(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
09 January 2020 (09.01.2020)

WIPO | PCT

(10) International Publication Number
WO 2020/007840 A1

(51) International Patent Classification:
B63B 1/24 (2006.01) *B64C 21/10* (2006.01)

(21) International Application Number: PCT/EP2019/067700

(22) International Filing Date: 02 July 2019 (02.07.2019)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
1810843.1 02 July 2018 (02.07.2018) GB

(71) Applicant: NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY (NTNU) [NO/NO]; Sem Sælandsvei 14, 7491 Trondheim (NO).

(72) Inventor: SELBO STORLI, Pål-Tore; Byåsvegen 146A, 7021 Trondheim (NO).

(74) Agent: ONSAGERS AS; P. O. Box 1813 Vika, 0123 Oslo (NO).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Declarations under Rule 4.17:
— *as to the identity of the inventor (Rule 4.17(i))*
— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*
— *as to the applicant's entitlement to claim the priority of the earlier application (Rule 4.17(iii))*
— *of inventorship (Rule 4.17(iv))*

Published:
— *with international search report (Art. 21(3))*

(54) Title: A FOIL FOR ARRANGEMENT RELATIVE TO A FLOW OF LIQUID

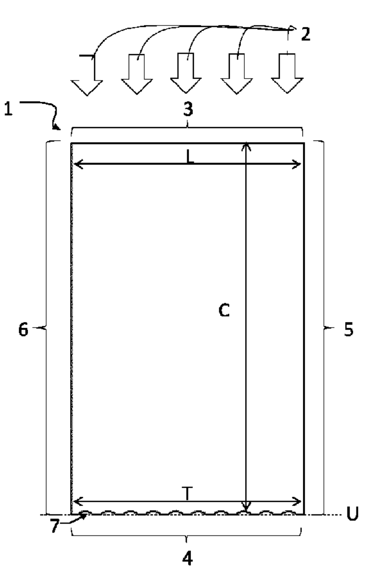

Fig. 5A

(57) Abstract: The present invention relates to a foil (1) for arrangement relative to a flow of liquid (2) where a relative velocity (V) is substantially even along a length (L) of a leading edge (3) of the foil (1), and where the foil (1) comprises: - a leading edge (3) - a trailing edge (4), comprising a plurality of indentations (7), wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio to a boundary layer thickness (δ) at the trailing edge (4) between $0.01<B/\delta<100$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.01<D/\delta<100$, such that vortex shedding characteristics and thus the oscillating pressure force formed by uniform vortex shedding along a trailing edge of the foil are reduced. Furthermore, the invention relates to a hydrodynamic system comprising such a foil, a method of modifying a foil in a hydrodynamic system and the use of said foil.

WO 2020/007840 A1

A FOIL FOR ARRANGEMENT RELATIVE TO A FLOW OF LIQUID

Technical Field

The present invention relates to a foil for arrangement relative to a flow of liquid, where said foil has a shape which reduces vortex shedding characteristics and thus the oscillating pressure force formed by uniform vortex shedding along a trailing edge of the foil. More specifically, the invention relates to foils where the flow of liquid has a substantially even fluid relative velocity along the leading edge of the foil, such as guide vanes, stay vanes, rudders, hydrofoils and other foils which are typically not meant for providing or extracting energy, to or from, a flow of liquid, such as propellers and turbines.

Background Art

Vortex shedding, caused by a fluid flowing past a body at certain velocity, is a well-known and often undesirable phenomenon in fluid dynamics as it may cause oscillations of the body and ultimately fatigue in connected mechanical parts.

In hydrodynamics, i.e. the branch of science concerned with forces acting on or exerted by moving liquids, the consequences of vortex shedding can be particularly severe due to the higher density of liquids relative to gases. Foils in hydrodynamic systems where a fluid relative velocity is substantially even along a length of a leading edge of the foil are especially susceptible to the negative consequences resulting from vortex shedding at the trailing edge of the foil. This is because the even fluid relative velocity exacerbates the problem of vortices which periodically detach from each side of the trailing edge, often uniformly along the length of the foil. The periodical uniform vortices cause an oscillating net pressure force on the trailing edge, leading the foil to move and interact with the fluid. This movement is propagated by the foil into the surrounding system to which the foil is attached, and may eventually cause fatigue on the foil and cascading effects in the system. Hydrodynamic systems may be defined herein as any system to which a foil is connected, and where the foil is arranged for interaction with a flow of liquid having a relative velocity in relation to said foil.

Occasionally, the fluid foil interaction is unstable and resonance is observed, leading the foil to vibrate with a high amplitude and locking it to the frequency of the combined fluid-structure interaction. This “lock-in” or “singing” phenomenon can result in accelerated fatigue, if not avoided. The frequency might also come into resonance with other mechanical components of the hydrodynamic system resulting in high vibrations of the system.

Furthermore, foils may typically be arranged upstream of other components in a hydrodynamic system, such as the guide vanes leading water into the runner of a hydraulic turbine. The vortex shedding alters the pressure field in the flow of water downstream of the foil, and any component located behind the foil will thus be affected by the pressure pulsations resulting in dynamic loads on said component. The amplitudes of these dynamic loads can be high and, in some cases, result in high cycle fatigue due to resonance phenomena.

Moreover, the frequency of the vortex shedding is often in an audible range and presents itself as unacceptable high noise. Depending on the hydrodynamic system, foil and velocity of the flow of liquid the high noise may have different undesirable characteristics. In some cases, the frequency may be low but with a high decibel noise, whilst in others the frequency of the noise itself may be uncomfortable. For vanes in hydraulic turbines, this noise may be pose a challenge for HSE requirements to operators and technicians. In other uses, such as hydrofoils on submarines, noise is required to be kept to a minimum to avoid detection. The problems of vortex shedding is present in many hydrodynamic systems, and is not limited to hydrofoils and guide vanes.

The vortex shedding also increases drag on a foil. Theoretically, reducing the vortex shedding will therefore reduce drag, which is important for high velocity devices such as torpedoes.

In the prior art, a common approach to solve the problems of vortex-shedding has been by designing a foil with a uniform chamfer or other geometric cross sectional profile extending along the length of its trailing edge. This may alter, and hopefully reduce, the intensity and frequency of the vortex shedding, but a net oscillating pressure force is still present. Another problem with using a chamfer or profile is that its effect is highly sensitive to geometry, and small deviations during manufacture might worsen vortex-shedding rather than mitigating it. Different flow conditions (i.e. different operating points, or different relative velocities due to different speed of hydrofoils moving through the water) might also suffer from the chamfer not working as intended, which in practice gives a non-continuous operating range.

There have been attempts to solve the problems of vortex shedding by providing a foil with indentations on its trailing edge:

CN 10764640300 A describes a T shaped foil having a trailing edge with sinusoidal indentations arranged below the hull of a ship to provide a vibration and noise reduction effect.

WO 2015/193654 A1 describes fluid dynamic body having a serrated trailing edge which may be used as the control element of a waterborne vessel and which reduces noise produced at the trailing edge.

US 5088665 A describes a hydrodynamic lifting surface with a serrated trailing edge to provide reduced drag and increased lifting capabilities.

However, none of the abovementioned prior art are directed at reducing the effects of dynamic loads caused by vortex shedding on the foil or a surrounding hydrodynamic system nor do they discuss the geometry required to achieve this.

In view of the above, it is desirable to provide a foil that solves or at least mitigates one or more of the aforementioned problems of the prior art.

Summary of the Invention

With the abovementioned challenges and known solutions in mind, the present invention brings forward a foil with a trailing edge comprising a plurality of indentations, such that vortices are less likely to separate uniformly along the length of said edge.

Accordingly, the present invention relates to a foil for arrangement relative to a flow of liquid where a relative velocity is substantially even along a length of a leading edge of the foil, and where the foil comprises:
- a leading edge,
- a trailing edge comprising a plurality of indentations, where any of the plurality of indentations may have a breadth B defined by a ratio to a boundary layer thickness δ at the trailing edge between $0.01<B/\delta<100$, and a depth D defined by a ratio of a boundary layer thickness δ at the trailing edge between $0.01<D/\delta<100$, such that vortex shedding characteristics and thus the oscillating pressure force formed by uniform vortex shedding along a trailing edge of the foil are reduced.

Thus, the present invention provides significant improvements in relation to the prior art, as the indentations disrupt periodical vortex shedding from each side of a trailing edge's surfaces, thereby reducing the net force caused by such vortex shedding and reducing dynamic loads on the foil. Furthermore, the turbulent kinetic energy in the flow downstream of the trailing edge is reduced, there is a lower degree of vorticity, pressure is much more rapidly increased in the wake region and the amplitudes of pressure pulsations are reduced, with noise and vibrations resulting from these problems also being minimized.

Advantageously, the indentations may thus have a relatively high depth/breadth ratio, such that the indentations do not form narrow projections which may be susceptible to increase the probability of cracks, fatigue and structural problems in the foil. The breadth/depth ratio of an indentation may thus be dependent on its effect on disrupting vortex shedding and whether the indentation is likely to increase structural problems in the foil.

In aspects of the invention, any of the plurality of indentations may have a breadth B defined by a ratio to a boundary layer thickness δ at the trailing edge between $0.1<B/\delta<100$, and a depth D defined by a ratio of a boundary layer thickness δ at the trailing edge between $0.1<D/\delta<10$.

In aspects of the invention, any of the plurality of indentations may have a breadth B defined by a ratio to a boundary layer thickness δ at the trailing edge between $0.1<B/\delta<10$, and a depth D defined by a ratio of a boundary layer thickness δ at the trailing edge between $0.01<D/\delta<10$.

In aspects of the invention, any of the plurality of indentations may have a breadth B defined by a ratio to a boundary layer thickness δ at the trailing edge between $1<B/\delta<100$, and a depth D defined by a ratio of a boundary layer thickness δ at the trailing edge between $0.1<D/\delta<100$.

In aspects of the invention, any of the plurality of indentations may have a breadth B defined by a ratio to a boundary layer thickness δ at the trailing edge between $10<B/\delta<100$, and a depth D defined by a ratio of a boundary layer thickness δ at the trailing edge between $1<D/\delta<100$. In aspects, the flow conditions of the flow of liquid around the indented foil according to the invention are such that a vortex shedding frequency for a similar, yet non-indented foil is within a 10% range of any eigenfrequency of the non-indented foil.

In aspects, the foil may be arranged to be stationary in a flow of liquid. The foil may be arranged such that it directs the flow, as guide vanes for a hydraulic system or water turbine, or not to direct the flow, as stay vanes of a hydraulic system or water turbine. In other aspects, the foil may be arranged to travel through a liquid and create lift, such as the hydrofoils of a marine vessel. In both aspects, the foil has a velocity relative to the liquid, the term “flow of liquid” is therefore used herein to define foils arranged for moving through otherwise still standing liquids, such as a hydrofoil moving through a body of water. It will be apparent to the person skilled in the art that the invention disclosed herein is not limited to these explicitly mentioned types of foils or hydrodynamic systems, but these are merely examples, and any kind of foils or hydrodynamic systems may be applicable according to the scope of the invention. Furthermore, the invention may also relate to foils arranged relative to a flow of liquid.

