Prototype support structure for seabed mounted tidal current turbines

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Abstract: This paper introduces the patented concept of the Sea Snail, a pin-jointed tubular steel structure carrying an array of symmetrical section hydrofoils, which is used as a means of fixing a tidal turbine, or other devices, to the seabed. The concept is evaluated as a simple mathematical model, tested as a one-eighth-scale model and subsequently developed into a 21 t model fit for sea trials. Pressure differences created by the flow over the upper and lower surfaces of the hydrofoils generate negative lift, or downforce, which is communicated to the supporting structure. The effects of induced drag on low-aspect-ratio hydrofoils are discussed. This paper gives an overview of the evaluative techniques employed in the Sea Snail's concept and design. The need for the device is outlined and its conceptual basis discussed. In particular, the response of a hydrofoil to increasing angles of attack within a steady flow is examined. Field measurements of the drag and lift forces applied to an NACA0013 section hydrofoil is presented in the context of the Sea Snail. The fundamental design criteria are discussed and the Sea Snail's ability to match these criteria is demonstrated.

Keywords: tidal current turbines, Sea Snail, hydrofoils

1 INTRODUCTION

Tidal currents offer a considerable source of sustainable energy at many sites throughout the world, usually within easy reach of land and in relatively shallow waters. Tidal forces are generated by gravitational and centrifugal forces in the Earth–Moon–Sun system [**1**]. The flows associated with tidal influences are modified by a number of factors including the Coriolis force owing to the Earth's rotation, local topography, atmospheric pressure and temperature, and salinity gradients [**2**]. As well as the power density, the advantage of using the tides for power generation is their regularity, which can be predicted for years in advance.

The most rapid flows tend to occur in areas of restriction, by either width or depth [**3**]. Many of these areas, however, may not be suitable for commercial exploitation by large fixed devices, which require a minimum rotor area and therefore water depth, to justify the costs of installation and maintenance.

Tidal stream energy is, at the point of extraction, an energy-dense renewable resource. In principle, its exploitation is relatively simple, but there are the linked problems of installation, maintenance, and decommissioning.

Any tidal current energy conversion system needs to be secured against drag forces applied to the system and its support structure. Attaching machinery to the seabed is a difficult task and may involve drilling and/or piling with the associated disturbance to the benthic flora and fauna. One solution [**3**] requires sockets of 3 m diameter and 6 m depth (or more, depending on the seabed conditions) and, once in place, the turbine support is fixed until it is decommissioned. Another solution [**4**] employs considerable mass to resist the overturning moment induced by the tidal stream. This in turn requires a large vessel to deploy and recover the tidal generator.

Maintenance is difficult in tidal streams; with many sites offering no more than a few minutes of slack water every 6.2 h, the use of divers and/or remotely operated vehicles is not practicable. Recovering the equipment to the surface makes maintenance relatively easy, but installing the machinery to fulfil this infrequent task is expensive.

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Decommissioning of subsea structures is also awkward and costly, as the North Sea oil and gas industry is discovering, especially if the structure is permanently fixed.

Hence, there is a need for an easily deployed, cost-effective structure that can exploit shallow tidal streams with a minimal operational environmental footprint. The Sea Snail concept is an attempt to address these problems and to gather sufficient data to optimize future versions.

The Sea Snail concept has to meet certain design criteria, wherein the following are essential.

1. It must be prevented from moving horizontally by using the downforce that can be generated from a flow stream passing over a symmetrical-section hydrofoil with a given negative angle of attack.
2. It must be capable of passively altering its attitude to accept flows from opposing directions, as is found in many of the smaller sounds around Orkney. A sea trial site will be chosen which offers this type of bidirectional flow.
3. It must generate sufficient downforce at the correct distance to resist the overturning moment created by flow forces acting on the structure and a tidal turbine mounted thereon.
4. It must be cost effective and simple to manufacture, deploy and recover, leaving nothing behind when decommissioned.

2 OPERATIONAL PRINCIPLES OF THE SEA SNAIL

2.1 Hydrofoils

The National Advisory Committee for Aeronautics (NACA)0013 hydrofoils (Fig. 1) proposed for the Sea Snail have an aspect ratio of approximately 0.8 and their geometry is based on the rudder of a sailing craft. As a result, certain aspects of hydrofoil theory require greater emphasis, particularly with regard to lift-induced drag and its minimization. Lift-induced drag is created when there is flow around the hydrofoil tip from the high-pressure side to the low-pressure side. This effect is relatively simple to diminish by the use of end plates at each side of the hydrofoil to inhibit the vortex generation. It does, however, require that the hydrofoil be well aligned with the free stream.

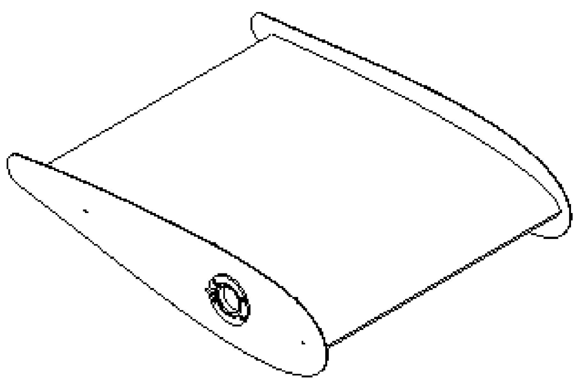

Fig. 1 Sea Snail: hydrofoil assembly showing end plates

The lift and drag forces created by a symmetrical-section hydrofoil structure are a function of the section characteristics, the flow speed, and the angle of attack. In this analysis, and for all marine situations, the flow is assumed fully turbulent.

