Physical principles of Harmonic Imaging

Min Joo Choi, PhD

Department Biomedical Engineering
College of Medicine, Cheju National University
School of Medicine, King’s College of London, University of London
Contents

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubbles to sound
- How can we extract harmonics from echoes?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Harmonic Imaging (HI)

Image of (non-linear) harmonic components of ultrasonic echoes
Concept of harmonic imaging
Contents

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Sound

**mechanical disturbance** *(vibration, wave)*

in a gas liquid or solid that travels outward from the source with some definite velocity.
What if a leaf is placed on the surface of water disturbed by a stone?

- $u$: particle disturbance velocity
- $c$: disturbance propagation velocity
Sound from a loudspeaker
Contents

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Ultrasound in **time** and **frequency** domain

(frequency $= 1/\text{period}$)
Pitch: frequency of sound
categories of sound

- infrasound
- audible sound
- ultrasound

Frequency (Hz):
- 20
- 20,000

(medical ultrasound: 1-10 MHz)
medical ultrasounds in time and frequency domain

- **continuous wave**
  - Time domain: Sinusoidal wave variation over time.
  - Frequency domain: Single frequency component.

- **pulse**
  - Time domain: Short duration, high energy signal.
  - Frequency domain: Broadband spectrum.

- **impulse**
  - Time domain: Very short duration, high energy signal.
  - Frequency domain: Wide frequency spectrum.

**Time domain**

**frequency domain**
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- **Nonlinear harmonics**
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Nonlinear harmonics

generated by

- **nonlinear propagation** depends on $\beta$, pressure, frequency

- **nonlinear response of bubbles** (ultrasonic contrast agent: UCA) much stronger
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- Non(linear) wave propagation
- (Non/linear) response of bubble to ultrasound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
wave propagation

question

solution  Burgers equation for 1-D wave propagation through a lossless medium

\[ \frac{du}{dt} + c \left(1 + \beta \frac{u}{c}\right) \frac{du}{dz} = 0 \]

- \(u\): vibrating particle velocity
- \(t\): time
- \(c\): propagation speed
- \(\beta\): nonlinear parameter
- \(z\): propagation distance
Geometrical interpretation of Burgers equation

\[ c(u, \beta) = c_0 + \beta u \]

- **linear** for \( \beta u \sim 0 \) (\( c \sim c_0 \)) (waveforms unchanged in shape)
- **nonlinear** for \( \beta u \) finite (\( c \neq c_0 \)) (waveforms progressively distorted)

\( c \): disturbance propagation velocity
\( c_0 \): propagation speed when \( u \) is infinitesimal
\( u \): particle disturbance velocity
\( \beta \): coefficient of nonlinearity of medium (=B/2A)
Progressive wave distortion resulting from nonlinear propagation

Time domain

frequency domain
Degree of the progressive wave distortion resulting from nonlinear propagation

is proportional to \( u \) amplitude

depends on medium \( \beta \)
Progressive wave distortion resulting from nonlinear propagation: frequency effect
Nonlinear propagation of diagnostic ultrasound through tissue

fundamental frequency band

2nd harmonic band

nonlinear propagation in tissue
Linear propagation of diagnostic ultrasound through tissue
Nonlinear wave propagation

Results in

wave distortion (time domain)

in other words,

harmonic generation (frequency domain)
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubbles to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Physical properties of ultrasound contrast agents (UCA)

- increase scattering
  - initial principle for the contrast agent
- (sub)harmonic generation
- (violent) collapse
scattering cross section
for a scatter sphere suspended in media

\[ A_s = \left( \frac{1}{144} \pi \kappa^4 a^6 \right) \left( \left( \frac{\kappa_s - \kappa}{\kappa} \right)^2 + \frac{1}{3} \left( \frac{3(\rho_s - \rho)}{2\rho_s - \rho} \right)^2 \right) \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( \kappa ) (cm(^2)/dyne)</th>
<th>( \rho ) (g/cm(^3))</th>
<th>value of [ ] (unitless)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>4.6E-11</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>air</td>
<td>2.3E-4</td>
<td>1,29E-3</td>
<td>2.5E3</td>
</tr>
<tr>
<td>Metal(Ni)</td>
<td>2.3E-13</td>
<td>8.8</td>
<td>1.75</td>
</tr>
</tbody>
</table>
Bubble oscillation in an infinitesimal ultrasonic field
Bubble response to an infinitesimal ultrasound stable oscillation
Bubble response to a finite ultrasonic pulse
unstable (transient) cavitation
Spectrum of reflected echo from SHU508 suspended in water

STOP PRESS !!!

nonlinear response of UCA to ultrasound

Results in Korean Society of Ultrasound in Medicine

(sub)harmonic generation
Harmonic Imaging (HI)

an image of

(nonlinear) harmonic components
of ultrasonic echoes
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
How do we extract harmonics from echoes?