The relative velocity may be defined as the average velocity of the flow of liquid relative to the foil for a given section along the length of the leading edge of the said foil. Depending on the use of the foil, it may experience different relative velocities over a period of time, for example a hydrofoil where the relative velocity is dependent on the speed of the vessel in a body of water. Thus, irrespective of the size of the relative velocity at a given point in time, the relative velocity along the entire length of a leading edge of the foil is substantially even at that point in time. Therefore, the leading edge of the foil may be divided into sections such that it is possible to measure the average velocity of the flow of liquid in that section, and compare it with the average velocity of the flow of liquid in the remaining sections to ascertain whether the relative velocity along the entire length of a leading edge is substantially even.

In contrast to foils arranged for continuous rotation during use, such as propellers and turbine blades, the invention relates to foils arranged to have a substantially even volume flow rate along the leading edge of the foil – which will be referred to as non-rotating foils herein. As mentioned in the description of the background art, these non-rotating foils are more susceptible to periodical vortex shedding. Rotating foils, which are defined herein as foils arranged to have a substantially increasing or decreasing relative velocity from a point of support, may typically be used to extract or provide energy to a liquid such as turbine and propeller blades. Thus, a substantially even relative velocity is contrasted herein to a relative velocity which gradually increases or decreases from a point of attachment of the foil, typically due to the foil rotating around an axis such that the distal end of the foil has a higher relative velocity compared to the point of attachment of the foil. The foil according to the invention may therefore be defined herein by an even relative velocity along the length of the leading edge to distance it from rotating foils.

In general, the foils of the current invention may therefore be suitable for only certain kinds of propellers, such as a cyclorotor, also known as a Voith-Schneider propeller, where the blades of the propeller experience a substantially even relative velocity of a liquid along the leading edge.

In some aspects, a non-rotating foil, i.e. not a propeller or a turbine blade for extracting or providing hydraulic energy, may also be arranged in flow of liquid where the relative velocity is not substantially even along a length of a leading edge of the foil. Such aspects may be common for foils arranged downstream of other components in a hydrodynamic system, such as the rudders or foils on marine vessels, where the hull of the vessel may cause the flow of water relative to the rudder to vary along the length of the leading edge of the rudder. The invention described herein may also provide advantageous benefits in such aspects. Therefore, the invention may also encompass foils for arrangement relative to a flow of liquid where a relative velocity does not substantially increase or decrease along the length of a leading edge of the foil.

The leading edge may be defined herein as the edge arranged to be the uppermost upstream edge along the foil making contact with the flow of liquid. Likewise, the trailing edge may be defined herein as the edge arranged to be the lowermost downstream edge along the foil, where the flow of liquid separated by the leading edge re-joins. A length of the leading edge, may preferably comprise the entire perimeter of the leading edge.

The prior art non-rotating foils typically have the shape of a quadrilateral polygon, for example a rectangle. Thus, the foils may comprise a first end extending between the leading edge and the trailing edge, and a second end extending between the leading edge and the trailing edge, said second end typically being located opposite to the first end. A foil may thus typically be arranged to be supported at least at any of the first end or second end. However, other shapes are also common as will be known to the person skilled in the art, and the invention is not limited to foils having two ends only. For example, the first end and/or the second end may be mere points of attachment, giving the foil the form of a lens. The foils known from the prior art may thus have a trailing edge with a linear or curved shape, i.e. concave or convex, and these shapes induce periodical vortex shedding as vortices release simultaneously along significant lengths of the trailing edge. The indentations are therefore shaped to disrupt the periodical release of vortices along the trailing edge.

An indentation may therefore be defined as a deviation of the foils chord length in relation to a reference line, where the reference line extends along the outermost points of the length of a trailing edge in a downstream direction. In aspects where a trailing edge has a convex or concave shape as is known from the prior art, the reference line may thus generally follow the convex or concave shape. Thus, an indentation is distinguished from a chamfered or profiled edge herein, in that an indentation will cause the perimeter of the trailing edge to be lengthened relative to a standard linear, concave or convex edge. A chamfered or profiled edge will not cause the perimeter of the trailing edge to be lengthened. However, a chamfered or profiled edge may also comprise a plurality of indentations according to the invention.

Although designated an indentation herein, this is relative to the reference line traced along the outermost downstream points of a trailing edge. A prior art foil may therefore be altered and extended in chord length at certain areas providing protrusions, yet the reference line is traced along the outermost points of these protrusions, and therefore the shorter lengths between the protrusions may be regarded as indentations.

An indentation may be defined as having a depth, measured as the distance from a reference line to the point of the indentation furthest in an upstream direction. The indentation may also be defined as having a breadth, measured as the distance between two points at the reference line where the indentation is located between the two said points. In aspects, an indentation may for example have the shape of a parabolic cut-out along the trailing edge of the foil relative to reference line. In other aspects, an indentation may have the shape of a triangular cut-out along the trailing edge of the foil relative to reference line. In aspects, a plurality of indentations may have the shape of a sinusoidal wave along the trailing edge of the foil relative to reference line. Thus, it will be apparent to the person skilled in the art that many more geometrical shapes or combinations of geometrical shapes of indentations may be possible within the scope of the invention. However, it may be preferable that an indentation is formed to avoid straight edges and corners, as these may cause higher concentrations of stress in the foil, leading to fatigue and structural problems. Though the geometrical shape of an indentation may preferably also be dependent in its effectiveness on disrupting vortex shedding.

To achieve optimal disruption of vortex shedding, it may be preferable that the depth and width of an indentation is dependent on the boundary layer thickness at the trailing edge. The boundary layer thickness at the trailing edge may be defined as the thickness of the boundary layer at the separation point for vortex shedding on a trailing edge of a foil. The boundary layer thickness may be dependent on the relative velocity of the liquid, viscosity of the liquid and length of the chord of the foil. As a foil may typically be designed for a specific range of relative velocities of a certain liquid, the corresponding range of boundary layers thickness of said foil is typically also known. Thus, the boundary layers thickness may define the preferred range of the breadth and depth of an indentation.

In aspects of the invention, all of the plurality of indentations may have the same ratio between breadth and boundary layer thickness, and all of the plurality of indentations have the same ratio between depth and boundary layer thickness. In other aspects, each of the indentations may have different ratios. In further aspects, a plurality of indentations may have the same ratios whilst the remaining indentations have different ratios.

In aspects of the invention, all of the plurality of indentations may have the same geometrical shape. In other aspects, each of the indentations may have different geometrical shapes. In further aspects, a plurality of indentations may have the same geometrical shapes whilst the remaining indentations have different geometrical shapes.

In aspects of the invention, wherein all of the plurality of indentations may be spaced at even intervals along the length of the trailing edge. In other words, the intervals are of the same length. In other aspects, each of the indentations may be spaced at different intervals along the length of the trailing edge. In further aspects, a plurality of indentations may be spaced at similar intervals whilst the remaining indentations are spaced at different intervals along the length of the trailing edge.

Thus, many different aspects of indentations along the trailing edge may be possible. For example, a trailing edge may have any of a saw-toothed shape, a sinusoidal shape, serrated shape or a variety of different geometrical shapes according to which are most suited for a certain foil, liquid and relative velocity. The geometric shape, number of indentations, interval distance between indentations may be dependent on the boundary layer thickness, structural integrity of a foil and effectiveness in mitigating vortex shedding.

In aspects of the invention, the plurality of indentations may be arranged along a section comprising at least 10% of a length of the trailing edge.

In aspects of the invention, the plurality of indentations may be arranged along a section comprising at least 50% of the entire length of the trailing edge.

In yet further aspects, the plurality of indentations may be arranged along a section comprising at least any of 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90% or 100% of the entire length of the trailing edge. Arranging a plurality of indentations along a section comprising only part of the entire length of the trailing edge may be advantageous in aspects where only parts of a trailing edge are susceptible to vortex shedding, or it may only be necessary to avoid vortex shedding along one part.

In aspects, the foil may comprise
- a first end extending between the leading edge and the trailing edge,
- a second end extending between the leading edge and the trailing edge, said second end is located opposite to the first end,
- wherein the foil is arranged to be supported at least at any of the first end or second end.

In aspects, the foil may be arranged to be supported at the first end and at the second end. Typically, foils arranged to be supported at both ends may comprise hydrofoils or fixed foils for guiding a flow of liquid.

In aspects, the foil may be arranged to be rotationally supported around an axis extending from a point of support in at least the first end or the second end. Guide vanes of turbines may typically be rotationally supported as they are arranged to guide the flow of liquid on to the runner of a turbine. Further examples may include the rudders and guide fins on marine vessels.

In aspects, the foil may be arranged to be rotationally locked in a point of support in at least the first end or the second end. Typically, stay vanes in turbines may be locked against rotation.

The invention furthermore relates to a hydrodynamic system comprising a foil according to any of the aforementioned aspects, where the foil is arranged such that a relative velocity of a flow of liquid is substantially even along a length of a leading edge of the foil.

A hydrodynamic system may be defined herein as any system concerned with the manipulation of hydraulic forces exerted by or on liquids and where a foil according to any of the aforementioned aspects may be employed, such as a marine vessels, water turbines, pumps, hydraulic systems and others which will be apparent to the person skilled in the art. The invention furthermore relates to a hydraulic turbine comprising a foil according to any of the aforementioned aspects, where the foil is arranged as a guide vane or a stay vane, and the foil is arranged such that a relative velocity of a flow of liquid in the hydraulic turbine is substantially even along a length of a leading edge of the foil.

In aspects, the hydrodynamic system may comprise a turbine, and the foil may be arranged to guide a flow of liquid in said turbine. In aspects, the turbine may comprise any of; a Francis turbine, a Kaplan turbine, a bulb turbine or any kind of water turbine. In aspects, the foil may be arranged as any of; a guide vane and a stay vane in a turbine. The invention may be especially advantageous for use in turbines to reduce vibration and pressure pulses formed downstream of the trailing edge, as turbines may be extra susceptible to vortex shedding.

In aspects, the hydrodynamic system may comprise a hydraulic system where foils are arranged to guide a liquid.

In aspects, the hydrodynamic system may comprise a marine vessel, where a foil may be arranged to create lift such as a rudder or lift a vessel body out of the water. In aspects, a foil may also be arranged as a steering fin on an underwater marine vessel such as a submarine or torpedo.

The invention may furthermore relate to a method of replacing a foil in a hydrodynamic system with a foil according to any of the aforementioned aspects.

The invention furthermore relates to a method of modifying a foil arranged in a hydrodynamic system, where the foil is arranged such that a relative velocity passing through the hydrodynamic system is substantially even along a length of a leading edge of the foil, wherein the foil comprises:
- a leading edge,
- a trailing edge,
the method comprising the steps of:
- forming a plurality of indentations on the trailing edge.

In aspects, the method may comprise the steps of:
- removing the foil from the hydrodynamic system before forming the plurality of indentations. In other aspects, the indentations may be formed whilst the foil is mounted in the hydrodynamic system. Forming the indentations may be achieved by a variety of different methods, as will be apparent to the person skilled in the art. For example, by cutting, grinding or otherwise shaping the trailing edge. Indentations may also be formed by adding material to sections of the outermost edge of the trailing edge, such that the indentations are formed in between these extended sections.

The invention furthermore relates to a use of the foil according to any of the aforementioned aspects, where the foil is arranged in a flow of liquid such that a volume relative velocity is substantially uniform along a length of a leading edge of the foil during use.

