Prelim - Brandon Patterson

Slide 3

Ref on both images, might not be important

Slide 5

How good is MC techniques in general?

6th figure difficult to see where the method is good → better image?

What is shallow? How is that relative to the depth of importance relevant to the application?

Slide 7

Ref to figures? Don't know if they are needed

Slide 8

How many maximum bubble radius are experienced in the extreme cases of negative bioeffects? Once, twice? How does that connect w/ frequency?

Slide 12

"Richtmeyer" is misspelled, I believe.

Slide 18

"0.1.00" don't need this digit

Applications of computation in acoustics: Ultrasound bioeffects and transmission loss uncertainty

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MECHANICAL
ENGINEERING
UNIVERSITY OF MICHIGAN

NATIONAL INSTITUTES OF HEALTH

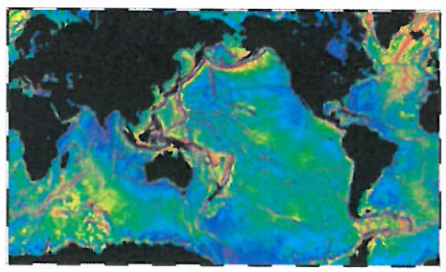
GRFP
NSF GRADUATE RESEARCH FELLOWSHIP PROGRAM

DEPARTMENT OF THE NAVY
ONR
Science & Technology

Part I

My work focuses on two very different problem areas of acoustics.

Acoustic uncertainty in the ocean



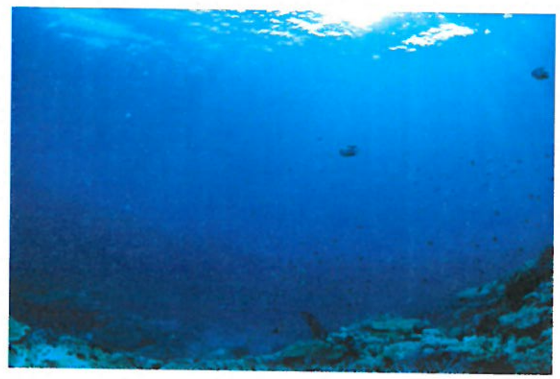
Ultrasound bioeffects

Could present as using sound to see

better explanation of motivation

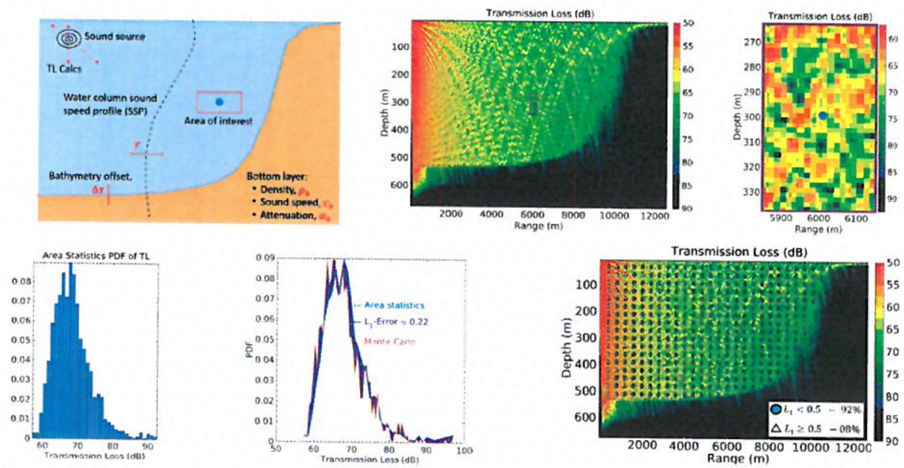
Past work: Efficient estimation of the probability density function of transmission loss in uncertain ocean environments

Transmission Loss, $TL = 20log_{10}\left(\frac{p_{source}}{p_{receiver}}\right)$, is useful for naval applications.



TL uncertainty is important for those making decisions based on TL, but traditional methods are slow and expensive.

Past work: We developed a computationally efficient way of computing TL in uncertain environments

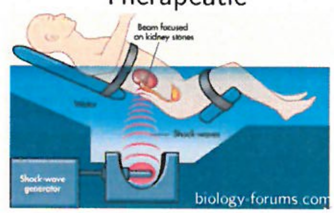


- Engineering level accurate (L_1-error < 0.5) in 93% of test cases in bottom reflecting environments.
- $\approx \mathcal{O}\left(10^{-6}\right)$ the cost of 1000-sample Monte Carlo Methods.

Background on medical ultrasound

Diagnostic

Therapeutic

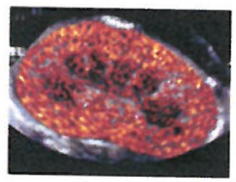


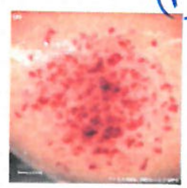
- High frequency (MHz) sound waves travel into the body and scatter at material interfaces.
- Acoustic energy is dissipated as heat or through mechanical means.

