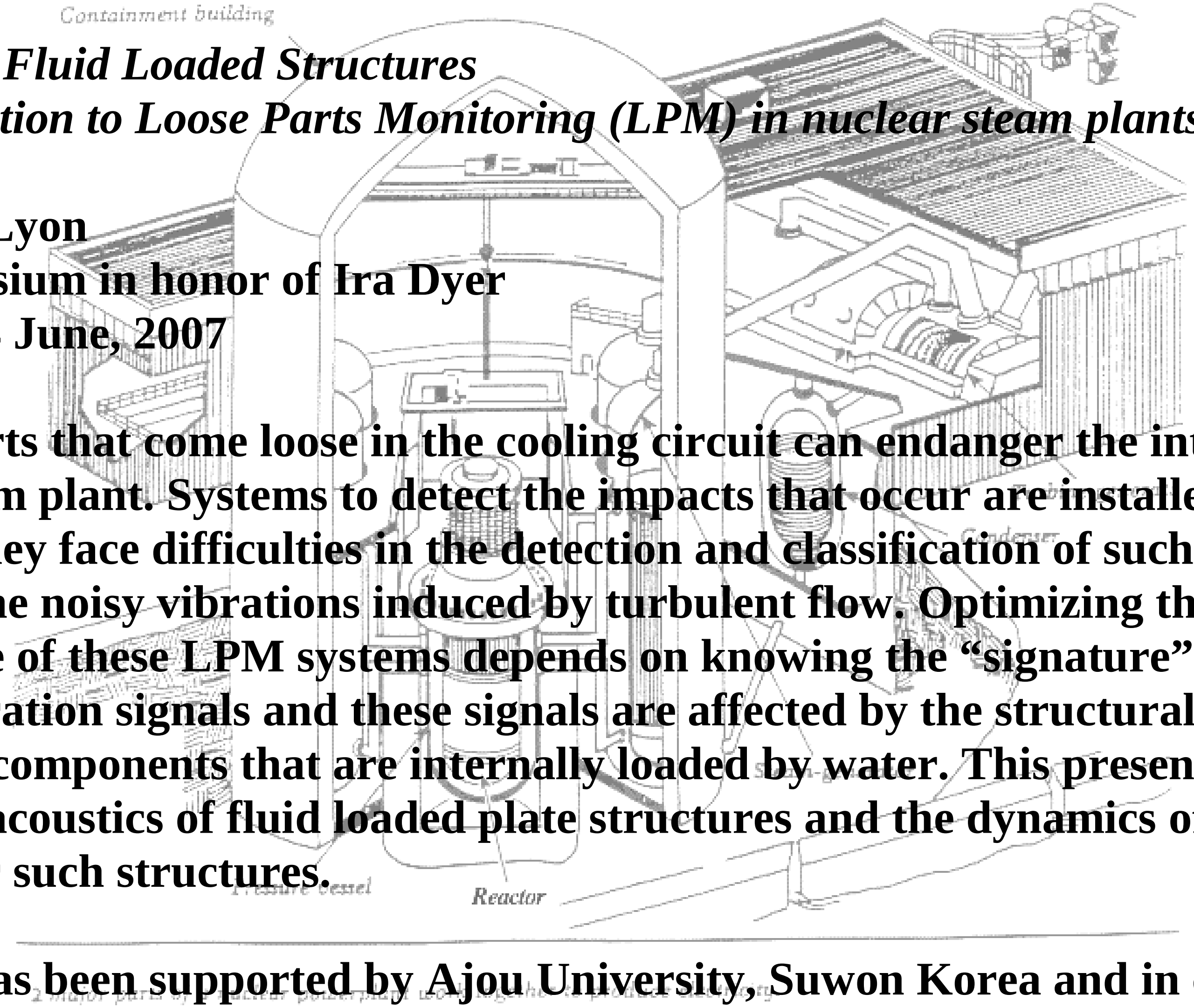
“Ideas, like ghosts, must be spoken to a little before they will explain themselves”

Charles Dickens, Dombey and Son



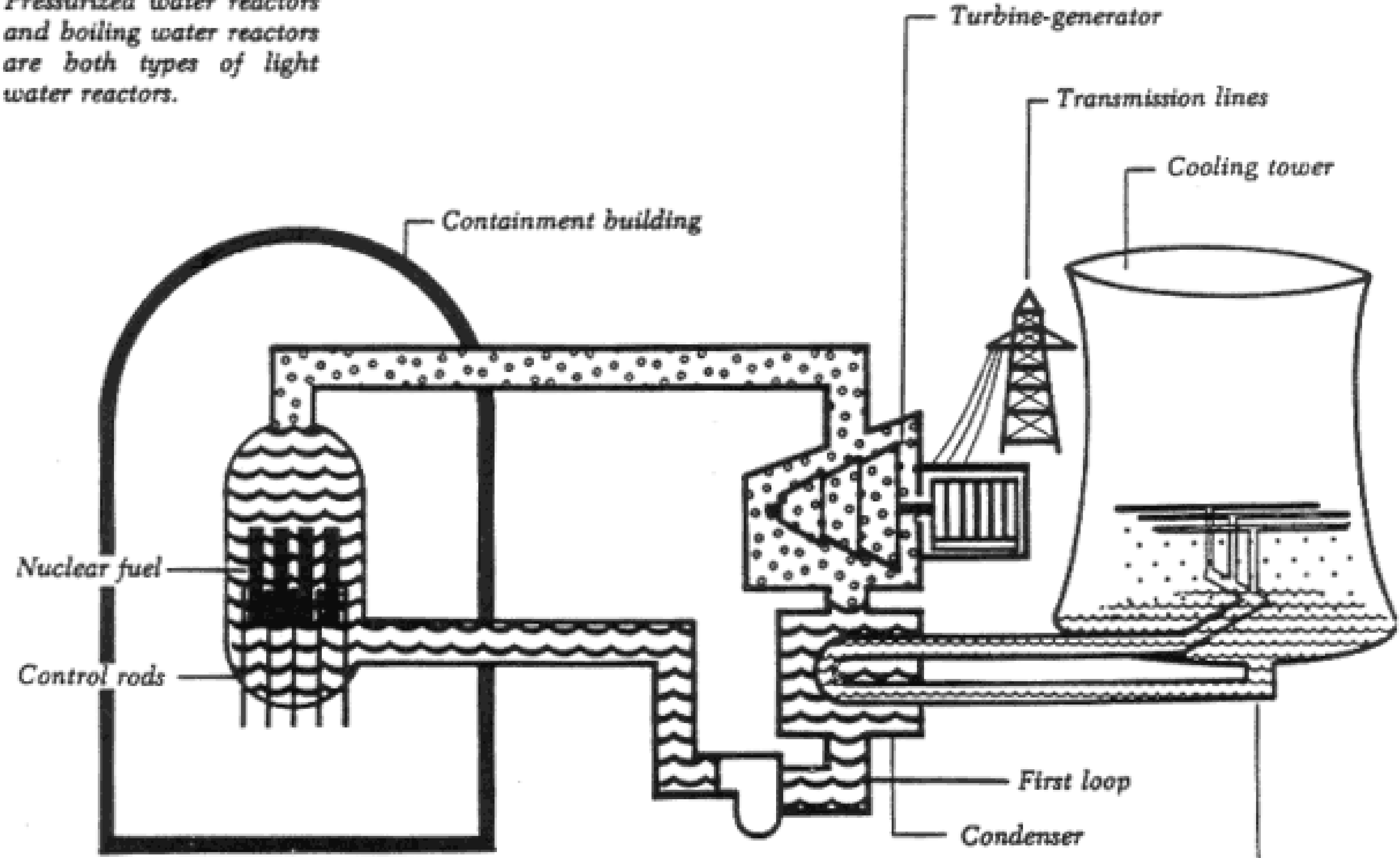
Dynamics of Fluid Loaded Structures
(with application to Loose Parts Monitoring (LPM) in nuclear steam plants)

Richard H. Lyon
MIT Symposium in honor of Ira Dyer
Thursday 14 June, 2007

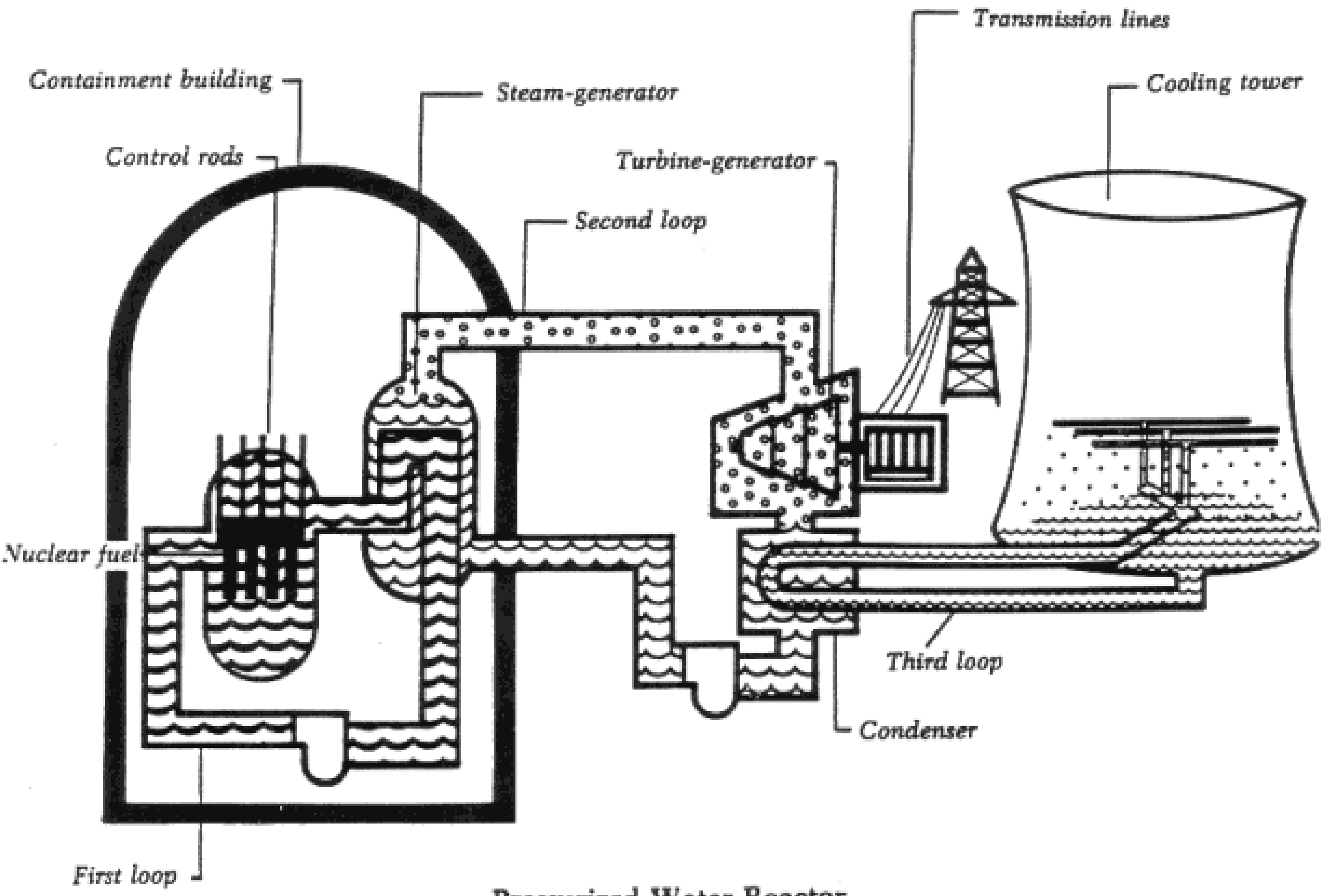
Abstract **Parts that come loose in the cooling circuit can endanger the integrity of a nuclear steam plant. Systems to detect the impacts that occur are installed in the plants but they face difficulties in the detection and classification of such impacts because of the noisy vibrations induced by turbulent flow. Optimizing the performance of these LPM systems depends on knowing the "signature" of the induced vibration signals and these signals are affected by the structural acoustics of the plant components that are internally loaded by water. This presentation reviews the acoustics of fluid loaded plate structures and the dynamics of impact collisions for such structures.**

This work has been supported by Ajou University, Suwon Korea and in cooperation with Prof. Jangbom Chai of the Mechanical Engineering Department

Pressurized water reactors and boiling water reactors are both types of light water reactors.

