



(51) International Patent Classification:

F03D 1/06 (2006.01) F03D 7/02 (2006.01)

(21) International Application Number:

PCT/DK2017/050280

(22) International Filing Date:

04 September 2017 (04.09.2017)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

PA 2016 70682 06 September 2016 (06.09.2016) DK

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(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).

Published:

— with international search report (Art. 21(3))

(54) Title: WIND TURBINE BLADE COMPRISING AN AIRFOIL PROFILE

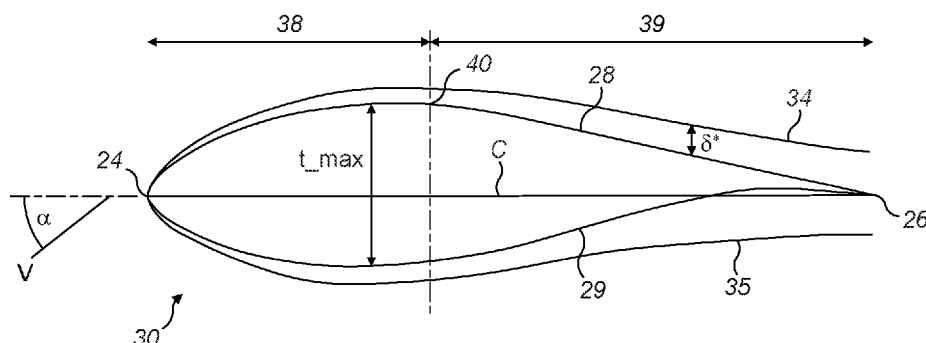


FIG. 3

(57) Abstract: A wind turbine blade comprising an airfoil profile, the airfoil profile comprising: a suction surface and a pressure surface; a leading edge and a trailing edge and a chord extending between the leading edge and the trailing edge; a maximum thickness location between the leading edge and the trailing edge; wherein the suction surface comprises a first inflection point and a second inflection point between the maximum thickness location and the trailing edge.



Wind Turbine Blade Comprising an Airfoil ProfileTechnical field

- 5 The present invention relates to a wind turbine blade comprising an airfoil profile. In particular, the present invention relates to a wind turbine blade airfoil which is designed to reduce trailing edge noise.

Background

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Wind turbines are used to convert kinetic energy from the wind into electrical power. In recent years, wind power has become a more attractive alternative energy source and the number of wind turbines, wind farms, etc. has significantly increased, both on land and off-shore. Traditionally, wind turbines have been located in relatively remote areas where noise
15 from the wind turbine has not been significantly problematic. However, as the number of wind turbines increases, the noise generated thereby has been receiving more attention. In this regard, wind turbines are being located closer to business and residential areas that may have various laws and regulations restricting noise levels.

20

There are two primary sources of noise for a wind turbine: mechanical noise and aerodynamic noise. Mechanical noise may be from the various wind turbine components, such as the gearbox, generator, pitch and yaw controls, hydraulic systems, etc. Aerodynamic noise, on the other hand, may be due to the interaction between the blade and the air flowing over the blade. While mechanical noise can be a significant contributor to
25 overall wind turbine noise, there are some known techniques for reducing mechanical noise, including using vibrations dampers and sound absorbing materials. In contrast, aerodynamic noise may be difficult to mitigate and is believed to be the primary source for wind turbine noise.

30

There may be several sources for aerodynamic noise, including trailing edge noise and blade tip vortex noise. Trailing edge noise, which may include blunt trailing edge vortex-shedding noise and turbulent boundary layer trailing edge noise, has received some attention by power producers and manufacturers. For example, various trailing edge designs, such as a serrated or saw tooth design, have been proposed for reducing trailing
35 edge noise. While such solutions for trailing edge noise are known in the art, the serrated or saw tooth design trailing edge designs can only mitigate the noise to a certain extent.

Accordingly, it is an aim of the present invention to provide a wind turbine blade which has reduced trailing edge noise.

Summary of invention

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According to the present invention there is provided a wind turbine blade comprising an airfoil profile, the airfoil profile comprising: a suction surface and a pressure surface; a leading edge and a trailing edge and a chord extending between the leading edge and the trailing edge; a maximum thickness location between the leading edge and the trailing edge;
10 wherein the suction surface comprises a first inflection point and a second inflection point between the maximum thickness location and the trailing edge.

