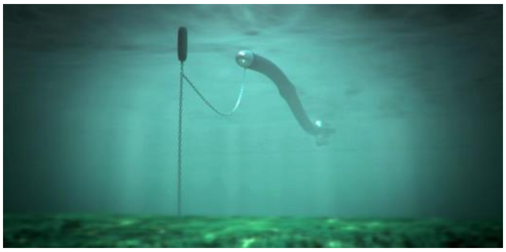
Case study: Anaconda



Dr Valentin Heller
Fluid Mechanics Section, Department of Civil and Environmental Engineering

4th CoastLab Teaching School, Wave and Tidal Energy, Porto, 17-20th January 2012

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)

Imperial College London

Introduction

Animation Anaconda wave energy converter

Checkmate SeaEnergy Ltd

Imperial College London

Introduction

Anaconda…

...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.

Imperial College
London

Introduction

Overview Anaconda research

Inventors (in 2005)

Prof RCT Rainey, WS Atkins Oil & Gas
Prof FJM Farley, Maritime Energy Development Ltd

Carbon Trust

Anaconda… "very promising and potentially cost-effective solution."

Experts
- Black & Veatch
- University College Cork

Checkmate SeaEnergy Ltd
Melksham, licensed manufacturer

Chief Executive Des Crampton and 2-3 engineers
Physical model tests (so far 1:25)

Aims
- Optimisation performance
- Looking for investors
- First prototype finished by 2014

University of Southampton
Funded by EPSRC

Physical model tests 1:25
Prof JR Chaplin, Dr V Heller, students
Numerical simulations
Prof GE Hearn, Dr A Bucchi, students

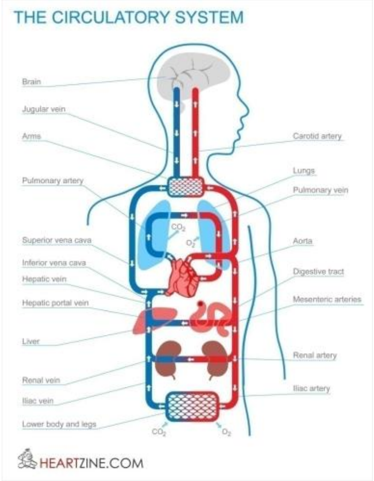
Aims
- Numerical simulations
- Investigation hydrodynamics
- Comparison with theory

5

Imperial College
London

Introduction

Bulge waves propagate also in human body



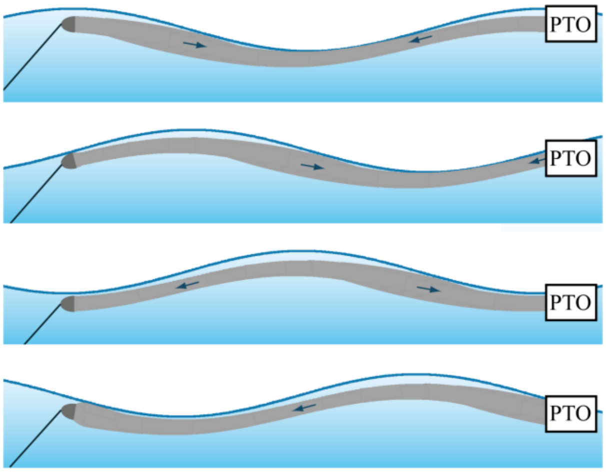
- Pressure pulses from the heart are propagating as bulge waves in aortas
- Literature available about bulge wave speed, bulge pressure losses and aneurysm, e.g. Pedley (1980) *The fluid mechanics of large blood vessels*.