The drag forces F_D on an object in a moving fluid can be simply expressed in terms of a drag coefficient C_D as

$$F_D = \frac{1}{2} C_D \rho A V_f^2 \qquad (1)$$

As the flow speed increases, so do the overturning moment on the turbine and the lateral forces on the structure. To take account of the lift-induced drag created by the low aspect ratio of the hydrofoils, the initial mathematical model of the forces applied to the hydrofoils assumes, as a reasonable starting point, a C_D of 0.03, compared with 0.01 as given for an NACA0012 aerofoil in reference [**5**]. By initially assuming a relatively high C_D, the model will be pessimistic and thus include a factor of safety until actual data can be recorded.

The Sea Snail concept uses the negative lift forces (downforce) generated by flow around an NACA0013 symmetrical-section hydrofoil, with $\alpha = -15^\circ$. The NACA0013 section is chosen for its low drag profile and ease of fabrication and α is chosen as the mid-point of the values employed in p. 8–4 of reference [**6**] which suggests a hydrodynamic stall for $\alpha = -30^\circ$, whilst reference [**5**] suggests an aerodynamic stall for $\alpha = -15^\circ$. Data for an NACA0012 section has been given in reference [**5**]. The negative lift forces on an individual foil section can be simply described in terms of a lift coefficient as

$$F_L = \frac{1}{2} C_L \rho A V_f^2 \qquad (2)$$

The initial mathematical model of the forces applied to the hydrofoils assumes a C_L of 0.8. This compares with a C_L of 1.6 as given for an NACA0012 aerofoil in reference [**5**] and 0.75 as given for an NACA0015 section rudder without end plates on p. 8–4 of reference [**6**]. Since the low aspect ratio implies that there will be lift-induced drag, then it also implies that the effective lift will be reduced for a given angle of attack.

The hydrofoils are arranged in three pairs (Fig. 2) such that the leading and upper hydrofoil pairs are generating a downforce whilst the trailing hydrofoil pair is assumed redundant. Upon change in flow direction, the trailing foil pair now becomes the lead foil pair and the previous lead foil pair become the trailing foil pair and thereby is assumed redundant. Only the upper hydrofoil pair consistently contributes to the downforce applied to the structure, regardless of flow direction.

2.2 General configuration

The general configuration of the Sea Snail, the essential components of which are the tubular steel frame and the array of hydrofoils, is shown in Figs 2–4. Since the Sea Snail is symmetrical in terms of its length and width, the centres of gravity and buoyancy are at its geometric centre when viewed from above and only change vertically according to its depth of submersion.

The present Sea Snail arrangement uses six hydrofoils mounted on reversing hubs arranged as shown, but further work is required in optimizing the structure and layout of the hydrofoil sets to obtain the best downforce for scale and cost, according to whatever specific site requirements apply. Designed for a bidirectional flow, the Sea Snail can respond to reversals in the tidal stream flow by allowing its hydrofoils to be rotated through 150° by the flow itself. When no flow is present, the hydrofoils, being positively buoyant, align themselves vertically and,