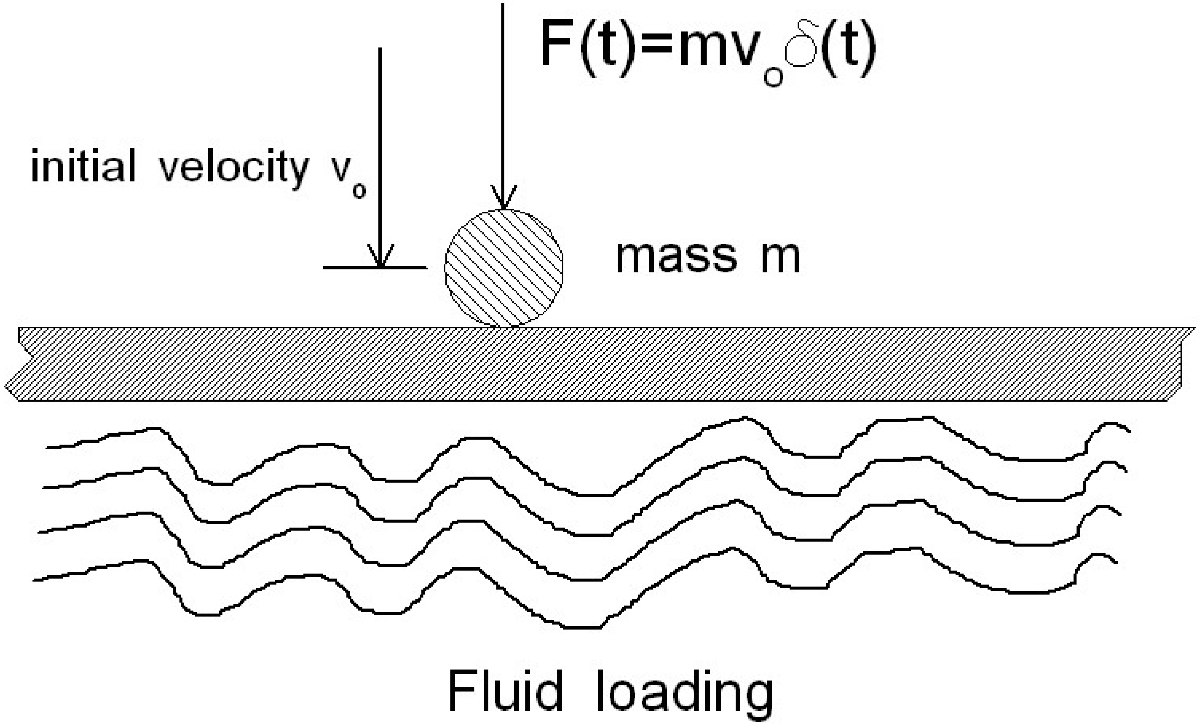


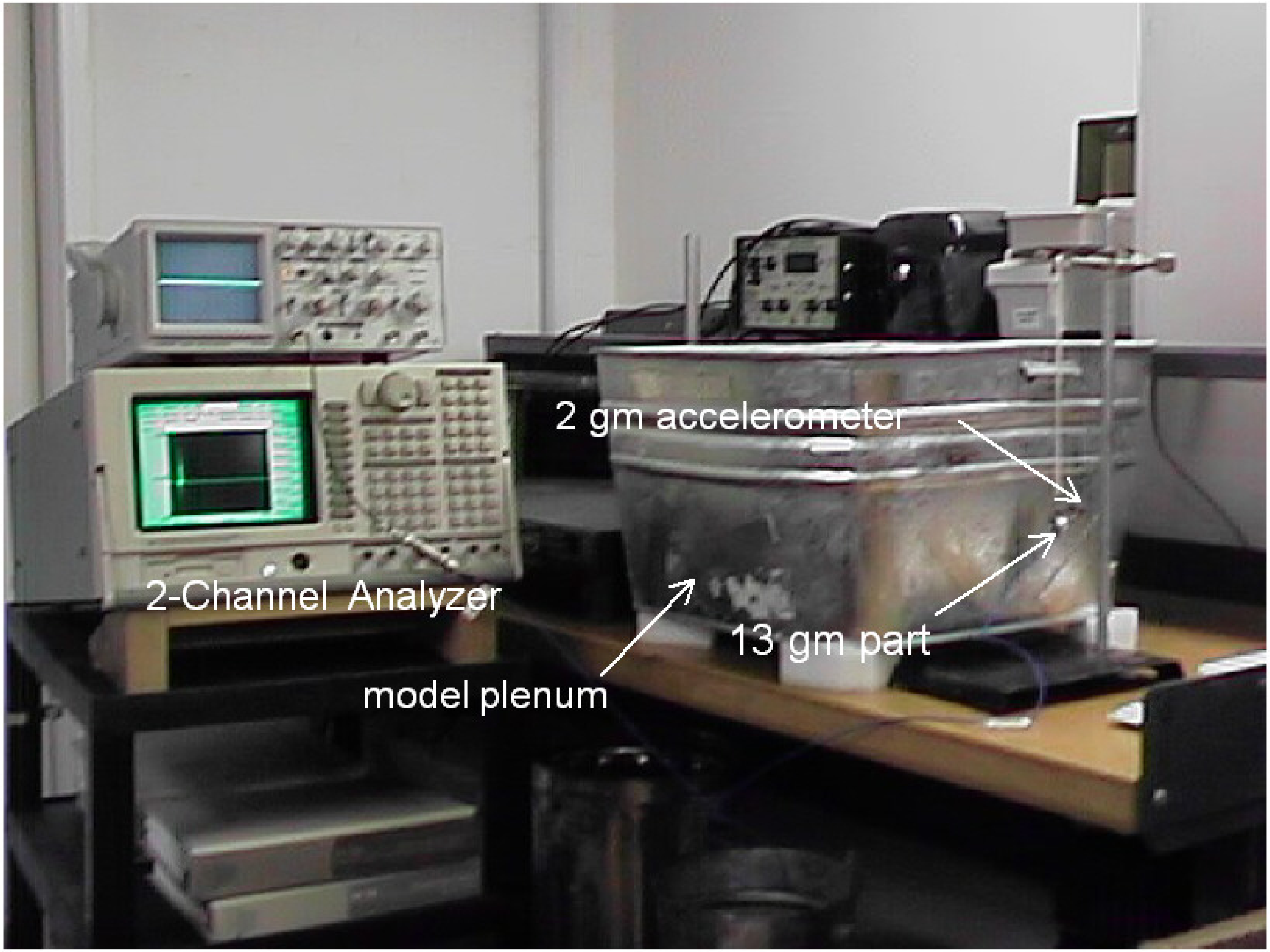
Boiling Water Reactor



Pressurized Water Reactor

Impact dynamics




2 gm accelerometer
2-Channel Analyzer
13 gm part
model plenum

Assumptions made in the structural analysis

- The structure can be modeled as an isotropic flat plate. This primarily means that the stiffening effect of curvature is ignored
- The structural waves of importance are bending waves Although in-plane dilatation and shear waves are generated, they likely store little energy and have small effect on the measurements of vibration.
- The fluid is assumed incompressible. This should be acceptable as long as the phase speed of the bending waves is small compared to the speed of sound in the fluid.
- The fluid is assumed inviscid. That means that the small amount of damping provided by viscous losses at the wall/fluid interface is incorporated as part of the structural damping.
- Bouncing of the part after collision with the wall does not occur. This is done for convenience, it would be possible to include bouncing in a more elaborate analysis.

Equations governing the structural dynamics of fluid loaded flat plate (phase and group speed and modal density)

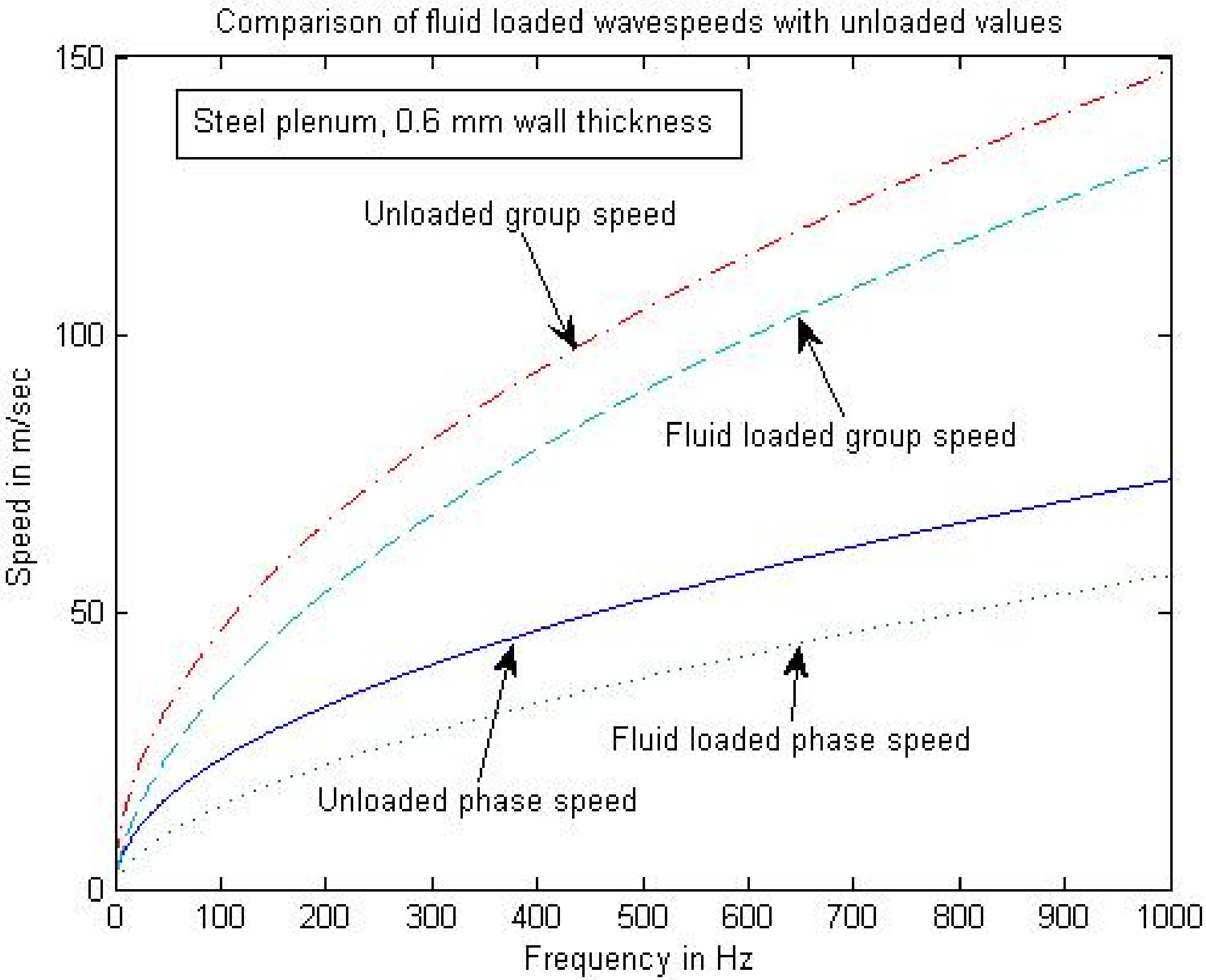
$$(EI\,\nabla^4 - \omega^2 \rho_s)y = EI(k^4 - k_b^4)y = -\omega^2 \rho_\mathrm{f}\, \mathrm{y}/k$$

