# Assessment of a multi-cell fabric structure as an attenuating wave energy converter

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**Abstract:** Fabriconda is an attenuating wave energy device constructed from inelastic fabric. It is a flooded distensible tube constructed from a series of smaller flooded tubes, called cells, joined longitudinally. This paper presents a theory to predict the shape a Fabriconda forms at different tube and cell pressures and shows it successfully predicts the shape of a model Fabriconda. A 1D linear finite difference simulation based on the conservation of fluid momentum and mass in both the central tube and cells provides a prediction of the free bulge wave speed along the device. Experiments using a piston to artificially generate a bulge wave within the central tube of a model Fabriconda have produced bulge speeds that demonstrate good agreement with these predictions.

***Keywords:*** *Wave energy, Wave power device, Finite difference model*

## Nomenclature

| | | |
|---|---|---|
| $\theta$ | *half-vertex angle* | |
| $n$ | *number of cells* | |
| $s$ | *cell arc-length* | *m* |
| $p_t$ | *tube pressure* | *Pa* |
| $p_c$ | *cell pressure* | *Pa* |
| $r$ | *radius of curvature of cell* | *m* |
| $T_1$ | *fabric tension of cell – external interface* | *N* |
| $T_2$ | *fabric tension of cell – tube interface* | *N* |
| $x$ | *cell horizontal chord length* | *m* |
| $R$ | *central tube radius* | *m* |
| $A_t$ | *central tube cross-sectional area* | $m^2$ |
| $A_c$ | *cell cross-sectional area* | $m^2$ |
| $A_0$ | *initial, static cross-sectional area* | $m^2$ |
| $\rho_o$ | *density* | $kg \cdot m^{-3}$ |

## 1. Introduction

The Anaconda wave energy converter [1], [2] consists of a submerged and flooded rubber distensible tube lying perpendicular to incoming wave fronts. As the waves pass over, they induce a series of travelling bulges in the tube, and an internal oscillatory flow. If the speed of free bulge waves is close to that of the external water waves, energy is progressively transferred to the flow inside the tube, terminating in a power take-off system.

The purpose of this paper is to outline initial work on a fabric version of the Anaconda, named the Fabriconda [3], [4]. In the Fabriconda, distensibility is provided not by the elasticity of the walls (as in the Anaconda), but by the form of construction of the tube. A number of tubes (or ‘cells’) made of inelastic fabric are joined together longitudinally to form a larger central tube (Fig.1). The tube and the cells are separately flooded. Local changes in the cross-sectional area of the tube are facilitated by changes in the shapes of the surrounding cells. When the cells are circular, the tube area is at a minimum; when the cells are flat it is at a maximum. The tube’s distensibility and the speed of free bulge waves in it depend on the ratio of the pressure in the tube to that in the cells.

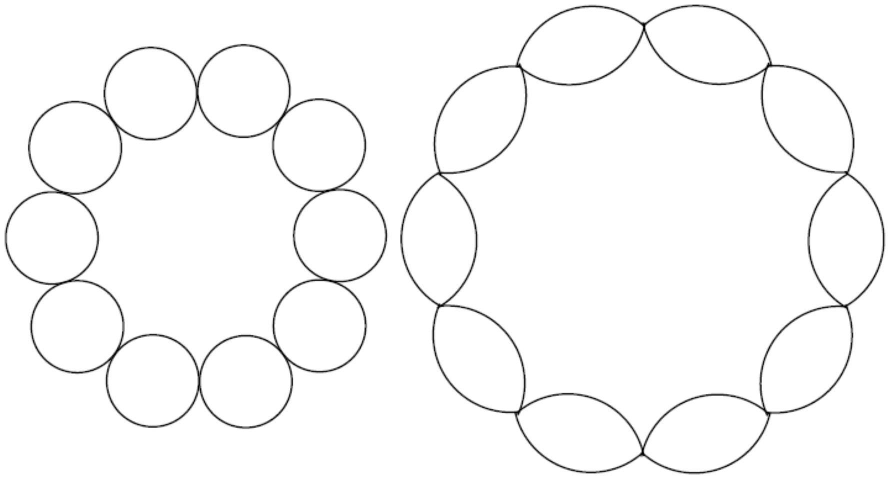

*Fig. 1. Example cross-section of a Fabriconda with 10 cells, showing the structure at its minimum cross-section and at its medium point [3].*