In the following, numerous specific details are introduced by way of example only to provide a thorough understanding of embodiments of the claimed foil, the system and the method. One skilled in the relevant art, however, will recognize that these embodiments can be practiced without one or more of the specific details, or with other components, systems, etc. In other instances, well-known structures or operations are not shown, or are not described in detail, to avoid obscuring aspects of the disclosed embodiments.

Brief Description of Drawings

Fig. 1 is a schematic illustration of vortex shedding downstream of the trailing edge of a prior art foil.

Fig. 2A is a side view schematically illustrating a prior art foil comprising a chamfered trailing edge.

Fig. 2B is a perspective view schematically illustrating a prior art foil comprising a chamfered trailing edge.

Fig. 3 is a table schematically illustrating various geometries of chamfered prior art foils.

Fig. 4A is simulation showing the turbulent kinetic energy contour downstream of the trailing edge of a prior art foil.

Fig. 4B is a simulation showing the turbulent kinetic energy contour downstream of the trailing edge of a foil according to the invention.

Fig. 5A is a side view of a foil with a trailing edge comprising a plurality of indentations according to an aspect of the invention.

Fig. 5B is a perspective view of a foil with a trailing edge comprising a plurality of indentations according to an aspect of the invention.

Fig. 5C is detailed view of the trailing edge according to the aspect illustrated in Fig. 5B.

Figs. 6A-F are side views schematically illustrating various trailing edges comprising indentations according to aspects of the invention.

Figs. 7A-D are side views schematically illustrating various trailing edges comprising indentations and or protrusions according to aspects of the invention.

Fig. 8A is a schematic illustration of boundary layer thickness on a surface of a foil.

Fig. 8B is a detailed view of boundary layer thickness at a point x along the chord length of a foil.

Fig. 8C is a detailed view of boundary layer thickness at a the trailing edge x=C of a foil.

Fig. 9 is a schematic illustration of an indentation comprising a combination of geometrical shapes.

Fig. 10A illustrates an indented foil tested in a hydrodynamic lab, the test results being illustrated in Fig. 11B.

Fig. 10B illustrates in a closer view the geometry and indentations of the indented foil of Fig. 10A.

Fig 11A illustrates the frequency spectrum measured by a strain gauge on a non-indented foil.

Fig 11B illustrates the frequency spectrum measured by a strain gauge on an indented foil with a geometry as shown in Fig. 10A and Fig. 10B.

Detailed Description of the Invention

The inventive concept will now be described more fully hereinafter with reference to the accompanying drawings.

Figs. 1 and 4A illustrate examples of vortex shedding in prior art foils. Figs. 2A,B and 3 are included herein to illustrate the various attempts in the prior art to mitigate vortex shedding.

Fig. 1 is a cross sectional view illustrating vortex shedding downstream of the trailing edge 4 of guide vanes 11 leading water into the impeller blades 12 of a water turbine. As such, Fig. 1 is an example of one of many areas where non-rotating foils 1 in a hydrodynamic system 9 cause vortex shedding. Accordingly, any hydrodynamic system 9 comprising a non-rotating foil 1 and a flow of liquid with a relative velocity to the foil 1 may experience similar problems, and the example in Fig. 1 is merely for illustrative purposes.

The arrows 2 in Fig. 1 illustrate a flow of water with a relative velocity V and a relative angle of attack substantially parallel to a chord C of the foil, i.e. a straight line extending between the leading edge 3 and the trailing edge 4. The angle of attack may however vary from that illustrated in the Figure, and the problems related to vortex shedding are not necessarily related to the angle of attack. Downstream of the trailing edge 4, vortices 13 are illustrated following the flow of water, eventually bouncing of the impeller blades 12 of the turbine’s runner. The vortex shedding behind these guide vanes 11 alters the pressure field behind the trailing edge 4, and since there are many guide vanes 12 in a typical turbine the runner will be moving through a pressure field which is not constant. This is felt by the runner as pressure pulsations resulting in dynamic loads. The amplitudes of these dynamic loads can be high and result in high cycle fatigue. The guide vanes 11 themselves may also be affected by the pressure fluctuations, leading to vibrations and possibly “singing” vanes.

Fig. 2A is a side view illustrating a typical prior art non-rotating foil 1. The exemplified foil 1 has a rectangular shape, with a parallel leading edge 3 and trailing edge 4, and a parallel first end 5 and second end 6. A first surface 15 and a second surface 16 are arranged on opposite sides of the foil 1. The length L of the leading edge 3 and the length T of the trailing edge 4 thus also have the same length L=T. The length between the leading edge 3 and trailing edge 4 is denoted the chord C, which in the case of the prior art foil in Figs. 2A-B has a fixed length along the length T of the trailing edge 4. A chamfer 14 is illustrated at the trailing edge 4 of the foil. Fig. 2B is a perspective view of the prior art non-rotating of Fig. 2A, giving a more detailed view of the chamfer 14 and the chord length C. As illustrated the chamfer 14 does not alter the length of the chord C, but provides a transitional edge between the trailing edge 4 and the first surface 15 of the foil 1. Figs. 2A and 2B thus illustrate an exemplary embodiment of a prior art non-rotating foil 1, and these foils 1 may have wide range of shapes and geometries as is apparent to the person skilled in the art.

Fig. 3 discloses various examples of chamfered 14 or profiled trailing edges 4 from the prior art. The illustrations exemplified in the table represent cross sectional views of trailing edges 4 of various foils 1, i.e. the foils 1 are designed for a flow of liquid from left to right in the illustration and only the trailing edge 4 is shown. As the trailing edges 4 illustrated in Fig. 3 are cross sectional views, the disclosed geometry may typically extend along the entire length T of a trailing edge 4. As with Fig. 2A and 2B, the cross sectional geometries of the profiles in Fig. 3 are not clearly visible in a side view since they do not alter the outer length of the chord C along the trailing edge T.

Fig. 4A illustrates a simulation of a prior art foil 1 comprising a uniform or linear trailing edge 4 and the turbulent kinetic energy contour downstream of said trailing edge 4. The stretches of downstream alternating darker and brighter regions substantially parallel to the trailing edge 4 show the impulses formed by periodic vortex shedding along the length of the trailing edge. In contrast to Fig. 4A, Fig. 4B illustrates a simulation of the kinetic energy contour downstream of a foil 1 with a trailing edge 4 comprising a plurality of indentations 7 according to the invention. The downstream alternating pulses are significantly reduced, and almost completely mitigated due to vortices no longer periodically shedding along the length of the trailing edge 4. Thus, the net force acting on the foil 1 is reduced, as well as any element located downstream of the foil 1 not being subjected to the pressure pulses as in Fig. 4A.

Fig. 5A is a side view schematically illustrating a foil 1 with a trailing edge 4 comprising a plurality of indentations 7 according to an aspect of the invention. A liquid flow is represented by arrows 2 with an even relative velocity along a length L of the leading edge 3 of the foil 1. The foil of Fig. 5A comprises a shape generally similar to that of the exemplary prior art foil 1 of Fig. 2A, however, the trailing edge 4 is not parallel with the leading edge 3. Instead, the chord C of the foil in Fig. 5 varies in length along the length T of the trailing edge 4. In comparison to the varying length of the chord C, there is traced a dashed reference line U which extends along the outermost points of the trailing edge 4 in a downstream direction. Thus, the indentations 7 may be regarded as shortened portions of the foil 1 in relation to the reference line U. Though not illustrated herein, the line U may be non-linear, for example slightly convex or concave. Furthermore, the leading edge 3 of a foil 1 may be non-linear, and as such, the chord C may vary along the length T of a linear trailing edge 4. Therefore, a trailing edge 4 according to the invention is not necessarily defined by the chord length C varying along the length T of the trailing edge 4 of a foil 1. Fig. 5B and Fig. 5C are perspective views of the foil 1 according to the aspect of Fig. 5A, giving more details on the chord line C in a cross sectional view, and the plurality of indentations 7.

Figs. 6A-F and Figs. 7A-7D are side views schematically illustrating various trailing edges 4 of similar sizes, extending between a first end 5 and a second end 6, but comprising a plurality of different shaped and sized indentations 7 according to the invention.

In Figs. 6A-6F the indentations 7 of each trailing edge 4 are evenly spaced, and have the same depth D and breadth B, illustrated by dashed lines, along the length T of the trailing edge 4. As illustrated in the Figures, the depth D is the distance upstream from the reference line U, which extends along the outermost points of the trailing edge T. The breadth B is the distance between two points on the reference line U where the indentation 7 is located in between the said two points.

Fig. 6A illustrates a trailing edge 4 comprising ten indentations 7, each being spaced at intervals I with each interval I being of equal length. The indentations 7 have geometric shapes of parabolic cut-outs in relation to the reference line U, where the reference line U is traced along the outermost points of the trailing edge 4 which coincide with the intervals I. Accordingly, in cases where the trailing edge 4 of Fig. 6A is arranged on a substantially rectangular shaped foil 1, such as in Fig. 5A, the chord length C will vary along the length T of the trailing edge 4.

The trailing edge 4 of Fig. 6B has ten similar parabolically shaped indentations 7 as Fig. 6A, but with larger depth D/ breadth B ratio. In comparison to the aspect of Fig. 6A, the aspect of Fig. 6B may be slightly more susceptible to structural weakness as the parts coinciding with the intervals I are relatively thin and long, although the intervals I may be of a similar length as in Fig. 6A.

Fig. 6C illustrates yet another trailing edge 4 comprising parabolically shaped indentations 7, however there are six indentations 7 which may have a larger depth D and longer breadth B compared to those of Figs. 6A and 6B. The intervals I in Fig. 6C are also of equal length and somewhat longer than those of Figs. 6A and 6B. Thus, the aspect of Fig. 6C may be less susceptible to structural weakness. However, dependent on the relative velocity V and viscosity of the flow of liquid, the aforementioned aspects may be suited to specific conditions.

Fig. 6D illustrates a trailing edge 4 comprising six straight edged indentations 7. The indentations 7 have geometrical shapes of triangular cut-outs in relation to the reference line U. The indentations 7 are spaced along equally long intervals I, as with the previously illustrated aspects, such that the reference line U runs flush with the outermost downstream points of the trailing edge 4 along the intervals I.

Fig. 6E also illustrates indentations 7 of triangular cut-out shapes, however, these are not spaced with intervals I to each other, thus forming a saw-tooth shaped trailing edge 4. Thus, the reference line U extends only along the outermost downstream points of the trailing edge 4. The triangular cut-outs of the aspects in Fig. 6D and 6E, may be easier to manufacture due to their straight edges, yet the innermost points of the indentations 7 may be subject to concentrations of stress.

Fig. 6F illustrates a trailing edge 4 comprising five indentations 7 together forming a geometric shape of a sinusoidal cut-out relative to the reference line U. Thus, there are no intervals I between the indentations 7, as the outermost points are tangent to the reference line U. A sinusoidal shape is characterized by its amplitude D/2 and wavelength B, where the wavelength B is the length before the same geometrical periodicity repeats itself. A sinusoidal shape may be beneficial as it mitigates straight edges and corners, thus reducing local areas of stress on the trailing edge 4 of the foil 1.