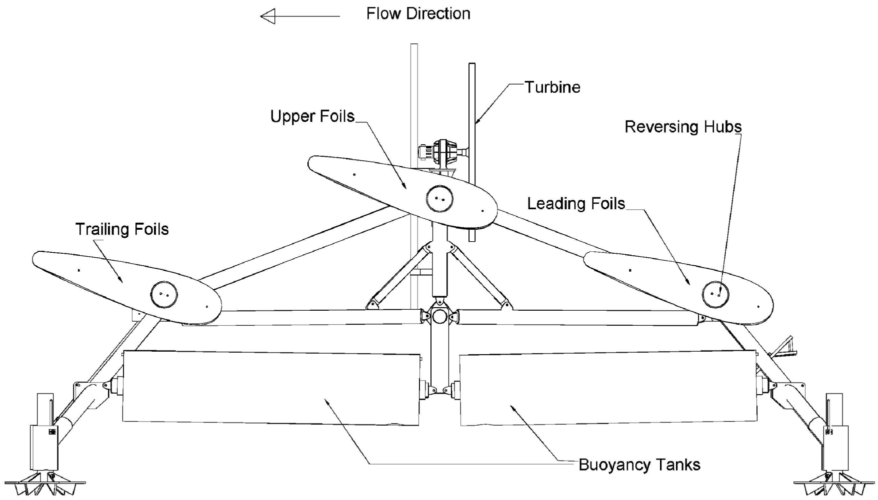

Fig. 2 Sea Snail: side elevation

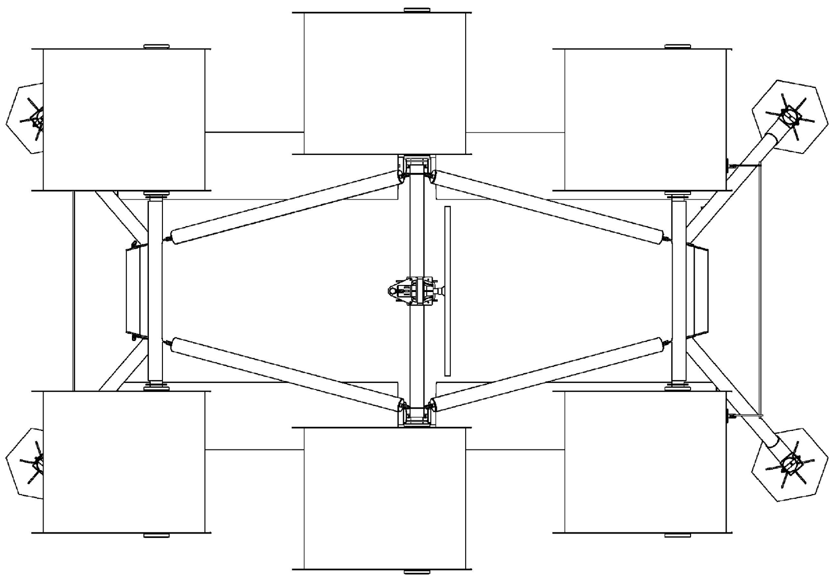

Fig. 3 Sea Snail: plan view

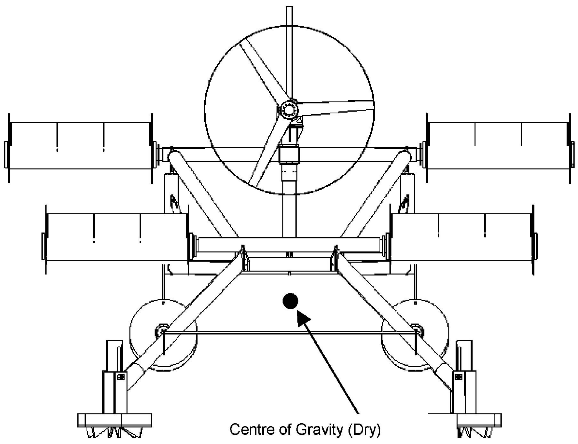

Fig. 4 Sea Snail: front elevation

at flow speeds greater than 0.5 m/s, sufficient force is generated to overcome their inherent buoyancy and force the hydrofoils down on to their stops (Fig. 5).

2.3 Downforce

As the flow speed increases, the hydrofoils begin to generate a downforce from the flow pressure of the stream. The velocity profile of the tidal stream is assumed to correlate with the one-seventh power law [**7**]

$$V_{\mathrm{f}}(z) = 0.85 V_{\mathrm{peak}} \left(\frac{z}{0.32h} \right)^{1/7} \tag{3}$$

where V_{peak} is the surface velocity and h is the overall depth.

From equation (2), the downforce F_{L} applied to each hydrofoil at an assumed flow speed of, say, 3.0 m/s is 23.2 kN.

Recall that it is assumed that this downforce is applicable to the leading and upper hydrofoil pairs only and therefore the total downforce generated is 92.8 kN. The sum of the applied downforce and the Sea Snail's own submerged mass pushes the serrated steel feet into the seabed material (usually bedrock in vigorous streams) and the Sea Snail is thus deterred from moving laterally.

2.4 Overturning moment

The flow of the tidal stream also applies an overturning moment to the structure and its turbine about the rearmost feet. In order to calculate the overturning moment the front elevation view is sliced horizontally to scale such that each slice represents 300 mm on the full-size device (Fig. 6).

With the exception of the hydrofoils and the turbine, both of which act at specific points, any components viewed through each slice are given a drag coefficient based on their section as presented to the flow, e.g. round tubes $C_{\mathrm{D}} = 1$ and the overturning moment is calculated from this.

Summing the moments for all the components in each slice, plus the foil drag moment based on equation (1) and the turbine moment, gives a total overturning moment for the structure in newton metres.

2.5 Restoring moment

If the flow is bilinear at approximately 180° separation, and the Sea Snail is correctly aligned with the flow, the hydrofoils will apply an opposing moment in proportion to the overturning moment. By virtue of their distance from the rearmost feet (12 m), the leading hydrofoils will contribute the greater portion of the opposing moment and the central upper foils (distance from the rearmost feet, 7.5 m) will provide the remainder. For this reason, the effect of the leading and upper foils on the flow over the trailing foils has been neglected at this stage. However, such flow interference would be a major component of any future work to optimize the structure.

