Towards Efficient Methods FOR Transcranial Ultrasound Monitoring & Control

Scott Schoen Jr
13 July 2020
Need to Monitor & Control Cavitation in Real-Time

- FUS & microbubbles localize forces
- Stable Cavitation
  - Correlated with reversible BBB opening\(^1,2\)
- Inertial Cavitation
  - Associated with ablation\(^3\)

Monitor

Passive Acoustic Mapping (PAM)
Passive Acoustic Mapping (PAM)

Receiver Array

Source

RF Data

Reconstructed PAM

Source Position

Angular Spectrum Approach (ASA)

**Pro: ASA is Fast**

- **Computation Time**

  - **ASA**
    - **Delay and Sum**
    - $O[N^2]$
    - $O[N \log N]$
**Pro:** ASA is Frequency Selective

![Graph showing ASA selectivity](image)

- **ASA** is Frequency Selective
- **Harmonics**
- **Ultraharmonics**
- **Fundamental**

\[
\frac{R}{R_0} = \text{Marmottant et al., J. Acoust. Soc. Am. 118(6) (2005)}
\]

- **Broadband**

\[
p_0 = 800 \text{kPa}
\]

\[
p_0 = 500 \text{kPa}
\]

\[
R(t)
\]
Pro: ASA is Frequency Selective

Transmit

Receive

Bubble Only!

Bubble & Tissue

Bubble Signal

Linear Scattering

Level [arb. dB]

Frequency [MHz]
Pro: ASA is Sensitive

SNR = $\infty$ dB

SNR = 30 dB

SNR = 0 dB
Con: ASA Does Account for Aberration

Source Position (?)

Reconstructed PAM

Source

Receiver Array

Skull
ASA-PAM Benefits

- **Fast** – Milliseconds vs Minutes
- **Sensitive** – Robust to Noise
- **Frequency-Selective** – Identify Bubbles

- Assumes Uniform Medium

**Challenge:**
Adapt ASA for Heterogeneity
HASA FOR Passive Acoustic Mapping
Heterogeneous
Heterogeneous ASA

\[ P = P_0 e^{i k_z z} \]

Measurement  Transfer Function

\[ \tilde{p}(x, y, z; \omega) \xrightarrow{\mathcal{F}_k} P(k_x, k_y, z; \omega) \]

\[ P^{n+1} = P^n e^{i k_z \Delta z} + \frac{e^{i k_z z}}{2 i k_z} \left[ (\Lambda \ast P^n) \times \Delta z \right] \]


Medium Properties
HASA Improves Accuracy
HASA Improves Accuracy

Sound Speed [m/s]
1500 2100

Vessel Region

2 cm

800 kHz

Error

Axial Distance [mm]

Corrected

Uncorrected

0.3 1

Transverse Distance [mm]

1 cm

800 kHz
HASA Improves Accuracy

1.2 MHz
Control

PAM-Based Cavitation Control
Harmonic Level Quantifies Cavitation

- **Harmonics** and **Ultraharmoics** indicate Stable Cavitation
- **Broadband** Emissions indicate Inertial Cavitation

\[
L_{H3} = \left| \hat{p}_{\text{rec}}(3f_0) \right|
\]

[Graph showing level vs. BBB Opening]

Frequency-Selective PAMs Visualize Cavitation

- Form PAMs at Harmonic and Broadband frequencies

Angular Spectrum Approach

\[ L_{H3} = \int_R |I(x, z)| \, dA \]
Idea: Use Harmonic Levels to Adjust Excitation

Use Measured Harmonic Levels to *Control* Excitation

[Diagram showing a system for adjusting excitation using harmonic levels]

Levels are Function of Pressure

- **H3**: 23 kPa
- **U3**: 38 kPa
- **BB**: 62 kPa

*Graph showing changes in amplitude with pressure.*
Sign of Step: Relative to Target

How Big of a Step?
Size of Step: Define Control Law

Harmonic Model

Level $L_0$

Pressure $P_0$

$\epsilon$

$L_{\text{meas}}$

Step Size

Level

$\epsilon$

$P$

1
Controller Parameters Chosen

- Third harmonic (H3) for target (direction)
- Third ultraharmonic (U3) for model (size)
- Broadband (BB) for safety
- Two control law shapes:
  - Smooth
  - Sharp
Controller Performance

- Level [Log AU]
  - 14
  - 12
  - 10
  - 8
- Pressure [kPa]
  - 60
  - 40
  - 20
  - 0
- Step
  - 5
  - 10
  - 15
  - 20
  - 25
  - 30
  - 35
  - 40
  - 45

- Transverse Distance [mm]
  - -10
  - 0
  - 10

- Axial Distance [mm]
  - 30
  - 35
  - 40

- Frequency [MHz]
  - 0
  - 2
  - 4
  - 6
  - 8
  - 10

- $\mathcal{F}(\epsilon)$
  - 1
  - 0.5
  - 0

- Georgia Tech

24
Controller Performance – Proximity Ratio

Smooth 0.63  Sharp 0.49
PAM Allows Spatial Specificity

Region 2 required higher pressure.
Emissions Associated with $K^{\text{trans}}$ Increase
Conclusions

• ASA can Image Cavitation Passively
  • Can form frequency-selective maps in real time
  • Type and location of activity can be discerned
  • Fast correction developed to deal with heterogeneity

• ASA can Enable Cavitation Control
  • Frequency selectivity allows characterization
  • Mapping enables spatial control
  • Fast enough for real-time feedback
Thanks!

PI: Prof. Costas D Arvanitis
Grad Students
Ashley Alva
Yutong Guo
Chulyong Kim
Henry Lee
Scott Schoen Jr
Alumni
Arpit Patel
Dr Anastasia Velalopoulou
Zhigen Zhao