Fluid flows driven by sound and their applications

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1. Mean flows driven by fluid oscillations

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Conservation of momentum in liquid (Euler)

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{1}{\rho} \frac{\partial p}{\partial r}
\]

Linear (small amplitude) oscillation

Nonlinear oscillation gives a net drift

Any fluid will \textit{rectify} oscillation, giving \textit{mean streaming}

2\textsuperscript{nd} order mean flow velocities are always much lower in magnitude than 1\textsuperscript{st} order oscillatory flow velocities

But the mean flows \textit{keep going}, so we can see them, unlike the oscillatory flows which cancel out
To create a net drift, the nonlinear term must exist. Thus, a gradient in the acoustic field must exist.

Streaming is significant if:

- power is high (gradient provided by dissipation or spreading)
- gradient is high
2. Acoustic Streaming

Ovarian cysts

Experimental variations

• Regular geometric shapes of various types (cylinders, boxes) and ovoid shapes investigated
• Different sizes, aspect ratios and angles to the transducer beam were investigated – 31 combinations, with dimensions ranging from a few mm to 12 cm
Velocity profiles generally show a jet at the far wall of the cyst... provided the cyst near face is in front of the transducer focus.
To create a net drift, the nonlinear term must exist. Thus, a gradient in the acoustic field must exist.

Streaming is significant if:

- gradient is high
3.1. Acoustic microstreaming and bubbles

- **Primary vortices**: flow within the *Stokes boundary* or *shear wave layer*
- **Secondary vortices**: flow outside boundary layer

\[ \delta = \sqrt{\frac{2\nu}{\Omega}} \]

- **Primary vortices**: Lane 1955, *JASA* **27**, 1082
3.1. Acoustic microstreaming and bubbles

Cavitation microstreaming

• Acoustic microstreaming observed around oscillating bubbles
• The flow is observed as a system of vortices around the bubble

3.1. Acoustic microstreaming and bubbles

Measuring bubble motion

- Apply an edge detection algorithm to image of bubble
- Take binary image data and determine centroid of image and radius

3.1. Acoustic microstreaming and bubbles

Linear translation
3.2. Acoustic microstreaming patterns

Linear translation

Streak photos show 3D flow

Z1 = 75 microns
Z2 = 250 microns
Z3 = 575 microns

3.2. Acoustic microstreaming patterns

3.2. Acoustic microstreaming patterns

Circular orbit

- A circular orbit
- Bubble moves in anticlockwise manner

3.2. Acoustic microstreaming patterns

Circular orbit

Z1 = 75 microns
Z2 = 250 microns
Z3 = 575 microns

3.2. Acoustic microstreaming patterns

3.2. Acoustic microstreaming patterns

Shape modes

3.2. Acoustic microstreaming patterns

A variety of different flow patterns - streaklines

The need for chaos

- For molecules to react they must be brought into intimate contact.
- Molecular diffusion is extremely slow; rate proportional to $1/L^2$.
- The regions of liquid containing reactants must be blended such that a short distance $L$ separates them, permitting fast diffusion.
- At macroscopic scales, turbulence rapidly lengthens interfaces, thinning $L$.

- But at microscopic scales, there is no turbulence!
- Liquids must be stirred.


4.1. The micromixing problem

The need for chaos

Stirring steadily with any given pattern always gives unmixed ‘islands’

4.1. The micromixing problem

The need for chaos

Chaotic mixing theory states that to eliminate ‘islands’, patterns must that have mutually intersecting streamlines must be alternated with time:

\[ V \rightarrow D \rightarrow V \rightarrow D \rightarrow V \rightarrow D \rightarrow V \rightarrow D \rightarrow \]

\[ V \rightarrow D \rightarrow V \rightarrow D \rightarrow V \rightarrow D \rightarrow V \rightarrow D \rightarrow \]

Vortex

\[ \text{Vortex} \]

\[ \text{Dipole} \]

4.2. Chaotic acoustic micromixing

The need for chaos

Vortex

Dipole

Chaotic

Sonoporation is when molecules (DNA, drugs) that would not normally enter cells are found to enter and deliver benefit (gene therapy, chemotherapy) under the action of ultrasound.

Sonothrombolysis is when dangerous blood clots are dissolved or broken up under the action of ultrasound.

Both sonoporation and sonothrombolysis are improved when microbubbles are present.

Why?

