Correlating inertial acoustic cavitation emissions with material erosion resistance

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Experimental work developed by a postgraduate student of the Brazilian Metrology Programme in the Acoustics Laboratory of the National Physical Laboratory (NPL/UK)

Correlating inertial acoustic cavitation emissions with material erosion resistance

Main interest:
To study cavitation erosion on engineering materials

This work:
Cavitation erosion on Aluminium-Bronze
Cavitation induced by an acoustic medium

Occurs when an acoustic wave propagates in a fluid experimenting a reduction in pressure (rarefaction) with respect to the saturation vapour pressure.
Cavitation erosion: a gradual loss of material from a solid surface due to its continuous exposure to cavitation [ASTM G32-2010]

1. Formation of bubbles on the surface of the material.
2. Collapses of the bubbles that damage the surface.
3. Modification of the surface and its exposure to erosion.
5. Collapses of bubbles eroding the surface even more.
Theoretical background

Standard ASTM G32-2010:

The erosion process undergoes the following stages:

• Incubation stage
• Acceleration stage
• Maximum rate stage
• Deceleration stage
**Theoretical background**

**CaviMeter:**

Designed by NPL to measure cavitation

**Field of Application/Measurement range:**
- **Medical application:** 40-60 kHz
- **Sonochemical application:** ≈ 20 kHz

**Technical characteristics of the CaviMeter:**

Piezoelectric type PVDF, 110 microns, coated with a thick layer of a special rubber (insulator).

The acoustic field induced by the bubbles is detected by the piezoelectric sensor.

**PVDF:** Polyvinylidene fluoride
Theoretical background

CaviMeter

Bubbles outside sensor produce MHz signals attenuated by sensor outer shield

Cavitating bubbles inside sensor produce MHz signals detectable by PVDF film
Outputs of the CaviMeter:

**DRIVING FIELD:** acoustic signal at the fundamental frequency (operating frequency of the transducer).

**CAVITATION LEVEL:** acoustic signal produced by the collapse of the bubbles (takes place in the frequency range 1.5 and 8 MHz).
Experimental procedure

**Fluid medium (cavitation erosion)**
Distilled water (5 micron filtered) at 22±2 °C (Tank: 15 l)

**Generation of Cavitation**: Ultrasonic transducer, 20 kHz (Model 23820A; Processor P100/3-20).

**Duration of Cavitation exposure**: 900 to 3600 s

**Erosion**: assessed by mass loss under a strict protocol
Experimental procedure

**Operating conditions:**

Experiments operating conditions: conducted for two values of sonotrode-sample *separation* \((\lambda)\) of the transducer horn with respect to the specimen, at a fixed value of the transducer *displacement amplitude signal* \((\delta)\):

**Experiment #1:**

\[
\lambda = 0.5\text{mm}; \quad \delta = 43.5\ \mu\text{m}
\]

**Experiment #2:**

\[
\lambda = 1.0\text{mm}; \quad \delta = 43.5\ \mu\text{m}
\]
Experimental procedure

Aluminium-Bronze Alloy investigated under erosion:

<table>
<thead>
<tr>
<th>Specific mass (mg/mm³)</th>
<th>Brinell Hardness (HB)</th>
<th>Dimensions (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.90</td>
<td>170</td>
<td>20 x 20 x 3</td>
</tr>
</tbody>
</table>

Equipment set up:
1. Focused on the cavitation phenomenon
   Variation associated with measurement of cavitation level

2. Focused on the erosion phenomenon
   - Mass loss
   - Inspection of the specimen surface after erosion

3. Correlating cavitation with erosion resistance
   Cavitation level and Erosion rate
Experimental results

Focused on the cavitation phenomenon
Analysis of the experimental results

Focused on the cavitation phenomenon

Measurement of cavitation level
Specimen: Al-bronze alloy; Transducer frequency: 20 Khz
Experiment #2: $[\delta = 43.5 \ \mu m; \lambda = 1.0 \ mm]$

