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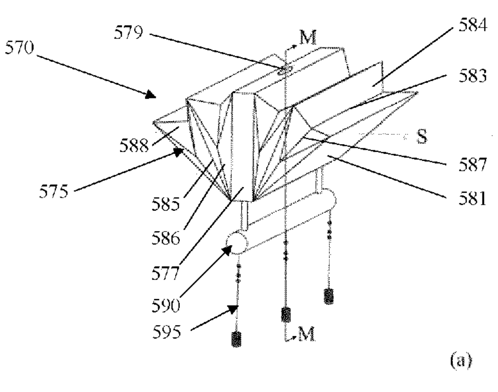

(a)

Figure 10

(57) Abstract: A wave energy converter is provided and comprises a vessel configured for alternative expansion and contraction. The vessel comprises two rigid panels configured for relative movement with respect to each other, and one or more pleated portions provided between the panels, in which the or each pleated portion has a polyhedral structure.

WAVE ENERGY CONVERTER

The present invention relates generally to the derivation of energy from natural sources and particularly to a wave energy converter (WEC).

Wave energy converters are devices that convert the kinetic and potential energy associated with moving waves into useful mechanical or electrical energy.

Introduction

Many energy conversion concepts have been proposed to capture power from waves, most of which are composed of rigid floats. Beyond these traditional rigid float-based wave energy converters, a flexible deformable body can work as a WEC. One such type of WEC is a floating clam-type wave energy converter. This heaving deformable body can be smaller and cheaper than a heaving rigid body due to its lower hydrostatic stiffness.

The first clam-type WEC concept was proposed and patented by Francis Farley [2] as shown in Figure 1 and with the following features labelled: 1 main vessel, 2 side faces, 3 rigid ribs, 4 flexible joints, 5 ballast, 6 mooring lines, 7 sea level, 8 interconnection, 9 fabric, 10 auxiliary vessel, 11 support, 12 air turbine.

This is a floating device comprising two or more pressure vessels 1 and 10 interconnected by an air turbine 12 for power take-off (PTO). The main vessel 1 had a V-shape composed of two rigid side plates connected by a hinge 4 at the bottom and flexible airtight fabric 9 on the top. During operation, it is inflated and pressurised with air or other gas. Under wave action, the main vessel 1 oscillates both vertically in heave and in clam action whereby the side plates of the device rotate in and out at the hinge. The varying hydrostatic pressure exerted on the side plates 2 causes the main vessel to contract and expand, driving the gas into and out of the auxiliary vessel 10. Therefore, energy carried by the waves is converted into the pneumatic energy of gas flowing through the air turbine connecting the vessels. The device is kept upright due to the ballast 5 underneath the main vessel.

Although conceptually viable from a hydrodynamics perspective, Farley's clam-type WEC is not structurally valid as the airtight fabric cannot support any load on its top.

Several simplified models have since been constructed, and preliminary investigations were conducted by Phillips [3] to understand the wave-structure interactions of a device at the

COAST laboratory, University of Plymouth. These simplified models used a hydraulic ram as the PTO. They were not enclosed and hence seawater could be trapped in the device.

Summary of Invention

The present invention seeks to provide the engineering designs of origami-inspired heaving deformable outer shell of WECs that can host multiple means of power take-off (PTO)

Aspects and embodiments of the present invention provide or related to a wave energy converter.

An aspect of the present invention provides a wave energy converter comprising a vessel configured for alternating expansion and contraction. The vessel comprises two rigid members (e.g. panels, plates, boards or the like), movable movement with respect to each other, along with, walls, sheets or layers positioned therebetween. The said walls, sheets, or layers may comprise or consist of a polyhedral structure or shape.

The wall, sheet, layer or the like may, for example, be a pleated portion comprising an elastic membrane and rigid facets with a polyhedral shape. They may be formed by interconnected plates.

An aspect of the present invention provides a wave energy converter comprising a vessel configured for alternative expansion and contraction, the vessel comprises two rigid panels configured for relative movement with respect to each other, and a pleated portion provided between the panels, in which the pleated portion has a polyhedral structure.

An aspect of the present invention provides a wave energy converter comprising a vessel configured for alternative expansion and contraction, the vessel comprises two rigid panels configured for relative movement with respect to each other, and a pleated portion (or a plurality of pleated and/or folded portions) between the panels, which has or comprises a polyhedral structure.

The panels may be joined by a hinge and the panels may approach and separate under interaction with waves. The hinge may be a rotational hinge (like a piano hinge) or a living hinge. In some embodiments the material from which a hinge is formed may contribute to water-tightness.

The converter may be clam-like.

The converter may comprise one or more pleated origami sections, each providing one or more polyhedral pleats. Some embodiments comprise two substantially identical pleated origami sections.

The or each pleated origami section may, for example, have two planes of symmetry.

The or each pleated origami section may have one or more mountain folds and/or one or more valley folds.

The or each section may have one or more oblique folds.

The converter may comprise one or more top pleats.

A pleated portion may have a crease pattern comprising one or more substantially triangular portions.

In some embodiments a pleated membrane is in a slack state in the folded state.

In some embodiments the vessel is enclosed. A chimney may, for example, be provided for venting if required.

In some embodiments the vessel is watertight.

Some embodiments comprise a watertight inner layer (a pleated waterproof bag) and an outer structural layer comprising plates (to bear the force). The outer plates may, for example, be joined by hinges.

A pleated structure may consist of elastic membranes and rigid plates. The membrane may be formed as a single piece, or multiple pieces may be provided.

In some embodiments the membrane is under strain during expansion and contraction. The strain may be minimised by design.

The elastic membrane may be strained in tension and may be slack under compression.

Some embodiments comprise dimensions exactly, approximately or substantially as specified in Table 1, Table 2 or Table 3.

The present invention provides an origami-inspired wave energy converter, substantially as hereinbefore described with reference to and as shown in the accompanying drawings.

In some embodiments the vessel is formed as an outer shell to host PTO means.

The present invention also provides a converter further comprising power take-off (PTO) means.

The present invention can be adapted for various types of PTO. Different structural designs may be configured or adapted for various types of PTO.

Examples of power take-off means include one or more of: pneumatic PTO (e.g. an air turbines), a mechanical linear generator, air springs, di-electric elastomer generator (DEG), di-electric fluid generator (DFG).

In some embodiments, a portion of wave energy is consumed to deform the outer shell of the pleated origami model and the rest is captured by the PTO.

In some embodiments the pleated portion has a plurality of facets.

In some embodiments a membrane is configured to minimise the strain on its facets while achieving the largest volumetric change of the device to maximise the power extraction by the PTO.

In some embodiments energy is generated through stretching and/or bending of facets which are placed within the origami outer shell.

In some embodiments the geometry of origami design is configured such that the strain in certain facets that are placed within the outer shell is maximised.

In some embodiments the geometry of origami design is configured such that hinge length is maximised.

In some embodiments the geometry of origami design is configured such that the area of the rigid plates is maximised for structural integrity.

Some embodiments provide or relate to an enclosed outer shell of a main vessel which is suitable for use in the marine environment.

Since an enclosed flexible polyhedral structure cannot change its volume without bending or stretching of facets according to the bellows conjecture [4, 5], the pleated origami model must be strained when it is in motion. In some embodiments a portion of the wave energy will be consumed to deform the outer shell of the device and the rest can be captured by the PTO.

The design of some embodiments of the pleated origami model may minimise the strain on its facets while achieving the largest swept angle change of the device to maximise the power extraction by the PTO.

In some PTO arrangements, e.g., the DEG or DFG, where energy is generated through stretching or bending of the facets, the geometry of the origami WEC may be configured such that the strain in certain facets that are placed within the WEC is maximised.

In further PTO arrangements, such as mechanical linear generators, air springs and air turbines, where energy is not generated through bending or stretching of the material, the design of the origami model in terms of such PTO arrangements shall aim to minimise the strain on its elastic membrane in order to maximise power extraction by the PTO.

An origami-inspired, enclosed heaving deformable offshore wave energy device may be constructed by connecting rigid panels and elastic membranes with rotational hinges, the rigid panels rotate about the hinges without facet deformation and allow stretching on elastic membranes, the strain on the elastic material shall be minimised for better structural integrity and minimal energy loss. The device has optimised geometry,

An aspect of the present invention provides an origami-inspired wave energy converter, which is a floating device comprising two side plates connected by a hinge that closes and opens under interaction with wave crests and troughs.