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Preferably the suction surface comprises: a first convex region between the maximum thickness location and the first inflection point; a first concave region between the first inflection point and the second inflection point; and a second convex region between the second inflection point and the trailing edge.

20

The first concave region may be the only concave region on the suction surface between the leading edge and the trailing edge. In particular, the first concave region may be the only concave region on the suction surface between the maximum thickness location and the trailing edge

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Preferably, the suction surface has only two inflection points between the maximum thickness location and the trailing edge. In particular, there may be only two inflection points between the leading edge and the trailing edge on the suction surface.

30

The first inflection point may be located between 50% and 80% chord. The second inflection point may be located between 65% and 90% chord. The airfoil profile may have a thickness to chord ratio of between 12% and 28%.

35

The airfoil profile may be within a region of the wind turbine blade extending over 50% of a span of the blade from a tip of the blade toward a root of the blade. Preferably, the airfoil profile is within a region of the wind turbine blade extending over 30% of a span of the blade from a tip of the blade toward a root of the blade. The trailing edge may have a thickness of between 0.1% and 0.4% chord.

Brief description of the drawings

In order that the present invention may be more readily understood, examples of the invention will now be described, by way of example only, and with reference to the following

5 Figures, in which:

Figure 1 is a schematic view of a wind turbine;

Figure 2 is a perspective view of a wind turbine blade;

Figure 3 shows a cross section of the wind turbine blade;

10 Figure 4 is a plot showing the curvature of the suction surface of an airfoil according to the invention;

Figure 5 is a plot showing the curvature of the suction surface of an airfoil according to the invention and a conventional airfoil;

Figure 6 is a plot showing the pressure distributions over airfoils;

15 Figure 7 is a plot showing the boundary layer displacement thickness over airfoils;

Figure 8 is a plot showing the curvature of the suction surface of an airfoil according to the invention; and

Figure 9 is a plan view of a wind turbine blade.

20 Detailed description of the invention

Figure 1 shows a horizontal axis wind turbine 10. The wind turbine 10 comprises a tower 12 supporting a nacelle 14 to which a rotor 16 is mounted. The rotor 16 comprises a plurality of wind turbine blades 18 that extend radially from a central hub 19. In this example, the rotor
25 16 comprises three blades 18.

Figure 2 is a view of one of the blades 18 of the wind turbine 10. The blade 18 extends from a generally circular root end 20 to a tip end 22 in a longitudinal 'spanwise' direction, and between a leading edge 24 and a trailing edge 26 in a transverse 'chordwise' direction. The
30 blade 18 comprises a shell 27 formed primarily of fibre-reinforced plastic (FRP). The blade 18 comprises a suction surface 28 and a pressure surface 29.

The blade 18 transitions from a circular profile to an airfoil profile moving from the root end 20 of the blade 18 towards a shoulder 25 of the blade 18, which is the widest part of the
35 blade 18 where the blade 18 has its maximum chord. The blade 18 has an airfoil profile of progressively decreasing thickness in an outboard portion of the blade 18, which extends from the shoulder 25 to the tip 22 of the blade 18.

One of the sources of noise from a wind turbine is so called trailing edge noise. The trailing edge noise is caused when a turbulent boundary layer around the blade 18 interacts with the trailing edge 26 of the blade. In particular, at rated power trailing edge noise is mainly dominated by a turbulent boundary layer on the suction surface of the blade. A boundary layer on the surface of the airfoil has a height above the surface of the blade and there is a correlation between increased boundary layer displacement thickness and increased trailing edge noise. Therefore, if an airfoil is designed such that boundary layer displacement thickness is reduced (compared to a conventional airfoil) then it is expected that the trailing edge noise will be reduced.

Figure 3 shows an airfoil 30 and the boundary layer over the airfoil profile. The airfoil 30 is a used on the blade 18. The airfoil comprises a leading edge 24 and a trailing edge 26 as noted above, and a chord line C which extends from the leading edge to the trailing edge. The airfoil has a thickness between the suction surface 28 and the pressure surface 29 and the maximum thickness is defined as $t_{\max}$. By "thickness" is meant the distance measured perpendicular to the chord line between the suction surface and the pressure surface. The oncoming wind for the airfoil profile 30 is shown as V and this is at an angle of attack α to the chord line C.

