Workshop 2: Acoustic Output Measurements

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Workshop material

• Background
  – Why measure?

• Measurement techniques
  – Hydrophones
  – Radiation Force balances

• Summary

Hands-on session
Background

Relevance of acoustic output information

• What is it?
  – Numerical data that describes the ultrasonic field generated by a source and transducer combination: provides information on ‘how much ultrasound is emitted’
  – Defined broadly in terms of
    • Forces exerted (pressure)
    • Energy transfer (power)
What is it used for?

- Safety and performance assessment
- Prototype evaluation
- Routine quality checks
- Acceptance testing
- Patient satisfaction
- Compliance with regulation
- Good manufacturing practice
- Research

Trends

- Significant advancements in technology
  - Diversity of applications
    - Diagnostic
    - Therapeutic (HIFU)
  - Need for increased imaging quality
  - Ever-increasing complexity of equipment
- Steady increases in acoustic output
  - Greater implications for safety
  - Necessary advancements in standards
    - Application-specific limits
    - On-screen displays
- Increased drive for equipment QA
Technology advances

M-mode - peak-negative pressure

Spatial-peak temporal-average intensity

(after Duck and Henderson, Safety of Diagnostic Ultrasound, 1998)

Where do you come across it?
Who needs to know about it?

- You do
- Your customers do
- Your regulatory authorities do

Standards and conformance

- National and international requirements exist to evaluate acoustic output
  - US Food & Drug Administration (FDA)
    - Conformance is a legal requirement before goods may be sold in North America and Canada
  - International Electrotechnical Commission
    - Supports the European Medical Devices Directive (CE marking)
- Local company procedures may exist
  - Periodic QA
What standards are important?

- FDA 510(k)
- IEC 61157
- IEC 61847
- IEC 62359
- IEC 60601-2-37
- IEC 60601-2-5
- AIUM/NEMA UD-3

- AIUM/NEMA UD-2
- IEC 62127-1
- IEC 61161

Measurement devices and techniques
Determining key acoustical parameters

- Need capability to make measurements of high spatial and temporal resolution
- Also need to make measurements of bulk parameters
- In general, ultrasonic fields can be described in terms of
  - Acoustic pressures
  - Acoustic intensities
  - Ultrasonic power

Measurement devices

- Acoustic pressure determined in ultrasound fields using calibrated hydrophones
- Operate via direct piezoelectric effect
Hydrophone construction

- Needle-type
  - Small hollow tube, with active element at tip; connections made via casing and inside

Hydrophone construction

- Membrane-type
  - Plastic ring, over which is stretched polymer film: “spot-poled” in centre to form active element
Commercially available devices

Precision Acoustics, UK
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Force Institute, Denmark

GEC-Marconi, UK
Multi-element hydrophone

- Nonlinear element spacing
- Smaller elements at centre
- Complex shielding mask

Operational differences

**PVDF needle hydrophones**
- Active element diameters as small as 40 μm: film thicknesses of 9 μm
- Less stable
- Complex frequency response below ~7 MHz
- Minimally-perturbing construction
- Fairly robust (tip excepted)
- Susceptible to electrical noise
- Less expensive

**Membrane hydrophones**
- Active element diameters as small as 200 μm: film thicknesses of 9 μm
- Very stable – established track record means that they are “gold standards”
- Flat frequency response
- Mechanical access can be limited
- More delicate
- More expensive
Measuring acoustic fields

- Hydrophones often used with associated amplifier
- Waveform-processing oscilloscope required to evaluate parameters
- Motion control required to derive spatial variation of acoustic field
- Hydrophone and system under test immersed in water tank

NPL Beam Plotting Facility  Sonora AMS
Ultrasound field propagation

- Wave motion is predominantly longitudinal (compressional and rarefractional)
- Speed of sound, frequency, wavelength
- Pulsed excitation; repetition rate, duration
- Attenuation
- Nonlinear propagation
Ultrasound field propagation

- Velocity of sound, $c$, depends on density, $\rho$, and elastic modulus, $\kappa$, of medium

\[
c = \sqrt{\frac{\kappa}{\rho}}
\]

- Velocity of sound, $c$, related to frequency, $f$, and wavelength, $\lambda$

\[
c = f \times \lambda
\]

- The product of the velocity of sound, $c$, and the density, $\rho$, is the acoustic impedance, $Z$

\[
Z = \rho \times c
\]
Describing ultrasound exposure

- 4 main parameters of interest:
  - Peak-negative acoustic pressure ($p_r, p_i$) \[ MI \]
  - Spatial-peak-pulse-average intensity ($I_{sppa}$)
  - Spatial-peak-temporal-average intensity ($I_{spta}$) \[ TI \]
  - Acoustic power output (W)
- Other parameters also needed
  - Acoustic working frequency ($f_{awf}$)
  - Beam widths
  - Pulse duration
- Attenuation in real tissue accounted for
  - Derating of 0.3 dB/cm/MHz

Measurement roadmap

1. Select suitable hydrophone
2. Mount source and sensor
3. Obtain trigger signals
4. Align acoustical and mechanical axes
   - Identify location of peak $I_{spTA.3}$ and $I_{spPA.3}$
   - Acquire required data
   - Determine spatial & temporal parameters
   - Generate reports as required