A linear power take-off (PTO) may be installed between the two side plates to convert the mechanical motions to electricity, or the volume change may be used to pump air between chambers and across an air turbine PTO.

Some aspects and embodiments provide or relate to an origami-inspired heaving deformable wave energy converter.

Some aspects and embodiments are based on an origami principle.

Some embodiments comprise an enclosed origami-inspired offshore device constructed by connecting rigid panels and elastic membranes with rotational hinges.

The rigid panels may rotate about the hinges without facet deformation and may allow stretching of elastic membranes. Strain in the elastic material can be minimised to improve structural integrity and minimise energy loss. Satisfying all the design requirements, the best geometric design may be obtained through an optimisation process.

Different embodiments can be designed with different strains for PTO arrangements such as mechanical actuator, air spring, air turbine, etc.

The optimisation methodology can, for example, be applied if DEG is used as the PTO and the strain on some facets is to be maximised instead.

Embodiments of the present invention provide or relate to the structural design of a flexible main vessel of a floating heaving deformable device that is responsive to wave motion. The main vessel may be constructed by plates with low elasticity such as CFRP and elastic membranes with higher elasticity such as reinforced rubber.

During the expanding and contracting motions of the main vessel, the plates may be allowed to rotate about hinges while minimum stretching of the faces of the plates is achieved.

Some embodiments possess open top channels for sea water to escape and also place minimal strain on the elastic facets during the flexing motion of the main vessel. However, its geometry cannot be folded from a flat piece of material, making it rather challenging for waterproofing.

The geometry of some embodiments can be folded from a flat piece of material. Two thin layers of waterproof material can be folded into the geometry and glued to the inner and outer surfaces of the main vessel, respectively. However, top pleats of some embodiments may form small reservoirs, which prevent trapped sea water from escaping easily.

Some embodiments possess open channels on top pleats.

Some embodiments can be folded from a flat piece of material for waterproofing. It may experience slightly larger strain on the elastic facets than other embodiments when the main vessel is expanding and contracting.

The outer shell of the device may be contracted and sink to seabed and thus suitable for use in the (adverse) marine environment.

A further aspect provides a wave energy converter comprising an origami-inspired vessel configured for alternative expansion and contraction under heaving motion, the vessel comprises two rigid side panels configured for relative movement with respect to each other, and a pleated structure provided between the panels, the pleated structure comprises top pleats and opposed end pleats.

Pleats may, for example, comprises one or more mountain and/or valley creases.

End pleats may, for example, be multi-faceted. Some facets may be rigid; some facets may be elastic.

In some embodiments a central frame may be required. A chimney may be provided in/or/by the frame.

A ballast system may be provided.

Mooring lines may be provided.

WECs formed in accordance with the present invention may used in conjunction with other forms of renewable energy converters, such as solar and/or wind. An origami-inspired WEC could, for example, be used to take energy out of wavefronts that could otherwise disturb a floating wind converter.

Aspects and embodiments of the present invention may be or form part of a deployable offshore structure.

The origami WEC could be used in conjunction with breakwater devices to absorb excess wave energy and protect offshore equipment or coastal defences.

WECs formed in accordance with the present invention could, for example, be used for large-scale energy production (e.g. for input into the grid), or smaller scale production for small and island populations.

Different aspects and embodiments of the invention may be used separately or together.

Further particular and preferred aspects of the present invention are set out in the accompanying independent and dependent claims. Features of the dependent claims may be combined with the features of the independent claims as appropriate, and in combinations other than those explicitly set out in the claims.

Description

The present invention will now be more particularly described, by way of example, with reference to the accompanying drawings, in which:

Figure 1. The Clam WEC proposed by Farley [2].

Figure 2. Main vessel design 1.

Figure 3. Contracted main vessel design 1.

Figure 4. Main vessel design 2.

Figure 5. Crease pattern of main vessel design 2.

Figure 6. Connecting two pleated origami sections on each side of the central frame for design 2.

Figure 7. Main vessel design 3.

Figure 8. Crease pattern of main vessel design 3.

Figure 9. A physical prototype made of plywood showing the contraction and expansion of the origami-inspired main vessel in its (a) fully expanded state, (b) equilibrium state, and (c) fully contracted state.

Figure 10. The full assembly of an origami-WEC design in (a) expanded and (b) contracted states.

The example embodiments are described in sufficient detail to enable those of ordinary skill in the art to embody and implement the systems and processes herein described. It is important to understand that embodiments can be provided in many alternate forms and should not be construed as limited to the examples set forth herein.

Accordingly, while embodiment can be modified in various ways and take on various alternative forms, specific embodiments are described in detail below only as examples. There is no intent to limit to the particular forms disclosed. On the contrary, all modifications, equivalents, and alternatives falling within the scope of the appended claims should be included.

Unless otherwise defined, all terms (including technical and scientific terms) used herein are to be interpreted as is customary in the art. It will be further understood that terms in common usage should also be interpreted as is customary in the relevant art and not in an idealized or overly formal sense unless expressly so defined herein.

Origami Model Design

Embodiments of the present invention relate to a floating device that extracts wave energy from the sea. Based on a clam concept originally proposed by F. Farley, three origami-inspired structural designs of the enclosed main vessel are described.

Minimal strain design

The main vessel is a deployable structure.

Figure 2 illustrates one embodiment, in which Figure 2 *a*) shows the main vessel in isometric view and a cross-sectional view of XX, whereas Figure 2(*b*) shows top, front, and side views of the vessel which consists of two identical pleated origami sections 100 that are connected to a central rigid frame 102. A central rigid frame connects the ballast 5 at the bottom of the main vessel (Figure 1).

Further, each pleated origami section 100 is designed with two planes of symmetry. It is attached to a side face 101, which can be constructed from rigid panels such as carbon fibre reinforced composites (CFRP) or plywood. Connecting the rigid side panel to the central frame, two identical trapezoidal shaped sheets 103 are used as top pleats and four abstruse triangular sheets 104 are used on two sides. These can also be manufactured from rigid materials such as CFRP or plywood. Another four identical triangular sheets 105 connect 104 with 103 and can be manufactured from reinforced rubber which is elastic and allows greater facet deformation when under strain. The elastic surface is only strained in tension whereas it is slack under compression. The planar strain ε is characterised as the root mean square of the tensile strain components in two orthogonal directions at the surface.

Further, we define θ_1 to be the swept angle of one pleated origami section 100. The connections between any two panels or sheets can be rotational hinges such as piano hinges or door hinges. The panels or sheets rotate about the hinges to decrease or increase angle θ with minimum planar strain on the rubber sheets.

The width w and the height h of the pleated origami section can be determined based on hydrodynamic requirements. Here, $w = 40m$ and $h = 20m$ are adopted. The other dimensions are calculated to minimise the strain on the rubber sheets during the contraction and expansion of the pleated origami section.

Table 1 lists two sets of dimensions that are calculated for a maximum θ_1 of 40° and 60°. The former operational range of motion θ_1 of one pleated origami section can range from 0° to 40°, resulting an 80° swept angle for main vessel design 1, whereas the swept angle of the main vessel for the latter is 120°. The maximum planar strains on the elastic triangular sheet 105 during their full range of motion are 1.27% and 1.78%, respectively.

The swept angle of the main vessel oscillates in heave motion, when interacting with waves that cause the hydrostatic pressure on the side plates to vary 101. At the wave crest, the main vessel contracts when the hydrostatic pressure increases and θ_1 decreases.

An example is illustrated in Figure 3. At the wave trough, the main vessel expands as the hydrostatic pressure decreases and θ_1 increases.

When an air turbine is used as the PTO, the volume of the main vessel compresses or expands as the side plates interact with wave crests and troughs, allowing gas to exchange between the vessels. When hydraulic ram or linear generators are used as the means of PTO, energy is captured when the swept angle of the device changes.

Table 1: Dimensions for minimal strain design

	$0 \leq \theta_1 \leq 40°$	$0 \leq \theta_1 \leq 60°$
$\angle A_1O_1C_1 = \angle A_1O_1D_1$	22.5°	30°
$\angle B_1A_1C_1 = \angle B_1D_1C_1$	44°	28.09°
B_1F_1	80% *w*	90% *w*
$A_1B_1 = B_1D_1$	21.57% *w*	26.48% *w*
O_1C_1	42.02% *h*	40% *h*
$A_1C_1 = C_1D_1$	63.26% *h*	68.35% *h*

In terms of adverse weather conditions such as storm and extreme waves, the device can adopt a survivability mode. The angle θ_1 can turn to close-to-zero degrees and sink underwater without bending or stretching of the elastic sheets because they are slack when in the fully folded state.