Fig. 7A illustrates a trailing edge 4comprising eight indentations 7, where six of these indentations 7 have identical size and geometrical shape, the remaining two having another size and shape. Although all eight indentations 7 are shaped as parabolic cut-outs, the two middle indentations 7 have a larger breadth B in comparison to the other six indentations 7. The intervals I between the indentations are also illustrated with different lengths.

Fig. 7B illustrates a trailing edge 4 comprising five sinusoidal indentations 7. The reference line U is traced along the outermost points of the trailing edge 4 in a downstream direction. In comparison with the aspect of Fig. 6F, the sinusoidal indentations 7 are not terminated at the reference line U at the first end 5 and the second end 6. Therefore, the indentations 7 may seem like protrusions, yet they are indentations 7 since they are defined by the reference line U which extends along the outermost downstream points of the trailing edge 4.

Fig. 7C illustrates an aspect of the invention where the indentations 7 comprise different geometrical shapes. Five of the middle indentations 7 have the shapes of a sinusoidal cut-out, with two jagged saw-tooth indentations 7 on each side of the sinusoidal indentations 7.

Fig. 7D illustrates an aspect of a trailing edge 4 comprising eleven parabolic indentations 7, with an inverse geometric shape in relation to those of Figs. 6A-6C and 7A. As with the aspect of Fig. 7B, the indentations 7 may look like protrusions since they do not extend to the reference line U at the ends 5,6 of the trailing edge 4. However, the reference line U extends along the outermost points of the trailing edge 4 in a downstream, direction, thus defining the indentations 7 as the upstream deviations of the trailing edge 4 in between. The intervals I are therefore not flush along the reference line U as with the aforementioned aspects of Figs. 6A-D and 7A, but form part of the innermost upstream sections of the indentations 7.

Fig. 8A illustrates boundary layer thickness δ with an example on a low pressure surface, denoted a second surface 16, of a truncated foil 1. The dashed line extending over the low pressure surface 16 of the foil in Fig. 8A thus illustrates the boundary layer thickness δ. A coordinate system is set up, extending from the leading edge 3 and parallel to the chord C. Fig. 8B illustrates the boundary layer thickness δ at two arbitrary points along the x-axis in closer detail. Fig. 8C illustrates the boundary layer thickness δ at the truncated trailing edge 4, where $x=C$, i.e. the end of the length of the chord C. For other aspects of foils 1, not comprising a truncated trailing edge 4, the boundary layer thickness δ at the trailing edge may be defined as the boundary layer thickness δ at the point of separation from the foil 1.

The optimal geometrical shapes, intervals I, breadths B, depths D and number of indentations 7 exemplified by the aspects in Figs. 6A-F and 7A-D to mitigate vortex shedding is dependent on the boundary layer thickness δ at the trailing edge 4. Thus, the breadth B and depth D of an indentation 7 may preferably be within the following ratio: $0.01<D/\delta(x=C)<100$ and $0.01<B/\delta(x=C)<100$. In certain aspects, it may be preferable to avoid a relatively high depth D/breadth B ratio which could lead to weak structural areas on the foil 1, accordingly the following ratio may be preferable: $0.1<D/\delta(x=C)<10$ and $0.1<B/\delta(x=C)<100$. In other aspects, the following ratio may be preferable: $0.1<B/\delta<10$ and $0.01<D/\delta<10$. In yet other aspects, the following ratio may be preferable: $1<B/\delta<100$ and $0.1<D/\delta<100$. In further aspects the following ration may be preferable $10<B/\delta<100$ and $1<D/\delta<100$.

The geometrical shapes illustrated in Figs. 6 and 7 are merely examples of indentations 7. Combinations of geometrical shapes may also provide an outline of an indentation 7, for example, Fig. 9 discloses a combination of a parabolic shape and triangular shape, which together form a parabolic outline at the innermost parts of an indentation 7, and the remnants of a triangular indentation at the outermost parts of said indentation 7.

Fig. 10A illustrates a foil with indentations having trailing edge with a length T=150mm and length of the reference line U=250mm, the foil having been fastened on two sides and tested in a hydrodynamic lab. The results of the tests are illustrated in Fig. 11B.

Fig. 10B illustrates the indentations on the foil as shown in Fig. 10A in more detail. Where the indentations have a breadth B=23,40mm and a depth D=9,00mm.

Fig. 11A illustrates the measurements taken by a strain gauge arranged on a non-indented reference foil with the geometry as illustrated in Fig. 10A. The reference foil did not comprise indentations and was therefore purely rectangular in shape with T=150mm and U=250mm. The strain gauge measured the frequency spectrum of amplitudes on the trailing edge caused by vortex shedding making the foil oscillate. Fig. 11A thus illustrates the frequency of oscillations in Hz along the x-axis and the amplitude of the oscillation along the y-axis for six different velocities U_{bulk} of flows of water. The maximum amplitude was found at a velocity U_{bulk} = 11,0m/s and all the amplitudes in the graphs of both Fig. 11A and Fig. 11B are therefore normalized with respect to this value.

Thus, Fig. 11A illustrates how the frequency of vortex shedding approaches the eigenfrequency of the foil as the velocity U_{bulk} increases. At U_{bulk} = 11,0m/s the frequency of vortex shedding corresponds to the eigenfrequency of the foil. This is referred to as the lock-in effect, where the amplitude is at its greatest and the foil experiences the highest dynamic loads. Thus, this is the effect which the invention aims to mitigate and reduce.

Fig. 11B illustrates the measurements taken from a foil comprising the geometry and indentations illustrated in Fig. 10A and Fig. 10B. The amplitudes in this graph are also normalized with respect to the value of maximum amplitude at U_{bulk} = 11,0m/s in Fig. 11A. The velocities where any significant vortex shedding is found is significantly higher than those of the non-indented foil, and therefore the measurement of the indented foil range from velocities of U_{bulk} = 11,6m/s up to U_{bulk} = 14,2m/s. As can be seen in Fig. 11B, the lock-in effect is not experienced before U_{bulk} = 13.6-14.2m/s and the amplitude is significantly smaller than for the non-indented foil of Fig. 11A when it experiences lock-in.

Thus, the invention allows foils to be used in higher velocities of flows of water without experiencing the lock-in effect, and reduces the dynamic loads and amplitudes caused by the lock-in effect when it occurs at high velocities. In the preceding description, various aspects of a foil 1 according to the invention have been described with reference to the illustrative embodiment. However, this description is not intended to be construed in a limiting sense. Various modifications and variations of the illustrative embodiment, as well as other embodiments of the foil, the system and the method which are apparent to persons skilled in the art, are deemed to lie within the scope of the present invention as defined by the following claims.

Reference Signs List

1 Foil
2 Flow of liquid
3 Leading edge
4 Trailing edge
5 First end
6 Second end
7 Indentation
8
9 Hydrodynamic system11 Guide vane
12 Impeller blades
13 Vortices
14 Chamfer
15 First surface
16 Second surface

ω Direction of impeller rotation
V Relative velocity
L Length of a leading edge
T Length of a trailing edge
C Length of the chord
I Interval length
D depth
B breadth
δ boundary layer thickness
U reference line

CLAIMS

1. A non-rotating foil (1) for arrangement relative to a flow of liquid (2) where a relative velocity (V) is substantially even along a length (L) of a leading edge (3) of the foil (1), and where the foil (1) comprises:
   - a leading edge (3)
   - a trailing edge (4) comprising a plurality of indentations (7), wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio to a boundary layer thickness (δ) at the trailing edge (4) between $0.01<B/\delta<100$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.01<D/\delta<100$, such that vortex shedding characteristics and thus the oscillating pressure force formed by uniform vortex shedding along a trailing edge of the foil are reduced.

2. The foil (1) according to claim 1, wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.1<B/\delta<100$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.1<D/\delta<10$.

3. The foil (1) according to claim 1, wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.1<B/\delta<10$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.01<D/\delta<10$.

4. The foil (1) according to claim 1, wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $1<B/\delta<100$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $0.1<D/\delta<100$.

5. The foil (1) according to claim 1, wherein any of the plurality of indentations (7) has a breadth (B) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $10<B/\delta<100$, and a depth (D) defined by a ratio of a boundary layer thickness (δ) at the trailing edge (4) between $1<D/\delta<100$.

6. The foil (1) according to any of the preceding claims, wherein all of the plurality of indentations (7) have the same ratio between breadth (B) and boundary layer thickness (δ), and all of the plurality of indentations (7) have the same ratio between depth (D) and boundary layer thickness (δ).

7. The foil (1) according to any of the preceding claims, wherein all of the plurality of indentations (7) have the same geometrical shape.

8. The foil (1) according to any of the preceding claims, wherein all of the plurality of indentations (7) are spaced at even intervals (I) along the length of the trailing edge (4).

9. The foil (1) according to any of the preceding claims, wherein the plurality of indentations (7) are arranged along a section comprising at least 10% of a length (T) of the trailing edge (4).

10. The foil (1) according to claim 9, wherein the plurality of indentations (7) are arranged along a section comprising at least 50% of the entire length (T) of the trailing edge (4).

11. The foil (1) according to any of the preceding claims, wherein the foil comprises:
- a first end (5) extending between the leading edge (3) and the trailing edge (4),
- a second end (6) extending between the leading edge (3) and the trailing edge (4), said second end (6) is located opposite to the first end (5),
- wherein the foil (1) is arranged to be supported at least at any of the first end (5) or second end (6).

12. The foil (1) according to claim 11, wherein the foil (1) is arranged to be supported at the first end (5) and at the second end (6).

13. The foil (1) according to any of claims 11 or 12, wherein the foil (1) is arranged to be rotationally supported around an axis extending from a point of support in at least the first end (5) or the second end (6).

14. The foil (1) according to any of claims 11-13, wherein the foil (1) is arranged to be rotationally locked in a point of support in at least the first end (5) or the second end (6).

15. A hydrodynamic system comprising a foil according to any of the preceding claims, where the foil is arranged such that a relative velocity (V) of a flow of liquid (2) of the hydrodynamic system is substantially even along a length (L) of a leading edge (3) of the foil (1)

16. A hydraulic turbine comprising a foil according to any of claims 1-14, where the foil is arranged as a guide vane or a stay vane, and the foil is arranged such that a relative velocity (V) of a flow of liquid (2) in the hydraulic turbine is substantially even along a length (L) of a leading edge (3) of the foil (1)

17. A method of modifying a foil (1) arranged in a hydrodynamic system (9), where the foil (1) is arranged such that a relative velocity (V) passing through the hydrodynamic system (9) is substantially even along a length (L) of a leading edge (3) of the foil (1), and wherein the foil (1) comprises:
- a leading edge (3)
- a trailing edge (4),
the method comprising the steps of:
- forming a plurality of indentations (7) on the trailing edge (4).

18. The method according to claim 17, wherein the method comprises the steps of:
    - removing the foil (1) from the hydrodynamic system (9) before forming the at least one indentation (7).

19. Use of the foil (1) according to any of claims 1-14 in a hydrodynamic system (9), wherein the foil (1) is arranged in a flow of liquid (2) such that a relative velocity (V) is substantially even along a length (L) of a leading edge (3) of the foil (1) during use.