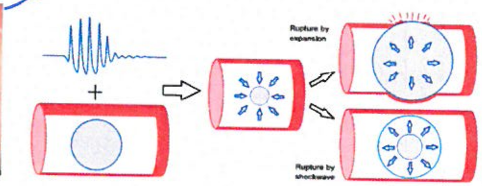
also heat

I focus on Diagnostic Ultrasound (DUS) bioeffects and relevant physics.

Background on DUS bioeffects







- Diagnostic Ultrasound (DUS) is ubiquitous and generally very safe.
- CEUS uses echogenic microbubbles for contrast, but these may act as cavitation nuclei and can lead to hemorrhage.
- Lung Hemorrhage (LH) is the only known bioeffect of non-contrast diagnostic ultrasound. under clinically safe conditions

Past work: Theoretical microbubble dynamics in a viscoelastic medium at capillary breaching thresholds

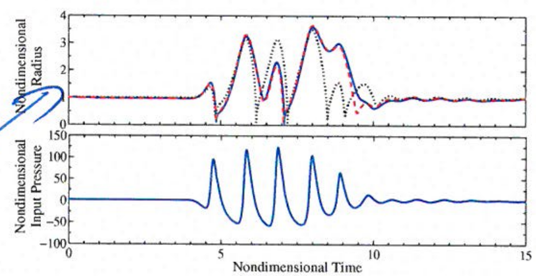
rd

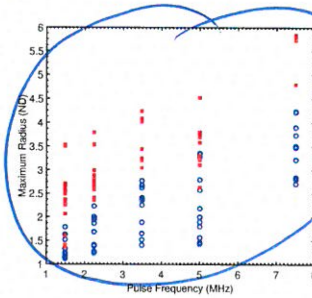
$$\left(1-\frac{\dot{R}}{C}\right)R\ddot{R}+\frac{3}{2}\left(1-\frac{\dot{R}}{3C}\right)\dot{R}^2=\left(1+\frac{\dot{R}}{C}\right)\left[p_B-1-p_a-\frac{R}{C}\frac{dp_a}{dt}\right]+\frac{R}{C}\dot{p}_B,$$

$$p_B=\left(1+\frac{2}{We}\right)\frac{1}{R^{3\gamma}}-\frac{2}{WeR}+\tau_R,$$

Parameter	Dimensional value		Dimensionless number
Viscosity	$\mu = 0.015$ (Pa s)	$\mapsto$	$Re = \rho u R_o/\mu = 2/3$
Elasticity	$G = 10^5$ (Pa)	$\mapsto$	$Ca = \rho u^2/G = 1.0$
Surface tension	$S = 0.056$ (N/m)	$\mapsto$	$We = \rho u^2 R_o/S = 2$
Sound speed	$c = 1570$ (m/s)	$\mapsto$	$C = c/u = 157$

2 plots





what are different curves

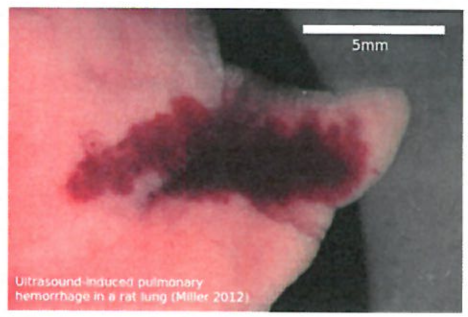
Patterson, B., Miller, D. L., & Johnsen, E. (2012). Theoretical microbubble dynamics in a viscoelastic medium at capillary breaching thresholds. JASA, 132(6), 3770.

Part II: Current Project

Diagnostic ultrasound-induced lung hemorrhage and acoustic wave interactions with liquid-gas interfaces

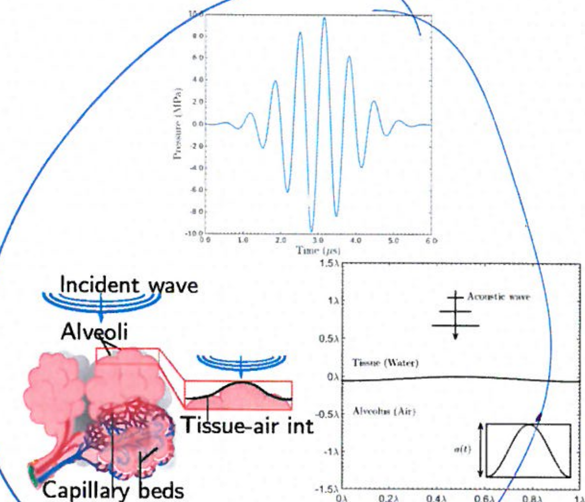
DUS-induced lung hemorrhage is not a new problem