Positions along the chord can be expressed as a percentage of the chord "c" (that is the chord length) measured from the leading edge to the trailing edge; i.e. the leading edge is at 0% chord and the trailing edge is at 100% chord. The maximum thickness $t_{\max}$ is at a maximum thickness location of 35% chord (which can also be expressed as $0.35c$) in this example.

As is well understood in the field of aerodynamics, a boundary layer is formed by the airflow over the airfoil profile. The boundary layer displacement thickness increases from a stagnation point at (or near) the leading edge to the trailing edge of the blade. The boundary layer profile is shown on the suction surface as 34 and on the pressure surface as 35 (as will be appreciated, the boundary layer is not drawn to scale). In particular, referring to the boundary layer 34 on the suction surface, from the leading edge 24 to the maximum thickness location at $0.35c$ the boundary layer is laminar. Downstream of the maximum thickness location the boundary layer becomes turbulent depending on the flow angle of attack and airfoil geometry. In Figure 3, the boundary layer on the suction surface 28 is laminar in region 38 and it is turbulent in region 39.

The skilled person will realise that the transition point 40 on the suction surface 28 between a laminar boundary layer and a turbulent boundary layer depends on the properties of the flow, in particular the Reynolds number and the angle of attack α .

- 5 During normal operation of the wind turbine blade 18 there is no flow separation from the airfoil profile 30. That is the angle of attack α is not so large that the flow over the airfoil profile separates from the suction surface 28. The boundary layer displacement thickness at any location is defined as δ^* .
- 10 The boundary layer displacement thickness increases moving from the leading edge to the trailing edge. As discussed above, a relatively thicker boundary layer results in a relatively higher trailing edge noise. The boundary layer trailing edge noise may be due to the scattering of turbulent fluctuations within the blade boundary layer at the trailing edge which results in noise generation. Therefore, the airfoil of the invention has been designed to
- 15 reduce the boundary layer displacement thickness on the suction surface of the airfoil in order to reduce the noise.

Figure 4 is an enlarged view of the suction surface 28 of the airfoil 30 between 50% chord and 100% chord, the chordwise position being shown on the horizontal axis. It should be

20 noted that the plots are not to scale – that is the length scale is different on the horizontal axis and the vertical axis. Between the maximum thickness location and the trailing edge, three regions are present in this section of the suction surface 28:

- A first convex region 42
- A concave region 43
- 25 • A second convex region 44

The concave/convex form is seen from a view point outside of the airfoil profile 30. That is the convex regions curve outwards and the concave region curves inwards.

A conventional airfoil shape (which is not shown in Figure 4) has a suction surface which is

30 convex in shape from the leading edge to the trailing edge.

The curvature change of the suction surface 28 helps to keep the boundary layer thin and therefore reduce the trailing edge noise, as will be described in more detail with respect to Figures 5 to 7. However, the geometry of the suction surface at the rear part of the airfoil will

35 first be described.

In this example, the first convex region 42 extends from the leading edge of the blade to a position at 70% chord; the concave region 43 extends from 70% chord to 85% chord; and the second convex region extends from 85% chord to 100% chord.

- 5 The first and second convex regions 42, 44 are defined by the slope of the suction surface 28 having a negative second derivative. The concave region 43 is defined by the slope of the suction surface 28 having a positive second derivative.

10 Expressed another way, in this example, at 70% chord there is a first inflection point 50 on the suction surface 28 where the suction surface changes from a convex shape to a concave shape; and at 85% chord there is a second inflection point 52 on the suction surface 28 where the suction surface changes from a concave shape to a convex shape. At the inflection points the second derivative of the slope of the suction surface 28 is zero.

- 15 When the airfoil 30 is oriented such that the suction surface 28 is at the top and the pressure surface 29 is at the bottom, the first convex region 42 can also be described as “a first concave down region”; the concave region 43 can be described as “a first concave up region”; and the second convex region 44 can be described as “a second concave down region”.

