Introduction and motivation:

Flexi-Fish project aims at answering a simple question: Is it possible, using only elastic waves in a solid beam, to create thrust in water? The idea is to apply a moment to a thin beam in order to produce waves which, through the deformation of the plate, would create thrust in water.

A physical model: Beam theory and solid/water interaction:

Beam equation with volumic forces:

$$\frac{dh}{dx}(x, t) + \rho A \frac{d^2 h}{dt^2}(x, t) = -m \left( \frac{d^2 h}{dx^2} + 2U \frac{d^2 h}{dx dt} + U \frac{d^2 h}{dx^2} \right)$$

Force equilibrium equation for stationary motion, Drag = Thrust:

$$\frac{1}{2} C_D \cdot \rho \cdot \text{water} \cdot S_{\text{beam}} \cdot U^2 + 2 \cdot 1.328 \cdot 2b \cdot \rho \cdot \text{water} \cdot U^2 \cdot \sqrt{h} - \frac{\theta}{\sqrt{2g}} = \frac{m}{2} (c^2 - U^2) h_x,$$

Analytical study - geometric and wave properties:

The following table sums up the geometric properties of the fish that were determined throughout an analytical study of the model:

<table>
<thead>
<tr>
<th>Property</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>ℓ</td>
<td>500</td>
<td>mm</td>
</tr>
<tr>
<td>Semi-width</td>
<td>b</td>
<td>30</td>
<td>mm</td>
</tr>
<tr>
<td>Thickness</td>
<td>e</td>
<td>0.5</td>
<td>mm</td>
</tr>
<tr>
<td>Young’s Modulus</td>
<td>E</td>
<td>210</td>
<td>GPa</td>
</tr>
<tr>
<td>Density</td>
<td>ρ</td>
<td>7800</td>
<td>kg.m⁻³</td>
</tr>
</tbody>
</table>

A relation between the pulsation $\omega$ and the wave number $k$ can be determined by introducing the harmonic response $h(x,t) = \overline{h} \cdot e^{i(kx - \omega t)}$ inside the beam equation:

This result can now be introduced inside the Drag-Thrust equation in order to determine the relation between the velocity $U$ and the pulsation $\omega$.

References:

- TY Wu. 2011. Fish Swimming. Annual review of Fluid mechanics
- C. Francois & JS Darues. Mecanique des Fluides Incompressible

Numerical simulation:

An approximation of the beam equation’s solution is determined using a finite element program. The resulting deformation is then used to compute the thrust produced as a function of time, by means of a finite difference method.

Mean thrust is plotted for different input frequencies: peaks of thrust are observed and tend to follow the natural frequencies of our model; thus, working at natural frequencies optimizes the energy and gives bigger thrust.

Finally, an iteration is done on the velocity $U$ to equal thrust and drag.

Experimental results (in air):

The time response of an impulse source is measured. The spectrum of the signal is calculated using an FFT. The displacement at the tail is about 2cm peak to peak without added mass for the first natural frequency of 12.5Hz.

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