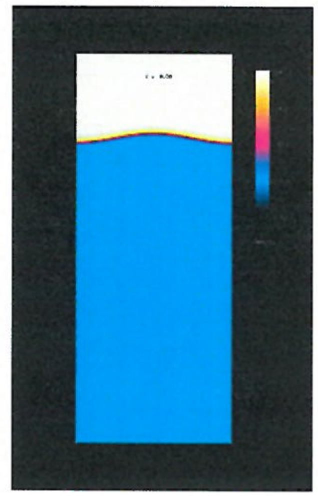
- Lung Hemorrhage (LH) is the only known bioeffect of non-contrast DUS
- Has been shown to occur in mice, rats, pigs, rabbits, monkeys (Child *et al.*, 1990; O'Brien & Zachary, 1997; Tarantal & Canfield, 1994).
- DUS-induced LH does not appear to be a result of cavitation or heating.
- The underlying physical damage mechanism is not understood.



To gain insight into DUS-induced LH, we aim to use computational modeling to investigate DUS-lung interaction.
+ simulations

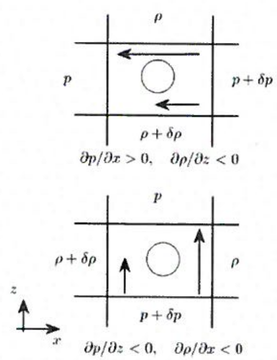
We simulated and US-pulse impinging on a water-air interface



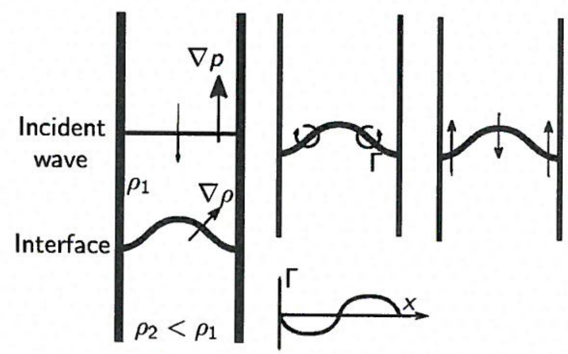


need to explain better if you're going to show movie

Shock-driven fluid-fluid interfaces have been studied extensively



Adapted from Heifetz & Mak (2015)



Adapted from Brouillette (2002)

- Shocks deposit baroclinic vorticity at perturbed fluid-fluid interfaces (Drake, 2006), which drives the interface perturbation to grow.
- This is the Rictymyer-Meshkov "instability".
- This problem is not well studied for acoustic waves. ← "So I sought to study it"

~~[illegible]~~ not a good way to justify study

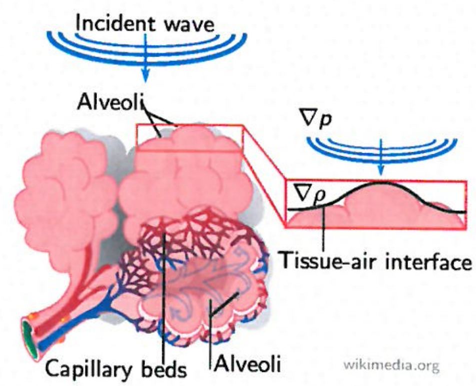
We hypothesize that US waves generate baroclinic vorticity at air-tissue interfaces in the lungs, straining fragile alveolar walls.

The vorticity generation equation

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\boldsymbol{\omega} = (\boldsymbol{\omega}\cdot\nabla)\,\mathbf{u} - \boldsymbol{\omega}\,(\nabla\cdot\mathbf{u}) + \frac{\nabla\rho\times\nabla p}{\rho^2} - \nabla\times\left(\frac{\nabla\cdot\boldsymbol{\tau}}{\rho}\right) + \nabla\times\mathbf{B}$$

$$\frac{\partial \boldsymbol{\omega}}{\partial t} + (\mathbf{u}\cdot\nabla)\,\boldsymbol{\omega} = \cancelto{0}{(\boldsymbol{\omega}\cdot\nabla)\,\mathbf{u}} - \boldsymbol{\omega}\,(\nabla\cdot\mathbf{u}) + \frac{\nabla\rho\times\nabla p}{\rho^2} - \cancelto{0}{\nabla\times\left(\frac{\nabla\cdot\boldsymbol{\tau}}{\rho}\right)} + \cancelto{0}{\nabla\times\mathbf{B}}$$

- Alveolar air-tissue interfaces have sharp density gradients
- US has strong pressure gradients
- US-induced baroclinic vorticity may cause strain, similar to shock-driven interfaces
- Linear acoustics does not capture this.