The advantage of design 1 is the low strain during expansion and contraction processes affecting the main vessel. However, more effort is required to make the vessel water-tight at the connections between plates.

To make the main vessel water-tight, one way is to seal all rotational hinges with a waterproof material such as rubber. However, excess rubbery material at the hinges or corners may interfere with the motion of the device. Another way is to fold a thin layer of waterproof material such as a thin plastic sheet into the same geometry of the main vessel and adhere it to the inner side of the vessel. Since the geometry of design 1 cannot be manufactured as a deployable surface, i.e., a planar surface, due to the saddle geometry at points B and F in Figure 2, its hinges and corners need to be sealed carefully. In the next section, two developable designs are presented.

Designs for water tightness

Figure 4 is an example of the developable design of main vessel 2 formed according to a further embodiment. Figure(*a*) shows an isometric view and a cross-sectional view of YY, whereas Figure(*b*) shows top, front, and side views of the vessel.

The vessel contains a central frame 202 with the same dimension as that of 102. Two identical pleated origami sections 200 are attached to each side of the central frame. Each pleated origami section 200 is designed with two planes of symmetry, and is attached to a side panel 201, which can be formed from rigid panels using carbon fibre reinforced composites (CFRP) or plywood. Connecting the rigid side panel to the central frame, two identical trapezoidal-shaped sheets 203 are used as top pleats and four abstruse triangular sheets 204 are used for the sides. These sheets can also be manufactured from rigid materials such as CFRP or plywood. Unlike the minimal strain design which creates a saddle geometry at connections between the top pleats and the side folds, the watertight design 2 makes four consecutive folds to connect its top pleats and the side facets. At each corner, two identical triangular plates 205 connect the edges of 203 and 204. Finally, the plates are connected by two elastic sheets 207 which can be manufactured from reinforced rubber and allow greater facet deformation under strain.

A developable design ensures that the folded structure can be created from a flat sheet of material without stretching, tearing, or shearing it. During the construction of a physical model, two thin layers of waterproof material, such as plastic sheets, can be folded into the main vessel geometry as shown in Figure 4, following the crease pattern in Figure 5. They can be attached to the outside and inside of the main vessel for waterproofing.

The solid lines denote mountain folds, and dotted lines indicate valley folds. At a dot-dash line, we make a 180° valley fold so that the shaded areas coincide with each other. For instance, a valley fold is made along F_2S_2 such that F_2Q_2 meets F_2R_2. Likewise, B_2P_2 meets B_2Q_2 when the flat sheet is folded up. After that, we glue the shaded surfaces such that they are invisible in the 3D model. Vertices P_2, Q_2 and R_2 meet at the same point, denoted O_2 in Figure 4. Readers are encouraged to print the crease pattern on a piece of paper and make a model by themselves.

Again, we define θ_2 to be the swept angle of one pleated origami section 200. The dimensions of the main vessel design 2 can be designed such that the strain on the elastic sheets 207 is small during its range of motion. In one possible design, θ_2 can go from 0° to 30°. Table 2 lists the dimensions of one pleated origami section. The maximum planar strain on the elastic triangular sheet 207 is 5.23% during its full range of motion.

Table 2: Dimensions of design 2.

$A_2G_2 = w$,	F_2R_2 (F_2O_2) $= h$,	$0° \leq \theta_2 \leq 33°$,	$\angle D_2A_2C_2 = 55°$,
$\angle B_2A_2C_2 = 22.5°$,	$E_2K_2 = 64.25\%\ w$,	$C_2D_2 = 15.62\%\ w$,	$A_2B_2 = 23.33\%\ w$,
$A_2C_2 = 16.91\%\ w$,	$B_2C_2 = 10.07\%\ w$,	$B_2P_2 = 35.45\%\ w$.	

Design 2 has a full swept angle of 66° because there are two identical pleated origami sections. More pleated origami sections can be attached to each side of the central frame to extend the range of motion of the main vessel. For instance, two pleated origami sections can be placed on each side of the central frame if a minimum of 120° swept angle is required. An example of the crease pattern is given in Figure 6.

Design 2 has good waterproof properties. The strain on the elastic material is larger than that of design 1 but not significant. However, one major drawback for design 2 is that the top pleats do not form a completely open channel. Sea water may be trapped as the triangular plates 205 and the top pleats 203 form a small reservoir, which stops water from escaping easily.

The next question is whether a main vessel can be designed with an open channel on the top pleats and also be waterproof. To achieve this, we remove some of the triangular sheets and extend the length of the top pleats. Figure 7 shows the resulting main vessel design 3, which consists of a central frame 302 of width *w* and height *h*. Two identical pleated origami sections 300 are attached to each side of the central frame.

Each pleated origami section 300 is designed to have two planes of symmetry, and is attached to a side panel 301, which can be manufactured as a rigid panel made from carbon fibre reinforced composites (CFRP) or plywood. Connecting the rigid side panel to the central frame, two identical trapezoidal shaped sheets 303 are used as top pleats and four abstruse triangular sheets 304 are used for the sides. These sheets can again be manufactured from rigid materials such as CFRP or plywood. At each corner, two identical triangular sheets 305 connect the top pleats 303 and side plates 304. These must be made from elastic material such as reinforced rubber and allow facet deformation under strain.

The geometry of design 3 can be folded from a flat surface. Its crease pattern is plotted in Figure 8 in which solid lines represent mountain folds, dotted lines represent valley folds, and dot-dash lines represent valley folds with 180° angle of rotation such that the shaded areas are coincident. For instance, the vertices P_3, Q_3 and R_3 merge into a single point when the creases are folded up accordingly. This point is denoted as O_3 in the 3D geometry in Figure 7. Again, two thin plastic sheets can be folded to conform to the geometry of the main vessel design 3 and then attached to the outside and inside of the vessel for waterproofing purposes.

Further, we define θ_3 to be the swept angle of one pleated origami section 300. Comparing design 1 with design 3, the saddle points B_1 and F_1 disappear by making the valley crease B_3F_3 longer than the width of the central frame *w*. Comparing the crease patterns of the two watertight designs, the valley creases A_2E_2, F_2E_2 and the mountain creases A_2D_2, F_2D_2 are eliminated. Besides, vertex C_3 is moved further away from B_3 to reduce the strain on elastic sheets when θ_3 changes. In one possible design, the swept angle θ_3 of one pleated origami section ranges from 0° to 34°. The dimensions are listed in Table 3. The maximum planar strain on the elastic triangular sheet 305 is 4.95% during its full range of motion. With two pleated origami sections, design 3 has a total swept angle of 68°. More sections can be connected to both sides of the central frame to have a larger swept angle.

Table 3: Dimensions of the design 3.

$A_3E_3 = w$,	A_3R_3 (A_3O_3) = h,	$0° \leq \theta_3 \leq 33°$,	$\angle B_3A_3C_3 = 45°$,
$\angle A_3B_3C_3 = 40°$,	C_3J_3 = 102.62% w,	A_3C_3 = 15.06% w,	A_3B_3 = 23.33% w,
B_3C_3 = 16.56% w,	B_3P_3 = 35.45% w.		

Embodiments of the present invention described herein relate to the structural design of a flexible main vessel of a floating origami WEC that is responsive to wave motion. The main vessel is constructed by plates with low elasticity such as CFRP and plates with higher elasticity such as reinforced rubber. During the expanding and contracting motions of the main vessel, the plates are allowed to rotate about the hinges while minimum stretching of the faces of the plates is achieved. Design 1 possesses open top channels for sea water to escape and experiences minimal strain on the elastic facets during the flexing motion of the main vessel. However, its geometry cannot be folded from a flat surface, making it rather challenging for waterproofing. The geometry of design 2 can be folded from a flat surface. Two thin layers of waterproof material can be folded into the geometry and glued to the inner and outer surfaces of the main vessel, respectively. However, the top pleats of design 2 form small reservoirs, which prevent trapped sea water from escaping easily. Design 3 possesses open channels on the top pleats. Design 3 can also be folded from a flat surface for waterproofing. It experiences slightly larger strain on the elastic facets than design 1 when the main vessel is expanding and contracting.

A physical prototype 450 has been constructed to demonstrate the minimal strain experienced during the contraction and expansion motions of one pleated origami section according to Figure 2. The strain level is so insignificant that the physical model can successfully contract and expand, even with all facets constructed using rigid plywood, as shown in Figure 9.