<table>
<thead>
<tr>
<th>Volt</th>
<th>0.5</th>
<th>0.45</th>
<th>0.4</th>
<th>0.35</th>
<th>0.3</th>
<th>0.25</th>
<th>0.2</th>
<th>0.15</th>
<th>0.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>time (s)</td>
<td>0</td>
<td>500</td>
<td>1000</td>
<td>1500</td>
<td>2000</td>
<td>2500</td>
<td>3000</td>
<td>3500</td>
<td>4000</td>
</tr>
</tbody>
</table>

- **Trend:** evaluated by the qui-square test

- **Variation associated with measurement of cavitation level** (Estimated uncertainty):
  - Calculate by the minimum square method

- $(t_i - t_f)$
  - 13500 s - 17100 s
  - (3600 s)
## Analysis of the experimental results

**Focused on the cavitation phenomenon**

<table>
<thead>
<tr>
<th>Discrete intervals</th>
<th>t&lt;sub&gt;i&lt;/sub&gt; (s)</th>
<th>t&lt;sub&gt;f&lt;/sub&gt; (s)</th>
<th>(t&lt;sub&gt;f&lt;/sub&gt; - t&lt;sub&gt;i&lt;/sub&gt;)</th>
<th>N&lt;sub&gt;m&lt;/sub&gt;</th>
<th>Experiment #1</th>
<th>Experiment #2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Q</td>
<td>χ²</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>900</td>
<td>900</td>
<td>60</td>
<td>5.73</td>
<td>11.34</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>1800</td>
<td>900</td>
<td>60</td>
<td>8.6</td>
<td>15.09</td>
</tr>
<tr>
<td>3</td>
<td>1800</td>
<td>3600</td>
<td>1800</td>
<td>30</td>
<td>38.33</td>
<td>21.7</td>
</tr>
<tr>
<td>4</td>
<td>3600</td>
<td>7200</td>
<td>3600</td>
<td>60</td>
<td>27.5</td>
<td>16.81</td>
</tr>
<tr>
<td>5</td>
<td>7200</td>
<td>10800</td>
<td>3600</td>
<td>60</td>
<td>18.53</td>
<td>11.34</td>
</tr>
<tr>
<td>6</td>
<td>10800</td>
<td>13500</td>
<td>2700</td>
<td>45</td>
<td>9.56</td>
<td>13.28</td>
</tr>
<tr>
<td>7</td>
<td>13500</td>
<td>17100</td>
<td>3600</td>
<td>60</td>
<td>24.5</td>
<td>13.28</td>
</tr>
<tr>
<td>8</td>
<td>17100</td>
<td>20700</td>
<td>3600</td>
<td>60</td>
<td>9.5</td>
<td>13.28</td>
</tr>
<tr>
<td>9</td>
<td>20700</td>
<td>24300</td>
<td>3600</td>
<td>60</td>
<td>22.8</td>
<td>15.09</td>
</tr>
<tr>
<td>10</td>
<td>24300</td>
<td>27900</td>
<td>3600</td>
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<td>900</td>
<td>60</td>
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<td>16.81</td>
</tr>
</tbody>
</table>

Total Number of measurements N<sub>m</sub> = 615

\[ N_m = \text{Number of measuring point} \]

\[ Q = \text{Statistics of the qui-square test} \]

\[ X^2 = \text{value of qui-square table} \]

**If** \( X^2 > Q \), the cavitation measuring follow a uniform pattern

\[ u_s = \sqrt{\sum_{i=0}^{N_m} \frac{[y(x_i) - y_i]^2}{N_m - z - 1}} \] ; in this equation: \( u_s \) a measure of uncertainty

\[ y(x_i) = \theta(t_i) = \text{Adjusted value of the cavitation level} \]

\[ y_i = \theta_i = \text{Measured value of the cavitation level} \]

\[ z = \text{Degree of polynomial adjustment (y(x_i))} \]
### Analysis of the experimental results

**Focused on the cavitation phenomenon**

<table>
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<th>Discrete intervals</th>
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</tr>
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<tbody>
<tr>
<td></td>
<td>Q</td>
<td>(\chi^2)</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------</td>
<td>---------------</td>
</tr>
<tr>
<td>1</td>
<td>5.73</td>
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</tbody>
</table>