wikimedia.org

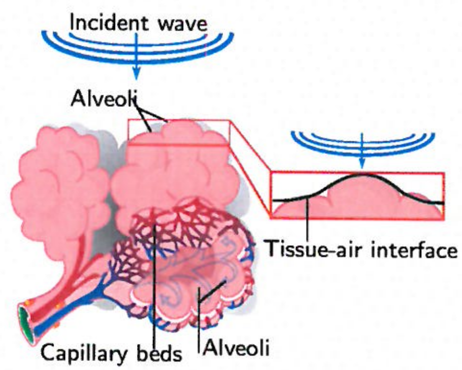
You want to make the point that $\nabla\rho \times \nabla p$ is generally small in acoustics ($\sim \Delta u^2$)

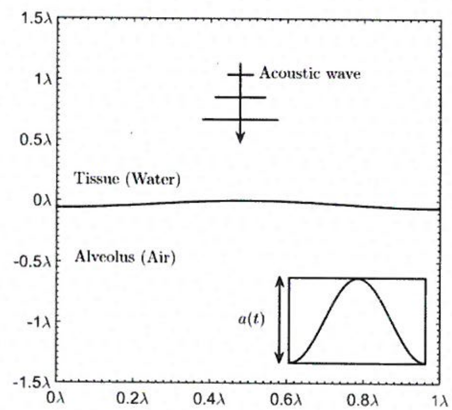
but acoustics simulation will not get this right b/c $\nabla\rho$ large (∞)
$\Rightarrow$ these effects can no longer be neglected

we think this vorticity may drive growth

we need fully nonlinear eqns

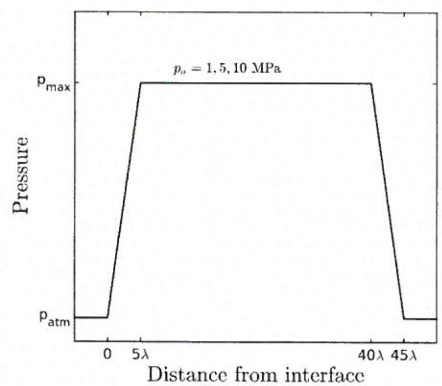
Problem setup: We model the ultrasound-alveolar interaction as a 2D, compressible, inviscid fluid system.

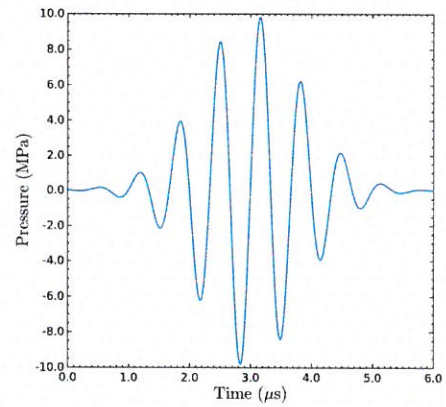




An acoustic wave impinges downward from water toward a perturbed air interface (a_0=0.03λ).

Trapezoidal and US pulse acoustic waveforms are used.





- The trapezoidal waves is simple for understanding physics and analysis, but able to capture feature of US pulse.
- Pulse waveforms are used to check relevance to DUS.

Governing Equations

Euler equations of fluid motion

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} &= 0, \\
\frac{\partial \rho u}{\partial t} + \frac{\partial}{\partial x}\left(\rho u^2 + p\right) + \frac{\partial}{\partial y}(\rho u v) &= 0, \\
\frac{\partial \rho v}{\partial t} + \frac{\partial}{\partial x}(\rho u v) + \frac{\partial}{\partial y}\left(\rho v^2 + p\right) &= 0, \\
\frac{\partial E}{\partial t} + \frac{\partial}{\partial x}\left[u(E+p)\right] + \frac{\partial}{\partial y}\left[v(E+p)\right] &= 0,
\end{aligned}
$$

Stiffened equation of state

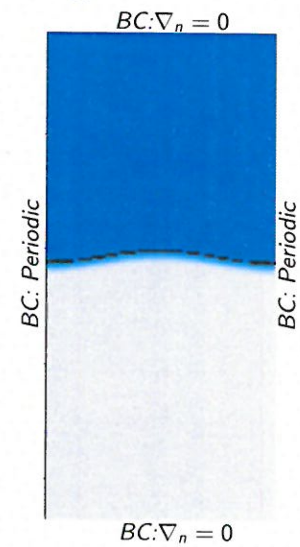
$$
E = \frac{\rho\left(u^2+v^2\right)}{2} + \frac{p+\gamma B}{\gamma - 1}.
$$

Advection equations for γ, B prevent interface pressure oscillations.