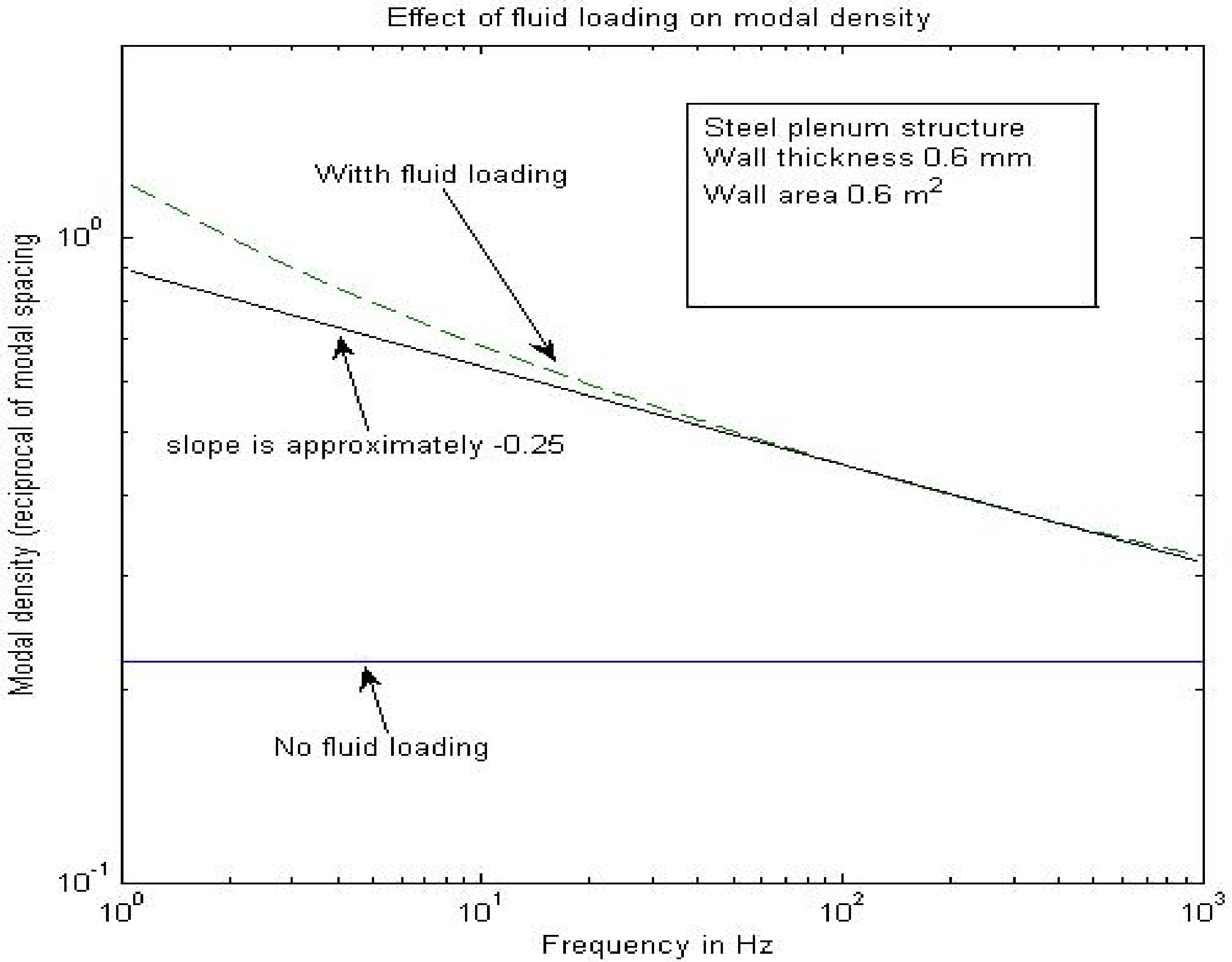
k=ω/c, kb=ω/cb

$$\frac{\rho_f}{\omega \rho_s} c^5 + c^4 - c_b^4 = 0$$

$$c_g = c(1 - d\,\ell n\, c \,/\, d\,\ell n\,\omega)^{-1}$$

$$n(\omega) = \omega\, A_p \,/\, 2\pi\, c\, c_g$$


Comparison of fluid loaded wavespeeds with unloaded values
Steel plenum, 0.6 mm wall thickness
Unloaded group speed
Fluid loaded group speed
Fluid loaded phase speed
Unloaded phase speed
Speed in m/sec
Frequency in Hz
0
50
100
150
0
100
200
300
400
500
600
700
800
900
1000


Effect of fluid loading on modal density
Steel plenum structure
Wall thickness 0.6 mm
Wall area 0.6 m^2
Witth fluid loading
slope is approximately -0.25
No fluid loading
10^0
10^{-1}
Modal density (reciprocal of modal spacing
10^0
10^1
10^2
10^3
Frequency in Hz

Conductance and Susceptance

$$G(\omega) = \pi\, n(\omega) / 2M(\omega)$$

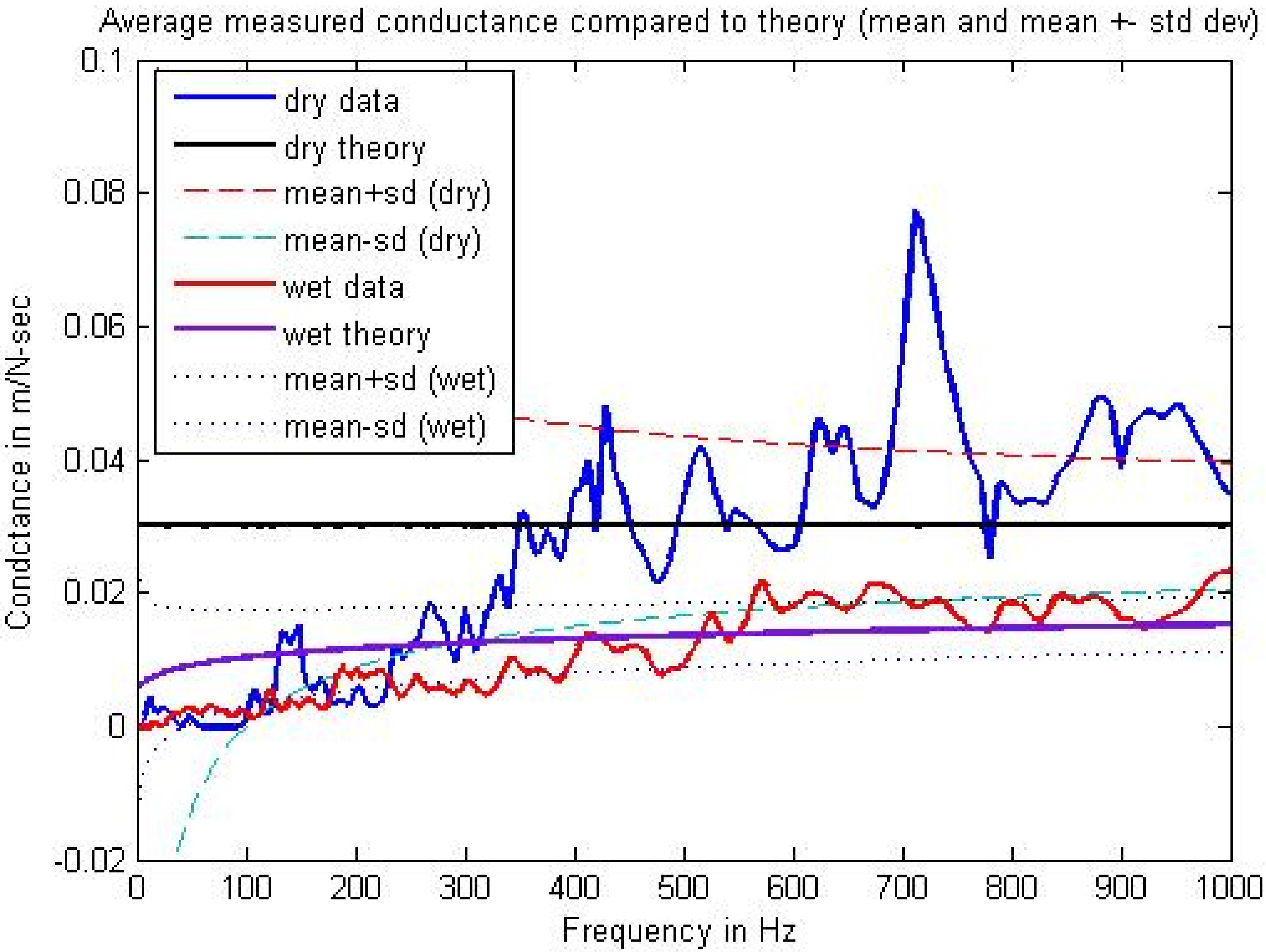
$$\frac{\sigma_G^2}{m_G^2} = \frac{1}{2M_o} \frac{<\psi_m^4>_x}{<\psi_m^2>_x^2} = \frac{9}{8M_o}$$

