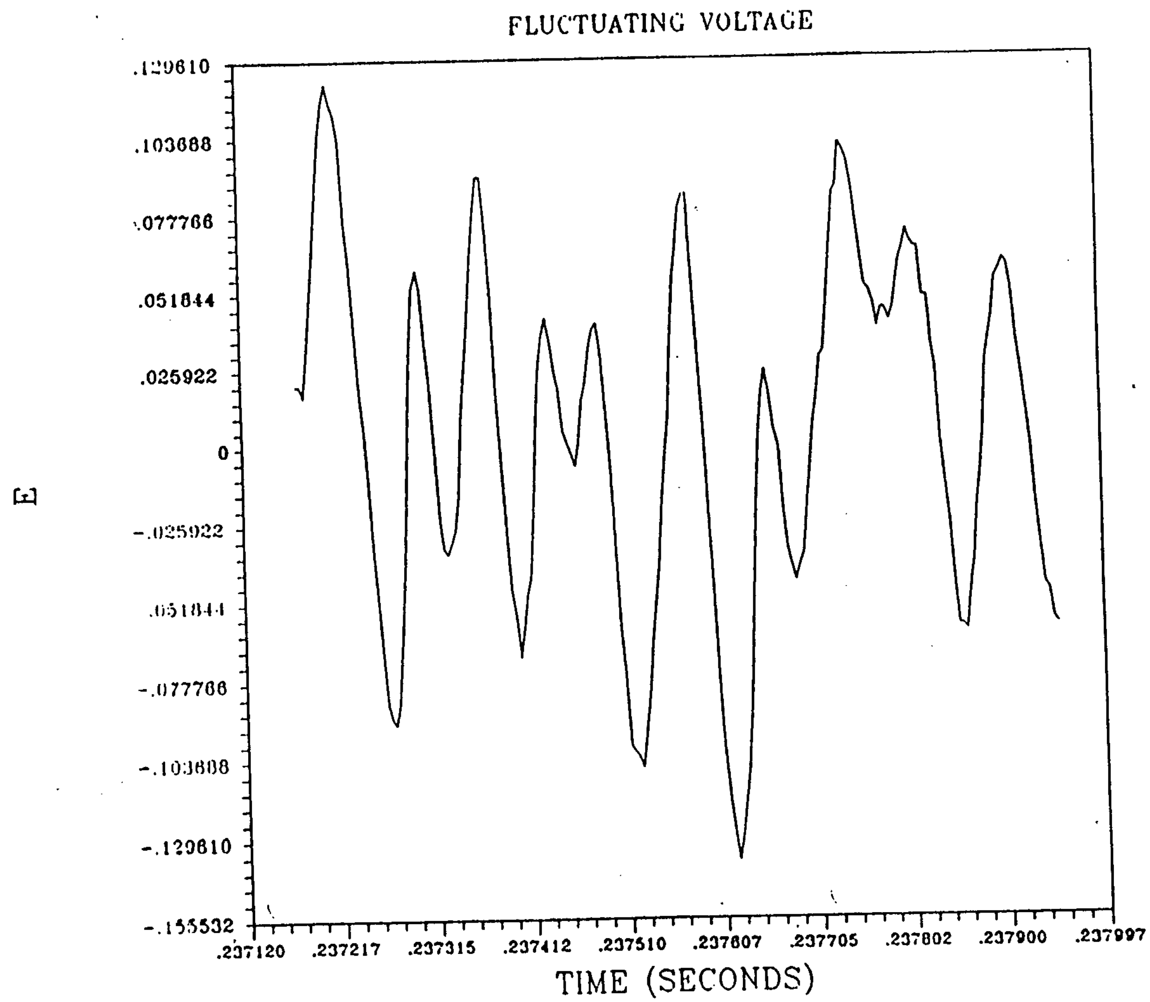


Fig. 6

Re/m = 2.3*10^6 - R = 738.1 - y/δ = .71