- harmonic band filtering
- pulse(phase) inversion
- mHI probe (Choi 2003)
probe as a band pass filter
Harmonic band filtering:
transmitted & received bandwidth
Principles of pulse inversion technique

transmitted pulse \( x(t) = (a_1)e^{jwt} \)

A: received pulse for \( x(t) \), \( y(t) = (b_1)e^{jwt} + (b_2)^2e^{j2wt} + \ldots \)

B: received pulse for \(-x(t)\), \( y(t) = (-b_1)e^{jwt} + (-b_2)^2e^{j2wt} + \ldots \)

\[ A + B = (0)e^{jwt} + 2(b_2)^2e^{j2wt} + \ldots \]
A. Incident pulse

linear echo

nonlinear echo

B. Incident pulse (inverted)

linear echo

nonlinear echo

A+B

pulse inversion technique
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
axial resolution

2d/c

d
better axial resolution

resulting from shorter pulse length at higher frequency
lateral resolution: for real beam

narrower lateral beam width results in better lateral resolution
lateral resolution: for ideal beam

Rectangular beam width

finite
cleaner image
resulting from lower side lobe level

![Graph showing power (dB) vs radial distance with fundamental, 2nd harmonic, and ideal lines.]

- Fundamental
- 2nd harmonic
- ideal

side lobe level
(virtually) no near field artifacts

is due to harmonics generated resulting from propagation

Figure. typical normalized axial beam profiles on fundamental and 2\textsuperscript{nd} harmonic components.
Sumup on advantages of HI

- better axial resolution
- better lateral resolution
- cleaner image

- no near field artefacts
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images
- Examples of harmonic images
Harmonic Imaging v.s. Fundamental Imaging

<table>
<thead>
<tr>
<th>Tissue</th>
<th>THI(NHI)</th>
<th>FI</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCA</td>
<td>(UCA)HI</td>
<td>contrast enhanced sonogram</td>
</tr>
<tr>
<td></td>
<td>SHI(BRI, FEI ...)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PHI</td>
<td></td>
</tr>
</tbody>
</table>

| conventional sonogram | contrast enhanced sonogram |
Classification of HI

- Incident pulse
  - linear propagation
  - nonlinear propagation through tissue

- Echoed pulse with (sub)harmonics
  - nonlinear bubble response/collapse

- Fundamental imaging (FI)
  - Native HI (NHI)
  - Tissue HI (THI)

- UCA HI (UHI)
  - Stimulated HI (SHI)

- Power HI (PHI)
  - UCA + HI + Power Doppler
  - suB HI (BHI)
Contents of the talk

- What is harmonic imaging?
- What is sound?
- (ultra)Sound in time & frequency axis
- Nonlinear harmonics
- (Non/linear) wave propagation
- (Non/linear) response of bubble to sound
- How do we get harmonics?
- Why harmonic imaging?
- Classification of harmonic images

- Examples of harmonic images
a longitudinal ultrasound image of the right lobe of the liver (4MHz)

**FI**

**THI/NHI:** identifies specific, multiple lobulated masses
Apical four chamber view of the human heart

FI: Fundamental image (3MHz)

THI: tissue harmonic imaging (T: 1.8MHz, R: 3.6 MHz)
human liver with a hepacellular carcinoma

THI/NHI

UCA HI: Optison™ administered
hepatic metastases from islet cell carcinoma of the pancreas
– transverse US image through the right lobe of the liver

FI: without ultrasound contrast agent

UCA (PI) HI:
5 min after IV injection of SH U 508A
hepatic metastases from islet cell carcinoma of the pancreas
- transverse US image through the left lobe of the liver

FI: without ultrasound contrast agent

UCA (PI)HI:
5min after IV injection of SH U 508A
Power Harmonic Imaging
(myocardial segments)
Frontiers of HI

- power harmonic imaging
- sub harmonic imaging
- HIFU monitoring
- mHI probe (Choi 2003)
...
Any query?

“How shall I torture you today? Put you on the rack? Boil you in oil? Make you call a technical support line?”