Controlled Shock Waves for Underwater Hull Grooming: A Feasibility Study

Xingsheng Sun
PhD Candidate

Kevin Wang
Assistant Professor

Department of Aerospace and Ocean Engineering
Virginia Tech

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Introduction

- **M2C Lab: Shock-dominated fluid-solid interaction problems**

predicting underwater implosion

understanding cavitation-induced damages

- development & coupling of CFD and CSD solvers
- high-performance predictive simulation
- “shock wave by design”
Motivation

- Designed shock waves for breaking kidney stones

- shock wave lithotripsy (SWL): a first-line treatment of urinary stone disease; non-invasive

- a complex nonlinear (shocks, interfaces, fracture), multiphysics (stone, tissue, liquid, bubbles) problem

- motivation: high-intensity focused ultrasound (HIFU) can break hard solids in a “non-contact” manner, without inflicting significant damage to soft tissues

Motivation

- Designed shock wave lithotripsy for breaking kidney stones
- Shock wave lithotripsy is a non-invasive treatment for urinary stone disease

Dornier Compact Delta II

- A complex nonlinear multiphysics (stone
- Motivation: high-intensity focused ultrasound (HIFU) can break hard solids in tissue damage (＞500 shocks)

Photo taken at the large-scale seawater test facility (LSTF), Port Canaveral, FL

**Why shock wave might be effective for hull grooming?**

- the mechanical and acoustic properties of barnacle shell/cement differ significantly from those of FR coatings

- Barnacle and FR coating will respond to shock waves differently

<table>
<thead>
<tr>
<th>Material</th>
<th>Density $\rho$ (g/cm³)</th>
<th>Young's Modulus $E$ (GPa)</th>
<th>Acoustic Velocity $c_L$ (m/s)</th>
<th>Acoustic Velocity $c_T$ (m/s)</th>
<th>Acoustic Impedance $Z_L$ (kg/(mm²s))</th>
<th>Acoustic Impedance $Z_T$ (kg/(mm²s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seawater</td>
<td>1.0</td>
<td>-</td>
<td>1500</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Barnacle soft tissues</td>
<td>1.0</td>
<td>-</td>
<td>1500</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>Barnacle shell</td>
<td>1.7</td>
<td>14.7</td>
<td>3170</td>
<td>1870</td>
<td>5.4</td>
<td>3.2</td>
</tr>
<tr>
<td>Barnacle cement</td>
<td>1.6</td>
<td>2.0</td>
<td>1670</td>
<td>681</td>
<td>2.6</td>
<td>1.1</td>
</tr>
<tr>
<td>FR top coat (RTV11)</td>
<td>1.2</td>
<td>0.0023</td>
<td>562</td>
<td>25</td>
<td>0.67</td>
<td>0.03</td>
</tr>
<tr>
<td>Bond coat (Silgan J501)</td>
<td>1.5</td>
<td>17.3</td>
<td>1390</td>
<td>62</td>
<td>2.1</td>
<td>0.09</td>
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<tr>
<td>Structural steel</td>
<td>7.8</td>
<td>210.0</td>
<td>6000</td>
<td>3210</td>
<td>47.1</td>
<td>25.2</td>
</tr>
</tbody>
</table>

- Properties of barnacle shell are estimated basing on gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$)
- Properties of barnacle cement is estimated basing on Hysol 1C pseudobarnacle
Shock Wave Hull Grooming

Why shock wave might be effective for hull grooming?

- what is shock wave?
  - in theory, a shock wave is a discontinuity in pressure, density, and velocity that propagates at Mach > 1 (unlike acoustic waves)
  - in practice, particularly in liquid water (which is nearly incompressible), a shock wave can be viewed as a sharp pressure wave propagating at Mach ≈ 1

- a typical shock wave generated by an electrohydraulic (EH) sparker
  - has a sharp compressive wave front
  - followed by a broad tensile tail
  - has a wide frequency bandwidth

- hypothesis: shock waves may be able to release fouling from FR coatings through pull-off, shear, shock-induced fracture, cavitation erosion
Literature Survey

Related work

- several research groups have tried acoustic (audio & ultrasonic waves) methods for preventing fouling settlement (Legg et al., 2015)

- a few groups have tried to use shock waves to remove biofouling in pipes
  - the (electrohydraulic) shock-generating device is called “acoustic sparker” or “pulser”
  - generates shock wave by locally vaporizing water
  - references: Walch et al. 2000, Brizzolara et al. 2003 (NSWC-Carderock), Mackie et al., 2000 (Army Engineer R&D Center), Schaefer et al., 2010 (Phoenix S&T Inc.)

