# Where DSP meets Measurement Science: A Sound Example

By Andrew Hurrell PhD

PRECISION ACOUSTICS LTD

# Measuring ultrasound – why bother?

- 6 million ultrasound scans within NHS during 2004-2005
- Ultrasound has potential for:
  - Thermal damage: enough to "cook" tissue as a form of cancer therapy
  - Mechanical damage: Many cleaning baths use ultrasonic sterilisation
- YET, ultrasound is one of the safest imaging modalities
  - Because it is non-ionising, but also <u>VERY WELL REGULATED</u>
  - UK is the world leader in ultrasound standards

PRECISION ACOUSTICS LTD

# Ultrasonic metrology: getting started

- Most ultrasonic pressure measurements use hydrophones

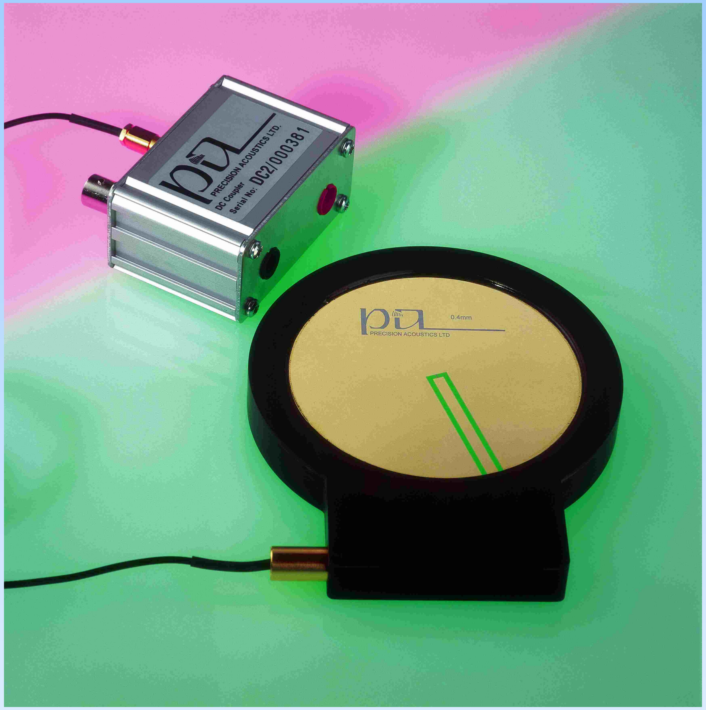
HYDROPHONE

*HYDRO*: associated with water

*PHONE*: associated sound/listening

PRECISION ACOUSTICS LTD

# Common hydrophone types



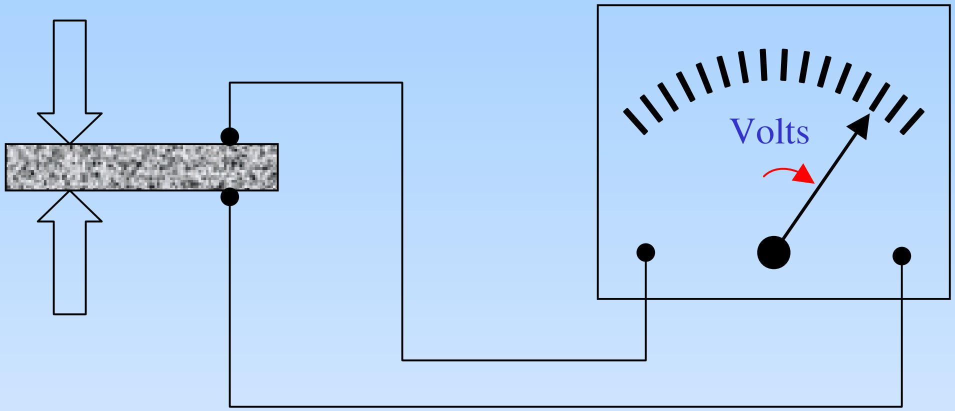

Membrane

Needle/Probe

PRECISION ACOUSTICS LTD

# Principles of hydrophone operation

- Most hydrophones use piezo-electric materials.
  - piezo – from Greek meaning “to press”.
- Applied pressure produces a voltage




BUT, we want to measure pressure not voltage

THEREFORE we require a means of deriving pressure waveforms from the voltages that have been measured

# The hunt for a pressure waveform

- Calibration
  - Any given hydrophone needs calibration (preferably by an accredited lab such as NPL) to derive the relationship between output voltage and measured pressure
  - Calibration figure (hydrophone sensitivity) is often frequency dependant