Total Number of measurements \(N_m\) 615

The Chi-square statistical treatment of instantaneous measurements indicates the existence of non-uniform distributions of the cavitation level.
Analysis of the experimental results

Focused on the cavitation phenomenon

Experiment #1 (λ = 0.5 mm):
- 6 of 11 accumulative time interval kept a uniform distribution based on statistical analysis (chi-square test)
- Maximum variation associated with measurement of cavitation level: 0.0049 V
- Cavitation level average: 0.181 V

Experiment #2 (λ = 1.0 mm):
- 6 of 11 accumulative time interval kept a uniform distribution based on statistical analysis (chi-square test)
- Maximum variation associated with measurement of cavitation level: 0.0101 V
- Cavitation level average: 0.295 V

Change of λ from 0.5 mm to 1.0 mm (δ kept constant):
- No significant influence on the distribution of the cavitation level.
- Maximum variation associated with measurement of cavitation level: increased from 2.7% to 3.4%.
- 62% influence on the cavitation level average.
Analysis of the experimental results

Focused on the erosion phenomenon

**Experiment #1**

\[ \delta = 43.5 \, \mu m; \lambda = 0.5 \, mm \]

- Acceleration stage of erosion
- Incubation stage of erosion

**Experiment #2**

\[ \delta = 43.5 \, \mu m; \lambda = 1.0 \, mm \]

- Acceleration stage of erosion
- Incubation stage of erosion
For \( \lambda = 0.5 \text{ mm} \), the bubbles are confined within the gap. The bubbles spread to the edges as \( \lambda \) increases.
Analysis of the experimental results

Surface aspect of the aluminum-bronze alloy, before and after exposure to erosion

### Al-Bronze Alloy

<table>
<thead>
<tr>
<th>Condition</th>
<th>Measurement</th>
<th>Time</th>
<th>Mass Change</th>
<th>Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>δ = 43.5 µm; λ = 0.5 mm</td>
<td>480 min</td>
<td>Δm = 67.0 mg</td>
<td>ξ = 37.44 µm</td>
</tr>
<tr>
<td>#2</td>
<td>δ = 43.5 µm; λ = 1.0 mm</td>
<td>480 min</td>
<td>Δm = 66.0 mg</td>
<td>ξ = 36.38 µm</td>
</tr>
</tbody>
</table>
Analysis of the experimental results

3. Correlating cavitation with erosion resistance

$\bar{\theta}_\lambda = 0.5 \text{ mm} < \bar{\theta}_\lambda = 1.0 \text{ mm}$ (more bubbles emitting in between the gap in $\lambda = 1.0 \text{ mm}$)

$\bar{\theta}$ = Cavitation level average

$\lambda$ = Sonotrode-sample separation

*Eroded surface may not affect the cavitation level average (new experiments with others materials are been doing to verify this)
Conclusions

• The experimental apparatus allowed the evaluation of cavitation during erosion tests performed with aluminum-bronze alloy.

• The study illustrated (quantitatively) the influence induced by the \( \lambda \) parameter. The results of the experiments showed that variation of \( \lambda \) (\( \lambda = 0.5 \text{ mm} \) and \( \lambda = 1.0 \text{ mm} \)) impacts 1.5 % on the mass loss of aluminum-bronze alloy.

• Results confirmed that over a similar timescale, the higher the erosion rate the higher the mass loss.

• Even though the study may suggest that the presence of the eroded specimen in the cavitation field may be held responsible for non-uniform distributions of the cavitation level, further experiments involving other engineering materials offering different resistance to erosion might be welcome to correlating inertial acoustic cavitation emissions with material erosion resistance.
Next steps

**Automation of the experiments**
To reduce associated errors and to improve data acquisition procedure.

**Implementation of new operation conditions**
By increasing transducer amplitude ($\delta$) and displacement ($\lambda$) of the transducer horn wrt specimen.

**Implementation of new experiments**
To express measurement results of cavitation in terms of the basic principle associated with the phenomenon of cavitation.
Main References


Thank you!