The potential advantages of this construction are that it removes the danger of aneurysm that can occur in rubber tubes. It also substantially reduces energy losses through hysteresis and construction may be cheaper. This paper presents the static shape theory of the Fabriconda and compares this with experimental results. A 1D finite difference model of the tube is introduced and used to predict the Fabriconda's free bulge speed. A comparison with measurements of free bulge speed is made.

## 2. Methodology

### *2.1. Static shape*

The cells are lenticular in shape and are formed by the intersection of two circular arcs (fig. 2.). The geometry of a Fabriconda with *n* cells can be defined via the half vertex angle, θ. The half vertex angle depends on the fluid pressures $p_t$ and $p_c$ within the tube and cells and the arc length s, the width of fabric from which half a Fabriconda cell is constructed.

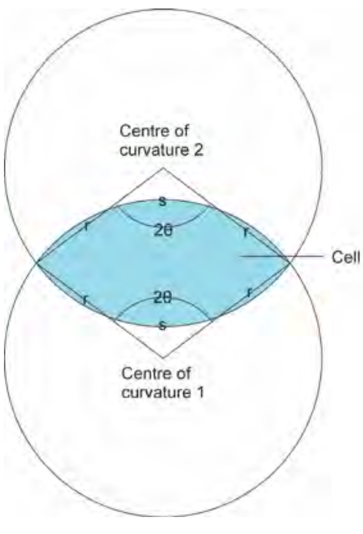


*Fig. 2. – The formation of a lenticular shaped cell by two circular arcs.*

By comparing the ratio that arc length s represents of the circle circumference to the ratio that 2θ represents of the whole circle equation 1 for circle radius is found:

$$r = \frac{s}{2\theta} \qquad (1)$$

Simple geometry now gives *x*, the cell chord length and *R* the central tube radius (fig. 3.).

$$x = \frac{s\sin(\theta)}{\theta} \qquad (2)$$

$$R = \frac{s\sin(\theta)}{2\theta\sin\left(\frac{\pi}{n}\right)} \qquad (3)$$

Finally cell and tube areas can be defined, again in terms of the variable θ.

$$A_c = 2\left(\frac{s^2}{4\theta} - \frac{s^2 \sin(2\theta)}{8\theta^2}\right) \tag{4}$$

$$A_t = n\left(\frac{s^2 \sin^2(\theta)}{4\theta^2 \tan\left(\frac{\pi}{n}\right)} - \frac{s^2}{4\theta} + \frac{s^2 \sin(2\theta)}{8\theta^2}\right) \tag{5}$$

Each cell has two boundaries, the first between the cell and the external environment and the second between the cell and the tube. The pressure difference across these two boundaries generates separate tensions in the fabric defining the boundary, $T_1$ and $T_2$ (fig. 3).