To illustrate the functionality of the prototype 450, a small force was manually applied to separate the two rectangular side plates in Figure 9 (a), bringing it to its fully expanded configuration. Conversely, a small force was applied to pinch the side plates together, achieving the fully closed state as depicted in Figure 9 (c). In Figure 9 (b), no external force was applied, and the model is shown in its equilibrium position with the hand being used solely to maintain the model in an upright position.

A full assembly of an origami-WEC design generally indicated 570 is illustrated in Figure 10, showcasing a main vessel 575, ballast 590, and mooring lines 595 from top to bottom. A representative sea level S is shown.

A central frame 577 of the main vessel 575 includes a chimney 579, depicted by an oval shape, to allow for volume changes. Additionally, various types of Power Take-Off (PTO) systems can be installed between the two rigid side plates 581 (flaps), for example.

Between the plates 581 a top pleated structure is provided by longitudinal top valley creases 583 (in this embodiment two creases 583 between each plate and the central frame) which define top pleats 584.

At the ends of the top pleats 584, the main vessel has side pleats 585 formed by side mountain creases 586.

The side pleats 585 are joined to the top pleats 584 by side valley creases 587 that define triangular facets (or “membranes”) 588. In this embodiment the pleats 584 and 585 are rigid and the facets 588 are elastic.

In Figure 10(a), the cross-section view of section MM is shown, in which a linear spring 597 is placed within the main vessel and is attached onto the two rigid flaps 581. The spring is compressed to counter the hydrostatic force that is exerted on the two rigid flaps.

During wave troughs, the origami-WEC expands due to the lower hydrostatic pressure as shown in Figure 10(a)During wave crests, increased hydrostatic pressure on the flaps 581 causes the origami-WEC to contract, as shown in Figure 10(b). The spring is further compressed, preparing to expend the main vessel for the next cycle. Power is captured through the cyclic expanding and contracting motion of the WEC.

The weight of the vessel must be well-balanced to ensure it always floats, enabling its cyclic expanding and contracting motion. During adverse weather conditions such as storms and extreme waves, the main vessel can be further contracted, temporarily locked in this configuration, and sunk to the seabed for survivability.
d sunk to the seabed for survivability.

In terms of hydrodynamics, the origami WEC utilises the combined efforts of the heave and the clam motion. In terms of structural design, the origami WEC has a minimal strain on its facets when air is breathing in and out of the device.

Although illustrative embodiments of the invention have been disclosed in detail herein, it is understood that the invention is not limited to the precise embodiments shown and that various changes and modifications can be effected therein by one skilled in the art without departing from the scope of the invention.

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CLAIMS

1. A wave energy converter comprising a vessel configured for alternative expansion and contraction, the vessel comprises two rigid panels configured for relative movement with respect to each other, and a pleated portion provided between the panels, in which the pleated portion has a polyhedral structure.

2. A converter as claimed in claim 1, in which the panels are joined by a hinge and the panels approach and separate under interaction with waves.

3. A converter as claimed in claim 1 or claim 2, in which the pleated portion comprises one or more pleated origami sections.

4. A converter as claimed in claim 3, comprising two substantially identical clam sections.

5. A converter as claimed in claim 3 or claim 4, in which each pleated origami section has two planes of symmetry.

6. A converter as claimed in any of claims 3 to 5, in which each claim section has one or more mountain folds and/or one or more valley folds.

7. A converter as claimed in any of claims 3 to 6, in which each pleated origami section has one or more oblique folds.

8. A converter as claimed in any preceding claim, in which pleats have crease patterns comprising one or more substantially triangular portions.

9. A converter as claimed in any preceding claim, in which the pleated portion comprises rigid plates and one or more elastic membranes.

10. A converter as claimed in any preceding claim, in which the pleated portion comprises membranes which are slack in a folded state.

11. A converter as claimed in any preceding claim, in which the vessel is enclosed.

12. A converter as claimed in any preceding claim, in which the vessel is watertight.

13. A converter as claimed in claim 12, comprising a watertight inner layer optionally comprising one or more rubber sheet and an outer layer optionally comprising rigid plates.

14. A converter as claimed in any preceding claim, in which an elastic membrane is strained in tension and is slack under compression.

15. A converter as claimed in any preceding claim, comprising a membrane complying with one or more dimensions specified in Table 1, Table 2 or Table 3.

16. A converter substantially as hereinbefore described with reference to and as shown in the accompanying drawings.

17. A converter as claimed in any preceding claim, in which the vessel is formed as an outer shell to host power take-off means.

18. A converter as claimed in any preceding claim, further comprising power take-off (PTO) means.

19. A converter as claimed in claim 18, in which the PTO comprises one or more of: hydraulic ram, linear generator; DEG; DFG; air turbine; air spring.

20. A converter as claimed in claim 20, in which a portion of the wave energy will be consumed to deform the outer shell of the model and the rest can be captured by the PTO.

21. A converter as claimed in claim 20 or claim 21, in which the pleats have a plurality of facets.

22. A converter as claimed in claim 21, in which its geometry is configured to minimise the strain on its facets while achieving the largest volumetric change of the device to maximise the power extraction by the PTO.

23. A converter as claimed in claim 21 or claim 22, in which energy is generated through stretching and/or bending of the facets if DEG is used as the PTO.

24. A converter as claimed in claim 23, in which the geometry of the membrane is configured such that the strain in certain facets is maximised.

25. A converter as claimed in claim 24, in which the geometry of the membrane is configured such that hinge length is maximised if DFG is used as the PTO.

