Case study: Anaconda

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Content

• Introduction
• Methodology
• Results
• Conclusions

This lecture excludes
• Numerical modelling with Abacus (structure) and MATTHEW (waves)
• Analytical details of developed theory (see Chaplin et al. 2012; Farley et al. 2012)
• Dynamic mechanical rubber analysis (see Heller and Chaplin 2011)
Introduction

Animation Anaconda wave energy converter

...is a closed rubber tube filled with water under pressure.
...is about 150 m long and 6 m in diameter.
...captures wave energy with bulge waves.
...aligns parallel to wave direction due to point mooring.
...is an attenuator (aligns parallel to wave direction).
...is environmental friendly (made of natural rubber).
...should produce about 1 MW power in 50 kW/m waves.
...is a floating offshore device (in deep-water waves).
...is distensible (advantage for extreme waves).
...has low construction and maintenance costs.
Introduction

Overview Anaconda research

<table>
<thead>
<tr>
<th>Inventors (in 2005)</th>
<th>Checkmate SeaEnergy Ltd Melksham, licensed manufacturer</th>
<th>University of Southampton Funded by EPSRC</th>
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</thead>
<tbody>
<tr>
<td>Prof RCT Rainey, WS Atkins Oil &amp; Gas</td>
<td>Chief Executive Des Crampton and 2-3 engineers Physical model tests (so far 1:25)</td>
<td>Physical model tests 1:25 Prof JR Chaplin, Dr V Heller, students Numerical simulations Prof GE Hearn, Dr A Bucchi, students</td>
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<tr>
<td>Carbon Trust</td>
<td>Aims • Optimisation performance • Looking for investors • First prototype finished by 2014</td>
<td>Aims • Numerical simulations • Investigation hydrodynamics • Comparison with theory</td>
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Anacondas… very promising and potentially cost-effective solution.6

Experts
- Black & Veatch
- University College Cork

Bulge waves propagate also in human body

- Pressure pulses from the heart are propagating as bulge waves in aortas
- Literature available about bulge wave speed, bulge pressure losses and aneurysm, e.g. Pedley (1980) *The fluid mechanics of large blood vessels.*
Introduction

Principle bulge wave generation

- The PTO transforms the captured wave energy in the bulge waves in electrical power
- Smoothing with accumulators is required to extract power continuously and not periodic in cycles

Principle power take-off PTO of Anaconda

- The PTO transforms the captured wave energy in the bulge waves in electrical power
- Smoothing with accumulators is required to extract power continuously and not periodic in cycles
Methodology

Side view set-up I with actuators (tube scale 1:25)

Power of mechanical components [Watts = Nm/s] = force [N] × velocity [m/s]

Wave basin at Danish Hydraulic Institute, 20 × 30 × 3 m³
Methodology

Air power (W) = flow rate (m$^3$/s) × pressure drop (N/m$^2$)

Side view set-up II with model PTO
Tube cross section at $x = 0.545$ m

Cross section power take-off

17 copper pipes, ID = 0.0266 m

2,000 tubes, ID = 0.0016 m, length = 0.800 m

1.80 m

Power take-off

Tow plate

2 pressure transducers

Hold in position

2.00 m

1.20 m

0.80 m

0.40 m

Aluminum

Rubber tube

Baffle wave

Disc with pressure transducer

0.200 m

0.350 m

Pressure reading

Imperial College
London

Methodology

Towing tank Solent University, Southampton, $60 \times 3.7 \times 1.87$ m$^3$
Methodology

Anaconda tube in regular waves

Methodology

Postpone onset of aneurysm
Methodology

Measurement system (power = flow rate × pressure drop)

- 3 pressure transducers (at tube bow, in PTO)
- Wave gauges (3 in PTO, up- and down-wave of device)
- 20 Galinstan strain gauges GSG (circumference of tube, bulge wave speed, indirect pressure, velocity and power of bulges in tube)

Cross sectional area measurements of tube

\[
\begin{align*}
\text{Cross sectional area } S &\text{ (m}^2) \\
\end{align*}
\]
Methodology

Videos of tests at Solent University, scale 1:25

Results: Bulge wave speed

Distensibility $D$ (1D linear theory from Lighthill 1978)

- $D$ indicates relative tube cross sectional area $S$ increase per unit increase of pressure $p$
  
  $D = \frac{1}{S} (dS/dp)$

  $D = \frac{2r}{(\delta E)}$ for thin-walled elastic tube with Young’s modulus $E$
  
  wall thickness $\delta$
  
  tube radius $r$

- Theoretical bulge wave speed $c_{bt}$
  
  $c_{bt} = 1/(\rho D)^{1/2}$
  
  $\rho$ = fluid density
Results: Bulge wave speed

Bulge wave speed

![Graph showing measured versus theoretical bulge wave speed.]