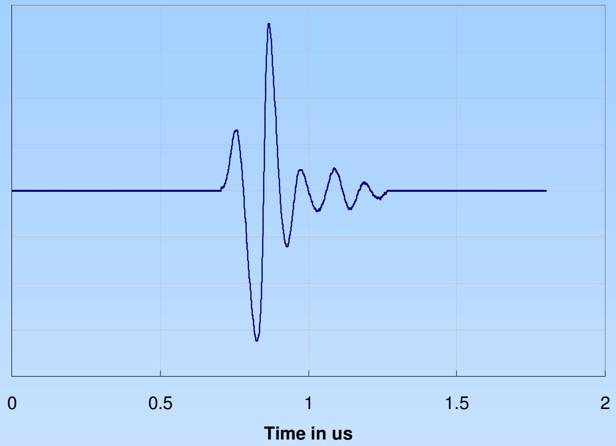
- Measurement
  - Hydrophone sensitivity applied to measured waveform to provide true pressure waveform

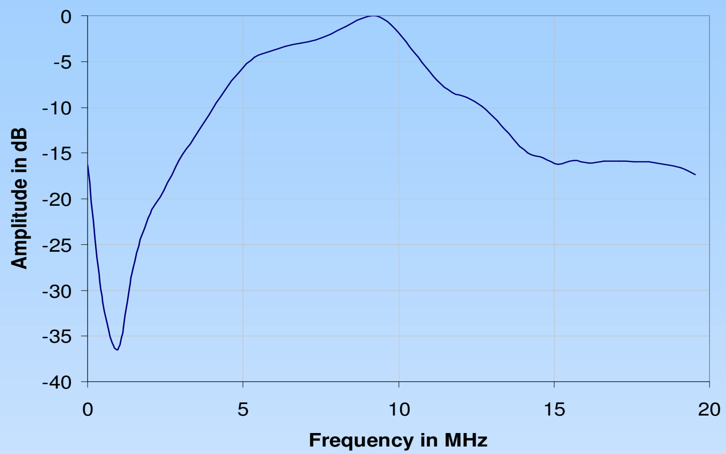
# Calibration – requirements

- Ultrasonic hydrophones operate over wide frequency range. For example
  - Lower frequency: 100 kHz to 10 MHz
  - Higher frequency: 1 MHz to 60 MHz