- a patent on using shock waves for hull cleaning
  Cioanta et al. (Sanuwave Inc.)

- the feasibility, efficiency, and safety (to coatings) of using shock waves for hull grooming is largely unknown
Pseudobarnacle Experiment

- Pseudobarnacle specimens

Pseudobarnacle A: 6 mm x 6 mm
Pseudobarnacle B: 10 mm x 10 mm

BegoStone Plus
(a super-hard dental stone, 99% gypsum + Fe₂O₃ & K₂O)

LocTite Super Glue

Steel plate w/ silicone coating (Dow Corning 3140), thickness of coating: 0.2 mm

| Material properties of BegoStone (powder-to-water ratio 5:1, dry) [22] |
|-----------------|-----------------|---------------|-------|-----|-----------------|
| \(C_L\) (m/s)   | \(C_T\) (m/s)   | \(\rho\) (kg/m³) | \(E\) (GPa) | \(\nu\) | Static Strength (MPa) |
| 4159            | 2319            | 1995           | 27.4   | 0.27 | 16.3            |

- Adhesion strength in shear: \(-0.17\) MPa (measured through ASTM D5618-94)
Pseudobarnacle Experiment

Experimental facility

- a modified Siemens EM lithotripter
- degassed water
- specimen holder
- focusing lens
- another lithotripter, not used

An electromagnetic (EM) lithotripter (P. Zhong et al., Duke)

Shock wave at focus

\[ p_{max} = 40 \text{ MPa} \]
Pseudobarnacle Experiment

➢ Pseudobarnacle A: 6 mm x 6 mm

The lithotripter is operated at very low freq. (~0.5 Hz) for the ease of observation.
Pseudobarnacle Experiment

Pseudobarnacle B, 10 mm x 10 mm

lithotripter is operated at very low freq. (~0.5 Hz) for the ease of observation
- the prescribed shock waves are able to remove pseudobarnacles (adh. strength: 0.17 MPa)
- no visible damage to the coating after ~150 shocks
- the size and material of pseudobarnacle matter
Computational Modeling & Analysis

Computational model

- goals
  • investigate the mechanisms of barnacle removal
  • design shock waveform, magnitude, frequency
- a 3D fluid-solid coupled computational model
  • a finite element solid dynamics model for the barnacle shell, barnacle cement, FR top coating, and the steel substrate
  • a finite volume compressible fluid dynamics model for seawater
Simulation

- approx. 20M elements in ¼ of the cylindrical domain (resolution: 0.05 mm)
- visualization of fluid pressure & max. principal stress in barnacle & coating:

* material damage & fracture are not modeled in this simulation
Simulation

- approx. 20M elements in ¼ of the cylindrical domain (resolution: 0.05 mm)
- visualization of fluid pressure & max. shear stress in barnacle & coating:

* material damage & fracture are not modeled in this simulation
- tensile stress in barnacle cement: up to 16 MPa (40% of $p_{\text{max}}$) …
  1 to 3 orders of magnitude greater than measured strength (barnacles & pseudobarnacles)
- tensile stress in FR coating: up to 2 MPa (5% of $p_{\text{max}}$) …
  2 to 3 orders of magnitudes lower than the static strength of FR coating
Shock-Induced Damage & Fracture

CFD-CSD coupled simulation, with a continuum damage mechanics model & element erosion
Effect of Shock Waveform

- **Effect of tensile tail**

  A shock wave with a tensile tail can induce much larger (4X) damage than one without a tensile tail.

Concluding Remarks

Summary

- a joint experimental and computational study, using pseudobarnacles
- the acoustic and mechanical properties of barnacle (cement, shell) differ significantly from those of silicone-based FR coatings
- shock waves with peak pressure $10 \text{ MPa} < p_{\text{max}} < 40 \text{ MPa}$, duration of $1-10 \mu\text{s}$ can remove pseudobarnacles from FR coating (adh. strength (shear): $0.17 \text{ MPa}$), without visible damage to the coating
- efficiency depends sensitively on prescribed waveform (e.g., tensile tail)

Future directions

- testing real barnacles and other fouling organisms
- developing a prototypical hull grooming device