20

The first inflection point 50 between the first convex region 42 and the concave region 43 is shown at 70% chord in the example of Figure 4. However, it could be located at other chordwise positions, such as between 50% and 80% chord. Similarly, the second inflection point 52 between the concave region 43 and the second convex region 44 is shown at 85%
 25 chord in the example of Figure 4. However, it could be located at other chordwise positions, such as between 65% and 90% chord depending on the design goal.

The first convex region 42, the concave region 43 and the second convex region 44 will all have a radius of curvature. The radius of curvature of the first convex region 42 will depend
 30 on the curvature of the suction surface 28 all the way to the leading edge and so it is not defined in Figure 4. The concave region 43 has a radius of curvature defined as R_1 , where the radius centre is above the suction surface 28 (when the airfoil is positioned with the suction surface pointing upwards). The second convex region 44 has a radius of curvature defined as R_2 , where the radius centre is below the suction surface 28 (when the airfoil is
 35 positioned with the suction surface pointing upwards).

Figure 5 shows (in a solid line) the suction surface 28 of the wind turbine blade airfoil of present invention having the first convex region, the concave region and the second convex region. Also shown (in a dashed line) is a suction surface 28' of a conventional airfoil, that is an airfoil that has a convex shape extending all the way from the leading edge to the trailing edge. The maximum thickness is the same for both airfoils and occurs at the same chordwise location, that is 35% chord in this example.

For convenience, the wind turbine blade airfoil 30 of the present invention will be referred to as the "modified airfoil" which will have "modified suction surface 28". The conventional airfoil will have a "conventional suction surface 28".

Referring to Figure 6, this shows the pressure distribution over the modified suction surface 28 and the conventional suction surface 28' which are shown in Figure 5. As per convention, the pressure distribution is shown in terms of the pressure coefficient C_p , where C_p is the difference between local static pressure and freestream static pressure, non-dimensionalised by the free stream dynamic pressure; and negative values of C_p are higher on the plot in Figure 6. Near the leading edge, the value of C_p is 1.0 at the stagnation point of the airfoil.

The pressure distribution over the modified suction surface 28 is shown by the solid line 55 and, for comparison, the pressure distribution over the conventional suction surface is shown by the dashed line 55'. From the leading edge to about 35% chord the airfoils have the same shape of suction surface so the pressure distributions are the same in this region.

Taking the pressure distribution 55' over the conventional airfoil first, the pressure coefficient decreases rapidly to a point near the near maximum thickness of the airfoil. The pressure distribution then rises until the pressure coefficient increases to a small positive value at the trailing edge. The region where the pressure coefficient rises (which corresponds to the region between the location of maximum thickness and the trailing edge) is known as the region of adverse pressure gradient. This adverse pressure gradient will retard the motion of the air flowing over the airfoil, i.e. the velocity of the airflow over the airfoil is reduced. At point 56' there is a kink in the pressure distribution 55' as the boundary layer transitions from laminar to turbulent.

Considering the pressure distribution over the modified suction surface 28 of the modified airfoil 30 which is shown by the solid line 55, it can be seen that in different regions it is above or below the pressure distribution over the conventional suction surface 28' of the

conventional airfoil. Three regions can be identified aft of the maximum thickness location moving toward the trailing edge:

First region 60: Here the pressure coefficient over the modified suction surface 28 is lower than that of the pressure coefficient over the conventional suction surface 28'. This is because the curvature of the modified suction surface 28 has a smaller gradient compared to the curvature of the conventional suction surface 28', and so the adverse pressure gradient is smaller.

Second region 61: Here the pressure coefficient over the modified suction surface 28 is higher than that of the pressure coefficient over the conventional suction surface 28'. This is because the curvature of the modified suction surface 28 has a greater gradient compared to the curvature of the conventional suction surface 28', and so the adverse pressure gradient is greater.

Third region 62: Here the pressure coefficient over the modified suction surface 28 is lower than that of the pressure coefficient over the conventional suction surface 28'. This is because the curvature of the modified suction surface 28 has a smaller gradient compared to the curvature of the conventional suction surface 28', and so the adverse pressure gradient is smaller.

It should be noted that the interfaces between the first, second and third regions 60, 61, 62 do not necessarily correspond with the first and second inflection points 50, 52.