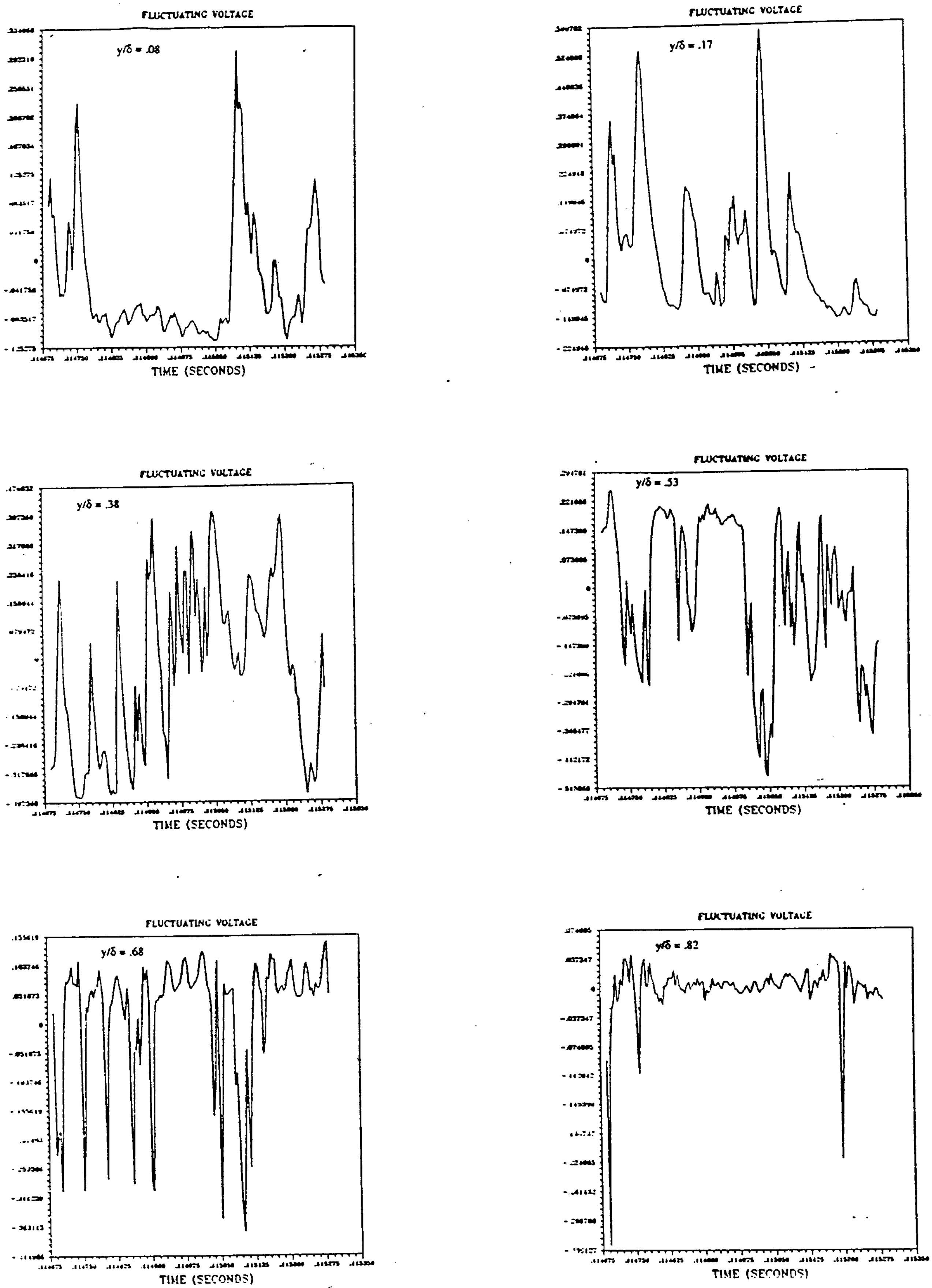


Fig. 7

$Re/m = 2.75*10^6$ - $R = 941.5$