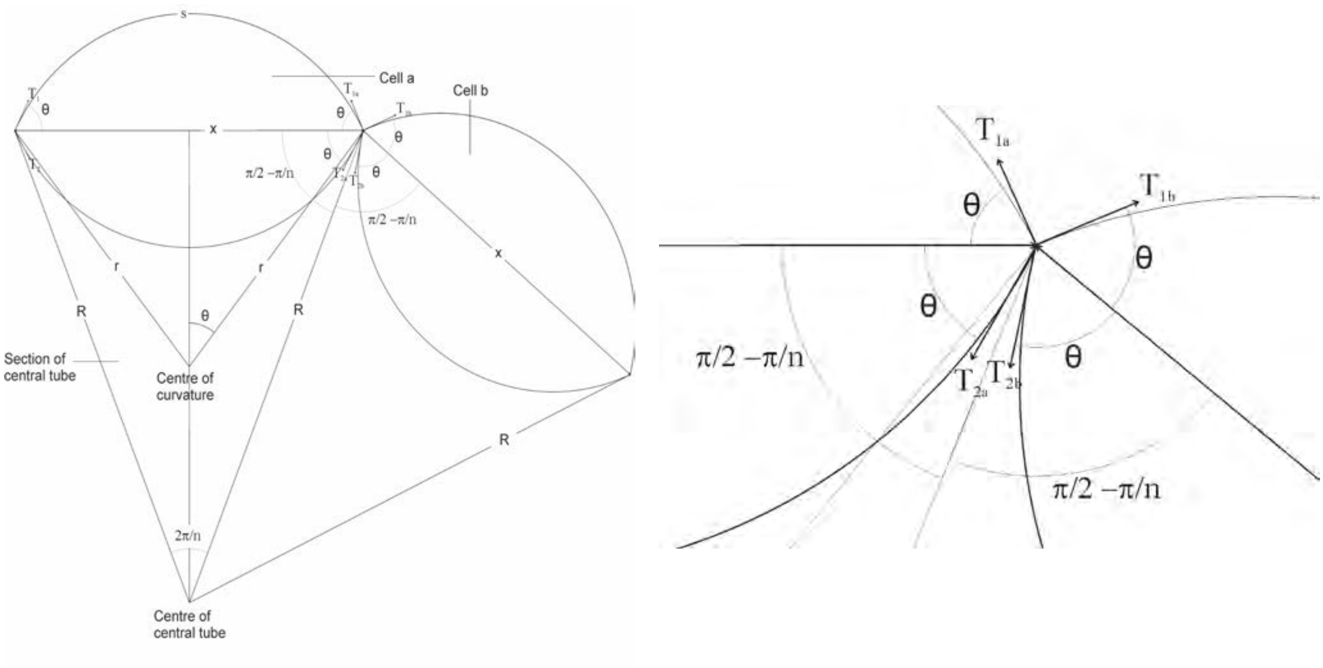


*Fig. 3. Geometry of two Fabriconda cells*

At the joint between cells the two tensions from each cell must balance. Using this condition a relationship between θ and $T_2$ and $T_1$ can be found:

$$\tan(\theta) = \frac{T_2 + T_1}{T_1 - T_2} \tan\left(\frac{\pi}{n}\right) \tag{6}$$

The two tensions are given by the pressure differences across the two boundaries and the cell radius of curvature. Applying this half vertex angle, and hence Fabriconda geometry, is defined in terms of cell and tube pressure:

$$\tan(\theta) = \frac{2p_c - p_t}{p_t}\tan\left(\frac{\pi}{n}\right). \tag{7}$$

### 2.2. 1D finite difference model

Predictions of how free bulge speed varies with the fluid pressure within the tube and cell have been made using a 1D finite difference model of the Fabriconda. The fabric is assumed to act as an inelastic membrane. Linear conservation of momentum (equation 8) and continuity (equation 9) are applied to the flow in a single cell and the 1/*n*th segment of central tube defined by that cell.

$$\rho_0 \frac{\partial u}{\partial t} = -\frac{\partial p}{\partial x} \tag{8}$$

$$\frac{\partial A}{\partial t} = -A_0 \frac{\partial u}{\partial x} \tag{9}$$

By differentiating equation 8 with respect to position and equation 9 with respect to time, velocity is eliminated from the problem, giving equation 10 to describe flow in the tube segment and equation 11 describing the flow in the cell.