Collis et al 2010 *Ultrasonics* 50, 273–279
5.1. Does microstreaming help?

There are *speculations* that *microstreaming* around microbubbles creates appropriate stresses on cells, or the extracellular matrix, to cause sonoporation or sonothrombolysis

Liu & Wu 2009, *JASA*. 125, 1319-1330;
Collis et al 2010 *Ultrasonics* 50, 273–279

• Can we understand these bioeffects?
• Can we *control* them?

• Measure microstreaming velocities quantitatively, using microPIV, in the presence of different surfactants: SDS, DTAC, DDAPS

• Surfactant concentrations adjusted to give the same surface tension, 50+/1 mN/m, irrespective of surfactant type

• Can we affect microstreaming velocities significantly by altering surfactant type?

### Table: Surfactants and Molecular Formulas

<table>
<thead>
<tr>
<th>Surfactant</th>
<th>Molecular formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium dodecyl sulfate (SDS)</td>
<td>CH$_3$(CH$<em>2$)$</em>{11}$SO$_4$Na</td>
</tr>
<tr>
<td>Dodecyl dimethyl ammonium chloride (DTAC)</td>
<td>CH$_3$(CH$<em>2$)$</em>{11}$N(CH$_3$)$_3$Cl</td>
</tr>
<tr>
<td>Dodecyl dimethyl ammonium propane sulfonate (DDAPS)</td>
<td>CH$_3$(CH$<em>2$)$</em>{11}$N(CH$_2$)$_2$(CH$_2$)$_3$SO$_3$</td>
</tr>
</tbody>
</table>

Increasing head-group size
5.2. Surfactants control microstreaming

**Bubbles**
- Single bubbles, pendant (bottom and side)
- Formed by syringe
- 30 – 400 µm in diameter

**Microchamber & transducer**
- 35 mm x 30 mm x (1 or 3) mm
- Additional wall to view bubble side on
- Transducer mounted onto cover
- 28 kHz CW
The PIV image pair were averaged over the data set to remove outliers and anomalies from the PIV analysis (30 – 200 image pairs).
The divergence in the \( x-y \) plane measured closest to the wall was calculated

\[
\nabla \cdot \mathbf{U} = \left( \frac{\partial}{\partial x} + \frac{\partial}{\partial y} \right) U
\]

Propose that divergence represents the stretching or compression of a cell membrane or tissue surface that the bubble is affecting.

The traditional biomedical measure is shear stress, but this is in a plane at right angles to the affected surface.

Collis et al 2010 *Ultrasonics* 50, 273–279
5.2. Surfactants control microstreaming

- Captured on occasions PIV particles adhered to bubble surface
- Velocity = $13 \pm 2$ mm/s, two orders of magnitude greater than secondary velocity

A 270 $\mu$m bubble excited at $f = 28$ kHz, amplitude = 20 $V_{p-p}$ and captured in the X-Z plane with varying exposure to estimate the velocity of primary vortices at a speed of $13.35 \pm 2$ mms$^{-1}$ a) exposure time of 5884 $\mu$s, b) exposure time of 8322 $\mu$s c) exposure time of 11767 $\mu$s
5.2. Surfactants control microstreaming

Recall the surface tension is the same (within 2%) only the type of molecule is different.

Velocity magnitude, bubbles driven at 28 kHz, 4.1 kPa
5.2. Surfactants control microstreaming

**Surfactant: DDAPS**

Maximum microstreaming velocities, bubbles driven at 28 kHz, 4.1 kPa
5.2. Surfactants control microstreaming

**Surfactant: SDS**

Maximum microstreaming velocities, bubbles driven at 28 kHz, 4.1 kPa
5.2. Surfactants control microstreaming

Max Divergence in the $x$-$y$ plane, bubbles driven at 28 kHz, 4.1 kPa
5.2. Surfactants control microstreaming

Threshold effect under identical physical and imaging conditions

Water: low velocities
DTAC: high velocities, surface instabilities

Conclusions

1. Fundamental nonlinearities create steady fluid flows when sound is applied: streaming and microstreaming

2. Streaming can be used for medical diagnostics

3. Microstreaming can occur in a variety of patterns

4. Microstreaming can be used for fluid mixing and may be relevant to new medical therapeutics

5. Even when the surface tension is maintained the same, surfactants with different molecular head groups create very different microstreaming velocities