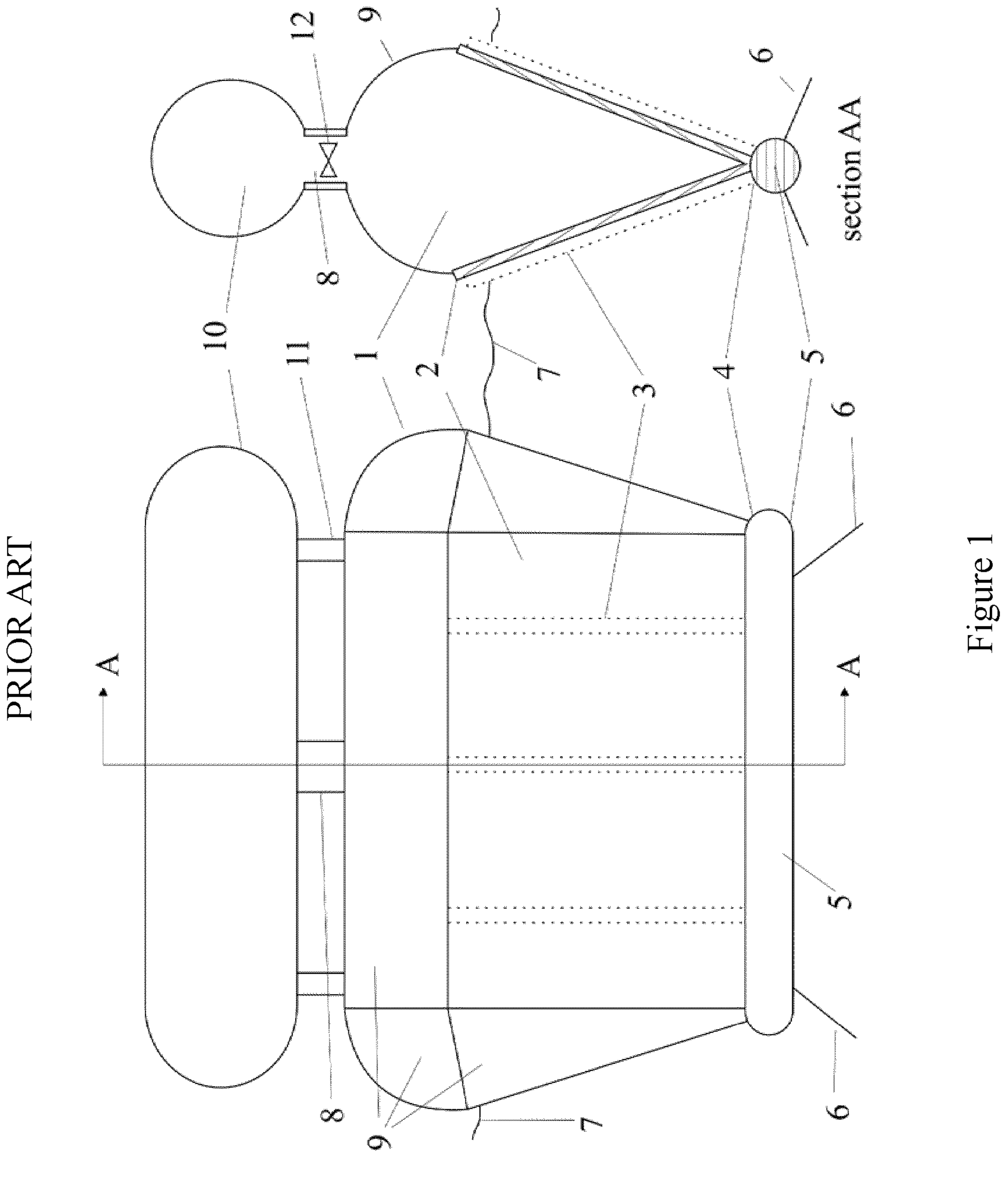
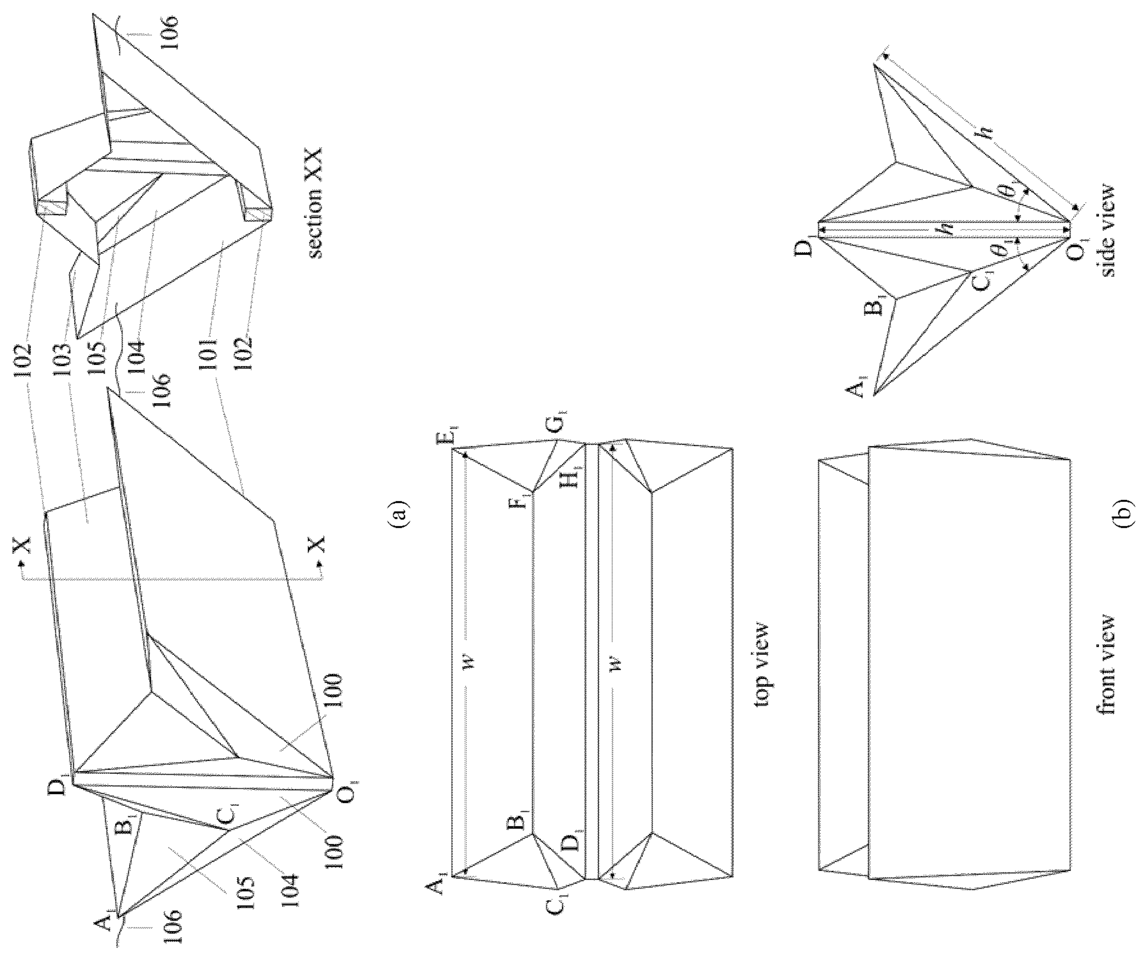


Figure 1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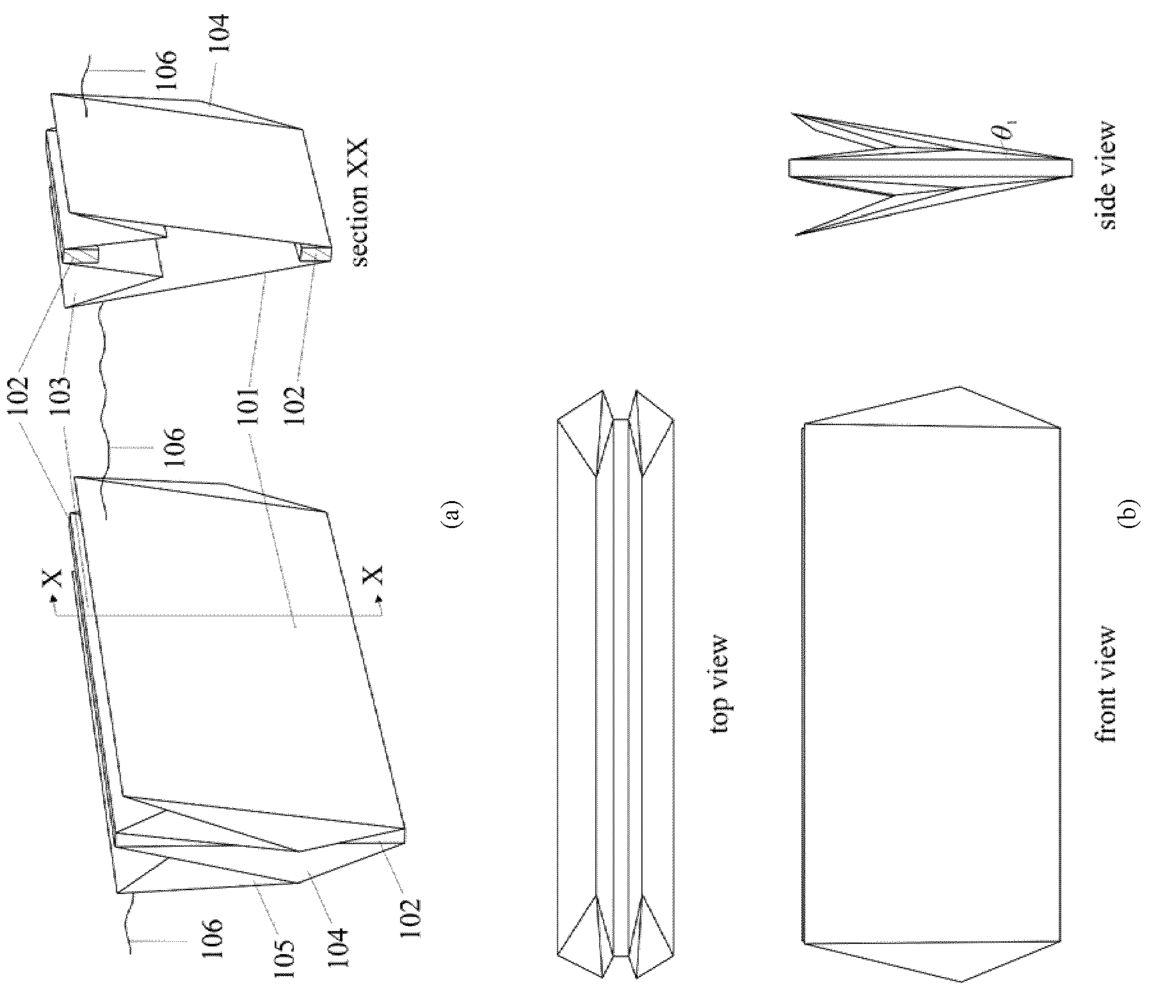
X
A1
B1
C1
D1
O1
100
100
101
102
102
103
104
104
105
105
106
106
106
section XX
(a)
A1
B1
C1
D1
E1
F1
G1
H1
w
w
top view
(b)
front view
A1
B1
C1
D1
O1
h
h
θ1
θ1
side view