$$\frac{\partial^2 A_t}{\partial t^2} = \frac{A_{to}}{\rho}\frac{\partial^2 p_t}{\partial x^2} \tag{10}$$

$$\frac{\partial^2 A_c}{\partial t^2} = \frac{A_{co}}{\rho}\frac{\partial^2 p_c}{\partial x^2} \tag{11}$$

Equations 4 and 5 are substituted into 10 and 11 to give two equations describing the dynamic properties of the device in terms of both tube and cell pressure. A Du Fort-Frankel finite difference scheme is applied to give two quadratic equations (equations 12 and 13) in terms of tube and cell pressure. The two pressures are solved at each time step using a Newton iteration method:

$$F = zp_{ti,j+1}^{2} + yp_{ti,j+1} + mp_{ti,j+1}p_{ci,j+1} + wp_{ci,j+1} + vp_{ci,j+1}^{2} + q = 0 \tag{12}$$

$$G = z_1 p_{ti,j+1}^{2} + y_1 p_{ti,j+1} + m_1 p_{ti,j+1}p_{ci,j+1} + w_1 p_{ci,j+1} + v_1 p_{ci,j+1}^{2} + q_1 = 0 \tag{13}$$

A sinusoidal fluctuation is applied to the bow boundary condition and the speed at which the resulting pressure bulge propagates along the Fabriconda tube is measured.

### 2.3. Experimental set-up and measurements

A 7.0m long, 10 cell, model Fabriconda with a cell arc length of 0.121 ± 0.003m was constructed to verify the static shape theory as well as to provide measurements of free bulge speed. The experimental set-up is shown in figure 4. The model was constructed from 450 decitex woven Nylon and each cell and the central tube had a 0.16mm latex inner tube inserted to make the device water tight. The central tube was connected to a 250mm diameter piston cylinder at one end and a 250mm diameter pipe with a $90^{o}$ bend at the other. This pipe was the first part of a power take off system not relevant to these measurements. The cells were closed at the piston cylinder end and connected to a cell reservoir via 1.4m long, 25mm diameter pipes at the other. The top of central tube was 100mm below the water surface.

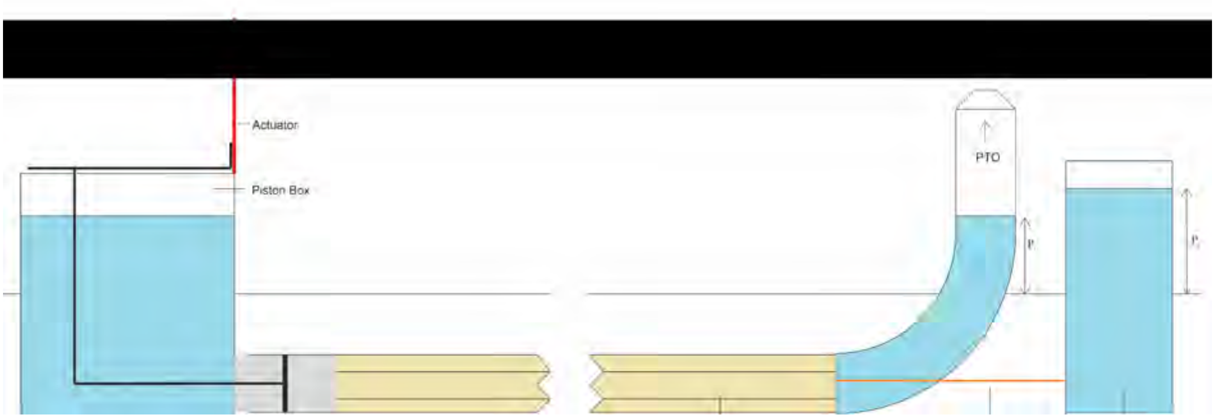


*Fig. 4. Experimental set-up with piston in the main tube to artificially generate bulge waves.*

Pressures within the model were measured simply using manometers connected to each cell and the central tube. To verify the static shape theory the model was inflated to various cell and tube pressure combinations and cell chord length ($x$) of the top cell measured using callipers.