6

Imperial College London

Introduction

Principle bulge wave generation



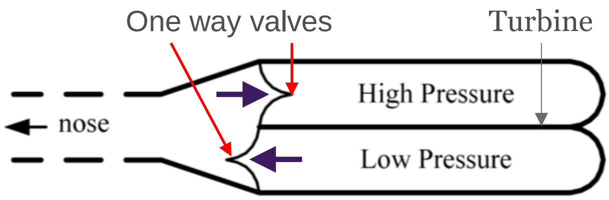
7

Imperial College London

Introduction

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

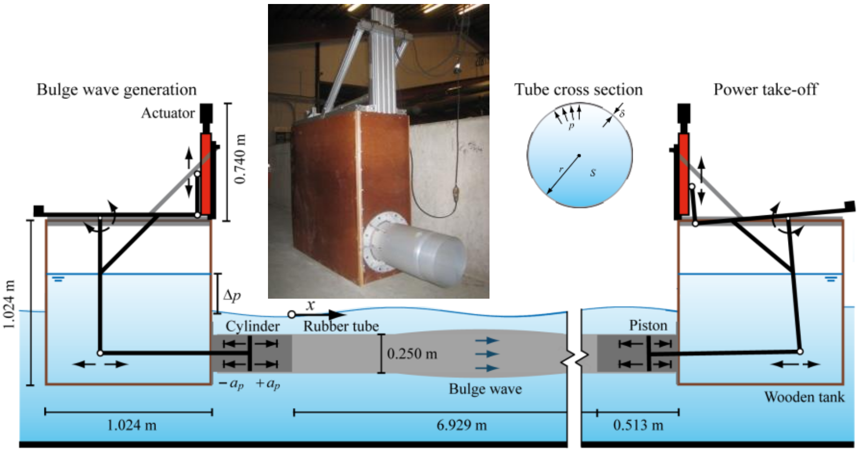


8

Imperial College
London

Methodology

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



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

9

Imperial College
London

Methodology

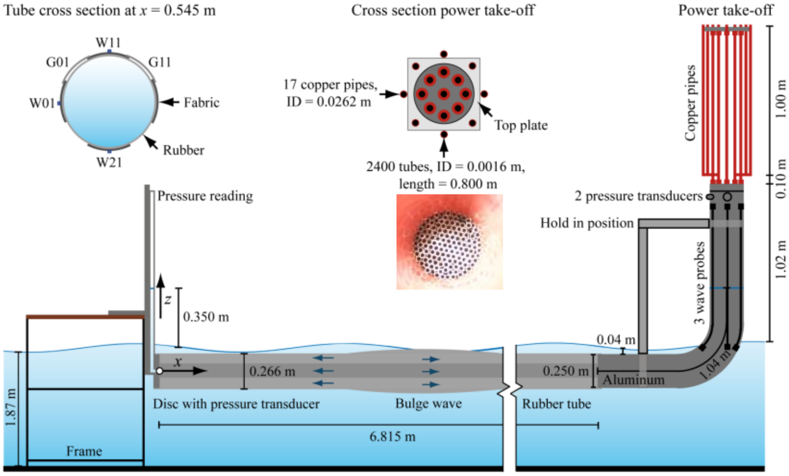
Wave basin at Danish Hydraulic Institute, 20 × 30 × 3 m^3

10

Imperial College London

Methodology

Side view set-up II with model PTO



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

11

Imperial College London

Methodology

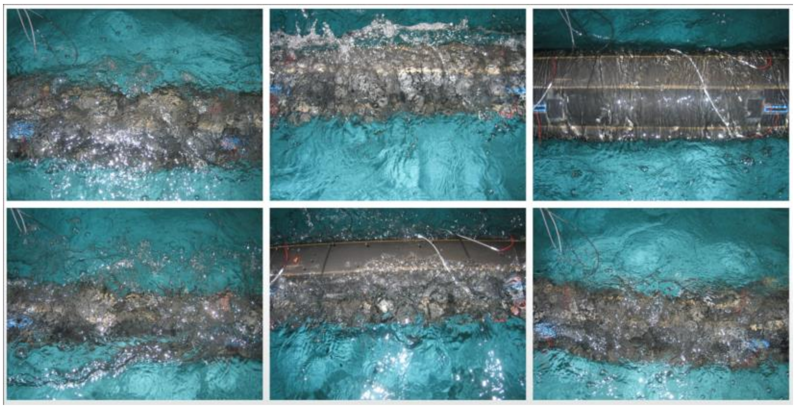
Towing tank Solent University, Southampton, 60 × 3.7 × 1.87 m^3

12

Imperial College London

Methodology

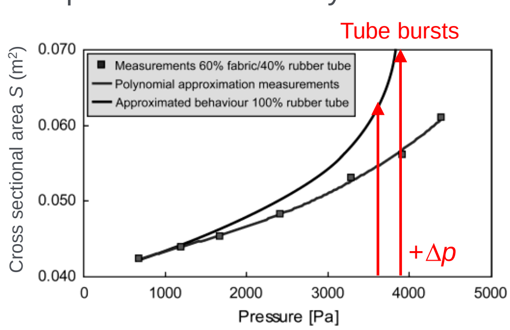
Anaconda tube in regular waves

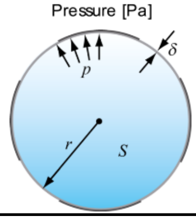


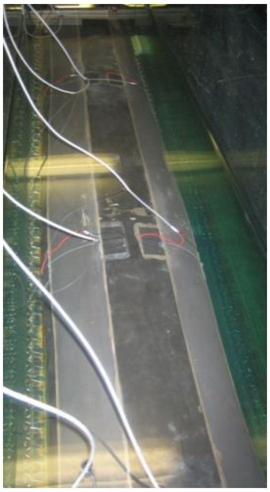
Imperial College London

Methodology

Postpone onset of aneurysm







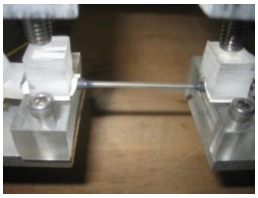
Imperial College London

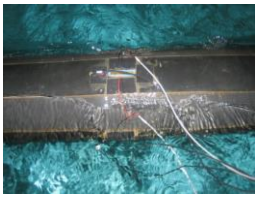
Methodology

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)