$n(\omega) \sim \omega p$

$$Y(\omega) = G(\omega)(1 - j2R/\pi);$$

$$R = 2p/(p^2 - 1)$$

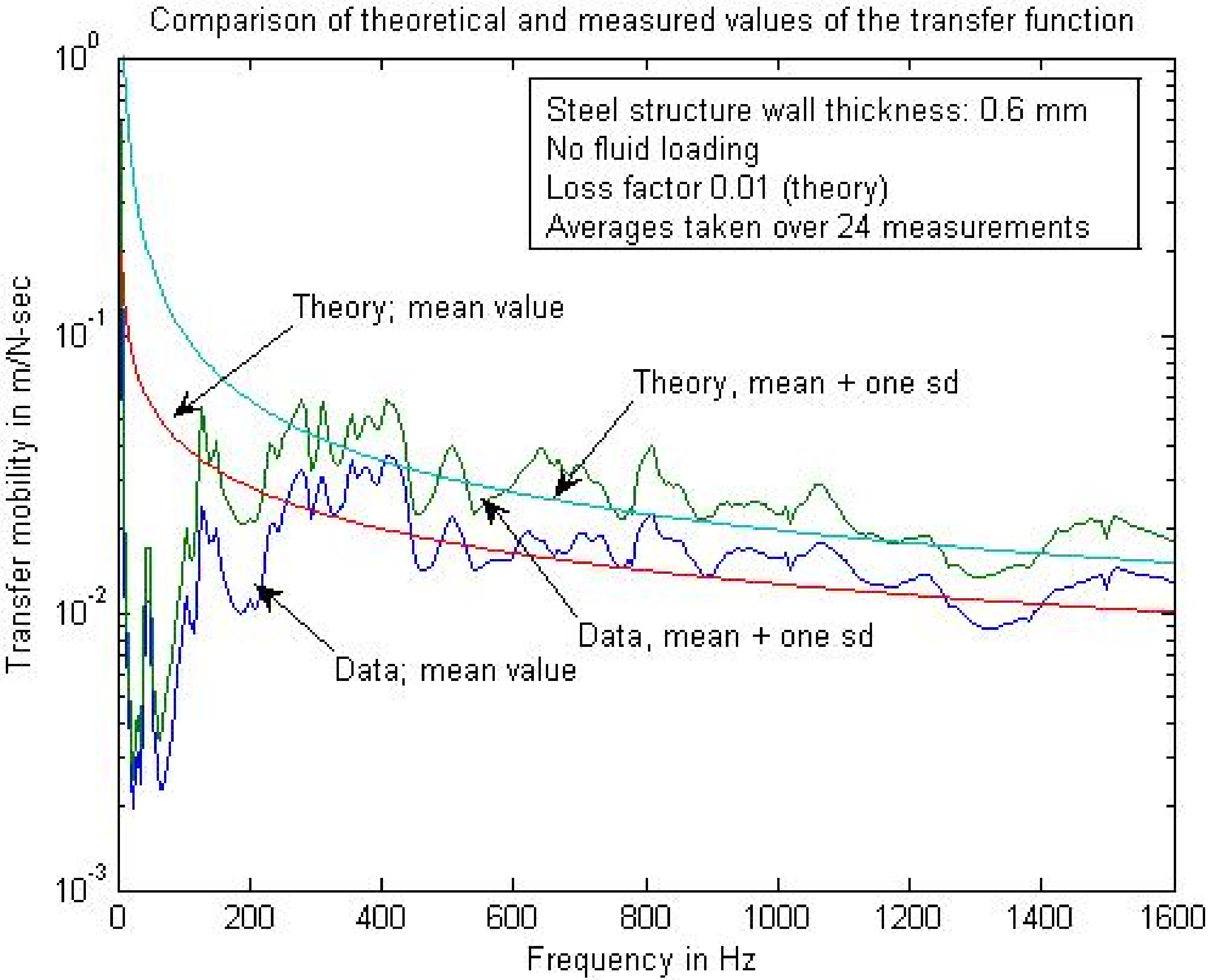

4

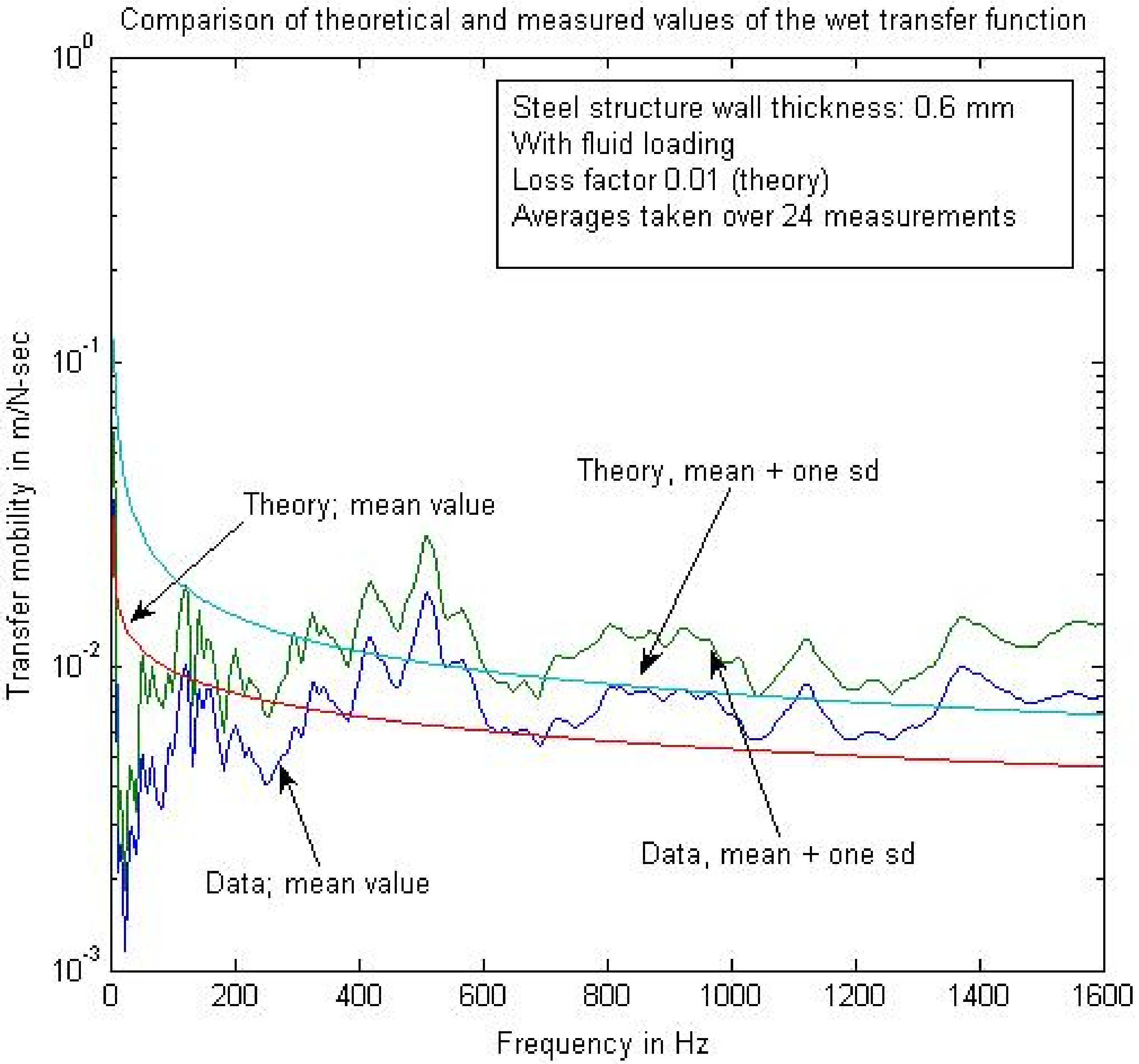

Average measured conductance compared to theory (mean and mean +- std dev)
dry data
dry theory
mean+sd (dry)
mean-sd (dry)
wet data
wet theory
mean+sd (wet)
mean-sd (wet)
Condctance in m/N-sec
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
100
200
300
400
500
600
700
800
900
1000
Frequency in Hz

Transfer functions

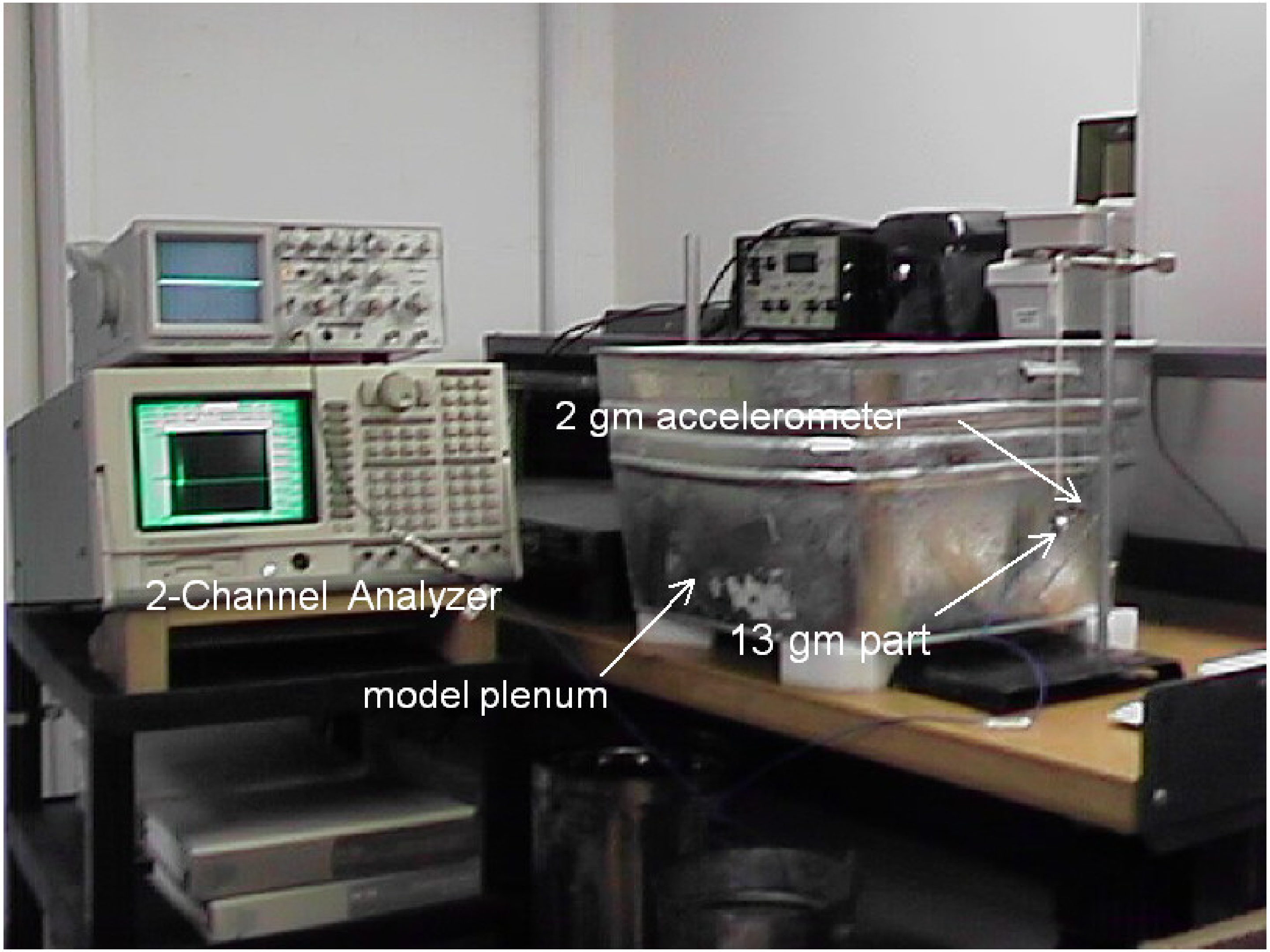
$$< f^2 > G(\omega) = \omega\eta M(\omega) < v^2 >$$

$$\frac{\sigma_{TF}^2}{m_{TF}^2} = 1 + \frac{1}{2M_o}\frac{<\psi_m^4>_x^2}{<\psi_m^2>_x^4} = 1 + \frac{2.5}{M_o}$$