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**Acoustic pressure**

- Acoustic waveform measured at focus of typical diagnostic scanner
- Short pulse duration
- Significant asymmetry
- c.f. atmospheric pressure of 100 kPa
- Important parameter is $MI = \frac{p_r}{(freq)^{0.5}}$

![Acoustic pressure waveform](image)

**Intensity**

- Derived from acoustic pressure waveform
- Several different parameters defined: is space and time-dependent
  - $I_{sp}$
  - $I_{app}$

![Intensity waveform](image)
Pulse-pressure-squared integral

- Derived from acoustic pressure waveform, by summation
- Used to define pulse duration, $t_d$

\[
I_p = 1.25 \left( t_2 - t_1 \right)
\]

Time-averaged intensity

- Derived from the time average of the instantaneous intensity in the pulse, taken over an integral number of acoustic repetition periods
- Assumes all pulses are identical
  - Pulse duration $PD$ (from time integral)
  - $I_{pta} = I_{spa} \times PD \times prr$

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Beam dimensions

- Can be determined at –6 dB or –12 dB level depending on standard requirement and field location.

Example of intensity profile
Measuring diagnostic fields

- Most commercial scanners have a large number of output settings
  - Focal zones (single and multiple)
  - Single and combination scanning modes
- Settings which produce maximum ‘acoustic output’ must be found
  - This can take a long time!
  - May require a priori knowledge of system

Actual measurement considerations

- Bandwidth
- Sampling rate
- Signal-to-noise
- Spatial-averaging and directionality
- Triggering
- Uncertainties
Sampling rate

![Graph showing acoustic pressure over time with sampling rate comparison]

Spatial-averaging and directionality

![Graph showing normalized component magnitude vs. angle of rotation and effective element radius vs. frequency]

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Uncertainties

Uncertainty budget:

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrophone calibration</td>
<td>16%</td>
</tr>
<tr>
<td>Oscilloscope</td>
<td>4%</td>
</tr>
<tr>
<td>Temperature</td>
<td>2%</td>
</tr>
<tr>
<td>Standing waves</td>
<td>15%</td>
</tr>
<tr>
<td>Noise</td>
<td>5%</td>
</tr>
<tr>
<td>Position</td>
<td>2%</td>
</tr>
<tr>
<td>Spatial averaging</td>
<td>4%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>6%</td>
</tr>
<tr>
<td><strong>Combined</strong></td>
<td><strong>31%</strong></td>
</tr>
</tbody>
</table>

Power measurement
Determination of power

- Acoustic power can be measured in two main ways:
  - Planar scanning using hydrophones
    - Performed close to output face of scanner head
    - Intensity integrated over beam area
  - Radiation force methods

- Often useful to perform both, to obtain independent check of results

Radiation force - principles

- Travelling acoustic wave has associated momentum
  - Net transfer of energy from transducer into medium

- A target placed in the path of the beam experiences a “radiation force”, which is proportional to the power contained in the beam
  - Requires target large enough to intercept whole beam

- Methodology and principles described in IEC61161
Radiation force balances

- Reflecting target balance
  - Incident energy reflected away to container edges
    - Flat plane target
    - Conical target
  - Requires acoustic absorber around edges of vessel to prevent multiple reflections
  - Needs ‘ideal’ reflecting target interface (air-water)

Radiation force balances

- Absorbing target balances
  - Incident energy absorbed by target
    - High quality material required
      - Totally absorbing
      - Totally non-reflecting
    - Energy deposition can cause target heating
      - Temporal drifts in balance response
      - Convection currents can be important
  - Less sensitive to alignment
Radiation force balances

\[ P = c \cdot F \]

\[ P = c \cdot F / (2 \cdot \cos^2 \Theta) \]

Radiation force balance targets

- **Absorbing target**
  - NPL Absorber
    - 30 dB cm\(^{-1}\) MHz\(^{-1}\) transmission loss
    - 40 dB echo-reduction
    - Polycarbonate-backed

- **Reflecting target**
  - Electroformed nickel cone, 80 mm diameter, 250 \(\mu\)m thickness
  - Air backed
Radiation force balances

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Radiation force measurements

- Beam geometry impacts on accuracy

**High ka transducer**
- Collimated beam intercepted by target
- Reliable measure of true radiation force

**Low ka transducer**
- Diverging beam misses target
- Underestimate of true radiation force

**Focused transducer**
- Converging beam strikes target at range of angles, depends on separation
- Over or underestimate of true radiation force

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Radiation force measurements

Radiation force measured with a conical reflecting target as a function of distance in a focused ultrasound field (F-number = 1.5)
Radiation force measurements

- Target size and transducer-target separation important

![Minimum target-transducer ratio at 1.5 mm](image)

Radiation force measurements

- Target heating can occur – limit ON-times

![Power vs Time](image)
Radiation force measurements

- Cavitation occurs – water quality is important

![Graph showing radiation conductance vs. drive voltage squared]

Main points to take away

- Measurement of acoustic output is important
  - Safety and efficacy assessments
  - Compliance with regulation
  - Prototype evaluation

- Good quality data can be obtained using a variety of measurement devices
  - Hydrophone-based systems
  - Radiation force balances
Hands-on session

• Sonora AMS Hydrophone test tank and acquisition system (Jim Gessert)

• Precision Acoustics radiation force balance and checksource (Mark Hodnett)