PTO


Bench testing GSG


GSG on tube

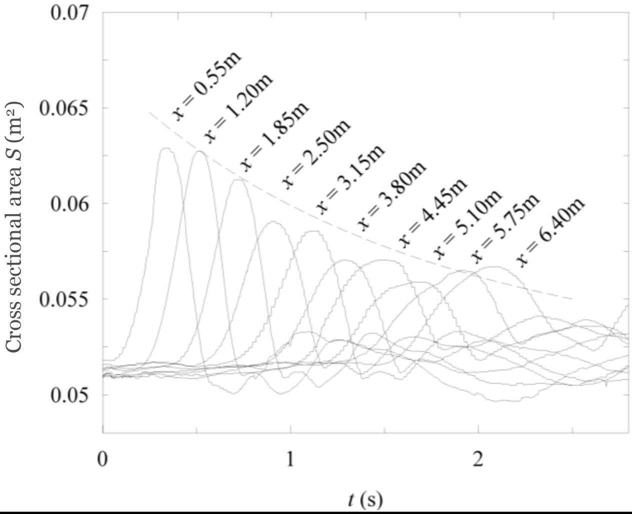
- 20 Galinstan strain gauges GSG (circumference of tube, bulge wave speed, indirect pressure, velocity and power of bulges in tube)

15

Imperial College London

Methodology

Cross sectional area measurements of tube



16

Imperial College London

Methodology

Videos of tests at Solent University, scale 1:25

17

Imperial College London

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

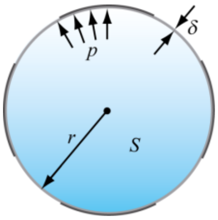
  $D = (1/S)(dS/dp)$

  $D = 2r/(\delta E)$ for thin-walled elastic tube

  with Young's modulus E

  wall thickness δ

  tube radius r



- Theoretical bulge wave speed c_{bt}

  $c_{bt} = 1/(\rho D)^{1/2}$

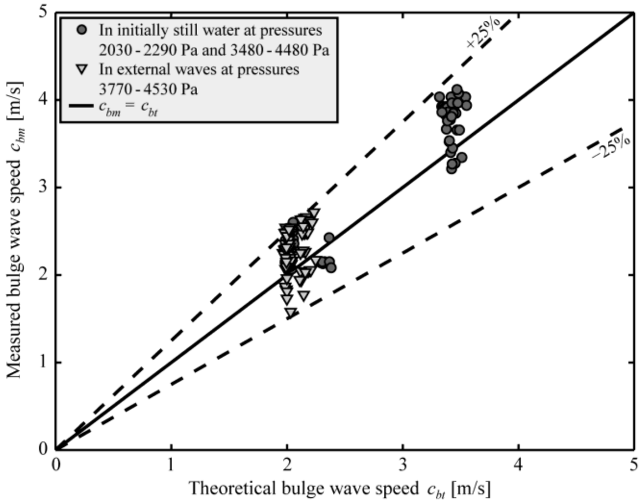
  ρ = fluid density

18

Imperial College London

Results: Bulge wave speed

Bulge wave speed



Imperial College London

Results: 1D linear theory

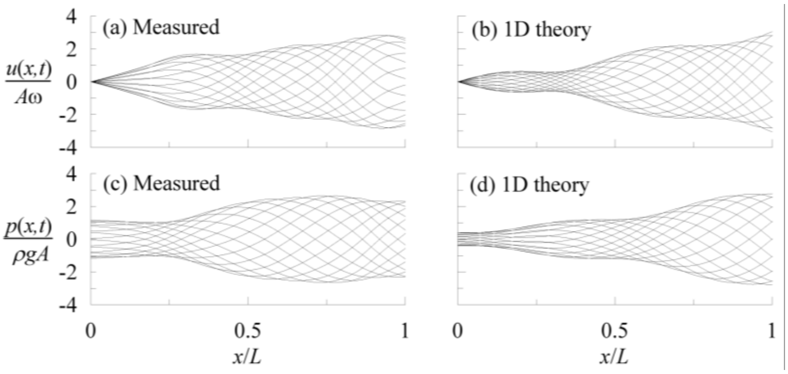
Linear theory

- 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

Imperial College London

Results: In tube

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



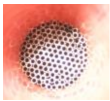
A (m)	= pressure head due to wave	ρ (kg/m³)	= water density
$\omega = 2\pi/T$ (1/s)	= wave angular frequency	L (m)	= tube length
g (m/s²)	= gravitational acceleration	x (m)	= x-coordinate