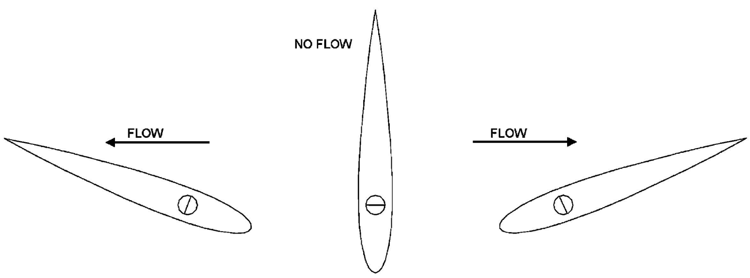

Fig. 5 Foil response to the change in the flow direction

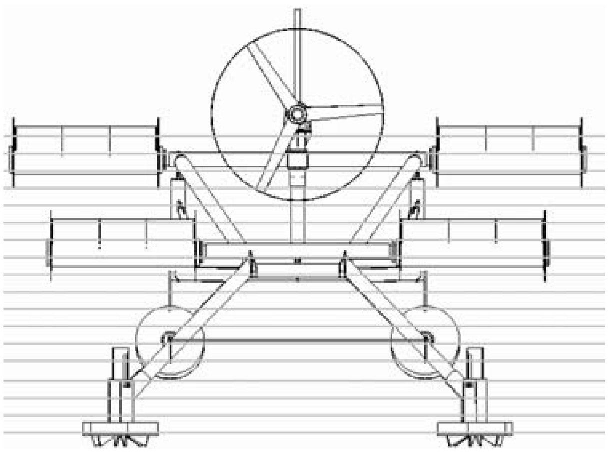

Fig. 6 Method of approximating moments applied to the structure

2.6 Mathematical model

In order to ensure that the concept is valid and that negative hydrodynamic lift can be used to oppose drag on a tidal system, it is necessary to construct a simple mathematical model.

As well as those given in the body of the text, the parameters used for the model are given in Table 1. The device is likely to move when the applied lateral force exceeds the sum of the downforce and the force due to gravity multiplied by the coefficient of static friction μ. The value of μ is not fixed and can vary considerably even for the same materials. Given that value of μ for rock varies from 0.7 to 0.9 and that the Sea Snail's feet are fitted with serrated steel teeth, it is assumed for this project that μ is approximately equal to one. Based on this assumption, the model indicates that, without the downforce, the device as specified would be moved or caused to slip by a flow stream velocity of 2.2 m/s whereas, with the downforce, the device would remain fixed in flow speeds approaching 5 m/s (Fig. 7).

A comparison of the calculated overturning moment (cumulative drag on the structure × H) and the calculated downforce moment (downforce applied to hydrofoils × distance from rearmost feet) indicates the margin of safety from overturning, which can be attributed to the downforce (Fig. 8).

Consequently, the mathematical model shows that a structure can, in principle, be secured within a vigorous flow using designed structure properties and profiles to manipulate the forces inherent in the fluid flow.

Table 1 Base model parameters

Structure	
Mass	13 000 kg
Overall dimensions	10 m wide
	8 m high
	15 m long
Hub Heights	Leading, 3.8 m
	Upper, 5.0 m
C_D (average)	1
C_L	NA
Foils (NACA0013)	
Mass	1200 kg each
Span	2.5 m
Chord	3 m
Hub centre	0.3 × chord
C_D	0.03
C_L	0.8
Environment	
Water depth	<20 m
Density	1025 kg/m^3
Velocity	<4 m/s

NA, not available.

3 EXPERIMENTAL PROCEDURES

The results of the mathematical model require validation by measurement and observation of scale models. Accurate section profiles for NACA four-digit symmetrical foil sections can be created using the equations given in reference [**8**]. The resulting profile is used to fabricate a number of scale foils for field testing. Since the minimization of drag is as important as the maximization of lift, and high-aspect-ratio hydrofoils are not an option because of width restrictions, the NACA0013 section was chosen as giving the best lift–drag ratio for a symmetrical foil section [**5**].

The present Sea Snail configuration has six hydrofoils arranged in two rows of three foils each. The

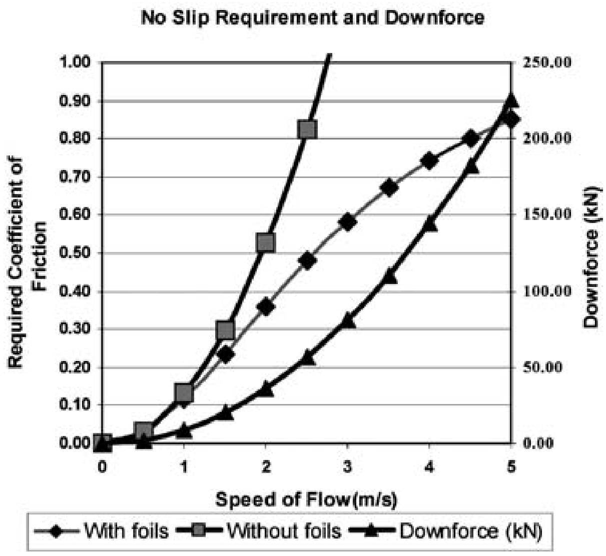

Fig. 7 Comparison of no-slip conditions, with foils and without foils, and downforce

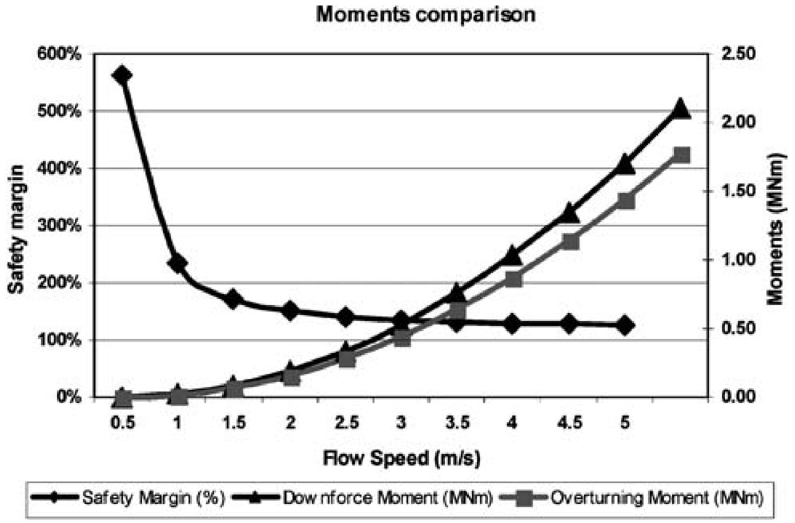

Fig. 8 Comparison of moments (overturning versus downforce)

field test model (Fig. 9) has the same configuration, as well as being equipped with load cells and axial flow meter suitable for field testing in a small river.