- Need ultrasound source capable of covering this wide range

# Calibration – sources

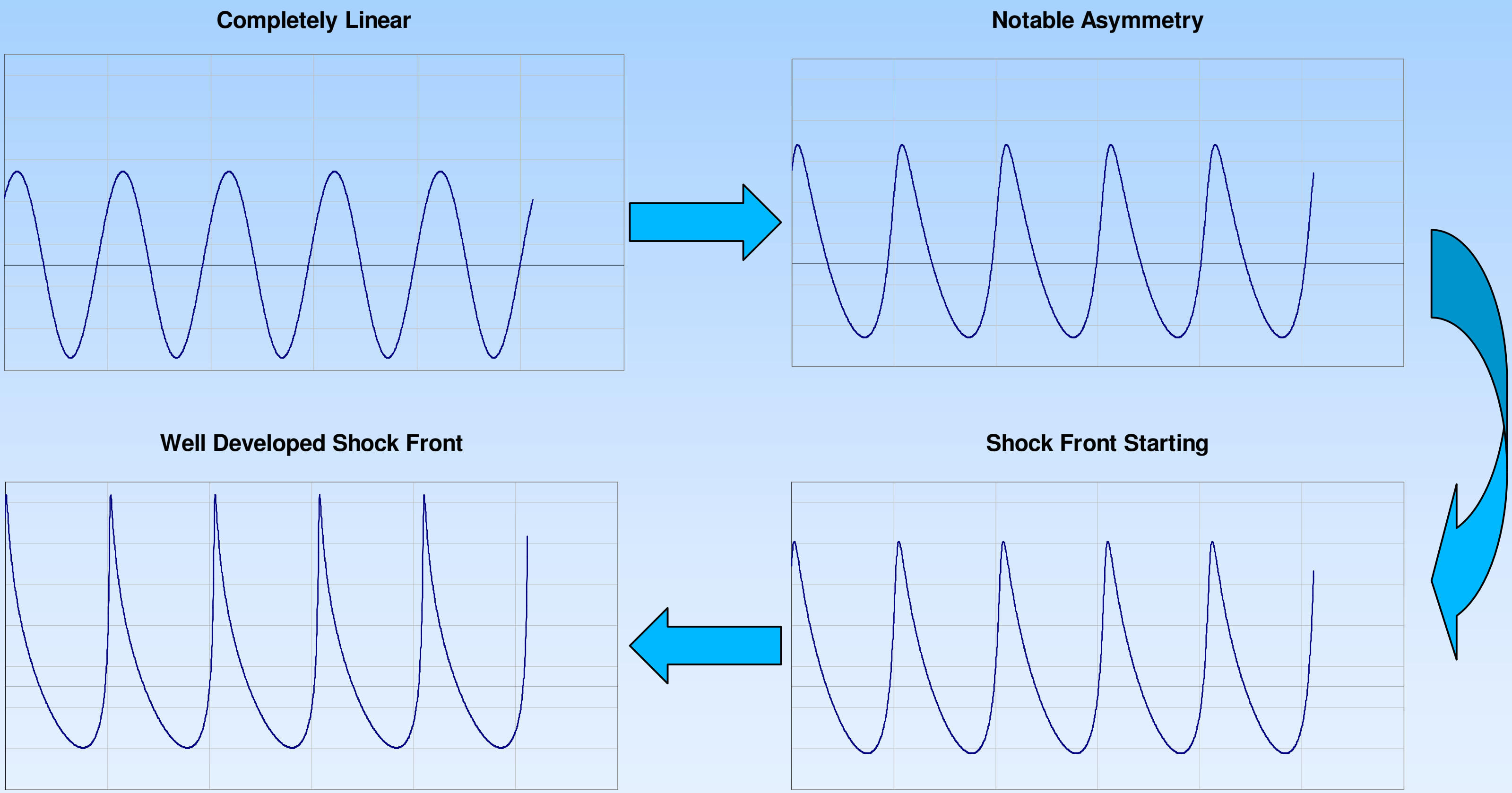


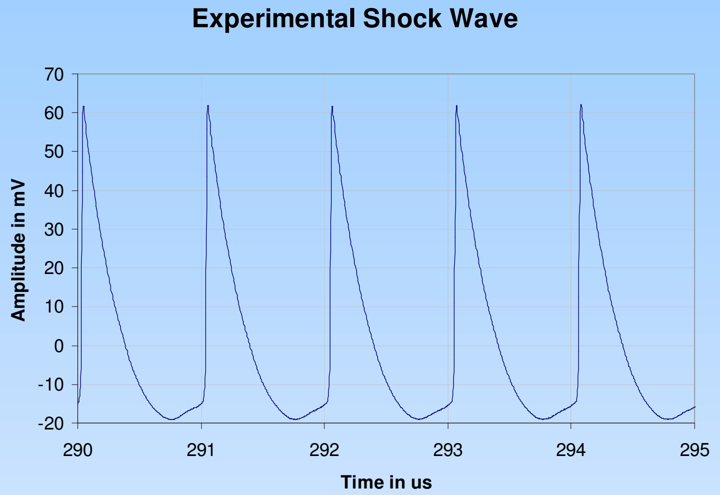

- Sources of ultrasound often have limited bandwidth (<100% of centre frequency)
  - e.g. 0.5-1.5MHz (centre 1 MHz), 5-15 MHz (centre 10 MHz)
  - Many sources required to cover required range
  - Multiple setup/alignments are VERY time consuming

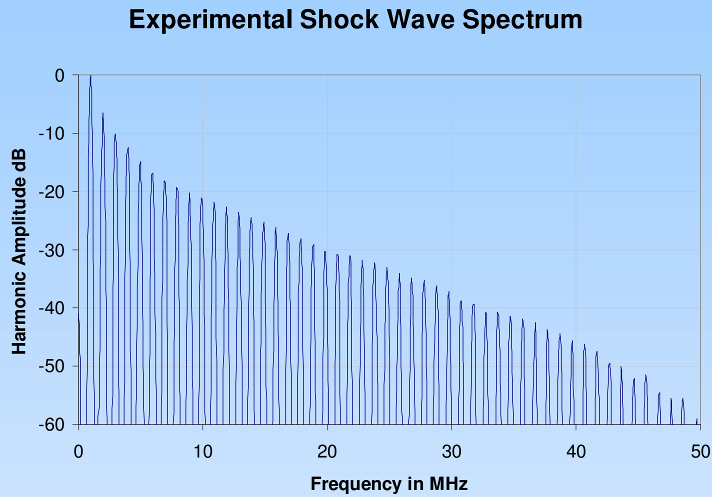
PRECISION ACOUSTICS LTD

# Calibration – nonlinear propagation



# Calibration – shockwave behaviour




- Nonlinear propagation has "pumped" energy into harmonics at integer multiples of fundamental
- Spectral amplitudes can be obtained via FFT of temporal waveform