The adverse pressure gradient results in the boundary layer displacement thickness increasing. Turning to Figure 7, this shows the boundary layer displacement thickness δ^* over the modified suction surface 28 and the conventional suction surface 28' of Figure 5. The solid line 70 is the boundary layer displacement thickness over the modified suction surface 28 and the dashed line 70' is the boundary layer displacement thickness over the conventional suction surface 28'. The boundary layer displacement thickness is plotted from 30% chord to the trailing edge. For convenience, the boundary layer displacement thickness for each suction surface 28 and 28' is shown as having the same height at 30%; and, the transition of the boundary layer from laminar to turbulent is not shown. It can be seen that the boundary layer displacement thickness 70 of the modified airfoil 30 has a smaller thickness at the trailing edge compared to the boundary layer 70' of the conventional airfoil. This is due to the pressure distribution on the suction surface of the airfoil which in turn is due to the suction surface having a concave region between two convex regions. As the

boundary layer displacement thickness at the trailing edge has been reduced, this means that the trailing edge noise of the airfoil will be reduced.

Referring again to Figure 6, aft of the maximum thickness location at 35% chord, flow over the suction surface of the airfoil decelerates due to the adverse pressure gradient. As has been explained above, this results in the boundary layer displacement thickness growing which will lead to trailing edge noise. The modified airfoil 30 can reduce the trailing edge noise by reducing the boundary layer displacement thickness at the trailing edge, as compared to a conventional airfoil.

The second convex region 44 on the suction surface is in effect a localised bump on the airfoil surface. As the air flows over the suction surface it is decelerating after the location of maximum thickness (in this example at 35% chord). But, when the airflow encounters the localised bump, this bump will accelerate the flow. As the airflow accelerates over the bump, (i.e. as it accelerates over the second convex region 44) the coefficient of pressure is increased slightly and there is now a favourable pressure gradient in this region of the airfoil (or there is a zero pressure gradient for some length).

The acceleration of the flow over the second convex region 44 has the effect of slowing down the growth rate of the boundary layer displacement thickness. As the rate of growth of the boundary layer displacement thickness is reduced, the boundary layer displacement thickness at the trailing edge will be smaller (than that of a conventional airfoil) and so the trailing edge noise will be reduced compared to a conventional airfoil.

The acceleration of the flow over the second convex region 44 also helps the boundary layer to stay attached to the surface suction, especially at high angles of attack. By helping to keep the boundary attached to the suction surface will also lead to a reduction of trailing edge noise.

The reason for the concave region 43 on the suction surface 28 is to allow the localised bump (i.e. the second convex region 44) to be smoothly blended into the airfoil profile. If there was no concave region then the addition of a localised bump would introduce a sharp corner on the suction surface which would in itself generate noise.

Figure 8 shows a further example of a suction surface 28 having a first convex region 42, a first concave region 43 and a second convex region 44. In this example the first concave region 43 has a minimum point at 90 and the second convex region 44 has a maximum point

at 91. It can be seen that maximum point 91 is higher than the minimum point 90 – or expressed another way, the maximum point 91 is further from the chord line than the minimum point 90. When compared with the example shown in Figure 4, this results in a more pronounced bump on the suction surface at the trailing edge. This more pronounced bump can accelerate the flow further and lead to a further reduction in the boundary layer displacement thickness at the trailing edge.

The airfoil 30 of the invention which comprises a first convex region, a concave region and a second convex region is used on the wind turbine blade 18. Figure 9 shows a plan view of the wind turbine blade 18. A wind turbine blade can typically be divided into three regions in a spanwise direction: An inboard region 100 adjacent to the root 20 and extending up to shoulder 25 of the blade 18. A mid-board region 101 extending from the inboard region 100 toward the tip 22. And, a tip region 102 extending from the mid-board region to the tip 22.

The airfoil 30 of the invention is used in the tip region 102 of the blade. As the tips of blades of horizontal axis wind turbine have the highest rotational speeds, the trailing edge noise from the tip region is higher than for other parts of the blade.

In the example shown in Figure 9, the tip region 102 extends over approximately 30% of the span as measured from the tip. However, the tip region 102 in other examples may extend over 20%, 25%, 35%, 40%, 45% or 50% of the span as measured from the tip. Preferably, the airfoil 30 will operate at a Reynolds number of between 3 million and 9 million.