Comparison of theoretical and measured values of the transfer function
Steel structure wall thickness: 0.6 mm
No fluid loading
Loss factor 0.01 (theory)
Averages taken over 24 measurements
Theory; mean value
Theory, mean + one sd
Data, mean + one sd
Data; mean value
Transfer mobility in m/N-sec
10^0
10^{-1}
10^{-2}
10^{-3}
0
200
400
600
800
1000
1200
1400
1600
Frequency in Hz



Comparison of theoretical and measured values of the wet transfer function

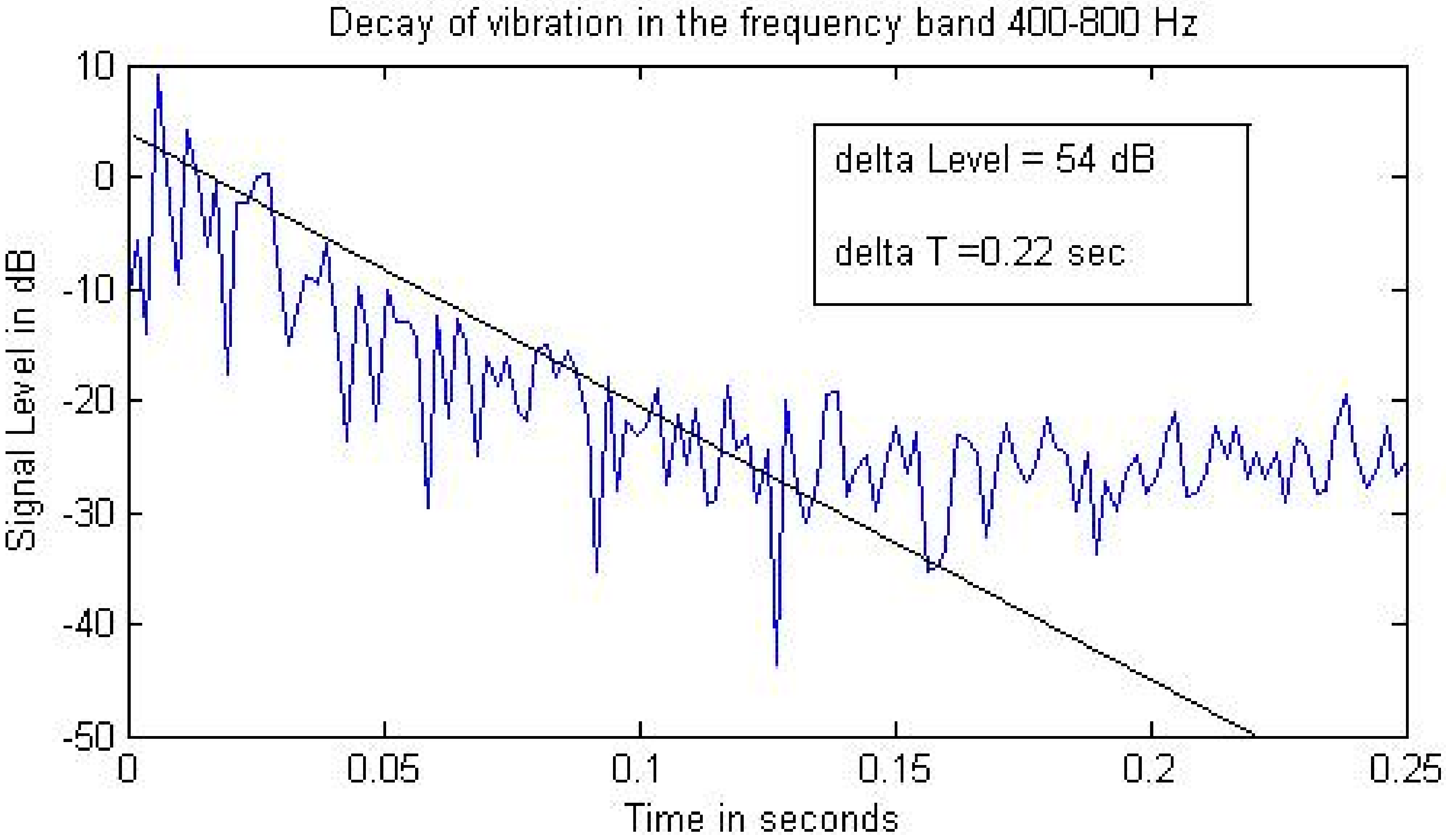

2 gm accelerometer
2-Channel Analyzer
13 gm part
model plenum

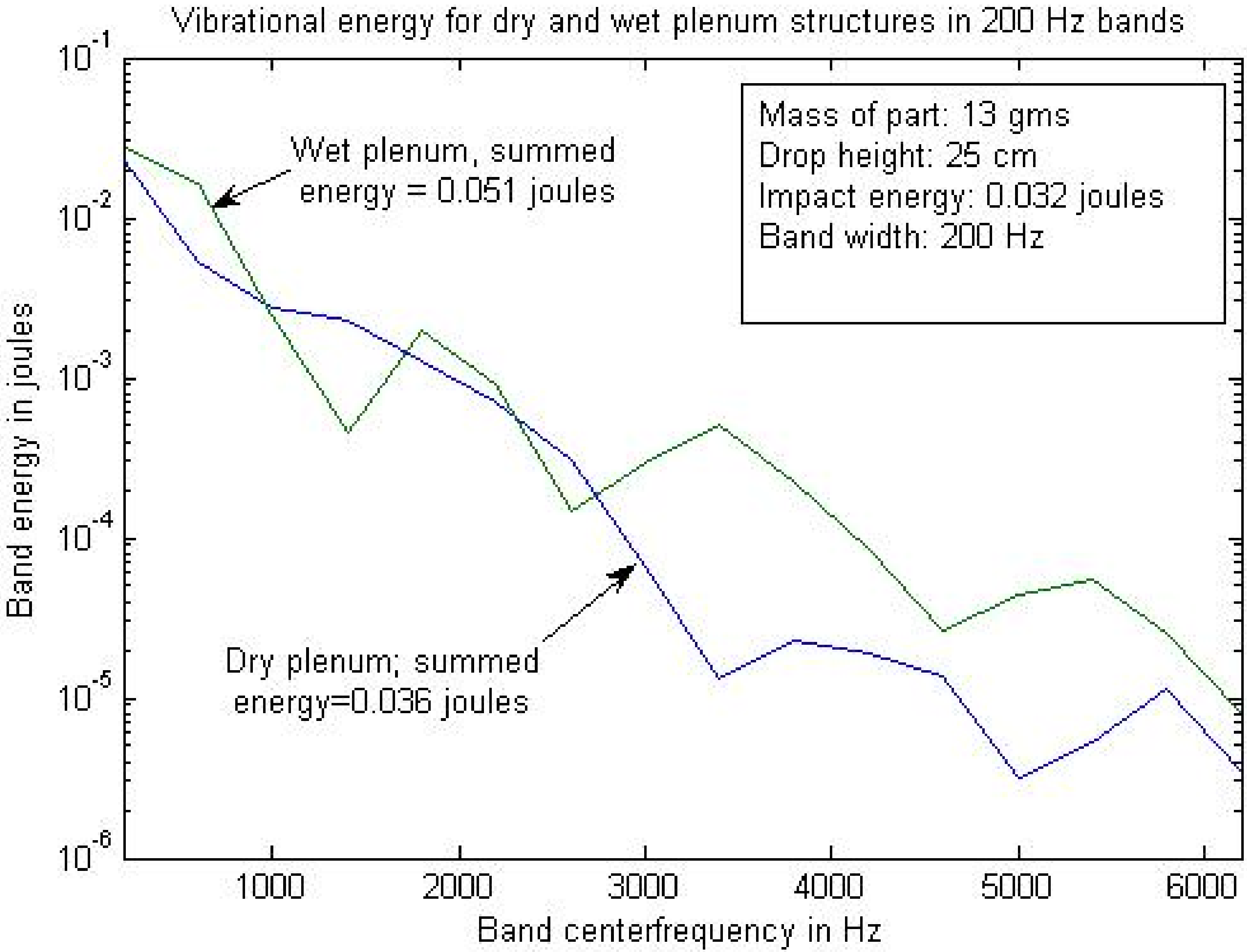
$$e(t)=M<v2>/2$$

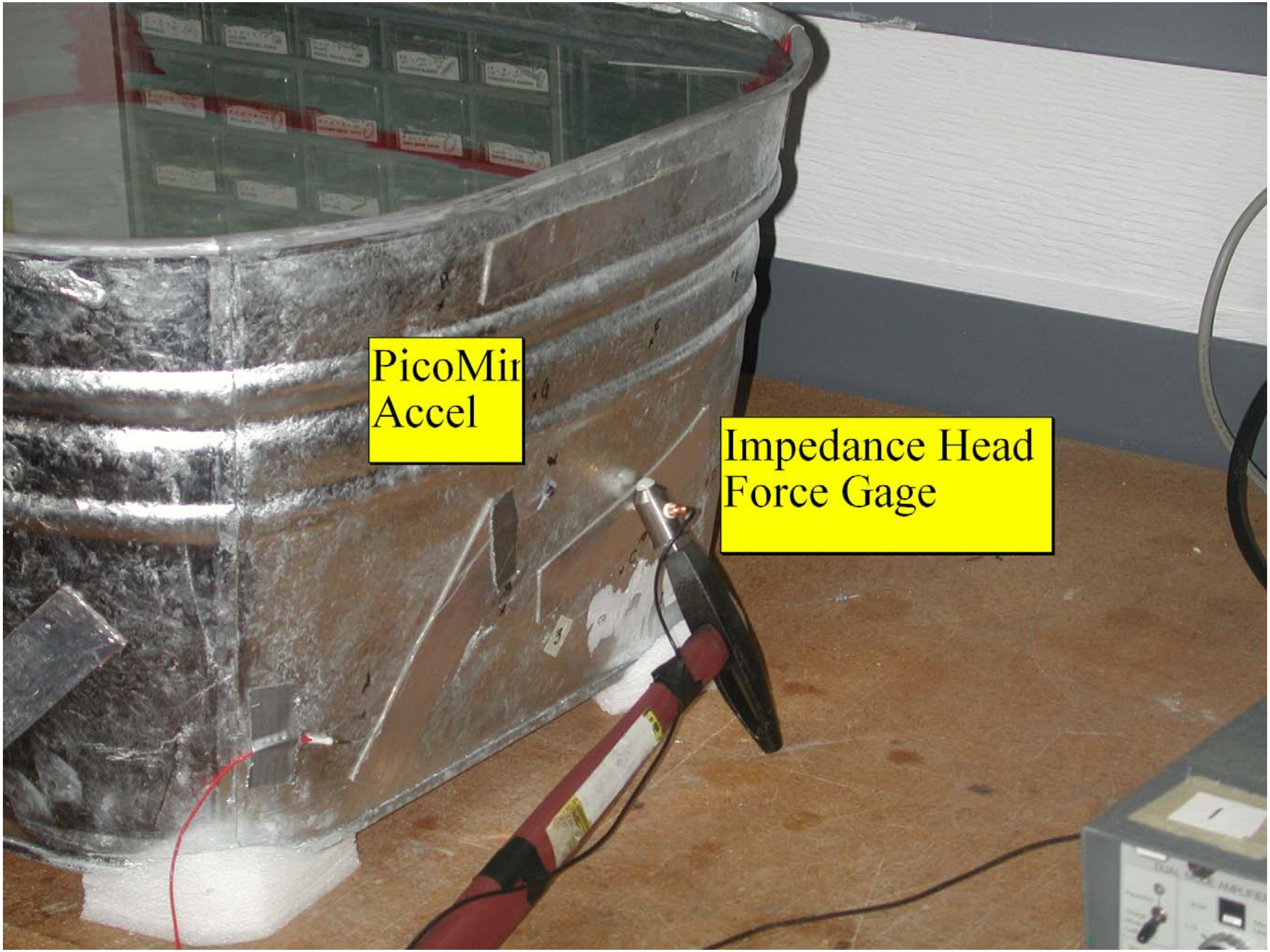
$$e(t)=E\exp(-\omega\eta t)$$

$$S(\omega)=\tfrac{1}{2}M \int<|v|2>dt=(\tfrac{1}{2}M/\omega 2) \int<|a|2>dt =E/\omega\eta$$

$$E(\omega)=\omega\eta S(\omega)$$




Vibrational energy for dry and wet plenum structures in 200 Hz bands
Band energy in joules
Band centerfrequency in Hz
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1000
2000
3000
4000
5000
6000
Wet plenum, summed energy = 0.051 joules
Dry plenum; summed energy=0.036 joules
Mass of part: 13 gms
Drop height: 25 cm
Impact energy: 0.032 joules
Band width: 200 Hz