PRECISION ACOUSTICS LTD

# Calibration – process overview

Measure ultrasonic field with device under test

Remove test device and replace with reference hydrophone*

Measure ultrasonic field with reference hydrophone

Compare spectra from two hydrophones to obtain calibration figure for test device

* Reference hydrophone's calibration will have been determined by other methods and often against (inter)national primary standards

# Calibration – pitfalls for the unwary

- Accuracy of calibration is dependent on determination of spectral amplitude at each frequency

- Therefore must carefully consider
  - Signal Bandwidth relative to Sampling Frequency
  - Signal Periodicity and Windowing

# Calibration – pitfalls – bandwidth

- Sampling frequency of digitise waveforms should satisfy Nyquist-Shannon criteria
  - 100$^{th}$ Harmonic easily generated with shocked waves

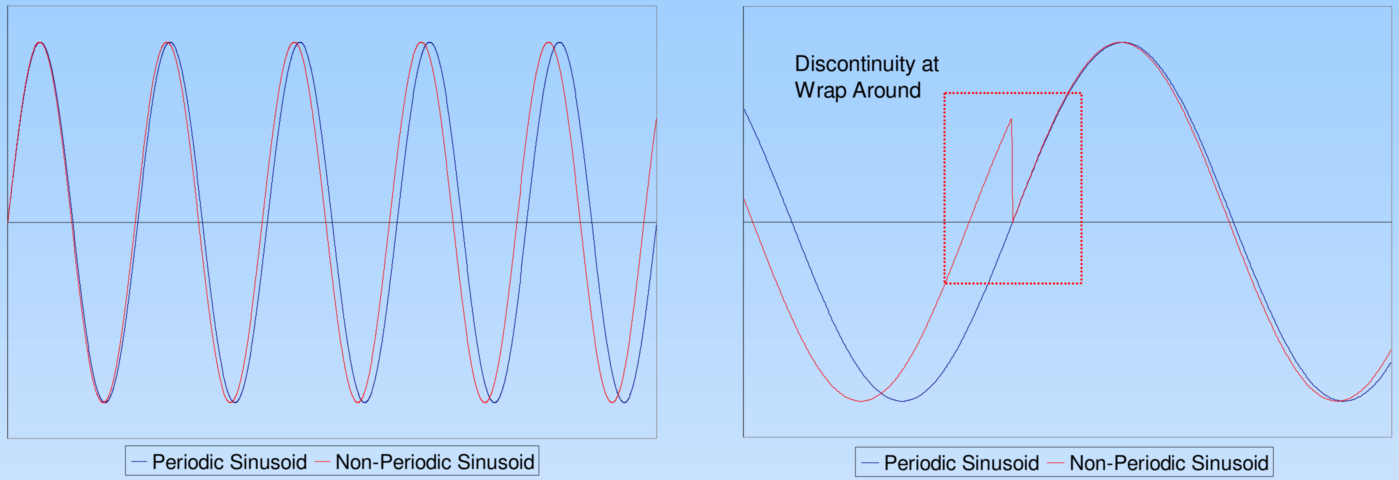
    If fundamental = 2 MHz, highest harmonic ≥200 MHz
  - Sampling frequency should be at least 400 MHz, preferably much higher (≥ 1 GHz)

  OR
  - Low-Pass filtered so that $2 * f_{max} < f_{sampling}$

- Inadequately sampled signal will suffer from aliasing causing <u>significant</u> amplitude errors