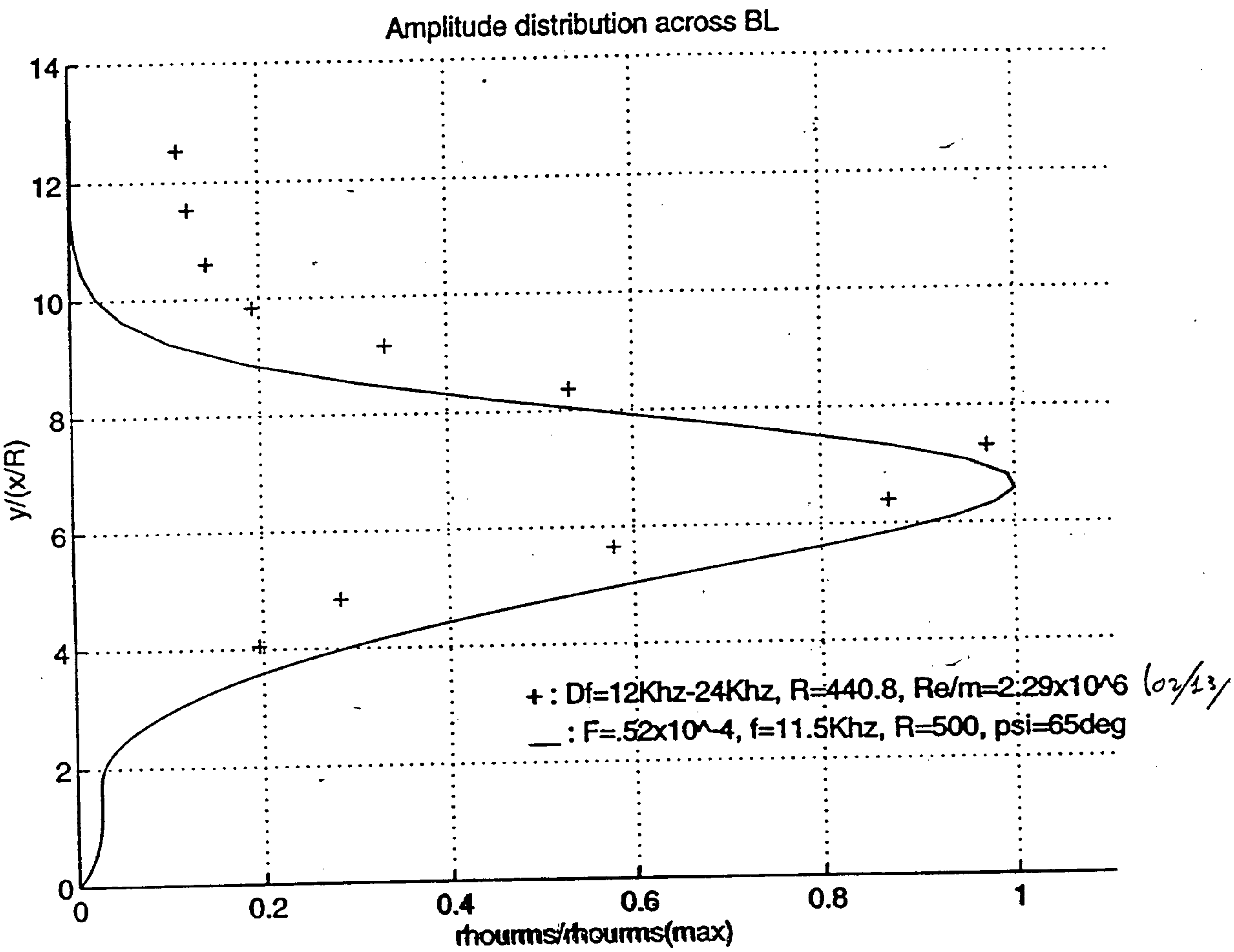
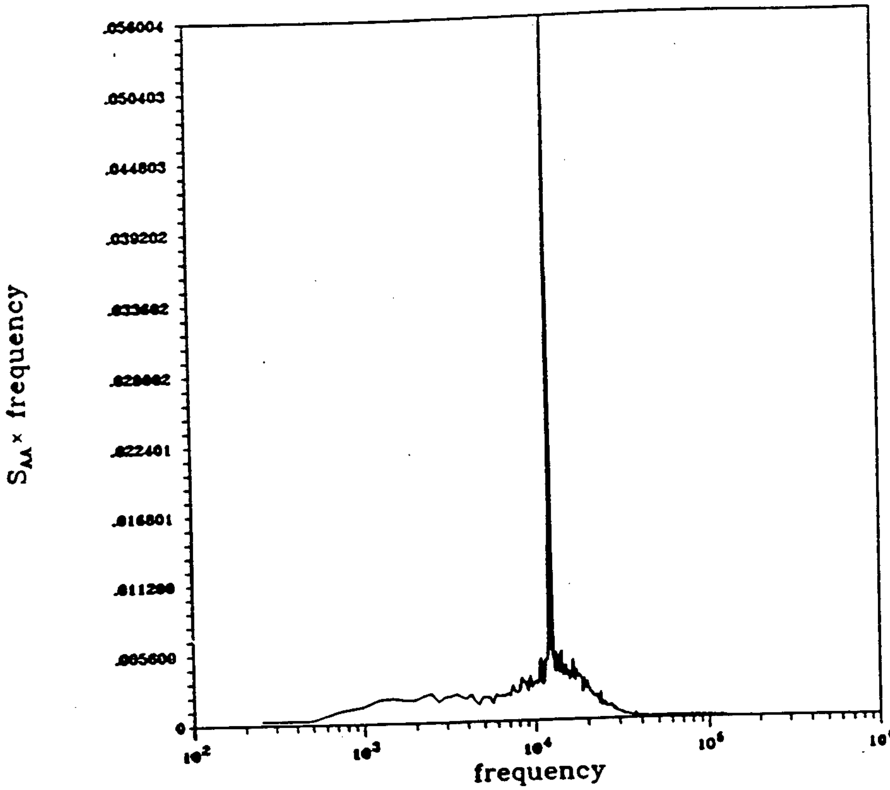