3.1 Description of field test model

The hydrofoils (chord, 0.43 m; span, 0.342 m) are supported by and are able to rotate around a steel tubular frame fixed normal to a central plate. A portion of their dry weight is supported by buoyancy forces when the model is submerged. Their angle of attack is controlled by threaded rod supporting the tail of the foil. Thus, the downforce created by the interaction of the hydrofoils with the flow stream is transferred to the longitudinal bar supporting the central plate. This bar is able to rotate about its axis whilst being attached at each end to full-bridge strain gauge load cells, two of which measure the force applied at the front and rear of the bar, whilst a third measures the drag force being applied to the hydrofoil structures. By permitting the complete hydrofoil assembly to rotate about a longitudinal axis, no moment is applied to the load cells. The drag force is minimized by supporting the hydrofoils in such a way that the supporting structure presents as small a frontal area as possible. The end frames are adjustable in height so that a range of stream depths can be accommodated. The field test model carries five transducers, consisting of three full-bridge strain gauges rated to 300 kg each, one PRT100 thermal probe forming the variable resistor in a Wheatstone bridge and a pulse count turbine flow meter. The

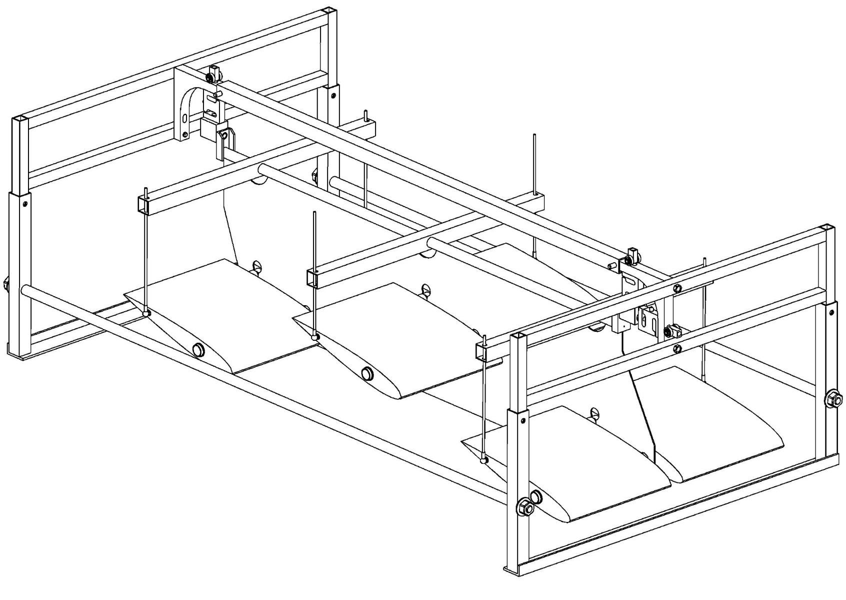

Fig. 9 Field test model

signals are sampled at 20 Hz for 60 s for each increment of 1° in the hydrofoils' attack angle.

Prior to testing, the free-stream velocity is measured upstream of the device and an average value of 0.81 m/s recorded. The device is positioned in the flow with the flow meter immediately upstream and, by allowing sufficient slack in the hydrofoil positioning rods, the foils are allowed to find their own no-lift position within the flow. Since the chord line of a symmetrical-section hydrofoil is coincident with the zero-lift axis, the foil will position itself within the flow at the point of least resistance. Hence, taking this position as zero, it obviates the need to level the device with respect to the flow.

The angle of attack is then increased at degree intervals whilst measurements are taken of the downforce at the front and rear of the device, overall drag on the foil assembly, water flow velocity immediately upstream of the leading foils, and water temperature. The results are plotted in Fig. 10.

3.2 Results and discussion of the field test model

The magnitude of the downforce created is clearly a function of the angle of attack, whilst the corresponding decrease in upstream flow velocity is due to the advancing stagnation point emanating from the leading edge of the leading foils. Based on the planform area of six hydrofoils and a free-stream velocity of 0.81 m/s, the average drag coefficient for the assembly is 0.036, which compares with a tank-testing drag coefficient of 0.01 for an NACA0012 section given on p. 10–2 of reference [**6**]. The overall drag coefficient includes an additional factor, which is created by the vortices at the sides of the foils. This additional drag, which is created by the presence of lift forces, is induced drag and has its own coefficient, additional to the section drag coefficient. The induced drag coefficient C_{Di}, proportional to the square of the section lift coefficient, is given by [**9**]

$$C_{\mathrm{Di}} = \frac{C_{\mathrm{L}}^2}{\pi \,\mathrm{AR}} \tag{4}$$

where AR is the aspect ratio of the foil, given by span²/(foil area), but is not generally applicable to low-aspect-ratio situations, i.e. AR < 4. (For the Sea Snail, AR for the foils equals 0.795.)