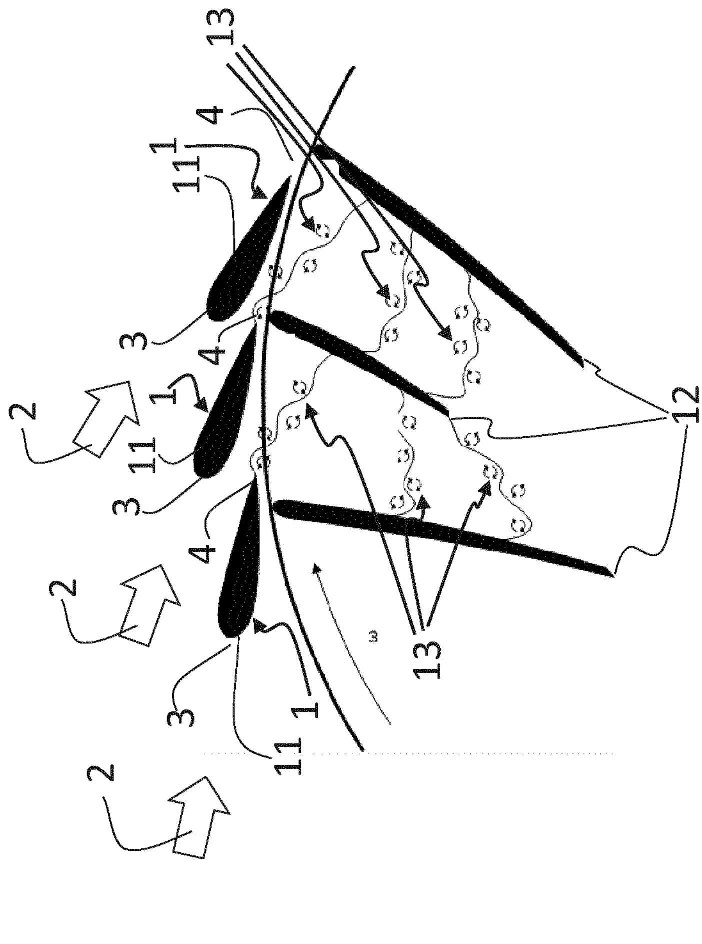

Fig. 1 Prior art

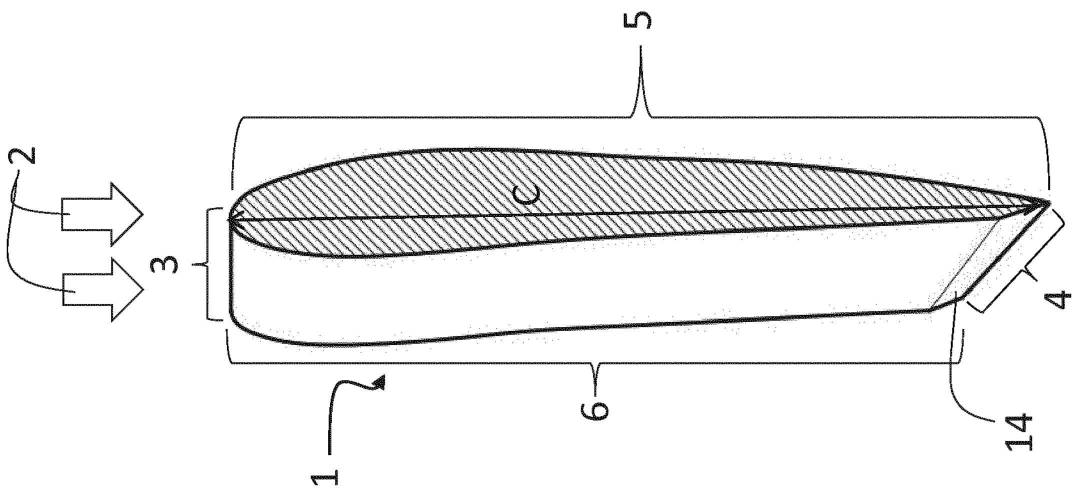

Fig. 2B Prior art

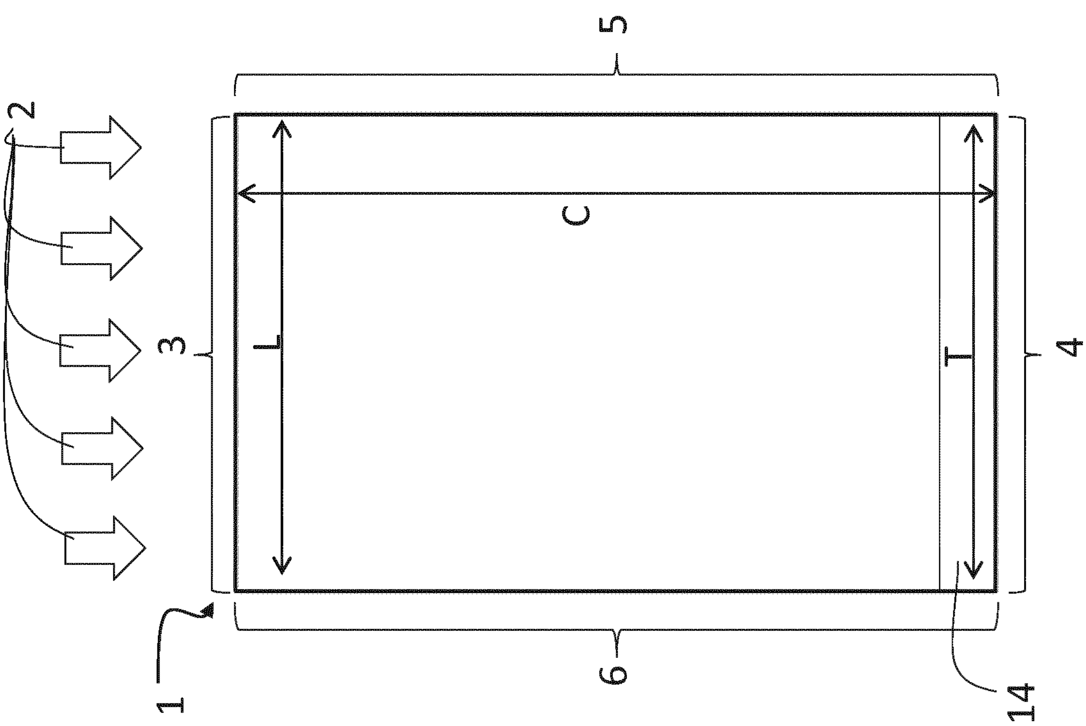

Fig. 2A Prior art

DONALDSON		HESKESTAD & OLBERTS		IPPEN		BLAKE ET AL			
GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	GEOMETRY	REL. AMP.	y_f/h	U_s/U_∞
60°	360%	60°	380%	60°	320%				
	260				230				
90°	230	90°	190						
	100		100		100		100	0.9	1.25
						6° h	100	1.0	1.05
60°	48	45°	43						
90°	22		31	90°	80				
45°	20	45°	38		70				
1.8h 45° T	> 1	45° R=2T	3		60	2.5h 45°	0.3-1.5	0.5	1.05
1.2h 90° T	> 1	45° R=3T	<1						
2h 60° T	> 1	30° R=4T	<1			h 25° R=5h	1.0	0.5	1.03
		30°	<1			25°	0.5-1.7	0.8	1.2

Source: Amirreza Zobeiri, «Effect of Hydrofoil Trailing Edge Geometry on the Wake Dynamics», M.Sc. Thesis, EPFL, 2012