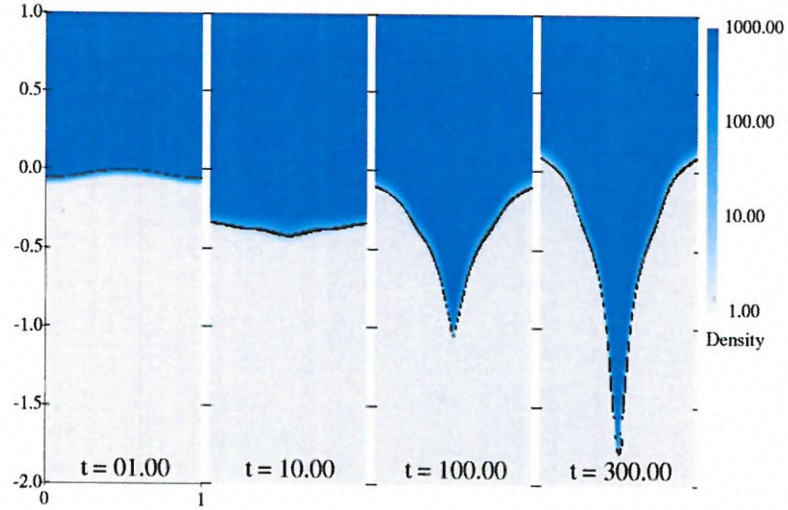
$$
\begin{aligned}
\frac{\partial}{\partial t}\left(\frac{\gamma B}{\gamma-1}\right) + u\frac{\partial}{\partial x}\left(\frac{\gamma B}{\gamma-1}\right) + v\frac{\partial}{\partial y}\left(\frac{\gamma B}{\gamma-1}\right) &= 0, \\
\frac{\partial}{\partial t}\left(\frac{1}{\gamma-1}\right) + u\frac{\partial}{\partial x}\left(\frac{1}{\gamma-1}\right) + v\frac{\partial}{\partial y}\left(\frac{1}{\gamma-1}\right) &= 0
\end{aligned}
$$

A high-order accurate computational solution strategy is invoked

- An in-house developed code is used to solve the Euler equations.
- Numerical methods
  - 3^{rd} order Discontinuous Galerkin method is used in space
  - 4^{th} order Runge-Kutta time marching
  - Roe Solver used to handle discontinuities
- Acoustic waves are prescribed within the domain.
- Grid stretching reduces reflections.
- Grid size: $\lambda \times 70\lambda\,(L_x \times L_y)$

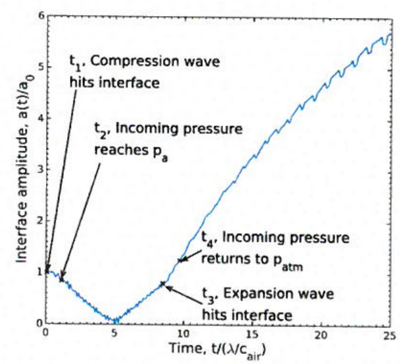


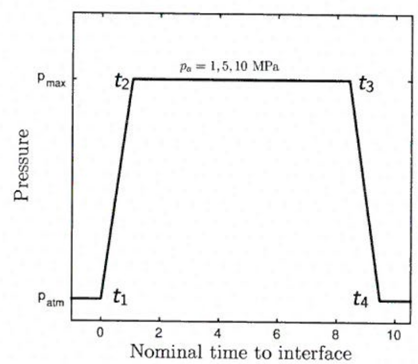
Results: Evolution of the interface after 10 MPa trapezoidal wave



The interface perturbation evolves from a smooth sinusoid into a sharp point.

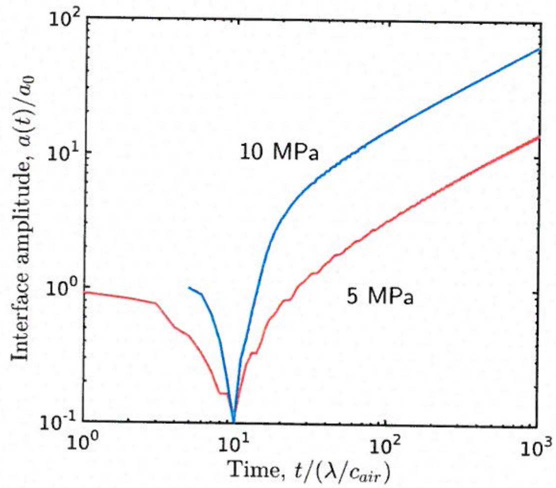
Results: Evolution of the interface





The interface perturbation is initially compressed ($0^+ \leq t \leq 5$), experiences a phase change ($t = 5$), then grows $t > 5$.

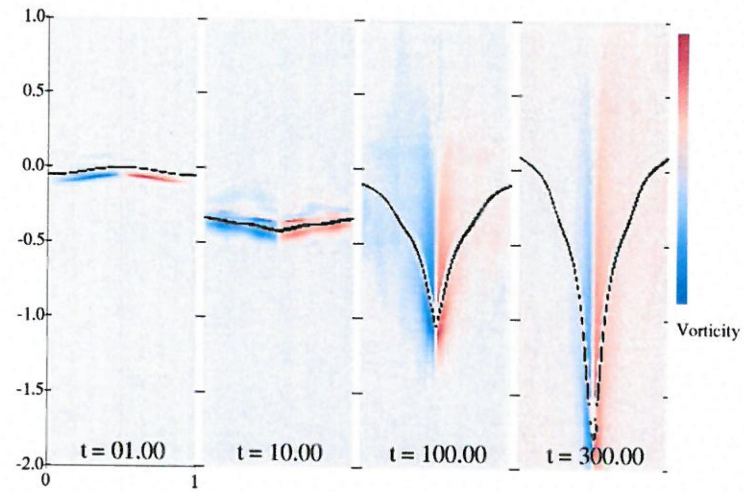
Results: Late-time evolution of the interface



We suspect vorticity is driving this late time growth.