Free bulge speed was measured by artificially generating bulge-waves using an actuator driven piston [5] producing a single sinusoidal oscillation. Nine pairs of 50mm long strain gauges were attached to a single cell, spaced evenly along the device with a separation of 75.0cm. These gauges recorded the curvature of the cell and hence the passage of the bulge produced by the piston oscillation. The time difference between the bulge arriving at each gauge allowed the bulge speed to be calculated.

## 3. Results

### *3.1. Static inflation shape*

For various tube and cell pressures, figure 5 compares measured cell chord lengths with those obtained from the static theory above. Values of θ are calculated using equation 7 from the measured inflation pressures.

Agreement is seen to be satisfactory; the coefficient of determination ($R^2$) value between experimental values and theory is 0.97.

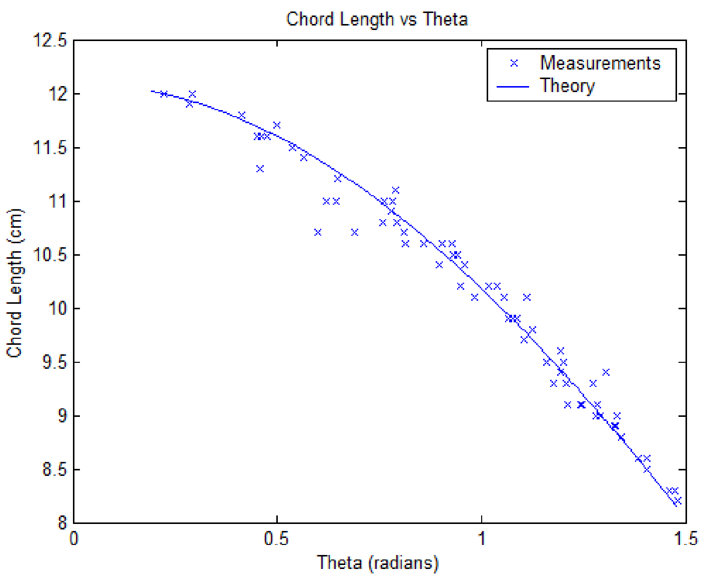


*Fig. 5. Chord length measured from modelled during the inflation of a model Fabriconda compared to the value predicted by theory.*

### *3.2. Bulge speed simulations and measurements*

Figure 6 shows an example output from the strain gauge pairs attached to a cell of the model Fabriconda as a bulge wave generated by a piston oscillation propagates along the tube. Two speeds were measured by identifying the time difference between the two sets of equivalent points indicated in figure 6, the trough and the peak of the pressure bulge. The outputs used are from the 1st and 7th gauges as these provided the data sets that covered the longest available interval, 4.5m. Specific measurement points for the 9th gauge could often not be obtained owing to strong reflections from the tube end.