PRECISION ACOUSTICS LTD

# Calibration – pitfalls – periodicity

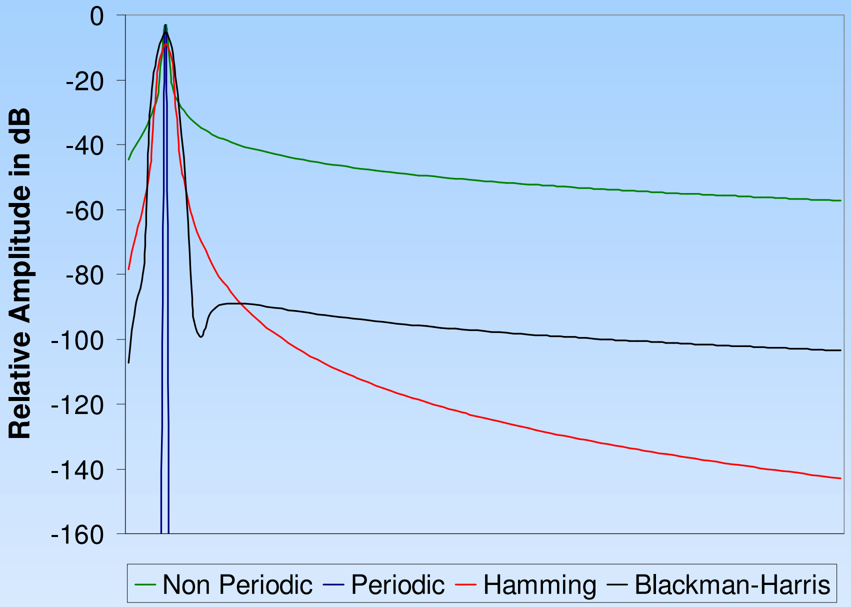



- Fast Fourier Transform methods implicitly assume that input signals are periodic
  - only true if the sampled data set contains a whole number of cycles
- Non Periodic signals have wraparound discontinuities
  - causes broadband spectral leakage

PRECISION ACOUSTICS LTD

# Calibration – pitfalls – windowing

- Window functions
  - Minimise spectral leakage at the expense of other factors, such as
  - Broader spectral peaks
  - Reduced amplitude of peaks




- Blackman-Harris window preserves amplitude well
  - Most important for this application

PRECISION ACOUSTICS LTD

# Calibration – summary

- A very broadband source is provided by non-linear propagation
- Calibration process reliant on accurate spectral amplitude measurement
  - Careful selection of window function
- Signal can have very wide bandwidths
  - High sample rate needed

Application of DSP principles and techniques are essential for accurate calibration

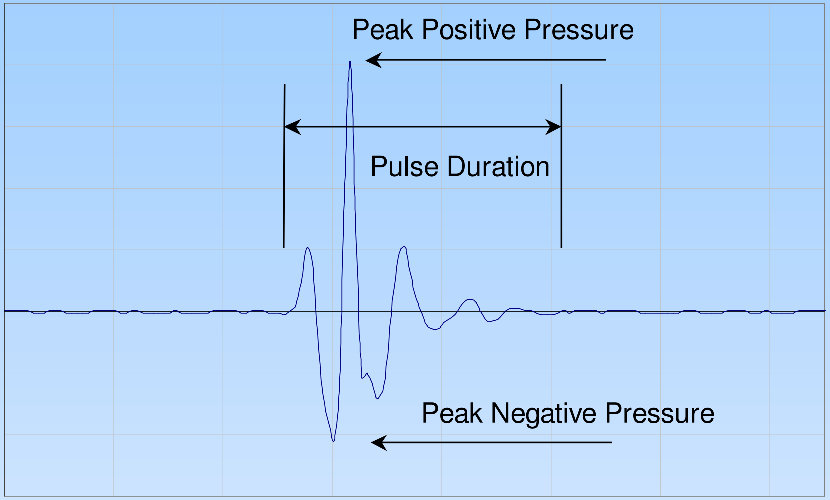
# Measurement – process overview

## voltage to pressure conversion

- Hydrophones calibration provides the conversion factor (hydrophone sensitivity) between voltage and pressure
- A hydrophone's sensitivity varies as a function of frequency and may be a complex quantity (magnitude and phase)

How best should this calibration data be used?

# Measurement – regulatory parameters




- International standards prescribe limits on many exposure parameters
- Pressure parameters
  - related to mechanical damage potential
  - often based on time domain waveform <u>shape</u>
- Intensity parameters
  - related to thermal damage potential