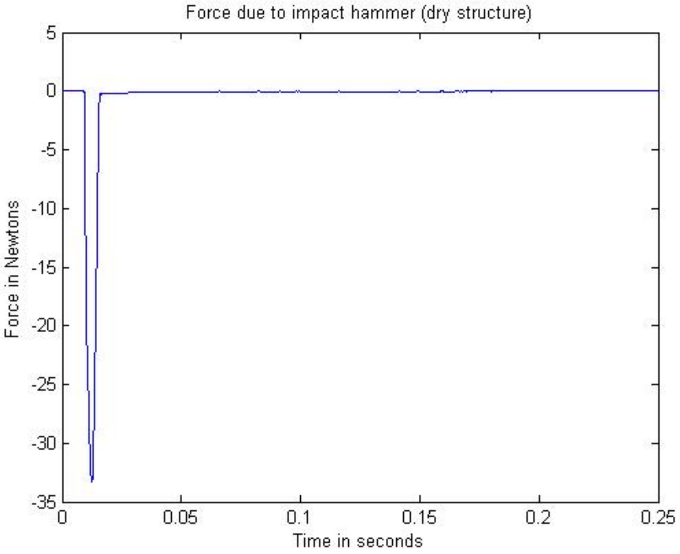
PicoMir
Accel

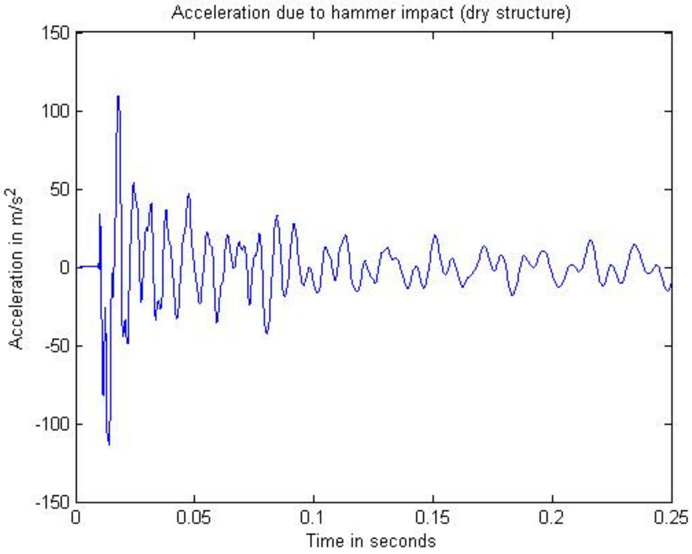
Impedance Head
Force Gage

Samples of impact forces and resulting acceleration

Dry

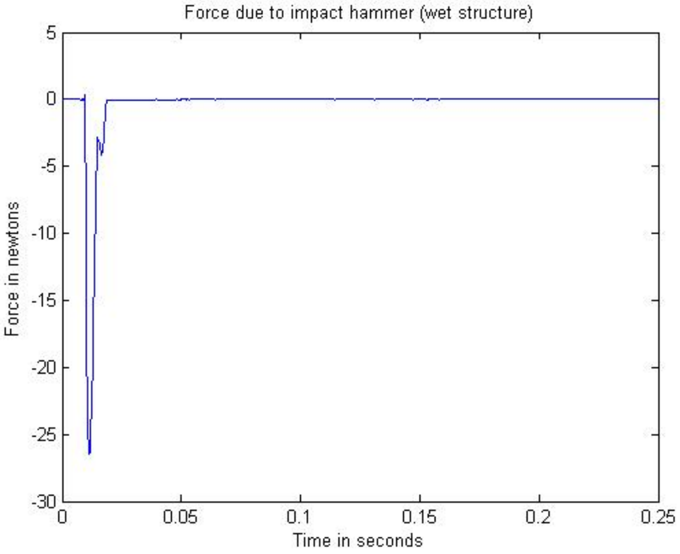
Structure

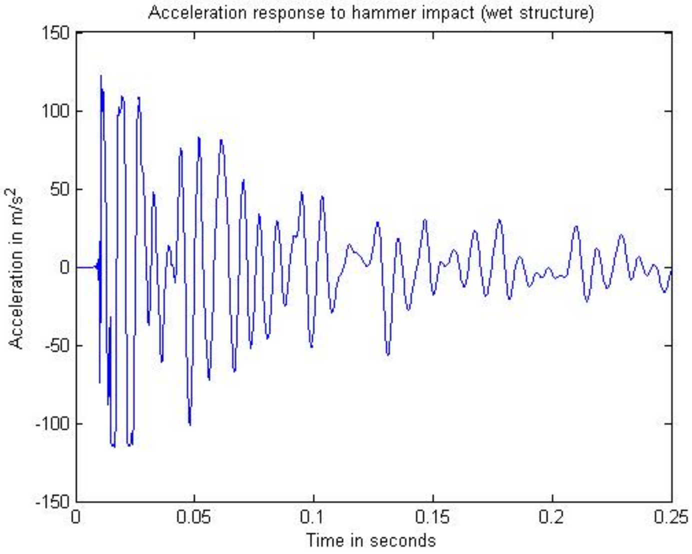

Force due to impact hammer (dry structure)


Acceleration due to hammer impact (dry structure)

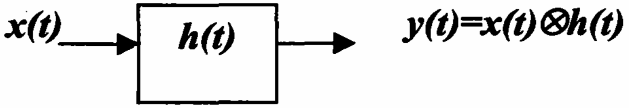
Wet

Structure


Force due to impact hammer (wet structure)


Acceleration response to hammer impact (wet structure)

Modal parameters as noise to be rejected



$x(t)$ $h(t)$ $y(t)=x(t)\otimes h(t)$

$x(t)=sin(2\pi f_o t)exp(-\beta_o t)$

parameters: f_o, β_o

$h(t)=\Sigma_m \psi_m^s \psi_m^o \, sin(2\pi f_m \, t)exp(-\beta_m \, t) \quad m=1,2,\ldots$

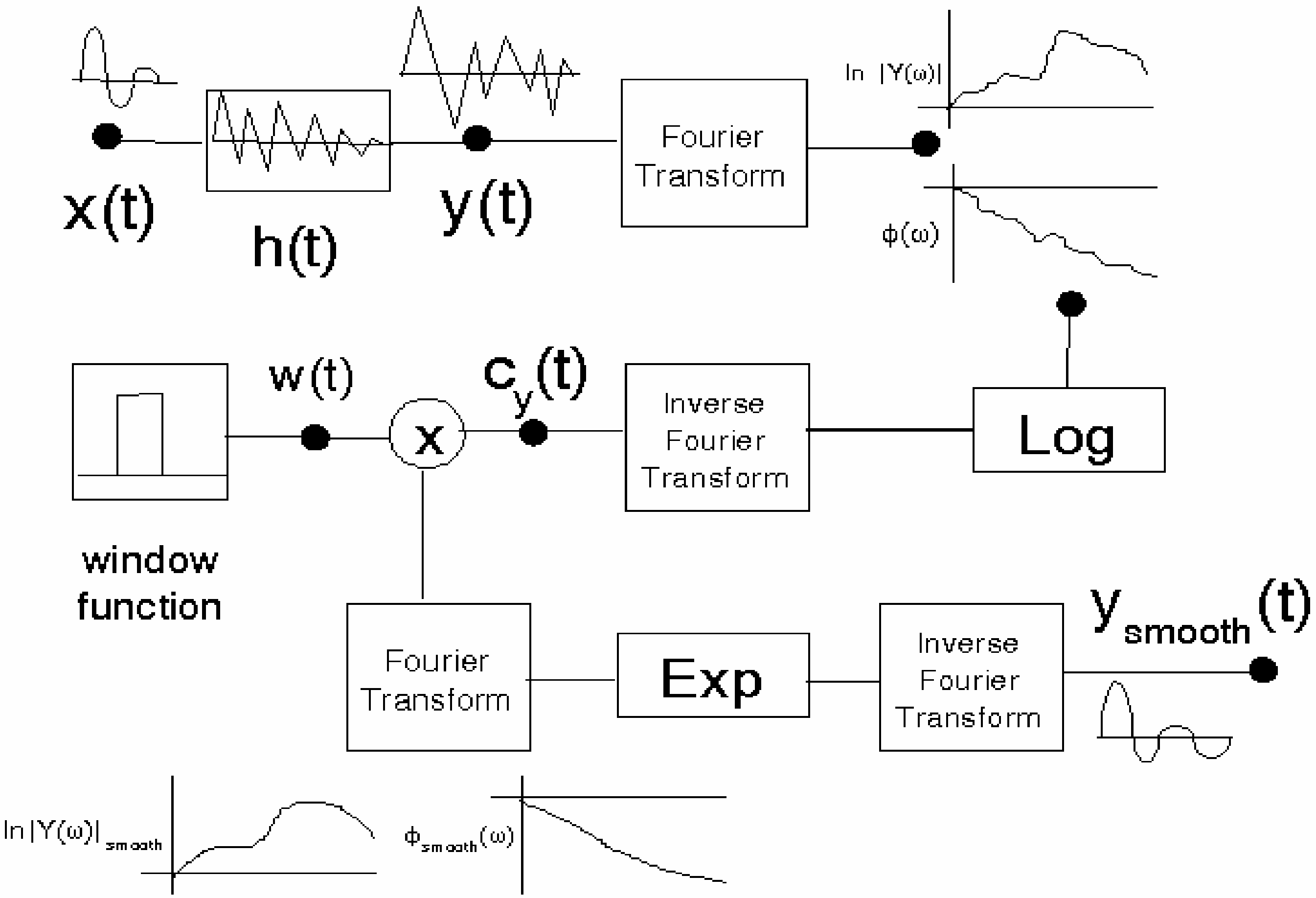
parameters: f_m, β_m, ψ_m^s, ψ_m^o $m=1,2,\ldots$

Therefore

$y(t)$: parameters: f_o, β_o; f_m, β_m, ψ_m^s, ψ_m^o $m=1,2,\ldots$

Question:

How to get rid of f_m, β_m, ψ_m^s, ψ_m^o $m=1,2,\ldots$ *and retrieve* f_o, β_o ?