Suffice it to say that, since the additional induced drag is included in the measured drag force, its effect is already accounted for.

The measured drag also includes a small contribution from the drag on the structure supporting the foils, whilst the measured lift force is not distorted by this flow. From theory, the lift coefficient of a foil section in an incompressible flow is proportional to $\sin(\alpha)$, which for small values of α means that the lift coefficient is proportional to α. The field test model data is in agreement with theory, and the lift and drag coefficients at $\alpha = -15°$ are 0.66 and 0.09 respectively (Fig. 11), with a Reynolds number Re of 3×10^5. Both C_{L} and C_{D} are based on the full planform area, as is the accepted practice for aerofoils (see p. 357 of reference [**10**]). In the case of a streamlined body or hydrofoil, the form or pressure drag can be assumed to be independent of Reynolds number, provided that $Re > 10^5$ [**11**].

The values of C_{L} and C_{D} for the hydrofoils are fed back into the initial mathematical model to ascertain that the original assumptions were reasonable. Whilst the values for the lift coefficient gave good agreement, the drag coefficient was three times that expected.

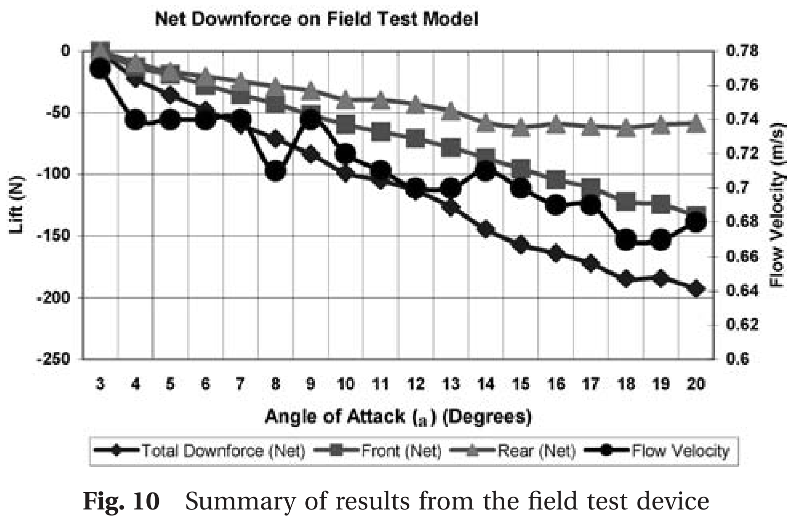

Fig. 10 Summary of results from the field test device

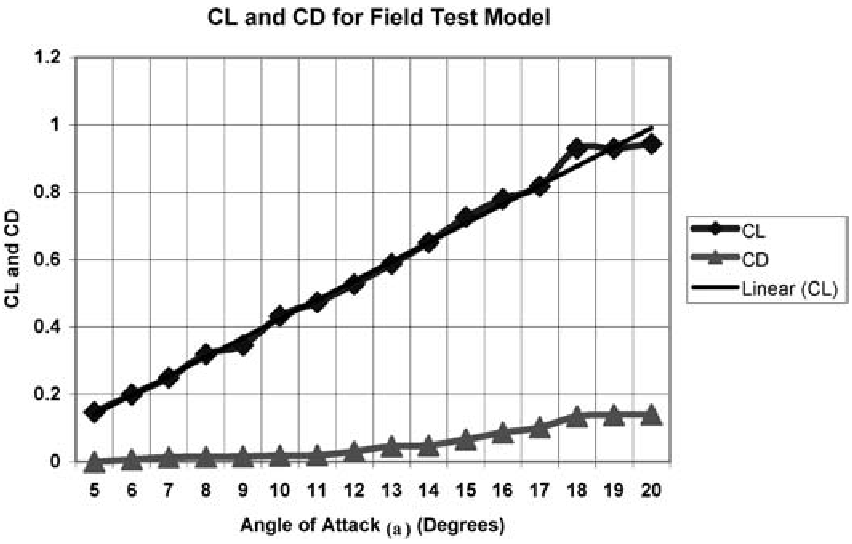

Fig. 11 Lift and drag coefficients for the field test model

4 FULL-SIZE DESIGN CONSIDERATIONS

Having established that the concept of using hydrofoils to secure a device against a vigorous flow stream is reasonable, there remain the tasks of fabrication, transport, assembly, deployment, and recovery of a device suitable for sea trials.

4.1 Fabrication

Since the device will be operating in a public place, it will need to be insured against third-party risks at least, and any potential insurer will require that the structure be reasonably fit for purpose. Yet, no formal standard exists for the structural integrity and fabrication of tidal stream devices; therefore a reasonable equivalent is required for guidance. The standard chosen, given in reference [**12**], incorporates much of the experience gained in the construction of offshore structures used in the North Sea and is therefore applicable to Scottish waters. In order to minimize fabrication costs, the structure primarily utilizes one size of tubular mild steel (273 mm × 8 mm; circular hollow section) and flat-plate profiles of 20 mm thickness, fillet welded together. Further cost reduction is achieved by minimization of machining operations which require a high level of accuracy.

The current Sea Snail design incorporates a pin-jointed tubular steel frame (the illustrative details are given in Fig. 12) carrying hydrofoils with skins of glass-reinforced-polyester (GRP) mounted on steel rib assemblies (Fig. 13).