# Measurement – the current approach

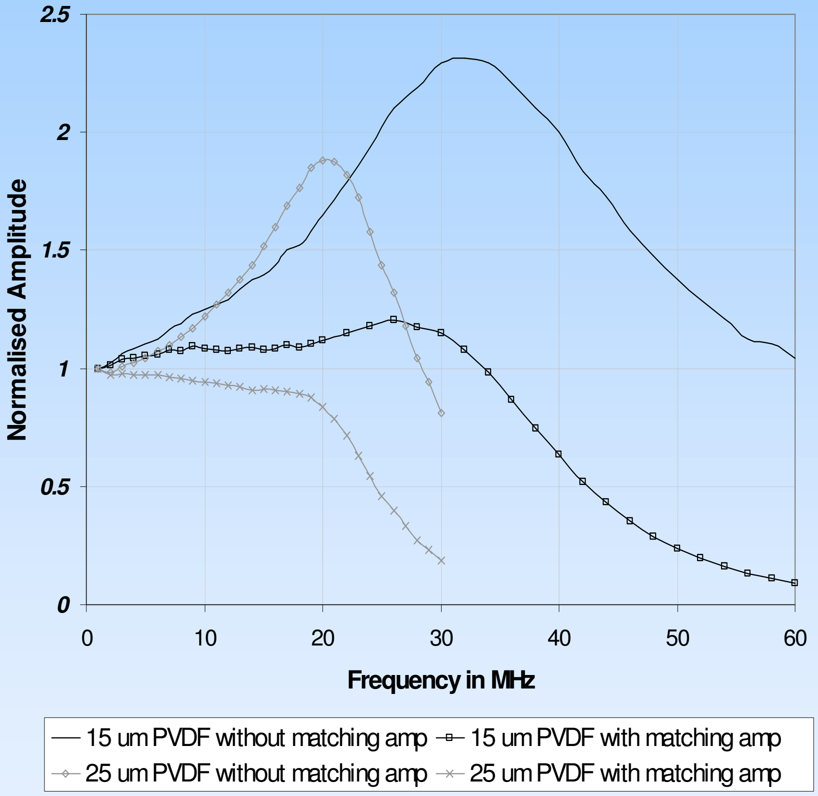
- Acoustic pressure is *approximated* from the measured voltage using the hydrophone sensitivity at the acoustic working frequency of the source

$$p(t) = \frac{v(t)}{M(f_{awf})}$$

  - v(t) is the measured hydrophone voltage
  - $M(f_{awf})$ is the hydrophone sensitivity at the acoustic working frequency
  - Only valid when hydrophone sensitivity has very little variation as a function of frequency
  - Has no possibility to account for phase response

# Measurement – distortion of reality to conform with existing standards

- Flattens frequency response up to thickness resonance frequency ($f_r$)
- Significantly attenuates beyond $f_r$
- Membrane hydrophones have inherent useable bandwidth at least 50% above $f_r$




PRECISION ACOUSTICS LTD

# Measurement – is bandwidth important ?

- Current diagnostic transducers often have centre frequencies in the range 10-15 MHz
- Current Standards require hydrophone bandwidth to extend to the minimum of :

| | |
|---|---|
| FDA | 5 times the centre frequency or 40 MHz |
| IEC | 8 times the acoustic working frequency or 40 MHz |

- Limited upper bandwidth will restrict the ability to resolve sharp peaks and may lead to poor determination of many intensity parameters

# Measurement – is phase important ?

- Phase information will not affect the total energy in a signal but may significantly change the waveform shape.
  - Many acoustic parameters may be affected

- A hydrophone's phase variations should not be neglected if they occur well within the bandwidth of the source signal,
  - Membrane hydrophones only exhibit deviation from linear phase near $f_r$
  - Needle hydrophones show significant phase variations at lower frequencies

# Measurement – hydrophone deconvolution

## A better approach?

$$p(t) = \Im^{-1}\left\{\frac{\Im\{v(t)\}}{M(f)}\right\}$$

- Where $\Im$ and $\Im^{-1}$ are the Fourier and inverse Fourier transforms and M(f) is the hydrophone sensitivity as a function of frequency

- M(f) can be a real (magnitude only) or complex (magnitude and phase) quantity

PRECISION ACOUSTICS LTD

# Measurement – the advantages of deconvolution

- Uses ALL available calibration data of the hydrophone
  - and is therefore a more accurate display of true acoustic pressure
- Can make use of phase data where available
- Real time display of acoustic pressure waveforms