Figure 2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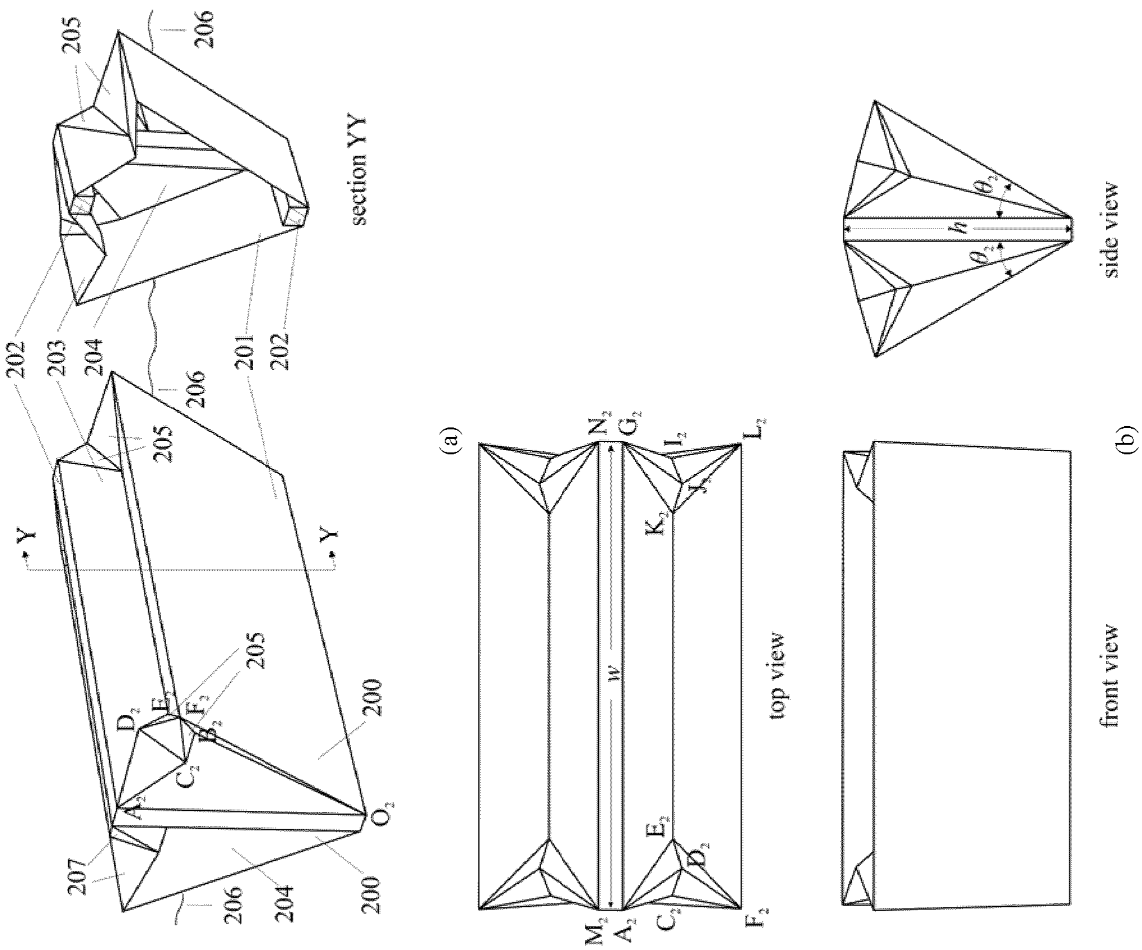
section XX
102
103
101
102
106
X
X
(a)
106
105
104
102
top view
side view
θ_1
front view
(b)

Figure 3

Figure 4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section YY
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201
202
206
205
Y
Y
D2
E2
F2
B2
C2
A2
O2
205
200
207
206
204
200
(a)
M2
N2
G2
I2
L2
w
K2
J2
A2
C2
E2
D2
F2
top view
h
θ2
θ2
side view
(b)
front view