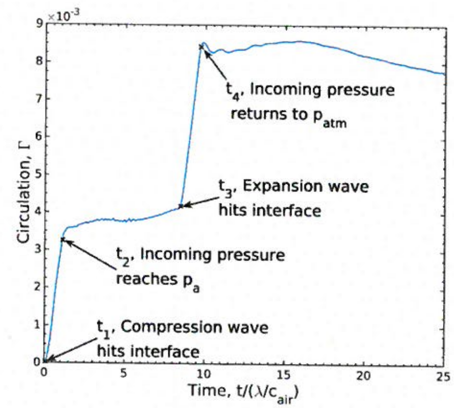
need at least one more
7.5 MPa?
(2.5 MPa?)

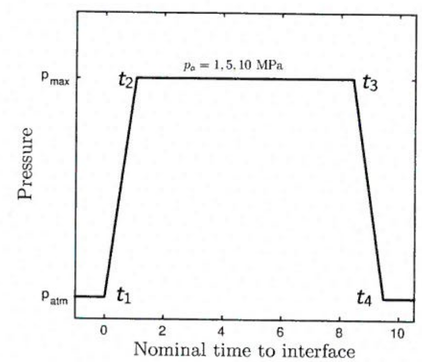
Results: Vorticity dynamics



Vorticity is initially deposited in the air-dominated portion of the interface region. As the interface evolves, some vorticity advects with it.

Results: A closer look at how circulation is deposited.

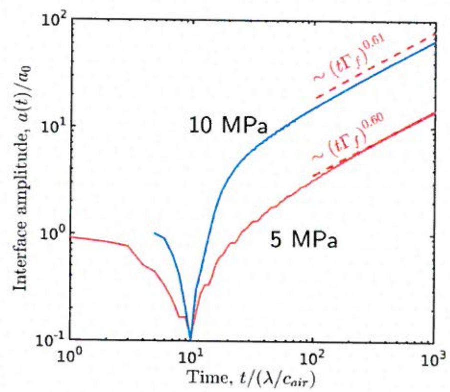


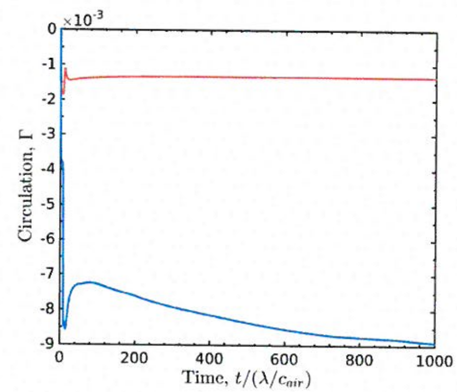


Both the compression and expansion deposit vorticity.

show contours to support your statements

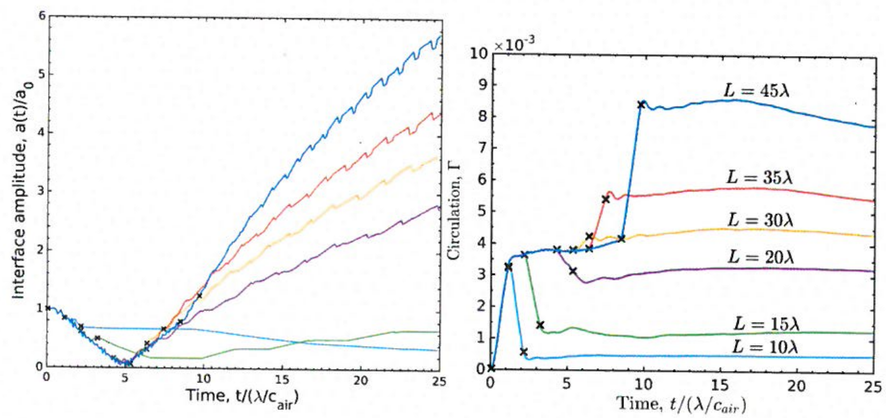
Results: Late-time evolution of the interface





From dimensional analysis, we expect a purely circulation driven interface to grow as $a(t) \sim \sqrt{\Gamma t}$.

Results: Dependence on the length of the wave



The length of the wave strongly effects the vorticity deposited and thus the long-term dynamics of the interface.