Amplitude distribution across BL
14
12
10
8
6
4
2
0
0
0.2
0.4
0.6
0.8
1
y/(x/R)
rhoumms/rhoumms(max)
+ : Df=12Khz-24Khz, R=440.8, Re/m=2.29x10^6
__ : F=.52x10^-4, f=11.5Khz, R=500, psi=65deg

Fig 8

forced response (spark source)

ENERGY SPECTRUM

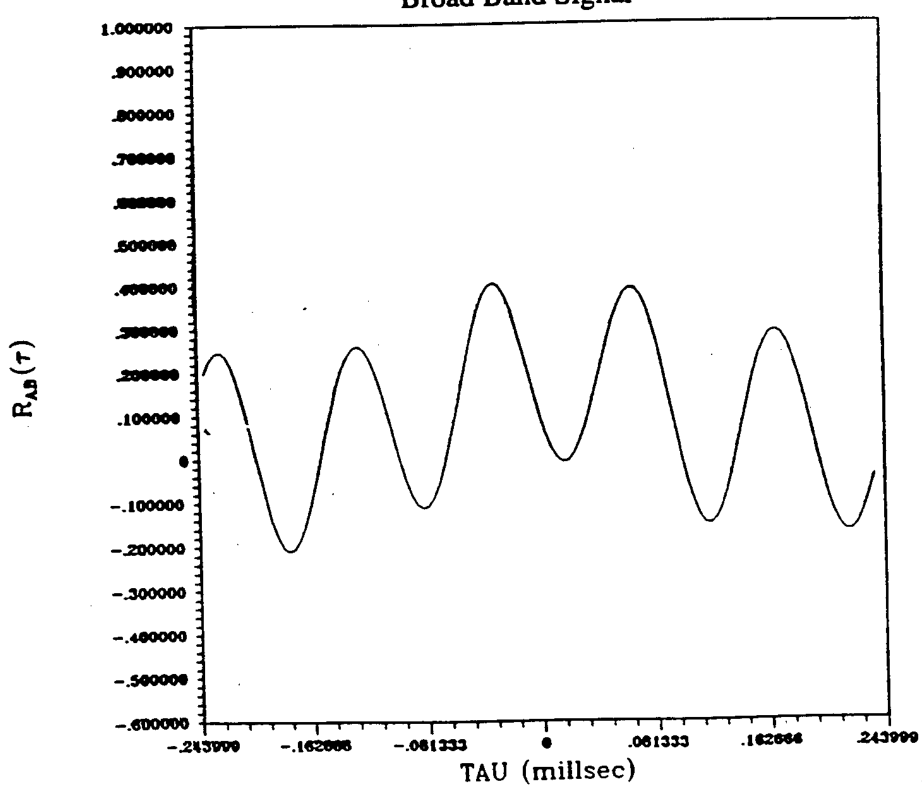
P0 = 4.2 Psia - R = 595 - y/δ = .74 - Vspark = 500 Volts



