RECENT DEVELOPEMENTS ON FIBER OPTIC AIR-BACKED MANDREL HYDROPHONES

• Introduction
• Possible applications
• Prototype
• Preliminary results
• Future planning

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Acoustic detection of pressure waves in water

Most interesting application:

• Military

• Tracking of mammals

• Detection of shock waves reflected by the sea bed

... and possibly

• Detection of hadronic shower produced by UHE $\nu$'s
G.A Askarian: hydrodinamical emission in tracks of ionizing particles in stable liquids. 1957

"... All this gives good reason to believe that the acoustical method of particle detection may find applications both at accelerators of the new generation and for detection of cosmic neutrinos in the Ocean"

experimentally confirmed by

L. Sulak, et al.: Experimental studies of the acoustic signature of proton beams traversing fluid media", Nucl. Inst. and Meth., 161 (1979), 203
Neutrinos from where?

Production mechanism

1. Emission of jets

2. Fermi acceleration mechanism →
   proton spectrum: \( \frac{dN_p}{dE} \sim E^{-2} \)

3. \( p+p \rightarrow p + N + \pi \)
   → Neutrinos from successive \( \pi \) and \( \mu \) decay

4. Another mechanism: from \( \pi \) decay
   produced in the interaction of \( p \) with CMB at energies above \( \sim 10^{19} \) eV
Why acoustic detection?

- High energy neutrinos interact via DIS with matter (1% probability in 1 km of water at $10^{20}$eV).

- Energy is shared between a quark and a lepton; on the average 80% to the lepton and 20% to the hadronic shower (≈ Joule for $10^{20}$eV neutrinos).

- The hadronic shower is confined (typically a 2 cm. Radius x 20 m length cylinder) and produces detectable pressure waves.

- The acoustic front has a typical disk shape (‘pancake’), the pressure wave is bipolar, ≈ 50 μs period, amplitude ≅ mPa or higher depending on the initial energy and distance.

- The signal propagates for several km (attenuation length of 1 km at 20 kHz).

→

At high energies ($\geq 10^{18}$eV) the acoustic detection may be an alternative to Cerenkov light detection (attenuation length ≅ 50 m).
The production mechanism
Hadronic Showers

- neglect primary electromagnetic showers due to LPM effect
- full 3D simulation of the energy deposition with GEANT4
  - shower extension (nearly) independent of energy
    ⇒ energy density scales linearly with energy
- numeric integration of energy density gives bipolar acoustic signal \( p(\bar{r}, t) \)
The acoustic signal

FIG. 4: Results of calculations of the acoustic signal from the hadronic part of the neutrino-induced shower [38], at the distance of 1000 m from the shower axis, for a primary hadronic energy of $10^{20}$ eV; (a) the pulse shape at the observation angle of $\theta = 0.6^\circ$, where the amplitude is maximal; (b) the pressure amplitude of the pulse and the total energy fluence in the pulse, $(\rho c)^{-1} \int_{-\infty}^{+\infty} p^2 dt$. These last two quantities are plotted as functions of observation angle as defined in Figure 3.
Signal Propagation

- attenuation length strongly frequency dependent
- central frequency of signal $\approx 20$ kHz
$\Rightarrow$ attenuation length $\approx 1$ km

$\sim 1$ mPa @1000m distance from a $10^{18}$ eV $\nu$ shower
The air backed mandrel hydrophone

- An optic fiber is wrapped outside a thin walled hollow cylinder.
- The cylinder is mounted outside a passive inner tube with sufficient clearance to provide air backing.
- This air gap allows the cylinder to deform in response to incident acoustic waves.
- This deformation, proportional to the pressure, is measured by sensing the corresponding fiber length variation.
- To this purpose a Michelson interferometer is used; Bragg gratings embedded in the core of the fiber reflect the light from a laser.
Main advantages

• Quite easy to fabricate
• Not expensive
• Driven by a laser source on shore
• Immune from electrical noise
• Do not require local power supply nor ADC conversion
• Can be arranged in large arrays by using multiplexing technique

Present achievement
• High sensitivity: below Sea State Zero at 5 kHz
• Bandwidth up to 5-10 kHz

Our purpose
• Increase upper limit of the bandwidth (20 kHz ?)
• Increase operational depth (1500 m ?)
1. Materials
Young modulus $E$ and Poissons’ ratio $\nu$ are the leading parameters in the design.