Figure 5

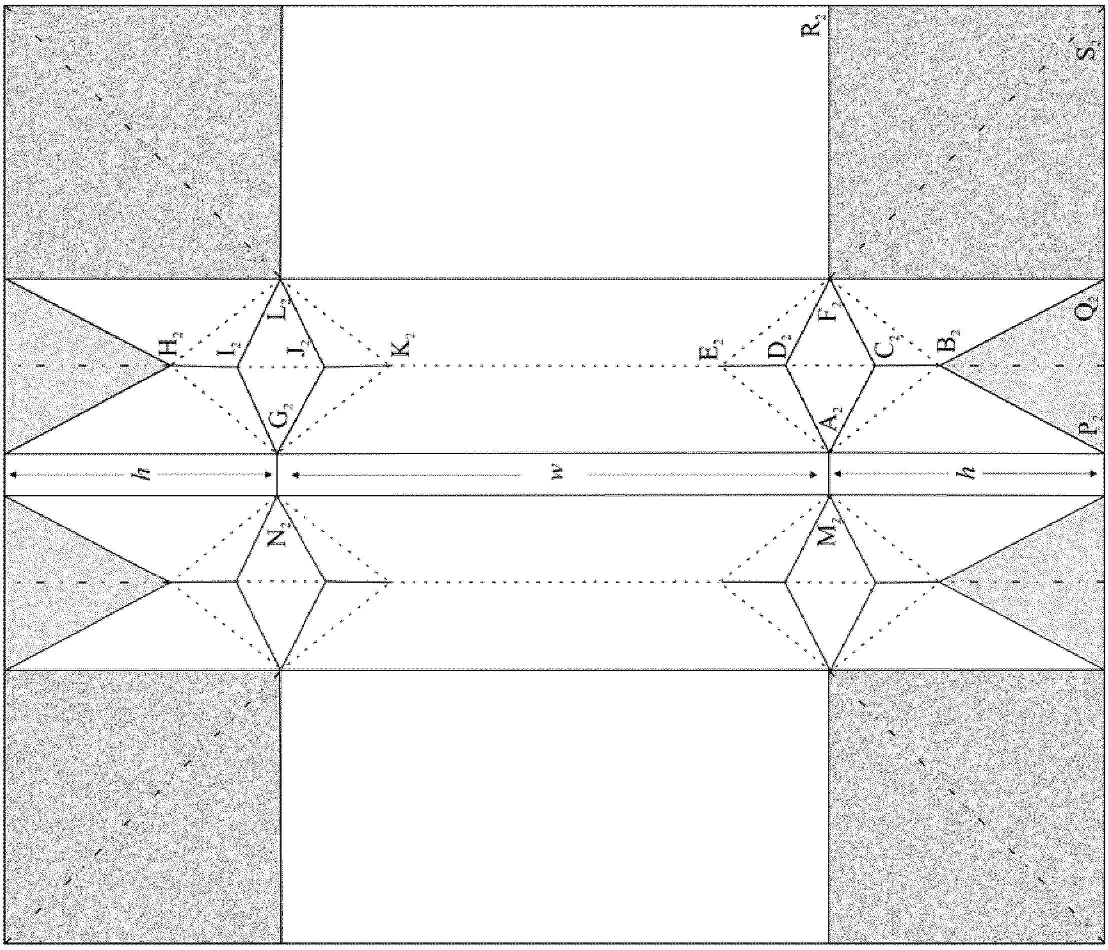
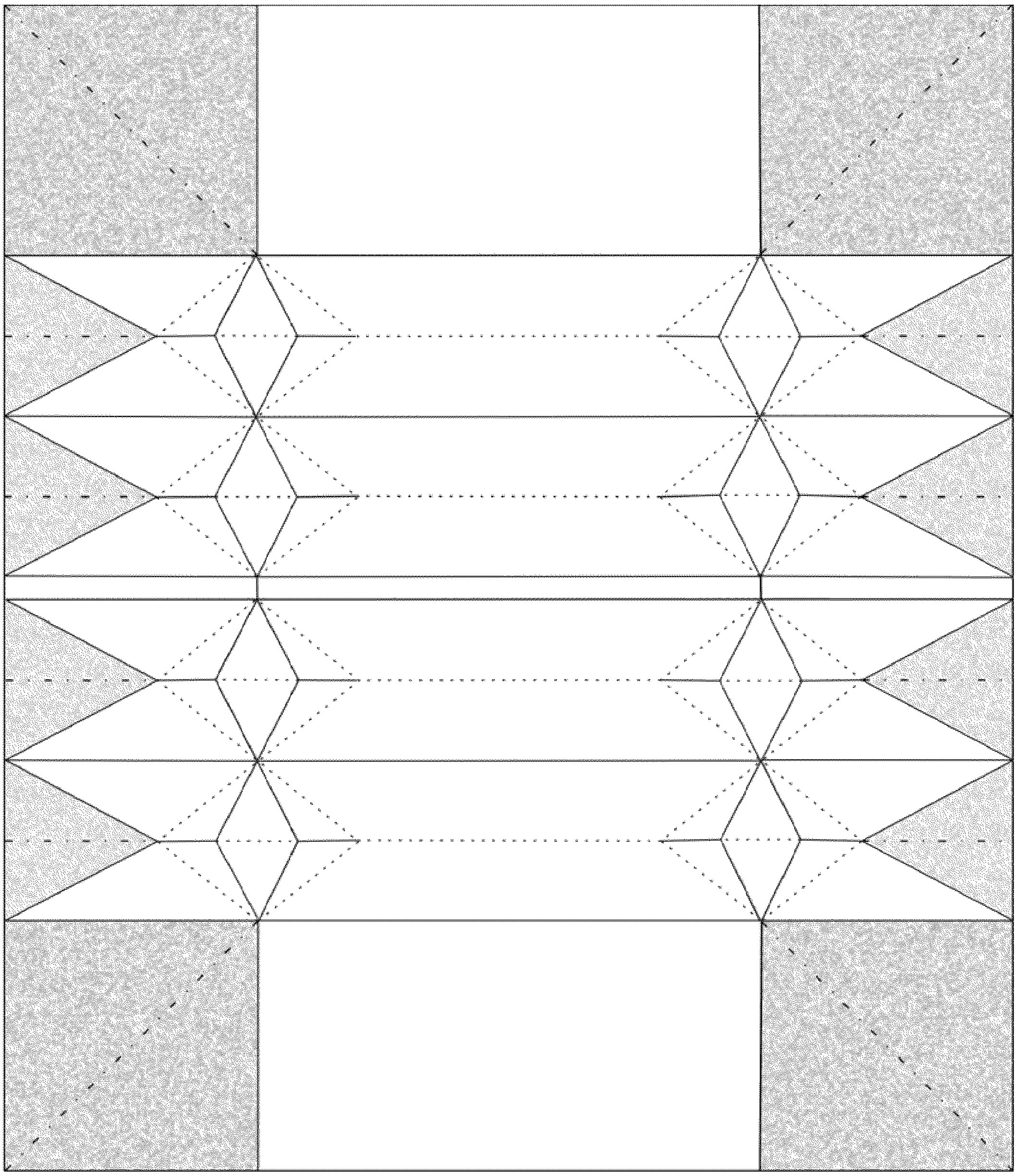
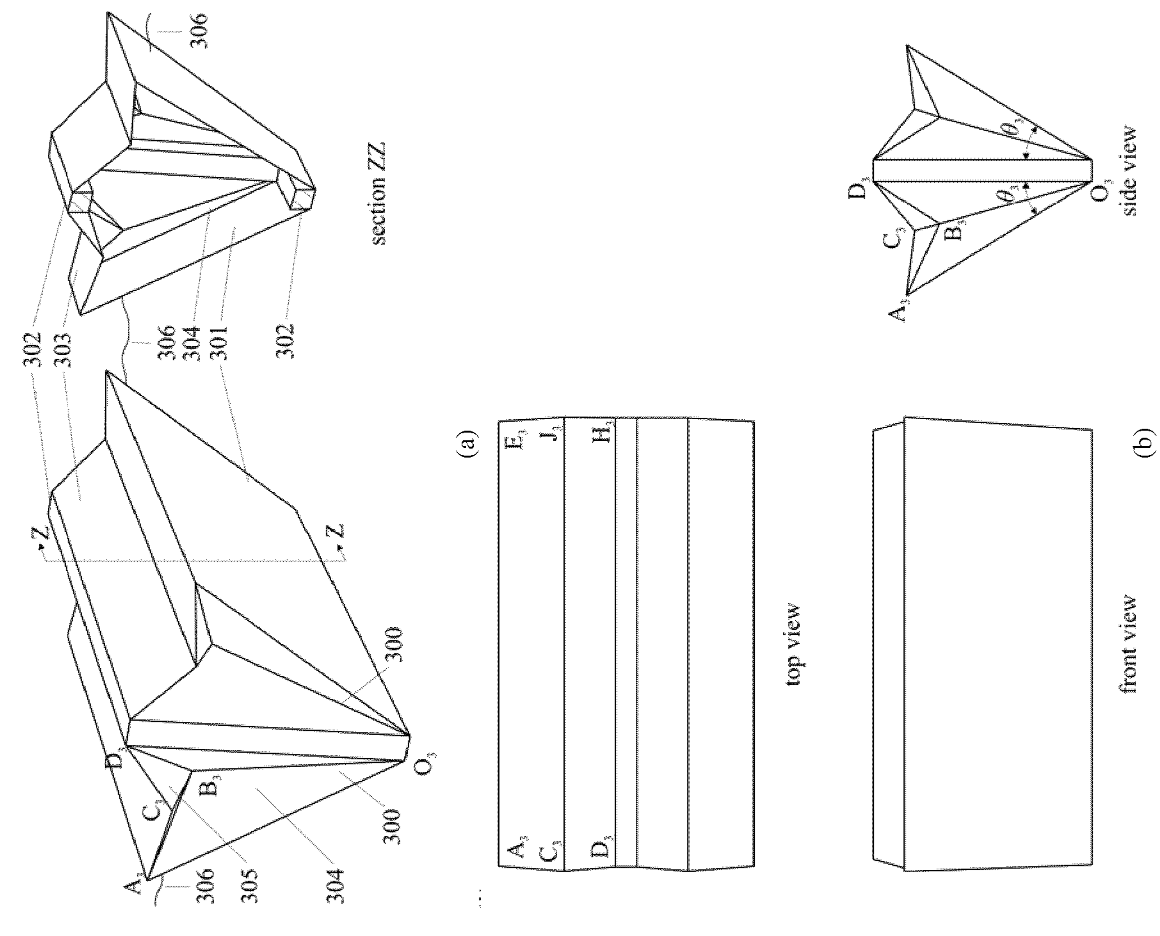