21

Imperial College London

Results: PTO

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



Power P = flow rate × pressure drop

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

Mechanical impedance is a measure of how much a structure resists motion when subjected to a given force. Here impedance I_{PTO} (Pa/[m³/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 a infinite continuation of the tube and no bulge reflection is expected. The generated power in the PTO is maximal.

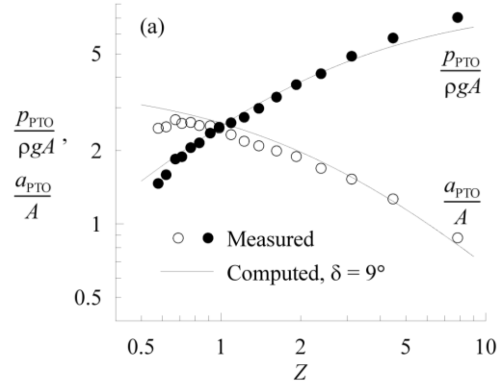
Over all: $P = P_{max}$ if $Z = I_{PTO}/I_{tube} = 1$ and if $c_{bt}/c_w = 1$ (resonance)

22

Imperial College London

Results: PTO

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



δ (º) = loss angle: δ is proportional to hysteresis losses (dissipation) in rubber and was measured as 6º; here δ = 9º was used (difference may account for radiation)

23

Imperial College London

Results: PTO

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:

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

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

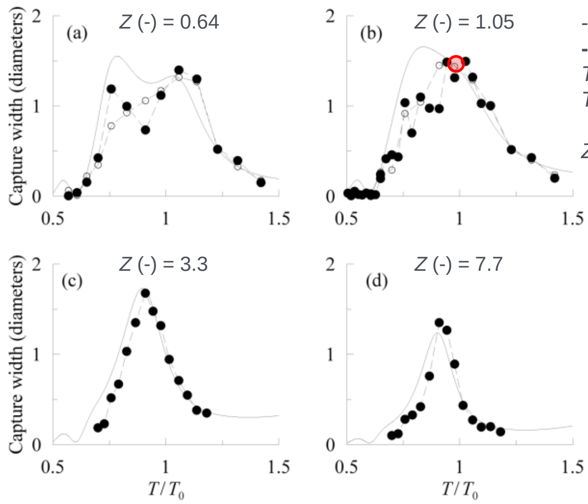
The characteristic length is often the diameter of a device.

24

Imperial College London

Results: PTO

Relative capture width versus relative period



- = 1D theory (with δ = 9°)
-- = measurements
T = water wave period
T_0 = resonance water wave period with $c_{bt} = c_w$
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

25

Imperial College London

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 δ 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

26

Imperial College London

References

Chaplin, J.R., Farley, F.J.M., Prentice, M.E., Rainey, R.C.T., Rimmer, S.J., Roach, A.T. (2007). Development of the Anaconda all-rubber WEC. Proceeding of the 7th European Wave and Tidal Energy Conference, Lisbon.

Chaplin, J.R., Heller, V., Farley, F.J.M., Hearn, G.E., Rainey, R.C.T. (2012). Laboratory testing the Anaconda. *Philosophical Transactions of the Royal Society A* 370:403-424.

Farley, F.J.M., Rainey, R.C.T., Chaplin, J.R. (2012). Rubber tubes in the sea. *Philosophical Transactions of the Royal Society A* 370:381-402.

Heller, V., Chaplin, J.R., Farley, F.J.M., Hann, M.R., Hearn, G.E. (2010). Physical model tests of the wave energy converter Anaconda. *1st European conference of IAHR*, Edinburgh, Paper MREc: 1-6, IAHR, Madrid.

Heller, V., Chaplin, J.R. (2011). Dynamic mechanical analysis of rubber used in Anaconda testing, Proc. 9th *European Wave and Tidal Energy Conference*, paper 373, 5. - 9. September 2011, Southampton.

Lighthill, J. (1978). Waves in fluids. Cambridge University Press, Cambridge.

Pedley, T.J. (1980). The fluid mechanics of large blood vessels. Cambridge University Press, Cambridge.