The foil skins are moulded in two symmetrical halves from GRP 10 mm thick. The skins are then positioned around the steel rib structure and bonded together. The resulting cavity is filled with expanded polyurethane foam which bonds the GRP skins and transmits the surface forces evenly to the steelwork. In order to minimize the induced drag, the foil sides are fitted with plywood side plates to reduce the vortices created by pressure differences on the upper and lower surfaces. The hydrofoils have a displacement of 1.765 m^3 and a mass of 1003 kg, giving a net buoyancy force of 7.9 kN each.

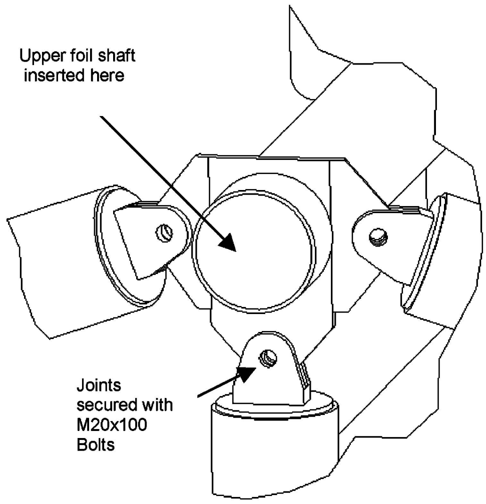

Fig. 12 Detail of the pin-jointed structure (top central frame)

4.2 Transport

The pin-jointed tubular steel approach means that the entire structure can be dismantled and carried on two standard articulated lorry trailers permitting easy transport to site and the operational device can

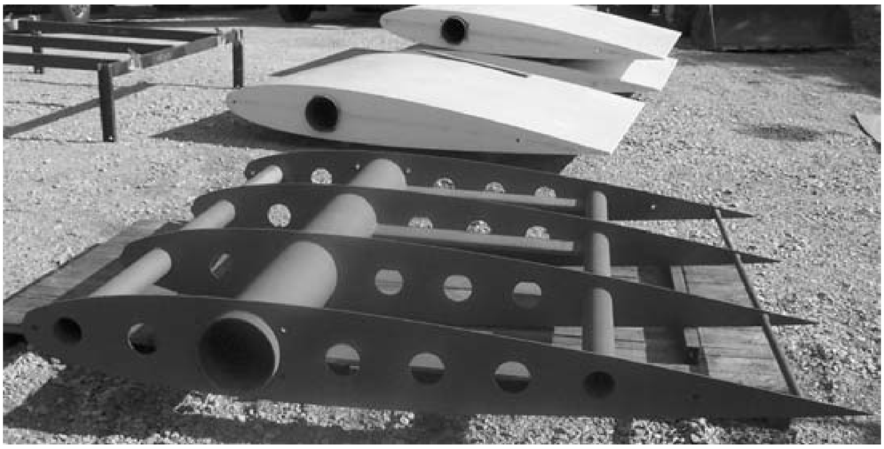

Fig. 13 Foil rib assembly with completed foils behind

be assembled by a team of three people and a road-going crane in three days. This style of structure also lends itself to mass production and scaling if required.

4.3 Deployment and recovery

For towing to the site, the structure's surface behaviour is important, and so the surface stability and metacentric height of the Sea Snail have been modelled on the basis of the dimensions shown in Fig. 14. If Beaufort scale force 4 is taken as the maximum sea state likely for launching, it will remain upright in the expected towing conditions. The centres of gravity, buoyancy, and metacentric height undergo maximum change vertically when the Sea Snail is fully submerged, owing to the inherent buoyancy of the six hydrofoils.

The four toroidal-section buoyancy tanks, with a displacement of 5.65 m^3 each, generating a total buoyancy force of 208 kN to support the 196 kN device, are used to float the Sea Snail to its launch site, whereupon the tanks are flooded and the device descends to the seabed in a controlled sink. A small computer algorithm was written to model the sinking characteristics and, taking into account the buoyancy and drag forces applied to the structure as it descends through the water column, it will impact the seabed at a terminal velocity of 1.845 m/s. With a large proportion of the submerged mass being in the feet, and a similarly large proportion of the submerged buoyancy being in the hydrofoils, the momentum force transmitted to the structure is minimized, and therefore the rate of descent is not expected to create any problems for the structure.

The structure has a dry mass of 21 t and a submerged mass of 8 t including the buoyancy of the foils and other components. With $\alpha = -15^\circ$ corresponding to a coefficient of lift of 0.66, and stream flow speeds of, say, 3.0 m/s, the downforce from the