**<u>Any other method of converting hydrophone voltage to pressure can only be a more crude approximation</u>**

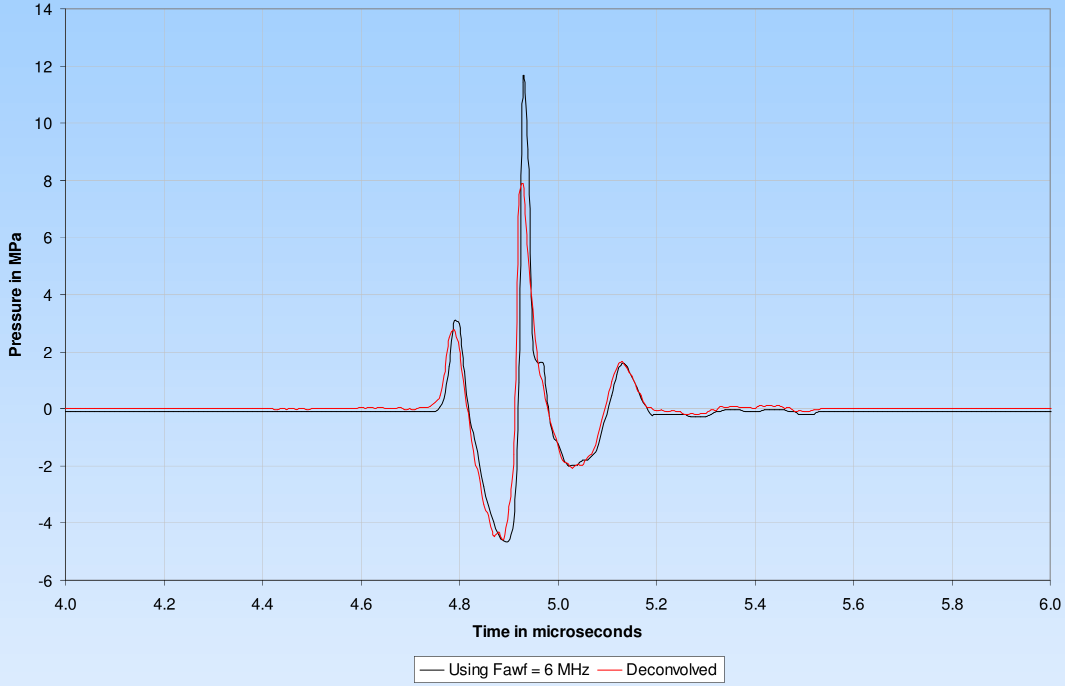
PRECISION ACOUSTICS LTD

# Measurement – possible disadvantages?

- Hydrophone calibration data is only available at sparse frequency increment
  - Cubic spline interpolation easily and accurately overcomes this issue, and this can be precomputed for any given hydrophone

- Full characterisation of a diagnostic ultrasound machine may require thousands of measurements
- The additional computation will increase the measurement time
  - FFTs take a few milliseconds on modern PCs
  - If efficiently implemented, the deconvolution operation can be done during the time taken to move the hydrophone to its next location

# Measurement example 1– output of ultrasonic scanner




- Membrane overestimates energy at higher frequencies due to frequency response curve (NB $F_{awf}$ = 6 MHz)