CROSS CORRELATION

P0 = 4.0 Psia - R = 801 - y/δ = .85 - Vspark = 700 Volts

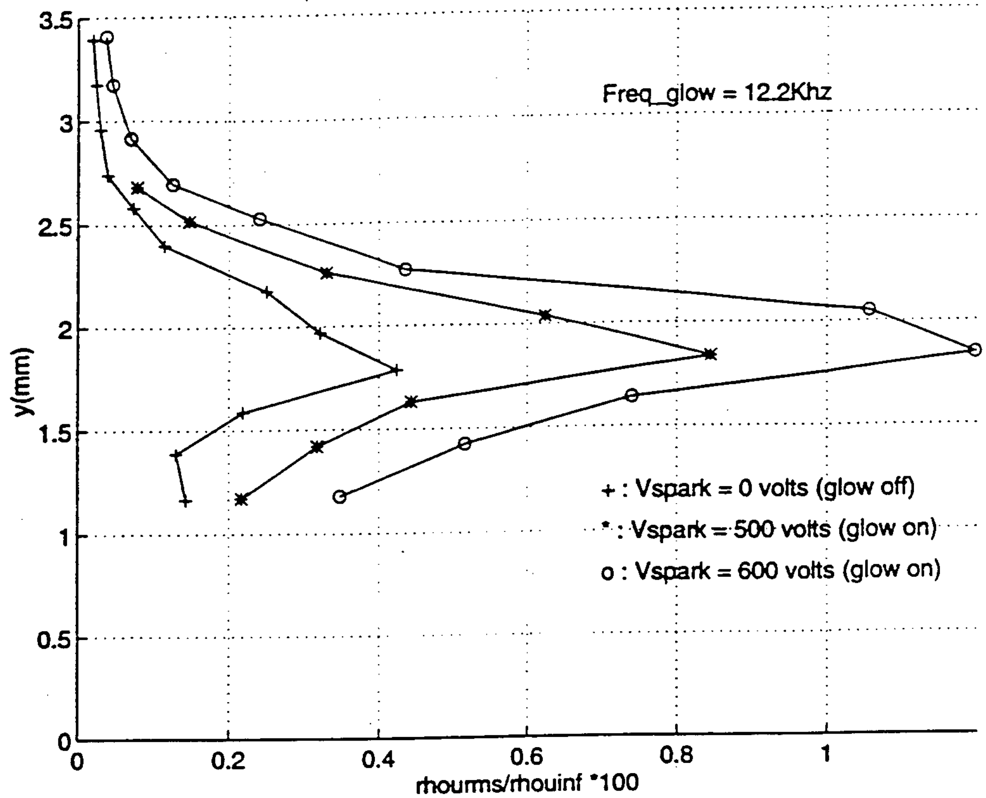
Broad Band Signal



wave angle ≈ 60°!

Fig 21

Narrow Band Amplitude Distribution, 11.7Khz - 12.7Khz, R=595, P0=4.2psia



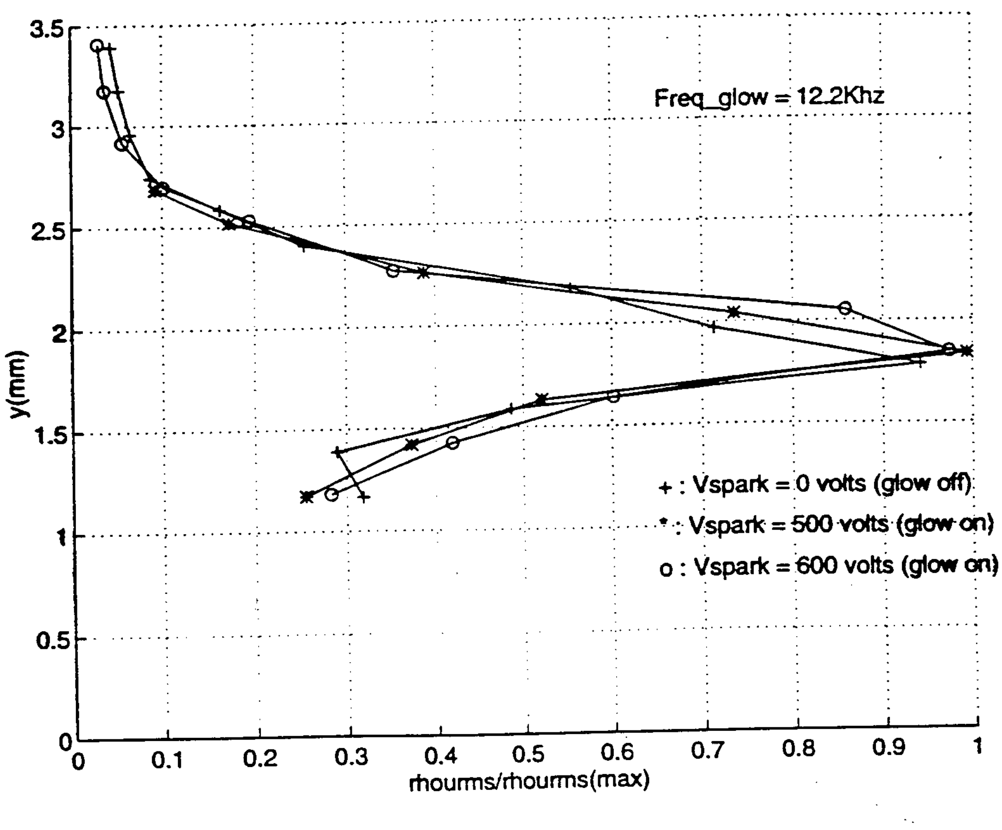


fig 10.