$x(t)$

$h(t)$

$y(t)$

Fourier Transform

$\ln\ |Y(\omega)|$

$\phi(\omega)$

window function

$w(t)$

x

$c_y(t)$

Inverse Fourier Transform

Log

Fourier Transform

Exp

Inverse Fourier Transform

$y_{smooth}(t)$

$\ln|Y(\omega)|_{smooth}$

$\phi_{smooth}(\omega)$

Matched Filtering

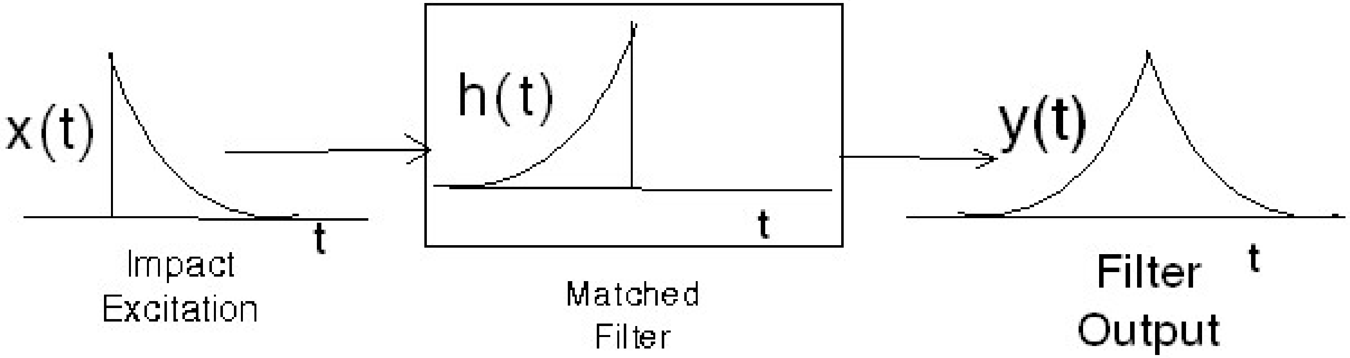
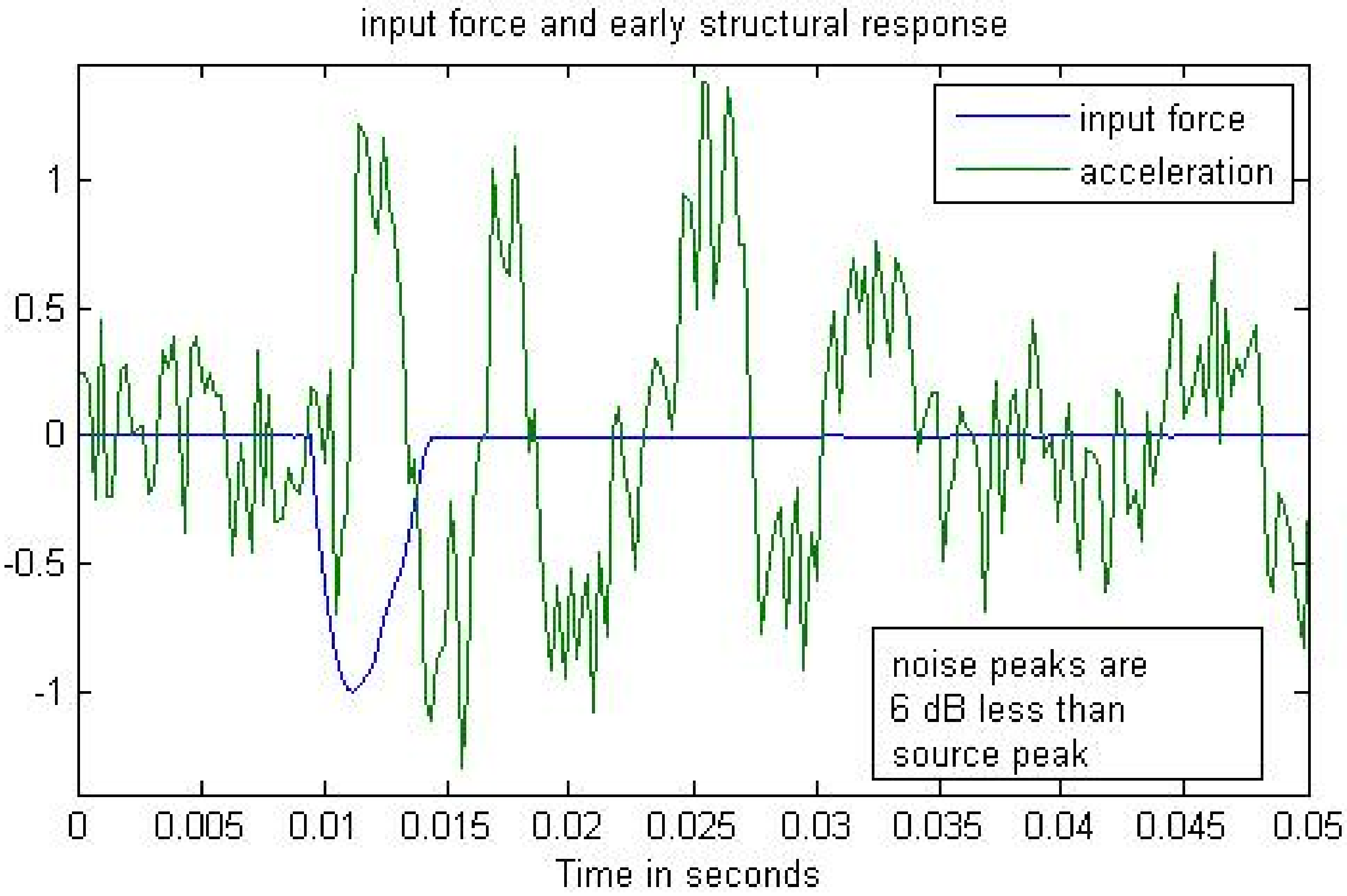
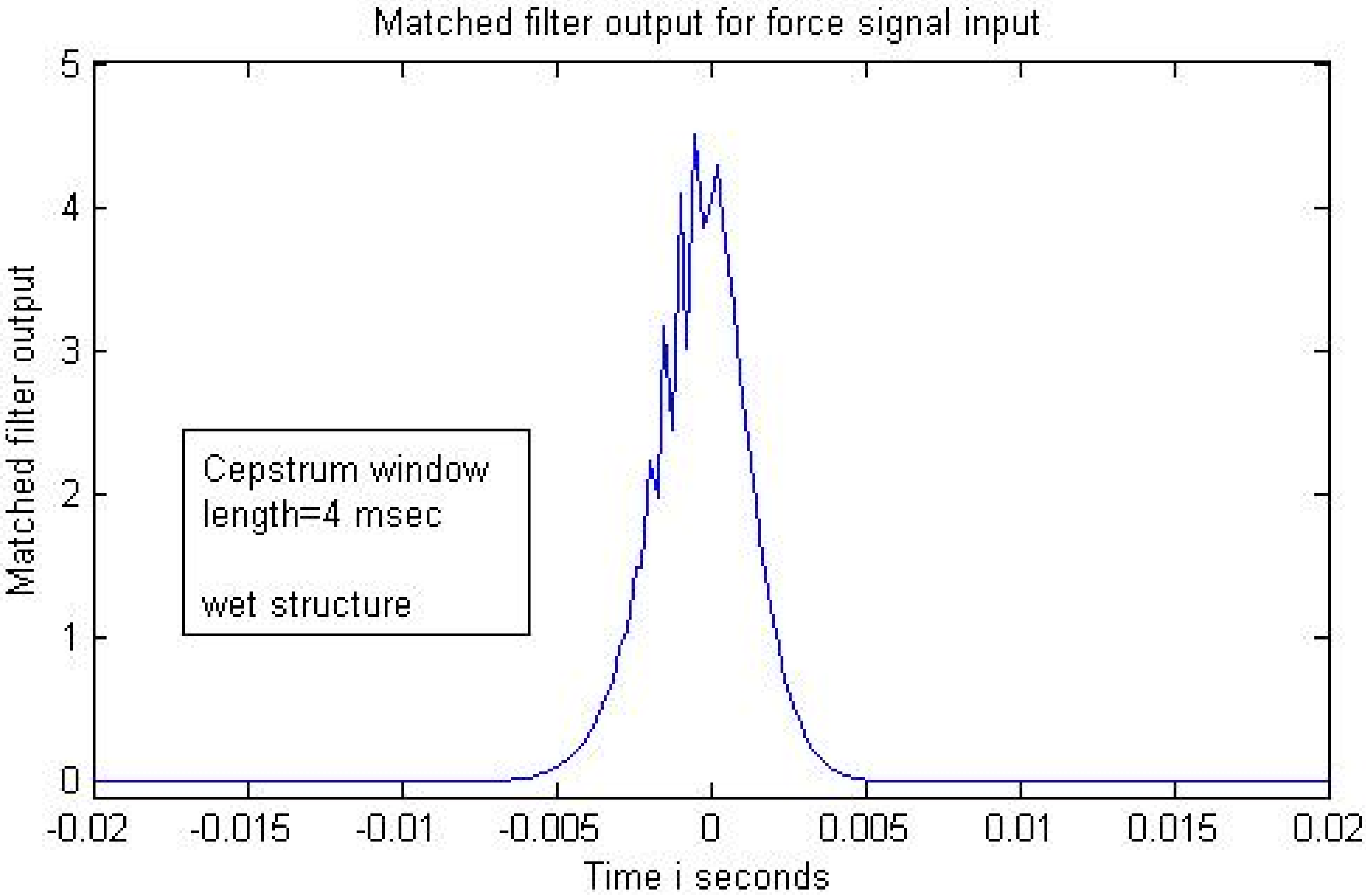
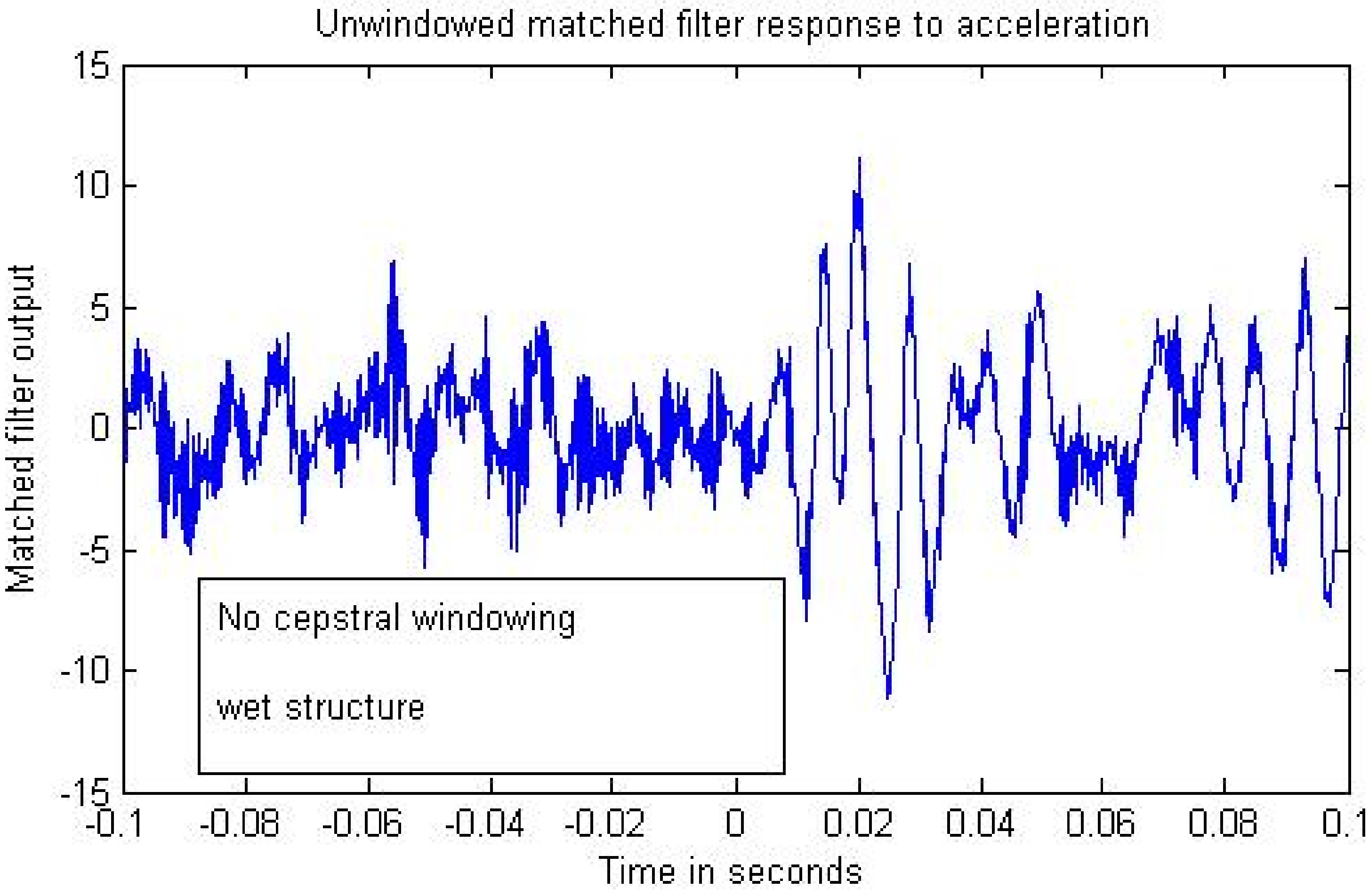