<table>
<thead>
<tr>
<th>Material</th>
<th>Young modulus</th>
<th>Poissons’ ratio</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>70</td>
<td>0.33</td>
</tr>
<tr>
<td>Ultem1000</td>
<td>3.3</td>
<td>0.44</td>
</tr>
<tr>
<td>Ultem2400</td>
<td>11.7</td>
<td>0.37</td>
</tr>
<tr>
<td>Core/cladding</td>
<td>72</td>
<td>0.17</td>
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<tr>
<td>Coating</td>
<td>1.1</td>
<td>0.45</td>
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</table>

For a composite material effective elastic parameters are obtained according to their cross sectional area.

e.g.: 0.5 mm thick Ultem1000 mandrel +5 layers 80/135 $\mu$m fibres: $E_{\text{eff}} = 13.4$ GPa

2. Geometry
Responsitivity mostly depends on:
- Radius, length, thickness, of the cylinder,
- number of optic fibre layers, type of optic fibre (80/135 – 80/165 $\mu$m)
- Effective Young modulus, Poissons’ ratio and density
3. Responsivity
relates the response of the hydrophone to its geometry and the external pressure;

\[
\frac{\Delta L}{L} \approx \frac{\Delta \phi}{\phi} \approx \varepsilon_{\phi\phi} \equiv \frac{1 - \bar{V}^2}{E} \frac{R}{t} P
\]

Ultem 2400
2R=40 mm
t = 1mm
5 layers of fibres
\(\varepsilon_{\phi\phi} = -303 \text{ dB re } \mu \text{Pa}\)

Ultem 1000
2R=15 mm
t=0.5 mm
5 layers of fibres
\(\varepsilon_{\phi\phi} = -308 \text{ dB re } \mu \text{Pa}\)

Must be corrected for the finite length of the cylinder !!
4. Correction due to the finite length and to the end-constraints

\[ \varepsilon_{\phi\phi} = \varepsilon_{\phi\phi}(1-C_1) \]

\[ \varepsilon_{\phi\phi} = \varepsilon_{\phi\phi}(1-C_2) \]

\( C_1, C_2 \) are a complicated function of \( E, \nu, r, t, L \)

<table>
<thead>
<tr>
<th>type</th>
<th>material</th>
<th>( r ) (mm)</th>
<th>( L ) (mm)</th>
<th>( T ) (mm)</th>
<th>#layer</th>
<th>No edge effects</th>
<th>free</th>
<th>glued</th>
</tr>
</thead>
<tbody>
<tr>
<td>'old'</td>
<td>Ultem1000</td>
<td>10</td>
<td>40</td>
<td>0.5</td>
<td>3</td>
<td>-302</td>
<td>-303</td>
<td>&lt;330</td>
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<tr>
<td>'slim'</td>
<td>Ultem1000</td>
<td>7.5</td>
<td>26</td>
<td>0.5</td>
<td>5</td>
<td>-308</td>
<td>-309</td>
<td>-326</td>
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<tr>
<td>'fat 1'</td>
<td>Ultem2400</td>
<td>18</td>
<td>10</td>
<td>0.5</td>
<td>5</td>
<td>-302</td>
<td>-307</td>
<td>&lt;330</td>
</tr>
<tr>
<td>'fat 2'</td>
<td>Ultem2400</td>
<td>18</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>-304</td>
<td>-311</td>
<td>&lt;330</td>
</tr>
</tbody>
</table>
5. Response in frequency

Obtained from the normal modes of vibration of a cylindrical shell in vacuum

Solutions expressed in terms of the displacements $u, v, w$ in the axial, circumferential and radial directions.

$$u = U_{m,n}(x)\cos(n\theta)\cos(\omega t) \quad 0<x<L$$
$$v = V_{m,n}(x)\sin(n\theta)\cos(\omega t)$$
$$w = W_{m,n}(x)\cos(n\theta)\cos(\omega t)$$

$n$, number of circumferential waves, $m$ number of axial half periods

The radial “breathing mode” $(m,n) = (1,0)$ gives the major contribution to the fiber length change i.e. to the frequency responsitivity of the idrophone
Behaviour in air

The frequency associated to the fundamental mode with n=0, m=1
- Increase with shell thickness t
- Decrease with radius R
- Decrease with length L

\[ \omega_{radial} = \frac{E}{\rho (1 - \nu^2) R^2} \left( 1 + \frac{t^2 \pi^4 R^2}{12 L^4} \right) \]