Results: 1D linear theory

Linear theory

- 1D linear theory for bulge wave speed and pressure in liquid-filled, thin-walled elastic tubes was further developed to include in addition:
  - Hysteresis losses in rubber
  - Effect of inelastic sectors of circumference
  - State of plane strain (tube fixed at both ends)
  - Effects of tube curvature (≈ 0.2%) and of surrounding water (≈ 1%) were found to be negligible for bulge speed (excluded)

- Equation was solved with boundary conditions of set-up II
  - Tube closed and stationary at up-wave end
  - Linear dashpot PTO at down-wave end

- Not included are wave diffraction and radiation
Results: In tube

Particle velocity $u(x, t)$ and pressure $p(x, t)$ in tube for 16 instances over one period

<table>
<thead>
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<th>(a) Measured</th>
<th>(b) 1D theory</th>
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<tbody>
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<td>$A(m)$</td>
<td>$\omega = 2\pi/T (1/s)$</td>
</tr>
<tr>
<td>$\rho (kg/m^3)$</td>
<td>= wave angular frequency</td>
</tr>
<tr>
<td>$g (m/s^2)$</td>
<td>= gravitational acceleration</td>
</tr>
<tr>
<td>$L (m)$</td>
<td>$x$ (m) = $x$-coordinate</td>
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$A$ (m) = pressure head due to wave
$\omega = 2\pi T$ (1/s) = wave angular frequency
$\rho$ (kg/m$^3$) = water density
$g$ (m/s$^2$) = gravitational acceleration
$L$ (m) = tube length
$x$ (m) = $x$-coordinate

Results: PTO

Impedance ratio $Z = I_{PTO}/I_{tube}$

Power $P = \text{flow rate} \times \text{pressure drop}$

- OWC completely open to atmosphere, no pressure (force) $\rightarrow P = 0$
- OWC completely closed, no fluid velocity $\rightarrow P = 0$

Mechanical impedance is a measure of how much a structure resists motion when subjected to a given force. Here impedance $I_{PTO}$ (Pa/[m$^3$/s]) is a measure of how much the PTO resists the flow when subjected to a given pressure. The optimum of $I_{PTO}$ is between completely open ($I = 0$) and closed ($I = \infty$).

$I$ can be measured in the PTO and $I$ can also be computed for the tube $I_{tube} = \rho c^2 / S$. If $I_{PTO}$ is adjusted such that $I_{PTO} = I_{tube}$ (impedance matching), then the PTO is like an infinite continuation of the tube and no bulge reflection is expected. The generated power in the PTO is maximal.

Over all: $P = P_{\text{max}}$ if $Z = I_{PTO}/I_{tube} = 1$ and if $c_{bt}/c_w = 1$ (resonance)
Results: PTO

Pressure $p_{PTO}$ and amplitude $a_{PTO}$ versus relative impedance $Z = I_{PTO}/I_{tube}$.

$$\delta (\%) = \text{loss angle; } \delta \text{ is proportional to hysteresis losses (dissipation) in rubber and was measured as 6\%; here } \delta = 9^\circ \text{ was used (difference may account for radiation)}$$

Capture width

Equivalent width in meter wave front where 100% of the incident wave energy is absorbed by a WEC. The capture width can be expressed in meter or dimensionless:

$$\text{Capture width } W (m) = \frac{\text{captured power (kW)}}{\text{power/meter wave front (kW/m)}}$$

$$\text{Relative capture width } (-) = \frac{W (m)}{\text{characteristic length (m)}}$$

The characteristic length is often the diameter of a device.
Results: PTO

Relative capture width versus relative period

- = 1D theory (with $\delta = 9^\circ$)
-= = measurements

$T$ = water wave period
$T_0$ = resonance water wave period with $c_a = c_w$
$Z$ = impedance ratio

$I_{PTO}/I_{tube}$

Up-scaled after Froude

Peak capture width 1.5 for $Z = 1.05$ results in
$P = 0.5$ MW at full scale
Powers 500 UK houses

Performance is not optimised
May involves significant scale effects → tests at larger scale are required

Conclusions

- Anaconda, invented in 2005, captures wave energy with bulge waves propagating like pressure pulses from heart in blood system
- Unlike almost all other marine systems, Anaconda is distensible (elastic or deformable): measurements, scale effects and development of theory was challenging (many optimisations required)
- Anaconda was investigated under idealised conditions at scale 1:25 at University of Southampton to better understand its hydrodynamics
- This investigation required some novel components (Galinstan strain gauges, model PTO) and an improved 1D linear theory
- The measurements match surprisingly well with this theory if the loss angle $\delta$ is increased to account for wave radiation
- The measured power looks promising and Checkmate SeaEnergy is currently looking for investment to test the device at full scale
References