Figure 6

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Z
A3
C3
D3
B3
O3
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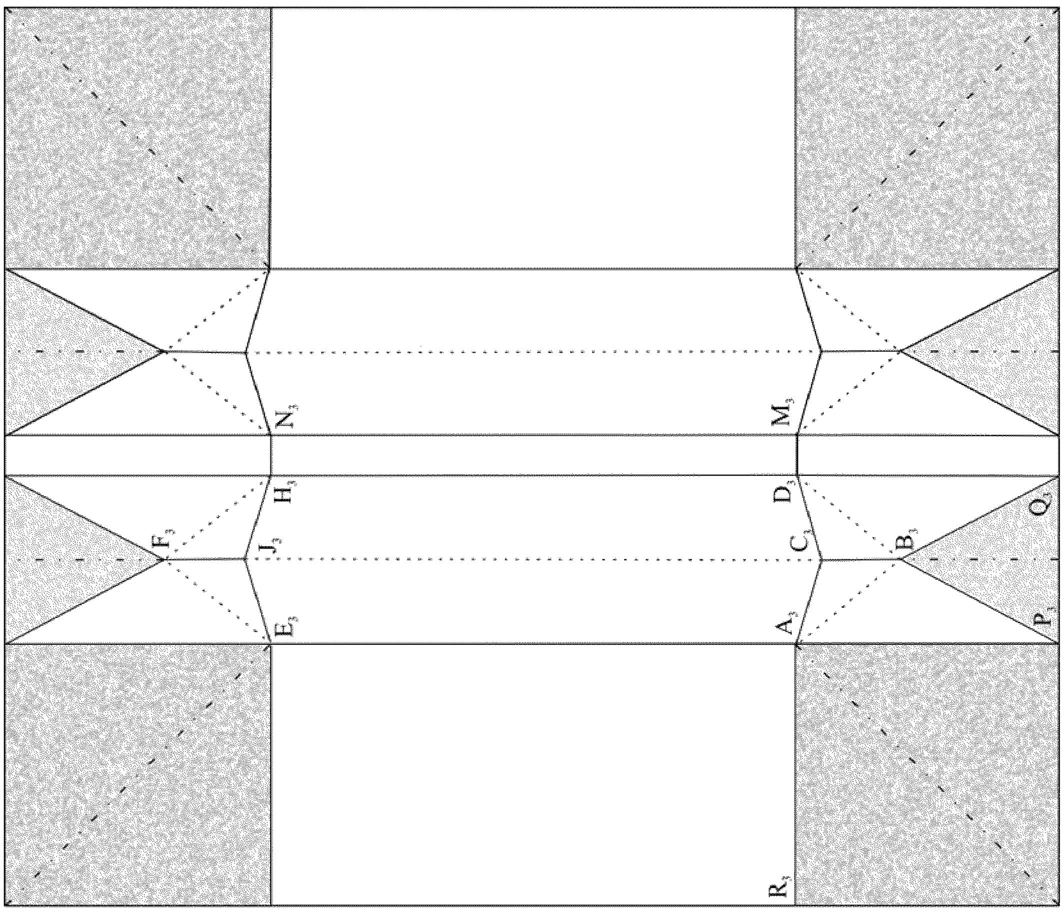
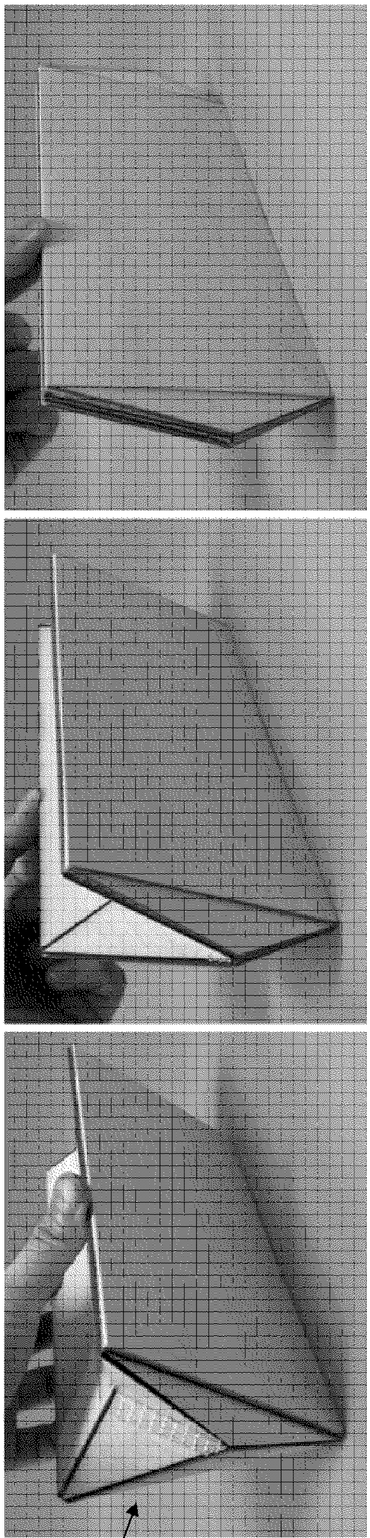
300
306
305
304
302
303
306
304
301
302
306
section ZZ
(a)
top view
A3
C3
D3
E3
J3
H3
(b)
front view
A3
C3
B3
D3
O3
θ3
θ3
side view

Figure 7

Figure 8

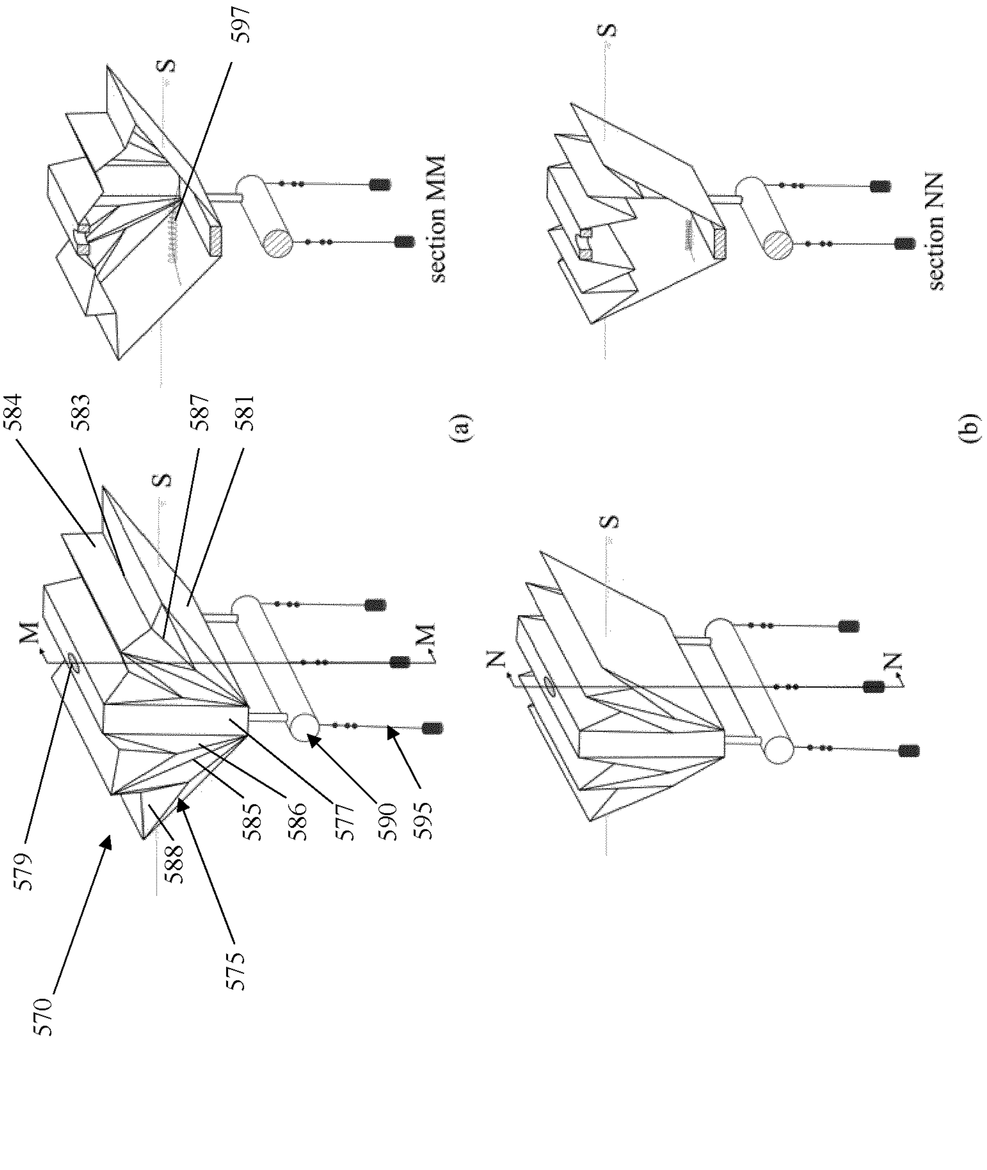




(a) (b) (c)

450

Figure 9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579
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595
584
583
587
581
M
M
S
597
section MM
(a)
N
N
S
section NN
(b)

Figure 10

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2024/065649

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03B13/18 F03B13/20
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
F03B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	WO 2022/153327 A1 (ANTHONY JOHN KIRAN [IN]; LOHITH IMMANUVEL [IN]; RAO RESHMA [IN]) 21 July 2022 (2022-07-21) page 4, line 17 - page 9, line 28; figures 1-7	1-25
X	JP S59 43987 A (HITACHI SHIPBUILDING ENG CO) 12 March 1984 (1984-03-12) figures 4,5	1-25
X	JP S59 203882 A (HITACHI SHIPBUILDING ENG CO) 19 November 1984 (1984-11-19) figure 1	1-25
X	US 2006/202483 A1 (GONZALEZ ENRIQUE J [US]) 14 September 2006 (2006-09-14) paragraphs [0007], [0011]; figure 1	1-25

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[x] Further documents are listed in the continuation of Box C.

[x] See patent family annex.

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"E" earlier application or patent but published on or after the international filing date

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance;; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance;; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
3 September 2024	01/10/2024

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Di Renzo, Raffaele

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Form PCT/ISA/210 (second sheet) (April 2005)

International application No
PCT/EP2024/065649

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	GB 2 488 185 A (FARLEY FRANCIS JAMES MACDONALD [FR]) 22 August 2012 (2012-08-22) page 3 - page 4; figures -----	1-25

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2024/065649

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2022153327 A1	21-07-2022	EP 4278082 A1	22-11-2023
		US 2023383719 A1	30-11-2023
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US 2006202483 A1	14-09-2006	NONE	
GB 2488185 A	22-08-2012	NONE	