Fig. 3 Prior art

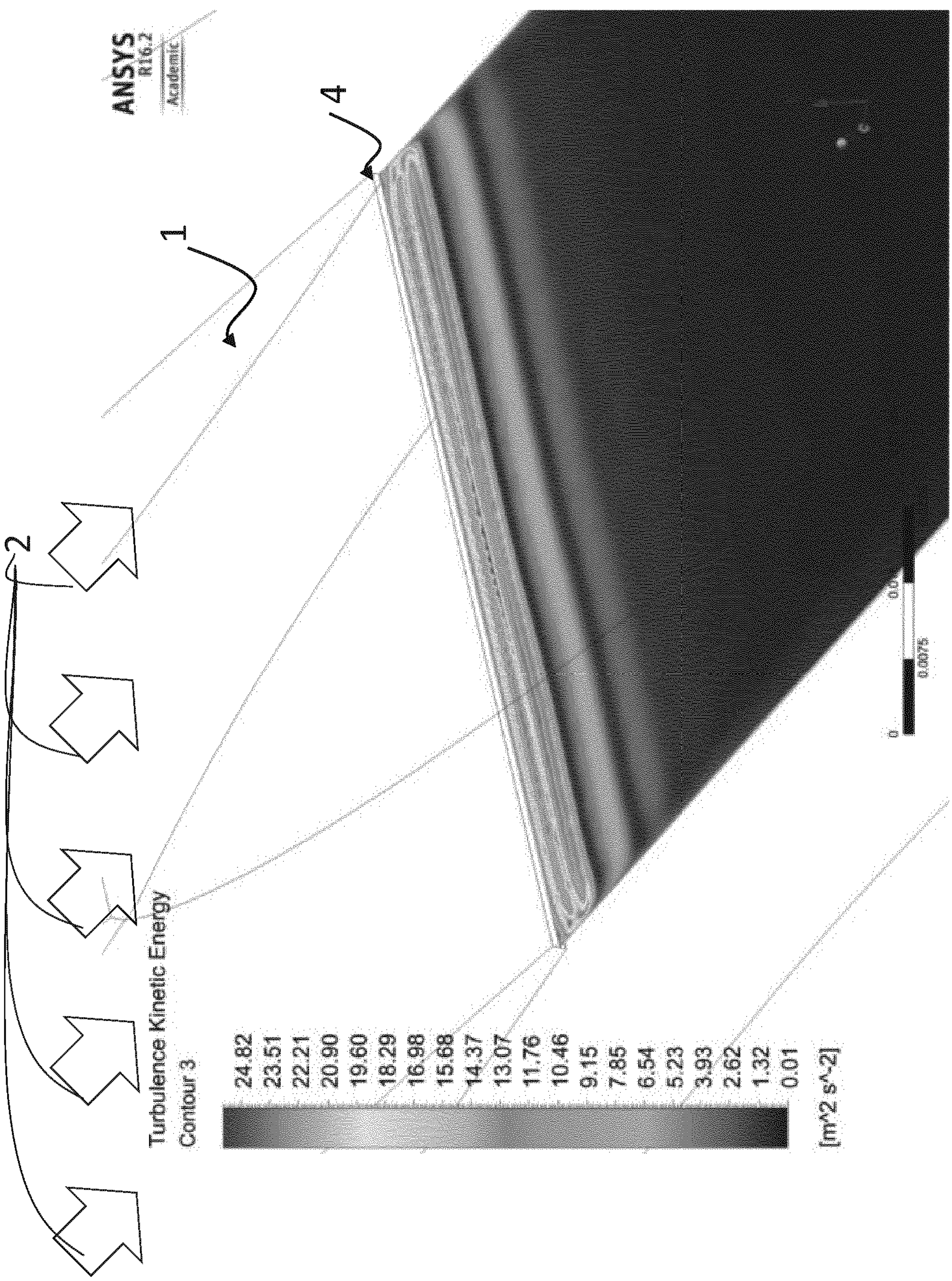

Fig. 4A Prior art trailing edge

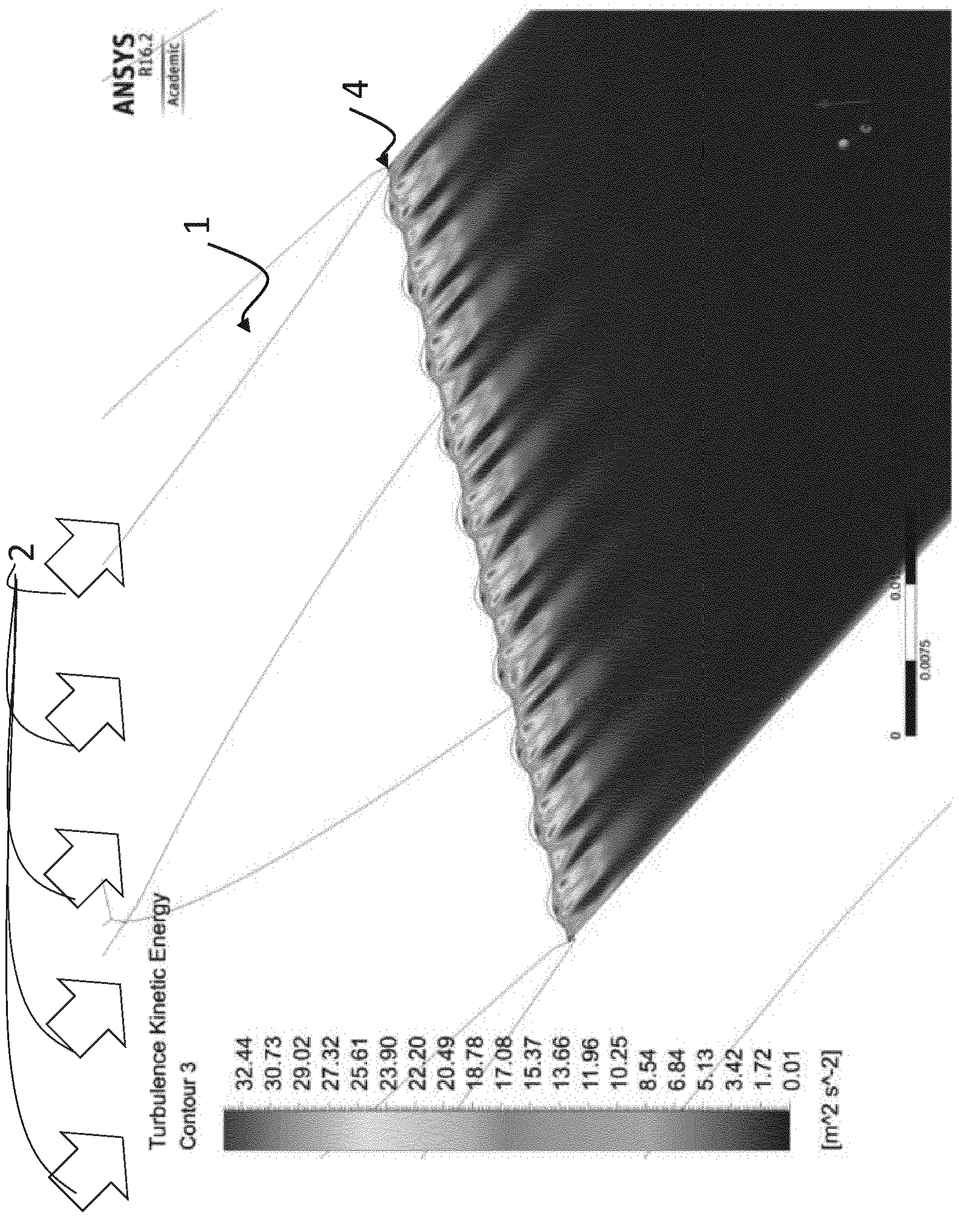

Fig. 4B Trailing edge according to invention

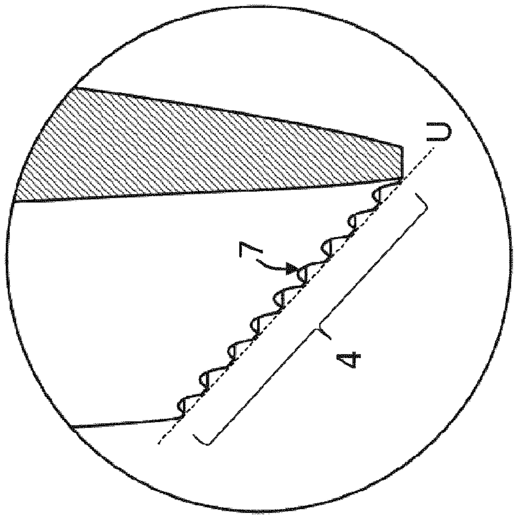

Fig. 5C

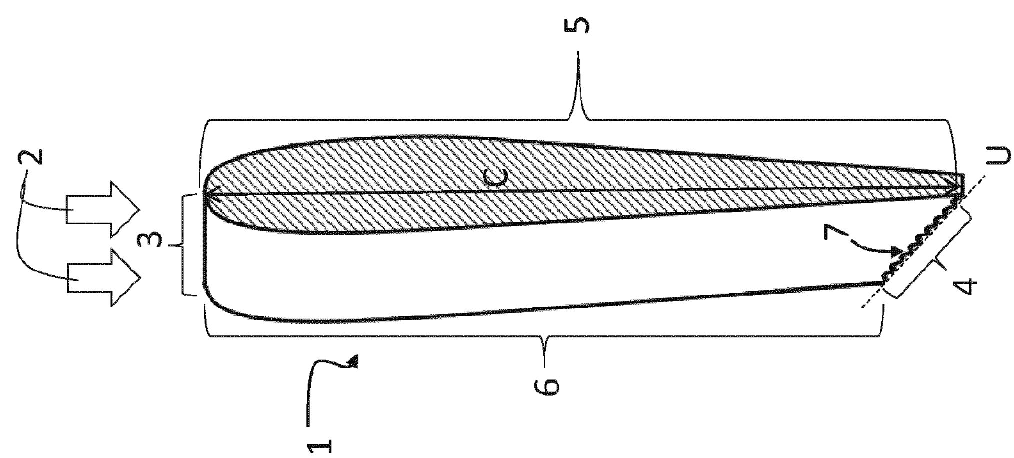

Fig. 5B

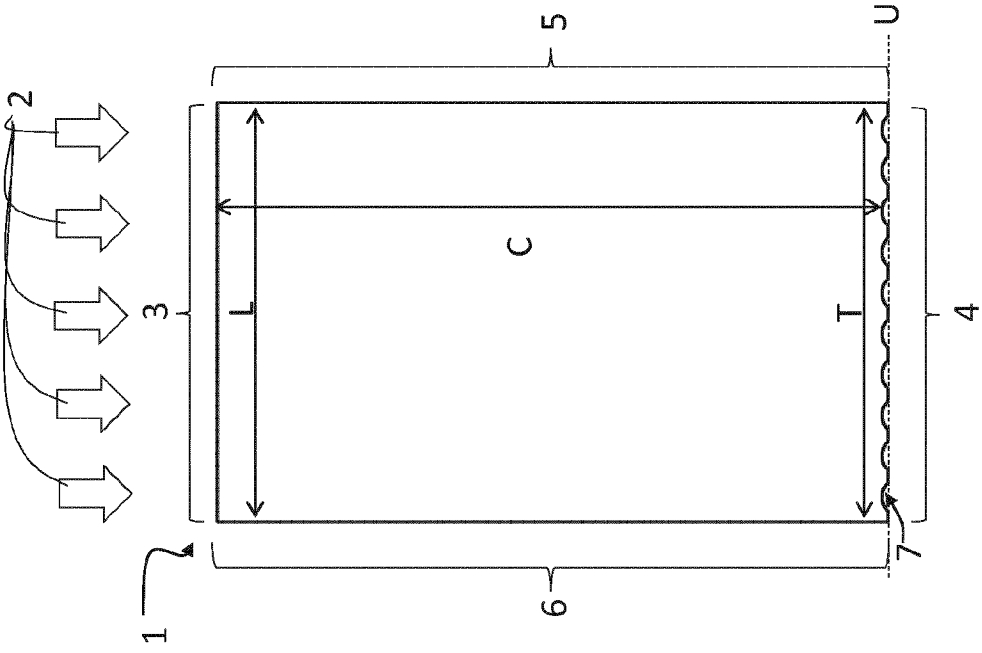

Fig. 5A

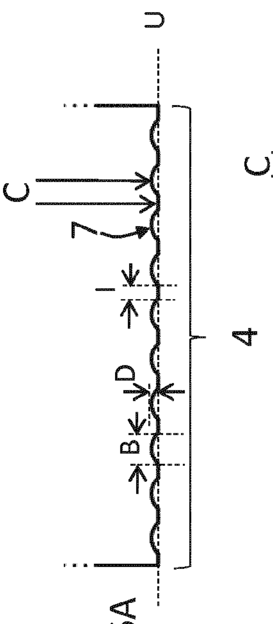

Fig. 6A

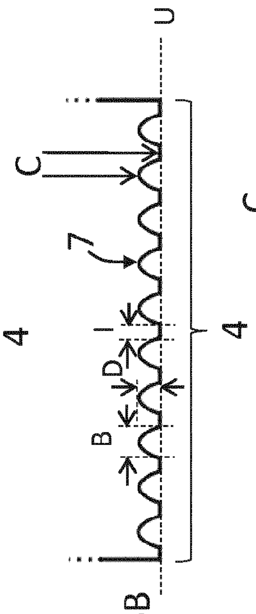

Fig. 6B

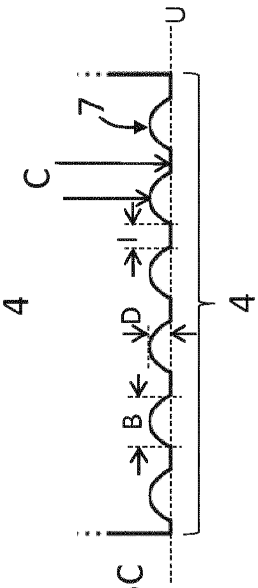

Fig. 6C

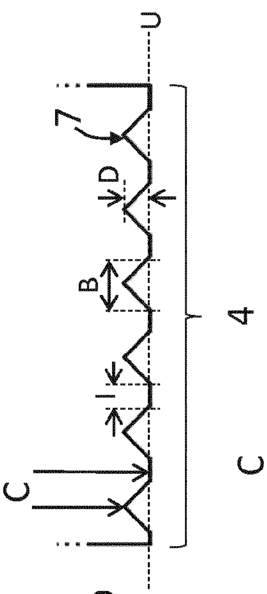

Fig. 6D

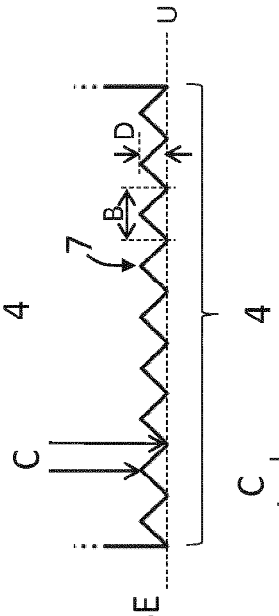

Fig. 6E

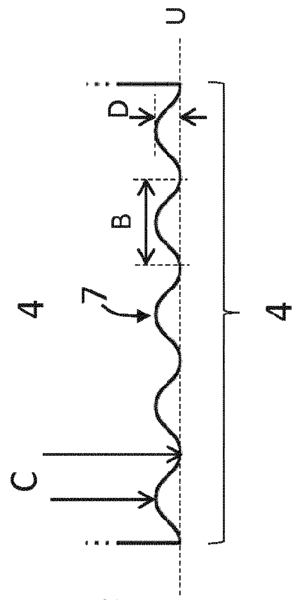

Fig. 6F

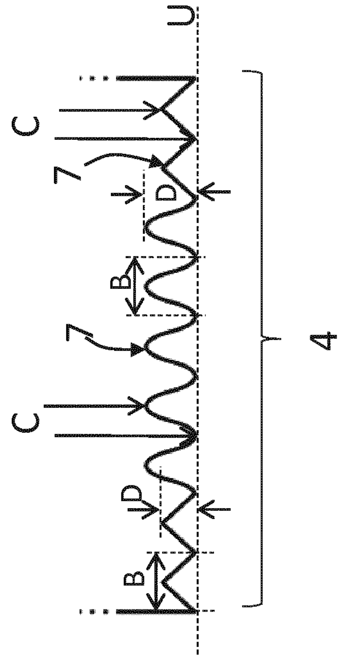

Fig.7C

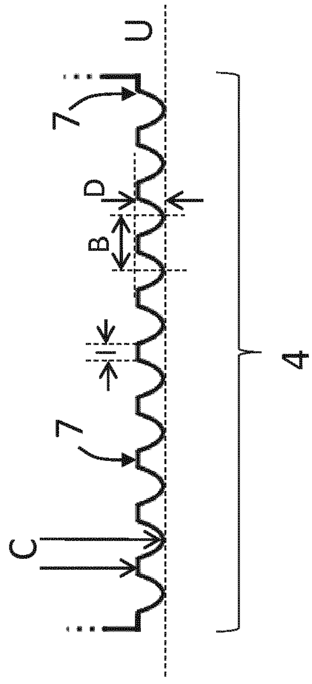

Fig. 7D

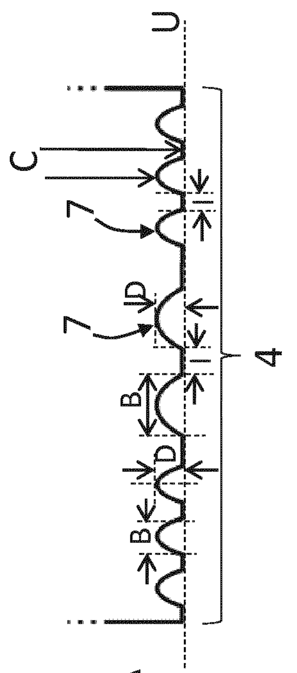

Fig. 7A

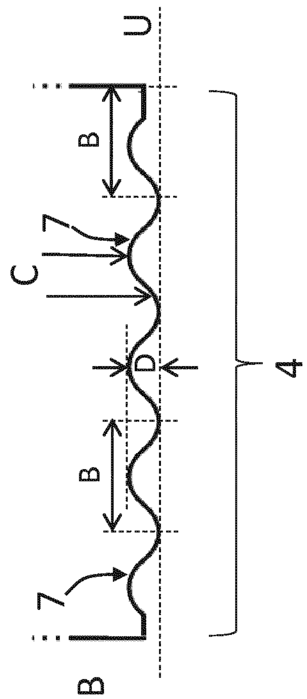

Fig. 7B

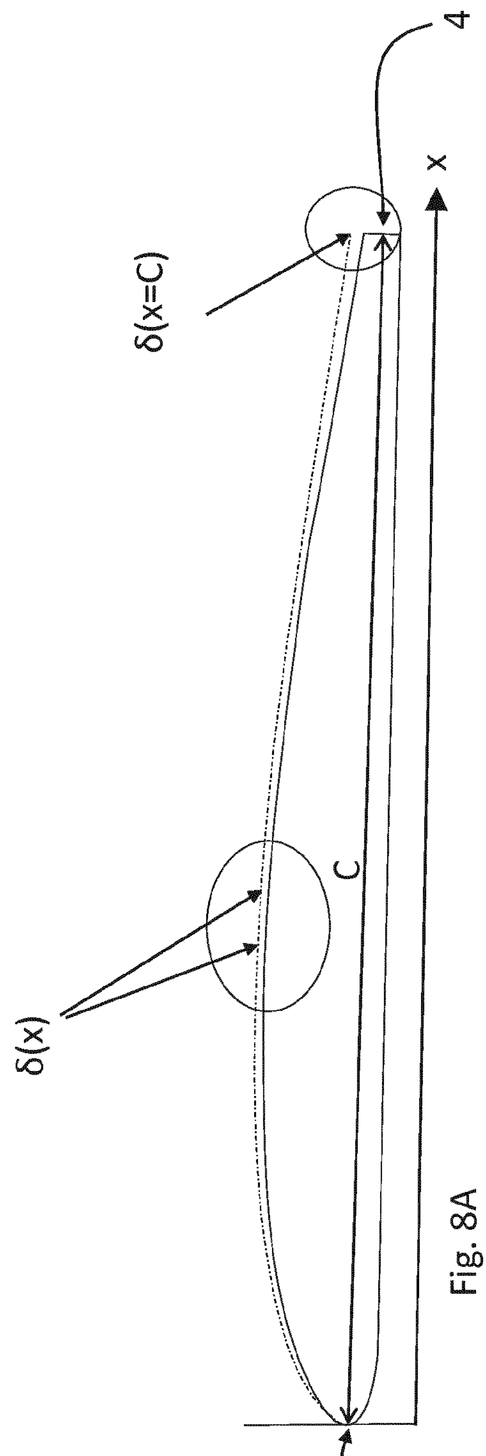

Fig. 8A

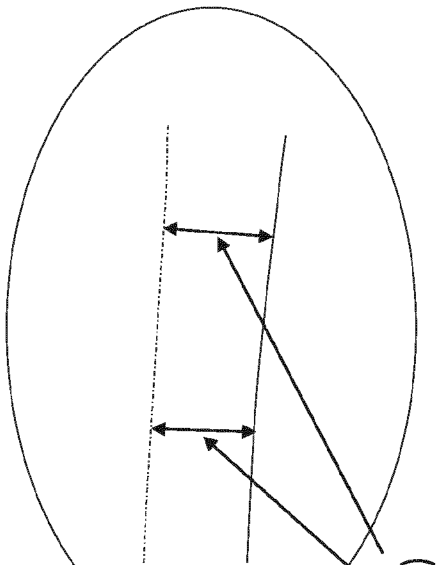

Fig. 8B

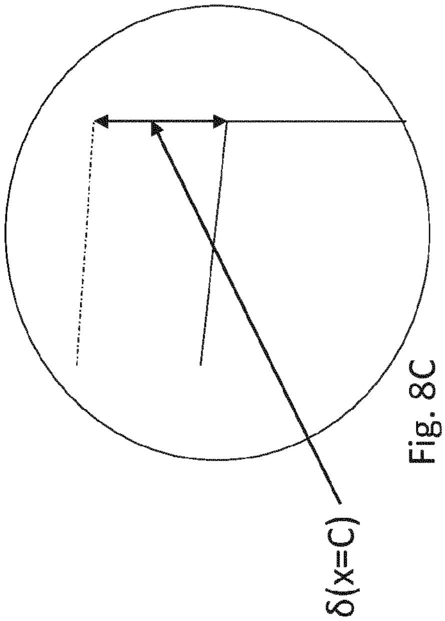

Fig. 8C

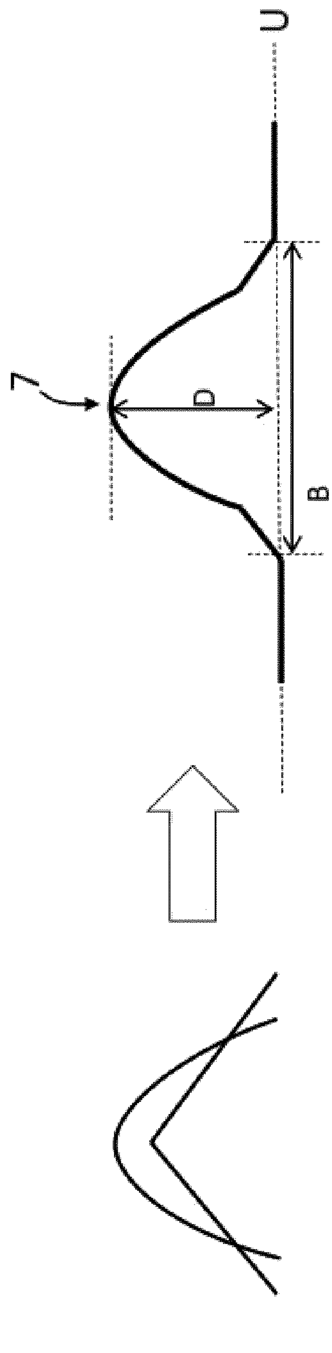

Fig. 9

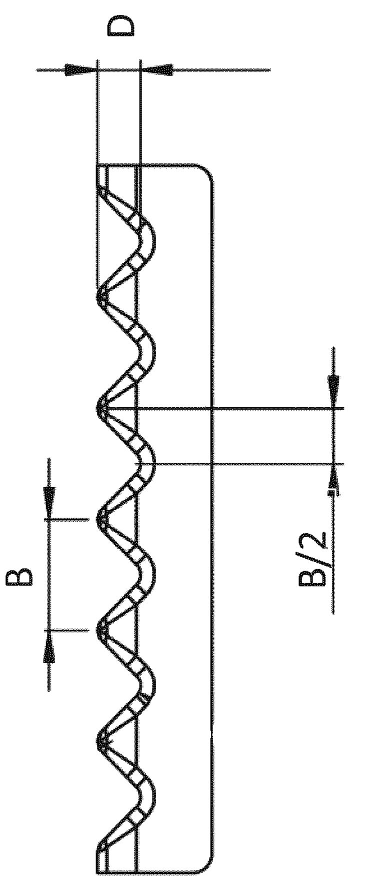

Fig. 10B

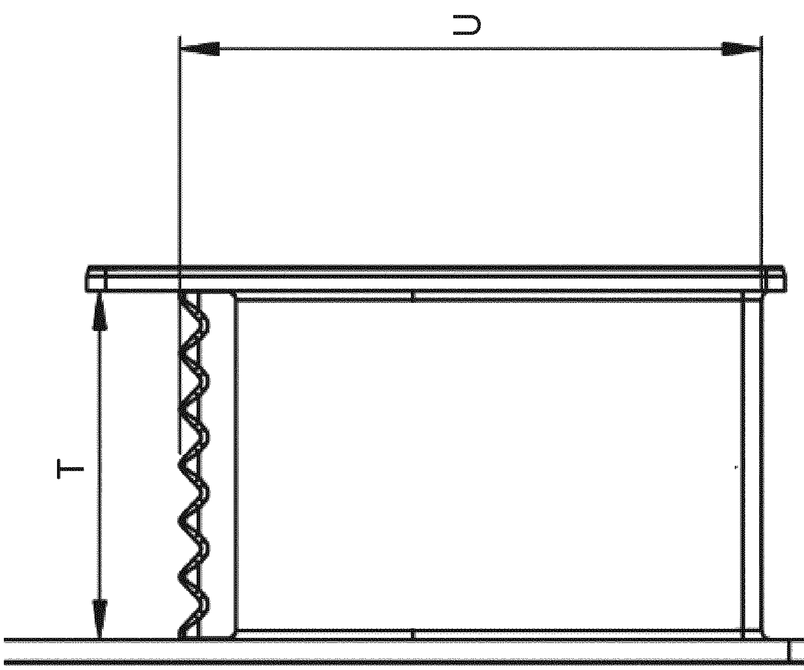

Fig. 10A

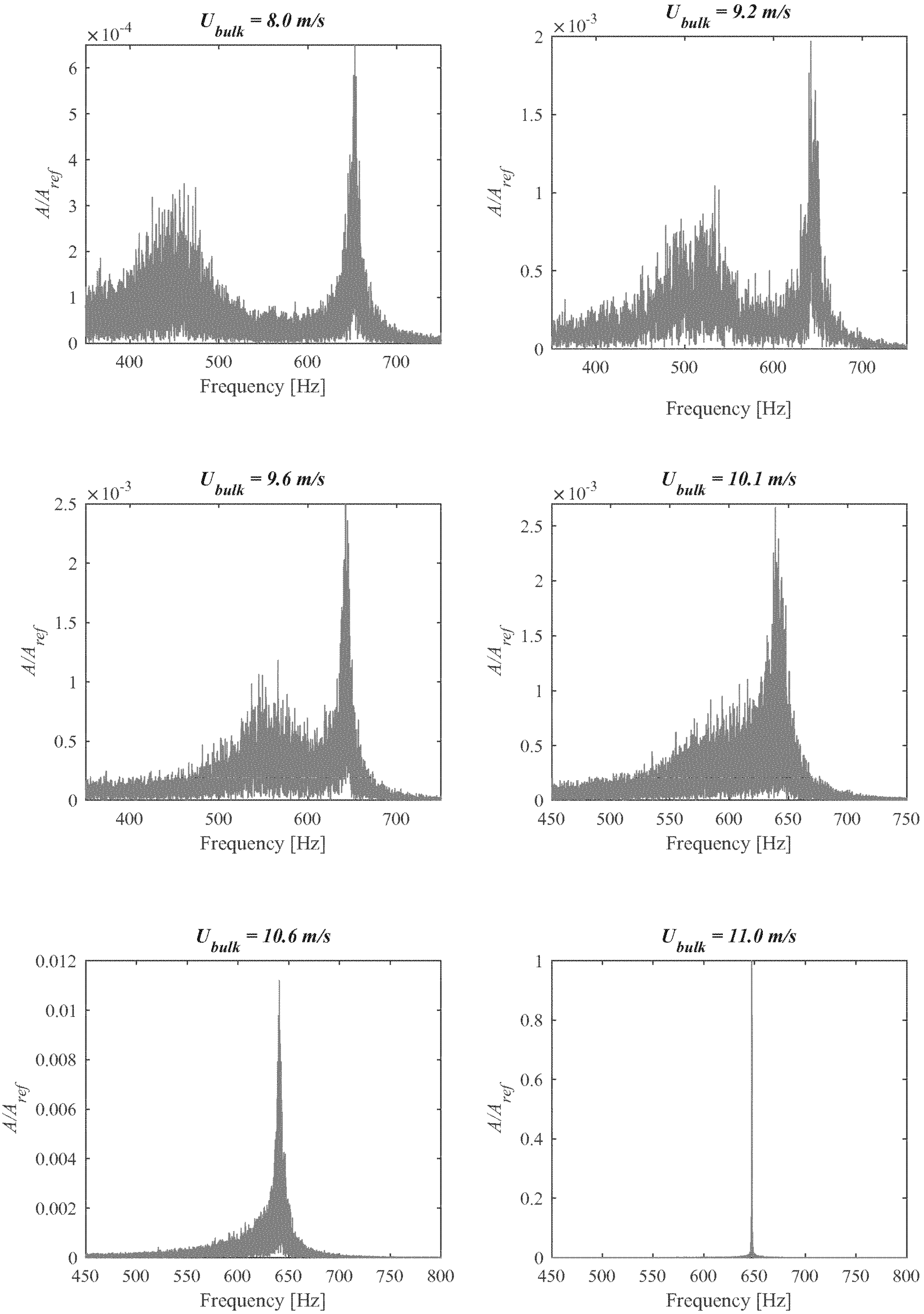