Changing width ⟹ changes time when wave hits

↓

at that time, interface has evolved ⟹ different amount of vorticity deposited

Order of magnitude analysis of vorticity generation

explain why this term should matter (e.g., you're not including viscous terms)

$$\frac{\partial \vec{\omega}}{\partial t} + (\vec{u}\cdot\nabla)\vec{\omega} = -\vec{\omega}(\nabla\cdot\vec{u}) + \frac{\nabla\rho\times\nabla p}{\rho^2}.$$

Acoustic Relations and operator treatments

$$\Delta p_a = \pm\Delta u_a \rho c = c^2\Delta\rho_a, \qquad \|\nabla f\| \sim \|\nabla\cdot f\| \sim \|\nabla\times f\| = \mathcal{O}\left(|\Delta f|/\Delta L\right)$$

Baroclinic vorticity generation

$$\left\|\frac{\nabla\rho\times\nabla p}{\rho^2}\right\| = \mathcal{O}\left(\frac{|\Delta\rho_I|}{|\Delta L_I|}\frac{|\Delta p_a|}{|\Delta L_a|}\frac{1}{|\rho|^2}|\theta|\right)$$

Advective and compressible vorticity generation - $\|\vec{\omega}\| = \int_0^{\Delta t_a}(\text{baroclinic term})dt$

$$\|(\vec{u}\cdot\nabla)\vec{\omega}\| \sim \|-\vec{\omega}(\nabla\cdot\vec{u})\| = \mathcal{O}\left(\left[\frac{|\Delta u_a|}{|\Delta L_a|}\right]^2\right),$$

Comparing terms for our our problem

$$\Delta t_a \approx 5\lambda/c_w, \qquad \Delta L_a = 5\lambda, \qquad \Delta p_a = 10MPa, \qquad \Delta L_I \approx 0.05\lambda$$

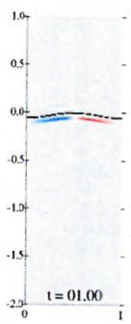
θ?

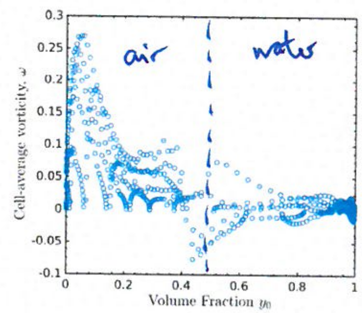
$$\frac{\left\|\frac{\nabla\rho\times\nabla p}{\rho^2}\right\|}{\|-\vec{\omega}(\nabla\cdot\vec{u})\|} = \frac{c}{|\Delta u_a|} = \frac{\rho}{|\Delta\rho_a|} = \mathcal{O}\left(10^2\right)$$

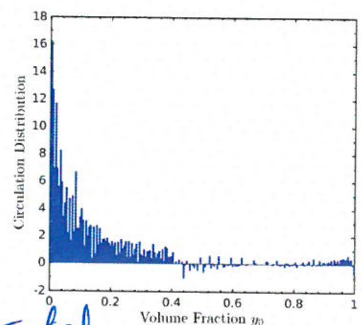
Calculated values at $t = 1$:

$$\frac{\nabla\rho\times\nabla p}{\rho^2} = 7.7\,\text{e}{-3}, \qquad (\vec{u}\cdot\nabla)\vec{\omega} = -5.3\text{e}{-5}, \qquad -\vec{\omega}(\nabla\cdot\vec{u}) = 2.7\text{e}{-5},$$

Vorticity generation occurs predominately in gas-dominated fluid







define

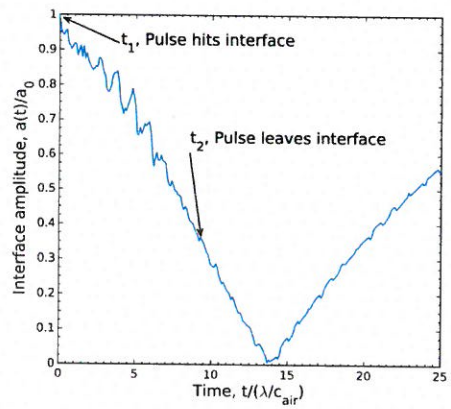
$$\frac{\left\|\frac{\nabla\rho\times\nabla p}{\rho^2}\right\|_{air}}{\left\|\frac{\nabla\rho\times\nabla p}{\rho^2}\right\|_{water}} = \mathcal{O}\left(|\mathbf{T}|\left(\frac{|\rho^-|}{|\rho^+|}\right)^2\right) \approx 357$$

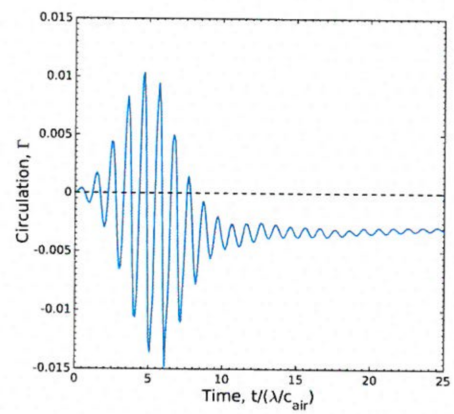
- 97% of circulation appears in fluid with $y_0 < 0.5$
- Computed circulation ratio from air($y_0 < 0.1$) to water($y_0 > 0.9$) is ≈ 27

define

dependence on Δx?