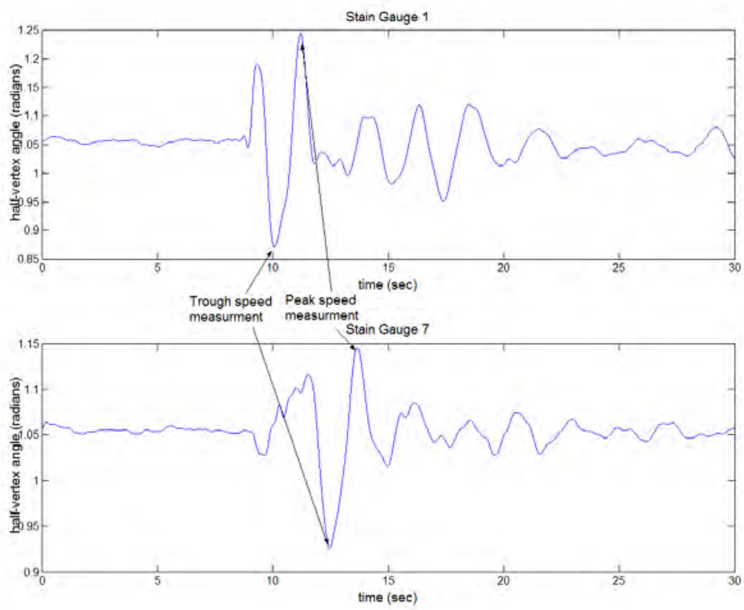


*Fig. 6. Example gauge output showing free bulge propagation when $p_t$ = 25.7m and $p_c$ = 82.7m*

Measurements of bulge speeds were made for a constant cell pressure at a head of 82.7cm, with tube pressures between a head of 4.2 cm and 39.0cm. The 1D finite difference model was used to provide predictions of how the speed of the free bulge propagation changed in this pressure regime. Figure 7 shows the results of these simulations and the experimental results found from the two pairs of points indicated in figure 6.

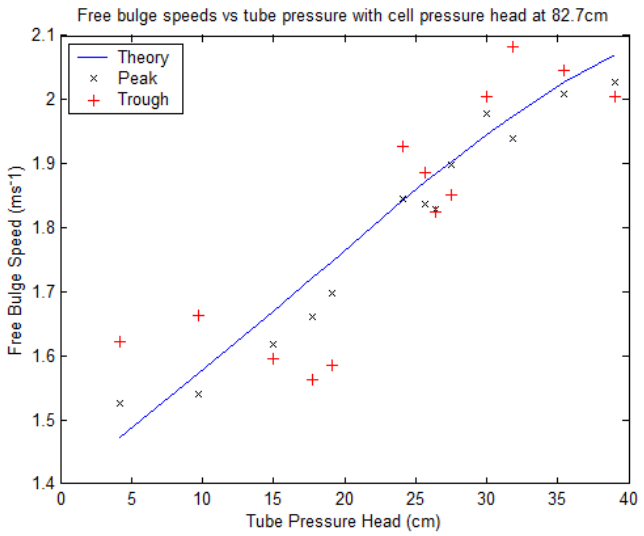


*Fig. 7. Simulated and measured free bulge speed vs. tube pressure at a constant cell pressure.*

## 4. Discussion

The results of the stationary inflation experiments (fig. 4) show good agreement between measured values and those predicted by theory. The theory assumes that the Fabriconda is fully submerged, which was the case during experimental measurements. An actual Fabriconda will actually be partially floating on the surface and bending in the vertical plane, potentially leading to distortions away from the symmetrical shape assumed in a similar fashion to that reported for floating cylindrical containers [6]. However the impact of this is likely to be small since changes in elevation along the device would be much less than the internal pressure head.

Measurements of the speed of bulge waves generated by an externally driven piston at one end of the tube show a good correlation with those predicted from numerical simulations, especially with respect to the propagation of the peaks in the strain gauge signals. These correspond to peaks in the half-vertex angle of the cell and correspondingly a trough in the bulge wave as the overall Fabriconda cross-section area reaches a minimum. The bulge speeds predicted by simulation in the tube pressure region investigated ranged from 1.47 $ms^{-1}$ to 2.07 $ms^{-1}$. It is predicted that greater tube pressures should result in higher bulge speeds. Further experimentation is planned for these higher pressures.

## 5. Conclusion

This paper has introduced the concept of the Fabriconda, a distensible tube attenuating wave energy converter made from inelastic fabric. A theory for the static shape of the device has been presented along with experimental confirmation of its predictions. One-dimensional linear finite difference modelling suggests that the Fabriconda can be tuned to a wide range of different bulge speeds, and experimental results seem to confirm these predictions over a limited pressure range. Future work will measure experimentally the propagation speed of a free bulge wave versus both tube and cell pressure at higher pressure combinations before numerical and experimental measurements are made of Fabriconda capture width and bandwidth.

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