U_{bulk} = 8.0 m/s
$\times 10^{-4}$
A/A_{ref}
Frequency [Hz]
U_{bulk} = 9.2 m/s
$\times 10^{-3}$
A/A_{ref}
Frequency [Hz]
U_{bulk} = 9.6 m/s
$\times 10^{-3}$
A/A_{ref}
Frequency [Hz]
U_{bulk} = 10.1 m/s
$\times 10^{-3}$
A/A_{ref}
Frequency [Hz]
U_{bulk} = 10.6 m/s
A/A_{ref}
Frequency [Hz]
U_{bulk} = 11.0 m/s
A/A_{ref}
Frequency [Hz]

Fig. 11A

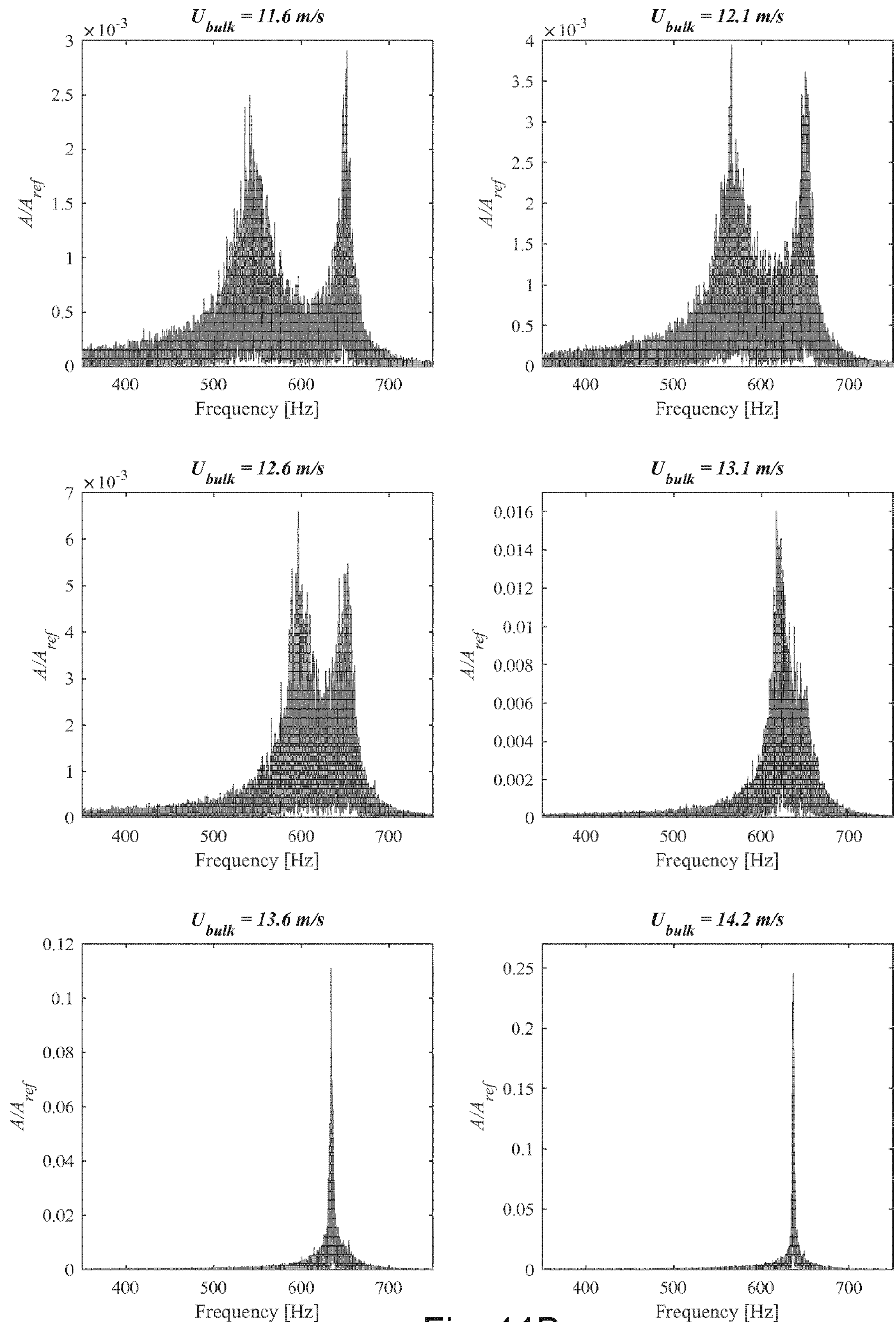
U bulk = 11.6 m/s
U bulk = 12.1 m/s
U bulk = 12.6 m/s
U bulk = 13.1 m/s
U bulk = 13.6 m/s
U bulk = 14.2 m/s
A/A ref
Frequency [Hz]

Fig. 11B

INTERNATIONAL SEARCH REPORT

International application No
PCT/EP2019/067700

A. CLASSIFICATION OF SUBJECT MATTER
INV. B63B1/24 B64C21/10
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)
B63B B64F B64C B63H

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, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 0 245 190 A2 (UNITED TECHNOLOGIES CORP [US]) 11 November 1987 (1987-11-11) column 3, line 44 - column 4, line 61 column 7, line 51 - line 42 figures 2,5A,5B,9-15 -----	1-19
Y	EP 0 375 296 A1 (MARCONI CO LTD [GB]) 27 June 1990 (1990-06-27) column 2, line 33 - column 3, line 7 -----	1-19