Interface response to a 10 MPa US pulse





- Qualitatively, the interface response for the 10 MPa US pulse looks very similar to the 10 MPa trapezoidal wave.
- The circulation deposited is of the same order as the equivalent amplitude trapezoidal wave.

- Interaction of finite duration wave (acoustic) w/ interface
  large density ratio
- ~~[illegible]~~

Conclusions thus far

- Acoustically-generated baroclinic vorticity is likely capable of significantly deforming perturbed liquid gas interfaces.

At interface

- Baroclinic vorticity is predominantly deposited in gaseous fluids.
- Changes in the acoustic waveform that have little effect on the interface during the wave-interface interaction can substantially effect the interface over long periods of time, via vorticity.
- Interface response from an US wave is qualitatively similar to that for a trapezoidal wave.

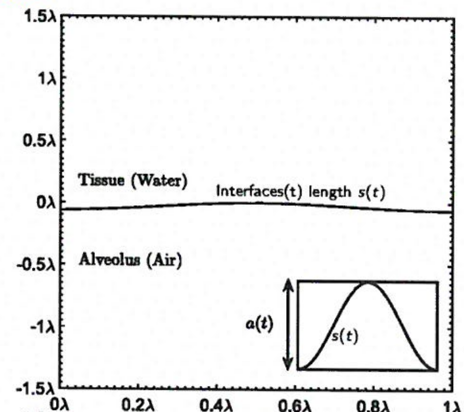
What matters is amount of $|\Gamma_{max}|$, which in these problems strongly depends on morphology of interface

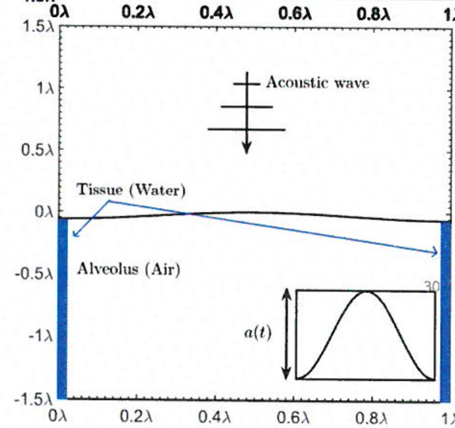
Part III: Future work

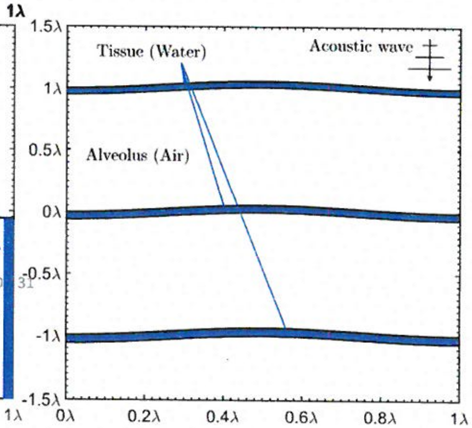
Curious is good but motivate in the form of hypothesis-driven research

I plan to increase the relevance to DUS

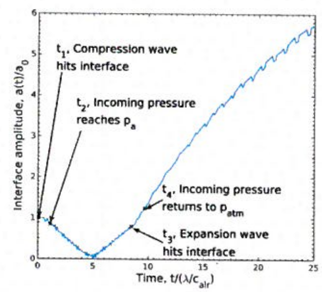
- Calculate interface strain
- Calculate stress at the interface
- Investigate the effects of alveolar side wall structures
- Investigate the propagation of acoustic waves into subsequent layers of alveoli

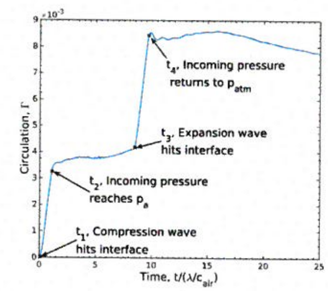






I aim to further our understanding of the relevant fluid mechanics





- Explain the discrepancies between numerical results and $a(t) \sim \sqrt{\Gamma t}$
- Develop a model to approximate the circulation deposited on a slightly perturbed interface by a compression or expansion wave
- Develop a model to predict the interface phase-reversal time for a compression wave
- Design an acoustic waveform to minimize circulation deposited and interface growth.
- Investigate cause of late time circulation growth

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