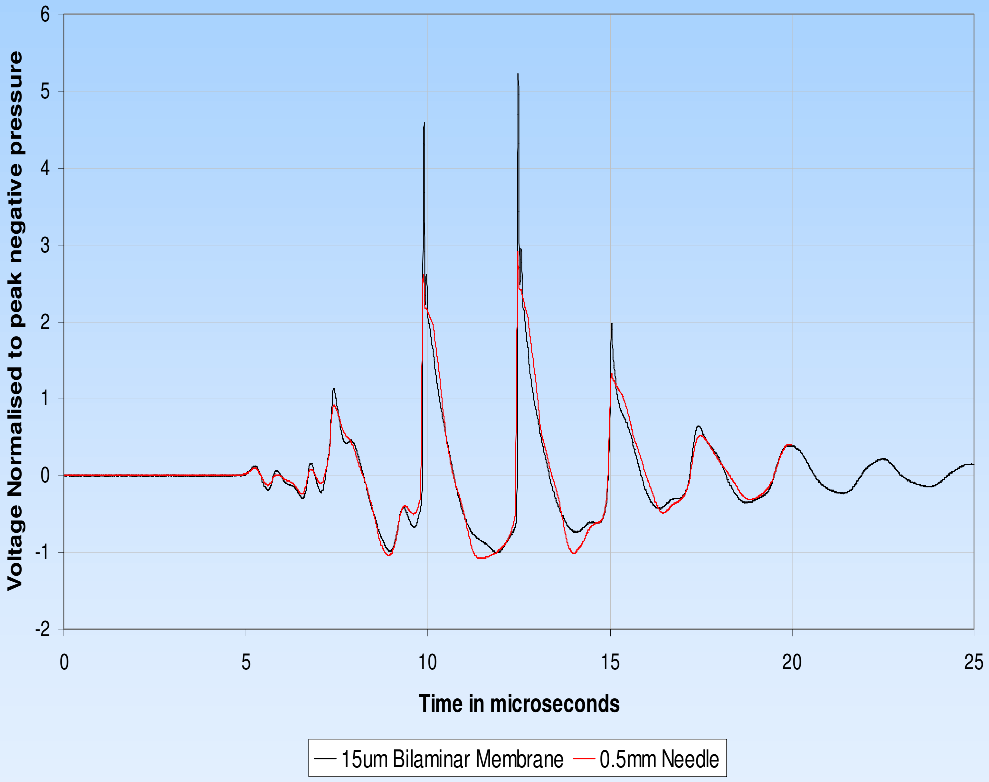
PRECISION ACOUSTICS LTD

# Measurement example 1– effect on exposure parameters

- Relative to deconvolution with magnitude and phase data, the single value method:
  - overestimated peak positive pressure by nearly 50%
  - underestimated peak negative pressure by 4%
    - NB a <u>critical</u> exposure parameter relies of peak negative pressure
  - overestimated intensity by nearly 20%

# Measurement example 2 – needle hydrophones

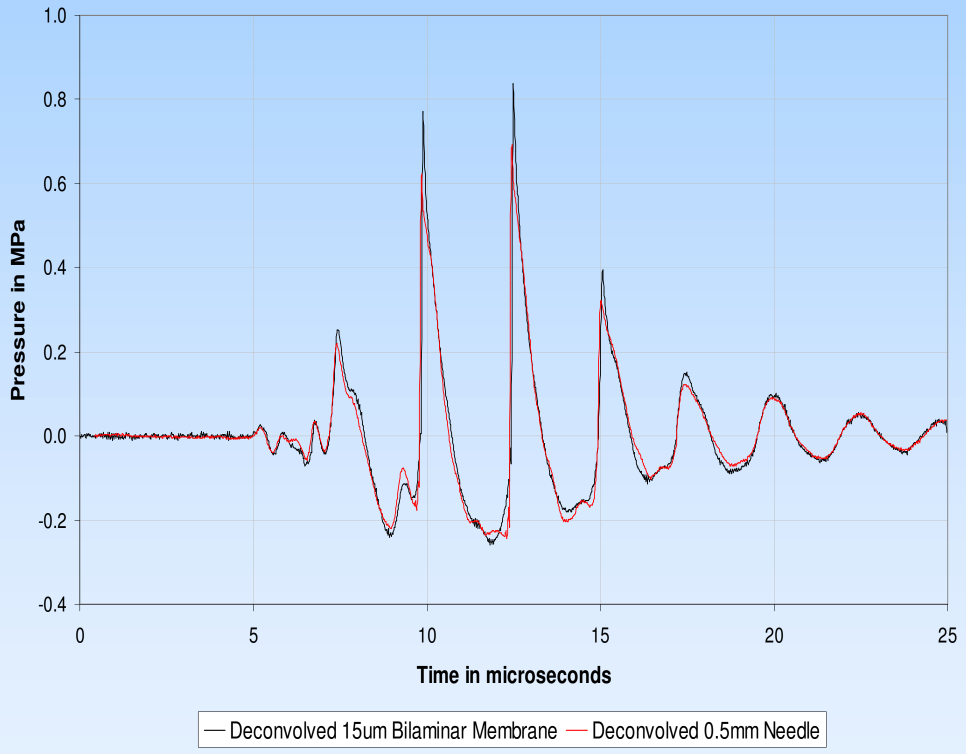
- A broadband field was measured with
  - a membrane hydrophone
  - a deliberately non-flat (poor) frequency response needle hydrophone




PRECISION ACOUSTICS LTD

# Measurement example 2 – needle hydrophone deconvolution

- **<u>Magnitude only</u>** deconvolution used (phase data not yet available)
- Deconvolved waveform shows much better agreement with the membrane reference



# Measurement example 2 – The effect on exposure parameters for needle hydrophones

- Using magnitude only deconvolution reduces:
  - Peak positive pressure error from 30% to 18%
  - Peak negative pressure error from 12% to 5%
  - Intensity error from 19% to 4%

# Measurement – Summary

- Hydrophone deconvolution:
  - Makes use of ALL available calibration data
  - Dramatically reduces measurement error - even with **magnitude data only**
  - Can easily incorporate phase response data where available
  - Utilises modern DSP techniques as its core computation
- These developments have only become available with increased computational speed/power/storage

New hydrophone usage standards now incorporate hydrophone deconvolution techniques

# Conclusions

- Ultrasound metrology inherently involves broadband signals
  - Mono-harmonic methods are inappropriate
- Most ultrasound data is acquired digitally and therefore DSP principles are essential for accurate measurements
- Application of FFT techniques is considerably reducing measurement errors

DSP – the only sensible way forward!