Y	US 2 800 291 A (VERYAN STEPHENS ARTHUR) 23 July 1957 (1957-07-23) column 2, line 40 - line 72; figures 1,1a,2,4 -----	1-19
A	EP 0 273 851 A2 (UNITED TECHNOLOGIES CORP [US]) 6 July 1988 (1988-07-06) column 10, line 60 - column 11, line 7; figures 2,17-23 -----	1-19

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"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
20 August 2019	28/08/2019

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	Mauriès, Laurent

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/EP2019/067700

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
EP 0245190	A2	11-11-1987	AU	599974	B2	02-08-1990
			BR	8702101	A	09-02-1988
			CA	1324999	C	07-12-1993
			DE	3772253	D1	26-09-1991
			EP	0245190	A2	11-11-1987
			ES	2025206	B3	16-03-1992
			FI	871930	A	31-10-1987
			IE	59880	B1	20-04-1994
			JP	S62276202	A	01-12-1987
			SG	7592	G	16-04-1992
			US	4786016	A	22-11-1988
EP 0375296	A1	27-06-1990	CA	2006081	A1	21-06-1990
			EP	0375296	A1	27-06-1990
			GB	2232724	A	19-12-1990
			JP	H03121992	A	23-05-1991
			US	5074376	A	24-12-1991
US 2800291	A	23-07-1957	NONE			
EP 0273851	A2	06-07-1988	DE	3770934	D1	25-07-1991
			EP	0273851	A2	06-07-1988
			JP	S63170195	A	14-07-1988
			US	4813633	A	21-03-1989