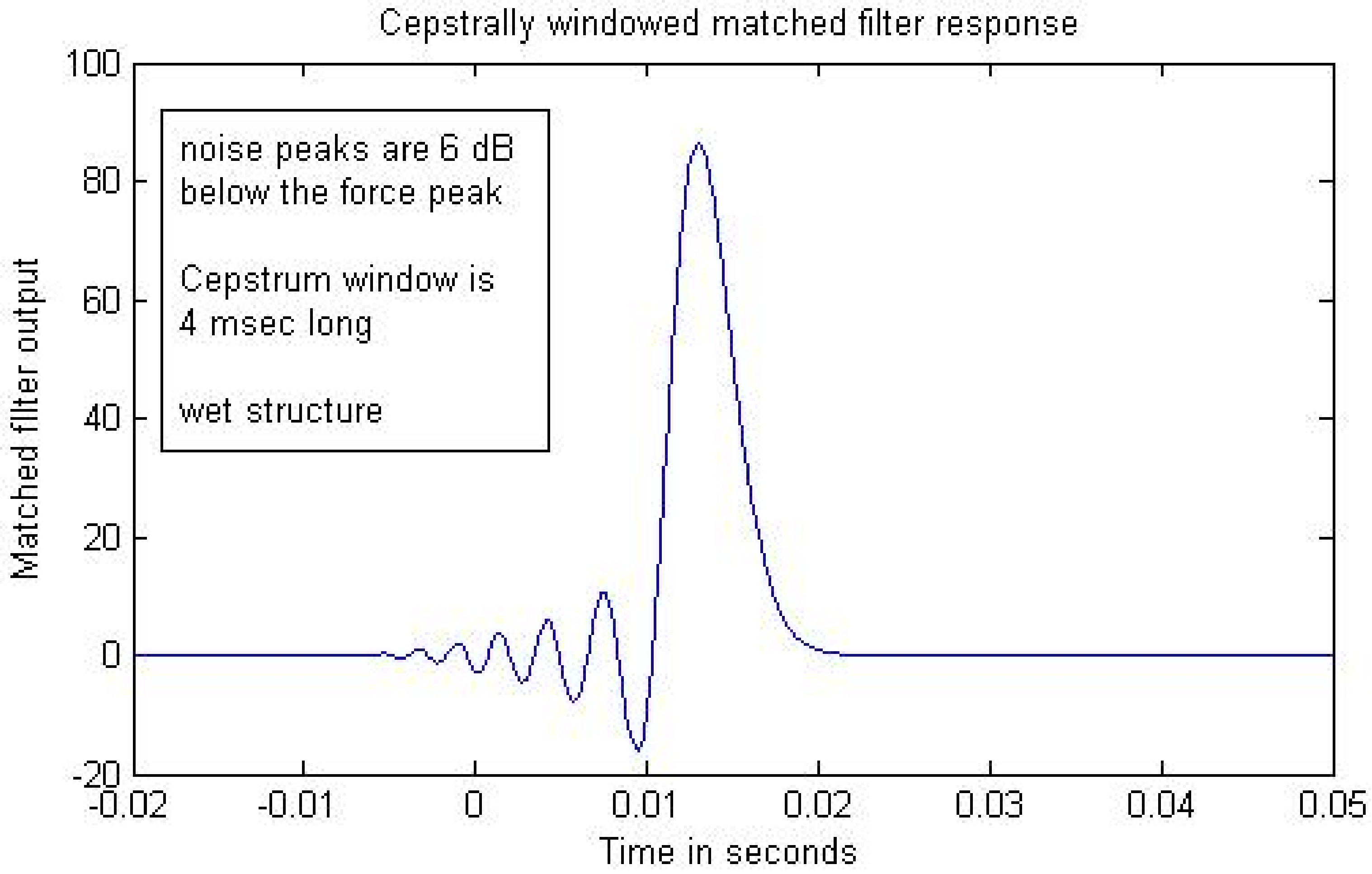
Figure 1. Matched filter applied to simple pulse waveform



noise peaks are
6 dB less than
source peak


Matched filter output for force signal input
Matched filter output
Time i seconds
0
1
2
3
4
5
-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02
Cepstrum window
length=4 msec
wet structure


Unwindowed matched filter response to acceleration
15
10
5
0
-5
-10
-15
Matched filter output
-0.1
-0.08
-0.06
-0.04
-0.02
0
0.02
0.04
0.06
0.08
0.1
Time in seconds
No cepstral windowing
wet structure

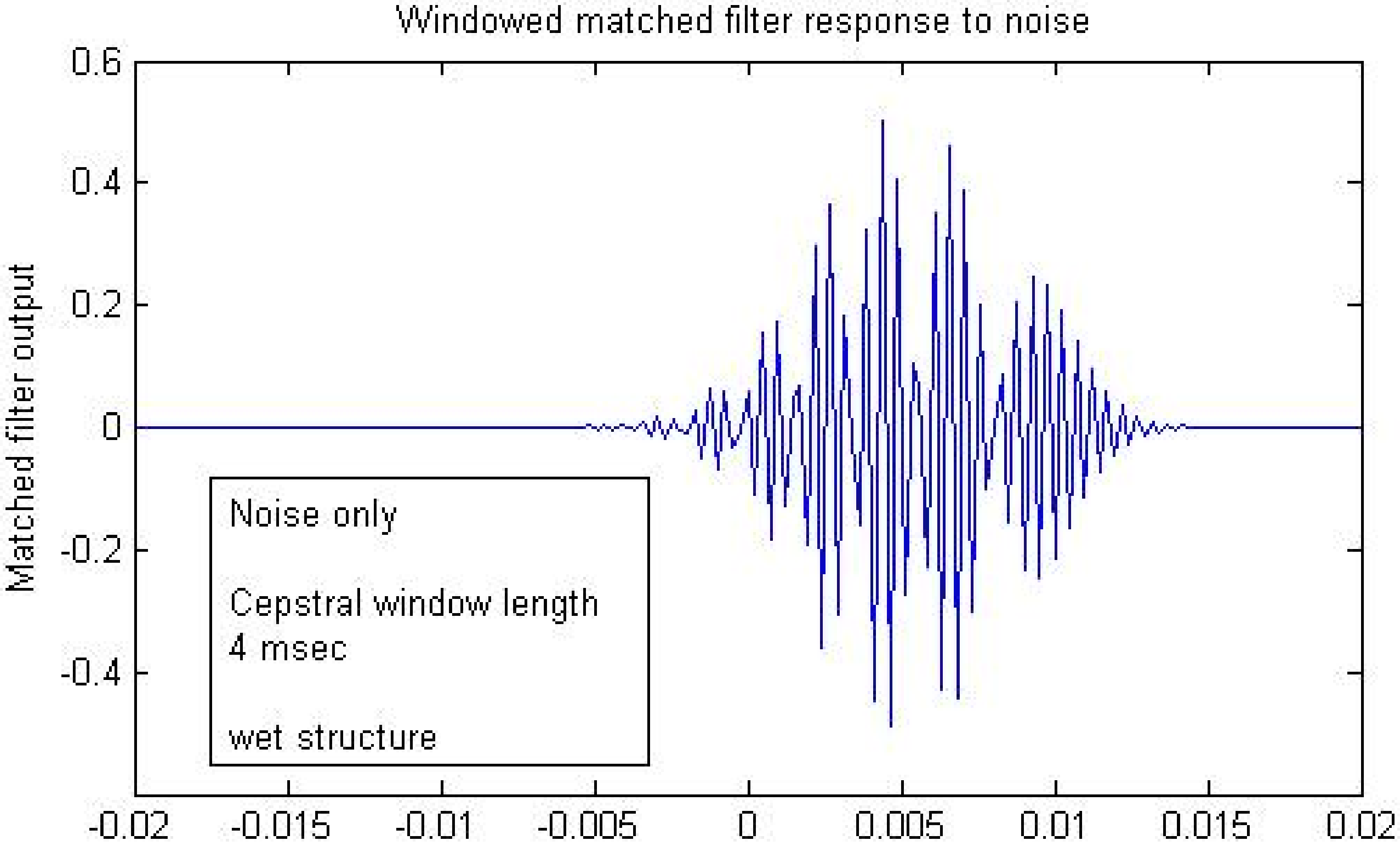


Cepstrally windowed matched filter response

noise peaks are 6 dB below the force peak

Cepstrum window is 4 msec long

wet structure


Windowed matched filter response to noise
Matched filter output
0.6
0.4
0.2
0
-0.2
-0.4
-0.02
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
0.02
Noise only
Cepstral window length
4 msec
wet structure