<table>
<thead>
<tr>
<th>type</th>
<th>r  (mm)</th>
<th>L  (mm)</th>
<th>T  (mm)</th>
<th>#layer</th>
<th>(\omega_{radial}) (kHz)</th>
</tr>
</thead>
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<tr>
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<td>10</td>
<td>40</td>
<td>0.5</td>
<td>3</td>
<td>50</td>
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<tr>
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<td>26</td>
<td>0.5</td>
<td>5</td>
<td>63</td>
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<tr>
<td>'fat 1'</td>
<td>18</td>
<td>10</td>
<td>0.5</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>'fat 2'</td>
<td>18</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>41</td>
</tr>
</tbody>
</table>
Behaviour in water

• The fluid lower the frequency of the resonance due to the added mass
• The fluid lower the amplitude of the resonance due to re-radiation of the acoustic wave

For the lowest radial ‘breathing mode’ the displacement $W_{1,0}(\omega)$

$$W_{1,0}(\omega) = \Delta p_\omega \frac{R^2(1-\nu^2)}{Et} \left( \frac{\rho_{\text{shell}}(1-\nu^2)R^2\omega^2}{E} \right) \left( 1 + \frac{\rho_{\text{fluid}}}{t\rho_{\text{shell}}} \frac{K_0(\gamma R)}{\gamma K_1(\gamma R)} \right) - 1 - \frac{t^2\pi^4R^2}{12L^4}$$

where

$$\gamma^2 = \frac{\pi^2}{L^2} - \frac{\omega^2}{V_s}$$

$V_s$ is the sound velocity in water

$K_0(\gamma R), K_1(\gamma R)$ Modified Bessel functions, may be complex
Response in water vs air

ALENIA hydrophone
(ULTEM 1000, 20 x 0.5 x 40, 3 layers)

*sensitivity = -302 dB re μPa*

"Stefano type" hydrophone
(ULTEM 1000, 15 x 0.5 x 26, 5 layers)

*sensitivity = -308 dB re μPa*
Response in water vs air

'fat'

sensitivity = -303 dB re μPa

'Slim and long'

sensitivity = -308 dB re μPa
Directionality

Sound wave at frequency $\omega$ and angle $\theta$:
\[ p = p_0 \exp(-ik.r), \quad k = \frac{\omega}{v_s} \]

Calculate the mean pressure $<P>$ over the cylinder surface of radius $R$ and length $L$:
\[
\frac{<P>}{P_0} = \frac{1}{L} \frac{1}{2\pi R} \int_0^L \int_0^{2\pi} \exp(-i(KR \sin \theta \cos \phi + Kx \cos \theta)) Rd\phi dx
\]

\[
\frac{<P>}{P_0} = \frac{\sin \left( \frac{\omega L}{2v_s} \cos \phi \right)}{\frac{\omega L}{2v_s} \cos \phi} J_0 \left( \frac{\omega R}{v_s} \sin \phi \right)
\]
Response in water ($v_s = 1500\text{m/s}$)

- 10 kHz
- 20 kHz
- 30 kHz

'Alenia' type: $R=10\text{mm}, L=40\text{ mm}$

'slim': $R=7.5\text{ mm}, L=26\text{ mm}$
Exemples of directionality in air: \( v_s \approx 1500 \text{m/s} \rightarrow 340 \text{ m/s} \)
\( \lambda_{\text{air}} \approx \frac{1}{4} \lambda_{\text{water}} \)
directionality much more pronounced
Modeling the ‘fat’ hydrophone

- 5 layers of optic fibre
- Mandrel in Ultem 2400
  - 40x10x1 mm
- Air gap
- O-ring to support the mandrel
Winding the optic fibre
Some tests performed to define the winding procedure

- Pre-tensioning of the fibre

- Different diameters of the hydrophone
One prototype already realized

The hydrophone without the polyurathane coating

Record of a phone ring

The frequency response in air
comparison with piezo hydrophone
Work is just started... a lot of things ahead

- Complete the present prototype: polyurethane coating.

- Possible alternative: ‘fat’ vs ‘slim’. Main advantages: less attenuation in the fibres, directionality (?), resistant to deeper depth. Detailed FEA calculations needed.

- Extend the present read out system from 10 to 20 kHz.

- Perform accurate calibration in air and water at different frequencies.

- Realize an hydrophone array.

- Start to calculate optimum geometry configuration and reconstruction tools for a large volume neutrino detector based on hydrophone arrays.
Cable with optic fibres

\( \approx 1000 \text{ m} \)

\( \approx 10 \text{ m} \)