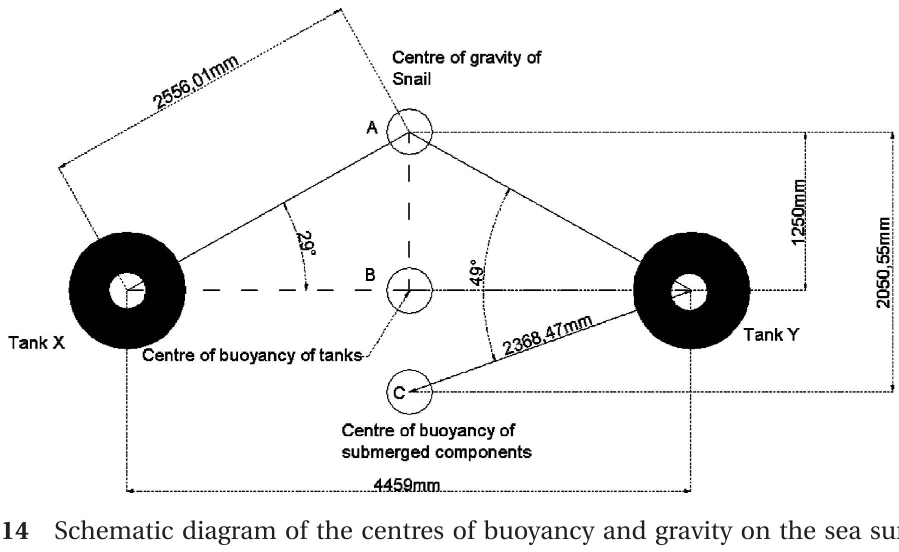

Fig. 14 Schematic diagram of the centres of buoyancy and gravity on the sea surface

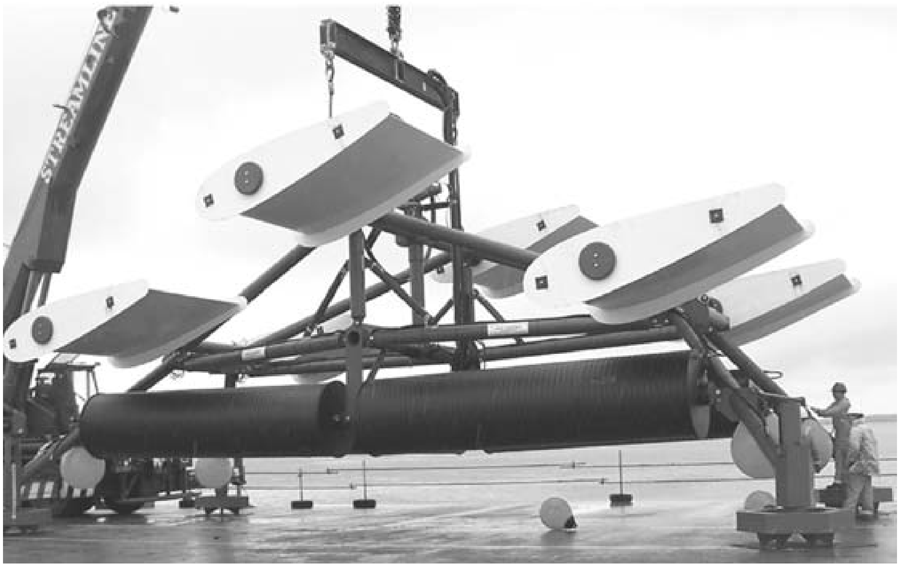

Fig. 15 The assembled Sea Snail readied for launch in Orkney

hydrofoils will induce a distributed load on the complete structure which equates to the addition of a mass of 10.0 t to the structure. The flow speed implies a Reynolds number of 5.4×10^6, which clearly does not agree with the Reynolds number obtained for the field test model. However, lift and drag coefficients at high Reynolds numbers depend primarily on the section profile (see p. 359 of reference [**10**]) and, since both flow regimes are clearly fully turbulent, the linear correlation of α and C_L for the field test model gives reasonable confidence that the full-size device (Fig. 15) will behave in a similar manner.

Recovery will be the reversal of sinking; blowing the buoyancy tanks with compressed air will refloat the Sea Snail back to the surface for recovery.

5 CONCLUSION

Whilst the original concept for the Sea Snail was as a base for a marine energy converter, it has developed as a free-standing self-securing structure, potentially capable of carrying a variety of payloads in a vigorous flow stream. The limited resources of the project made detailed upfront analysis impossible, and the device as is should be thought of as a large early-stage laboratory model rather than an advanced prototype. Whilst the downforce applied to the foils is proportional to the square of the flow speed, the lift-induced drag forces on the foils are proportional to the square of the downforce and are relatively small compared with the drag forces applied to the structure. However, the drag forces applied to the structure are also related to the downforce via the flow velocity but the structure has a higher overall C_D than the hydrofoils. Therefore, the limiting factor is when the drag force applied to the structure exceeds the downforce generated by the hydrofoils, which, in this case, should occur at a free-stream velocity of approximately 5 m/s. The present device is instrumented for measurement of applied forces and it is expected that these data will lead to considerable refinements in the next development stage. Although experiments are under way to utilize the concept within multidirectional flows, the device as built is designed only for sites offering predominantly bidirectional flows. The Sea Snail has just completed successful sea trials and will be further deployed in late 2005.

ACKNOWLEDGEMENTS

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APPENDIX

Notation

A	area perpendicular to flow (m^2)
AR	aspect ratio (dimensionless)
C_D	drag coefficient (dimensionless)
C_L	lift coefficient (dimensionless)
F_D	drag force (N)
F_L	lift force (N)
GRP	glass-reinforced polyester
h	water depth (m)
H	height above seabed (m)
NACA	National Advisory Committee for Aeronautics (pre-NASA)
V_f	velocity (fluid flow) (m/s)
$V_f(z)$	velocity as function of depth (m/s)
z	vertical depth (m)
α	angle of attack (deg)
μ	coefficient of static friction (dimensionless)
ρ	fluid density (kg/m^3)