The modified airfoil 30 will have a thickness to chord ratio (that is the maximum thickness to chord ratio). The thickness to chord ratio may be between 12% and 28%. Within this thickness range the modified airfoil has been found to reduce trailing edge noise.

In an example where the maximum thickness of the airfoil is $0.2c$ and maximum thickness $t_{\max}$ is at a $0.35c$, it has been found beneficial for the first inflection point to be at $0.7c$ and the second inflection point to be at $0.85c$ chord. The first inflection point is positioned above the chord line at a height of $0.07c$, and the second inflection point is positioned above the chord line at a height of $0.03c$.

The airfoil 30 itself is designed such that there is a reduction in trailing edge noise in comparison to a conventional airfoil. This can avoid the need to attach a separate noise reduction element, such as a serrated trailing edge, to the wind turbine blade. The wind turbine blade 18 comprising the airfoil 30 can be manufactured in a conventional process in

a mould and so the addition of the localised bump at the trailing edge does not add any additional cost to the manufacture of the blade. This is advantageous as the noise reduction is achieved without any increase in material or labour.

- 5 The wind turbine blade 18 is manufactured from two half shells which form the suction surface and the pressure surface. These half shells are bonded together at the trailing edge and then the trailing edge is trimmed to create a smooth trailing edge. The resulting trailing edge has some thickness, which may be in the order of 2mm or between 0.1% and 0.4% chord. In other words, the trailing edge of the blade does not have zero thickness and this
- 10 may result in trailing edge noise. However, the modified airfoil 30 will mitigate against this increase in noise, which may arise from the trailing edge having a non-zero thickness.

The skilled person will appreciate that the pressure distribution plots in Figure 6 and the boundary layer displacement thickness plot in Figure 7 are graphical representations of the

15 pressure distribution/boundary layer displacement thickness, rather than real values.

Many modifications may be made to the examples described above without departing from the scope of the present invention as defined in the accompanying claims.

Claims

1. A wind turbine blade (18) comprising an airfoil profile (30), the airfoil profile comprising:
 - 5 a suction surface (28) and a pressure surface (29);
 - a leading edge (24) and a trailing edge (26) and a chord extending between the leading edge and the trailing edge;
 - a maximum thickness location between the leading edge (24) and the trailing edge (26);
 - 10 wherein the suction surface (28) comprises a first inflection point (50) and a second inflection point (52) between the maximum thickness location and the trailing edge (26).
2. A wind turbine blade according to claim 1, wherein the suction surface (28) comprises:
 - 15 a first convex region (42) between the maximum thickness location and the first inflection point (50);
 - a first concave region (43) between the first inflection point (50) and the second inflection point (52); and
 - a second convex region (44) between the second inflection point (52) and the trailing edge (26).
 - 20
3. A wind turbine blade according to claim 2, wherein the first concave region (43) is the only concave region on the suction surface (28) between the leading edge (24) and the trailing edge (26).
25
4. A wind turbine blade according to any one of the preceding claims, wherein the suction surface has only two inflection points between the maximum thickness location and the trailing edge (26).
- 30 5. A wind turbine blade according to any one of the preceding claims, wherein the first inflection point (50) is located between 50% and 80% chord, as measured from the leading edge.
6. A wind turbine blade according to any one of the preceding claims, wherein the second inflection point (52) is located between 65% and 90% chord, as measured from the leading edge.
35

7. A wind turbine blade according to any of the preceding claims, wherein the airfoil profile (30) has a maximum thickness to chord ratio of between 12% and 28%.
8. A wind turbine blade according to any one of the preceding claims, wherein the airfoil profile (30) is within a region of the wind turbine blade extending over 50% of a span of the blade from a tip (22) of the blade toward a root (20) of the blade.
9. A wind turbine blade according to any one claims 1 to 7, wherein the airfoil profile (30) is within a region of the wind turbine blade extending over 30% of a span of the blade from a tip (22) of the blade toward a root (20) of the blade.
10. A wind turbine blade according to any one of the preceding claims, wherein the trailing edge (26) has a thickness of between 0.1% and 0.4% chord.
11. A wind turbine having a wind turbine blade according to any one of the preceding claims.

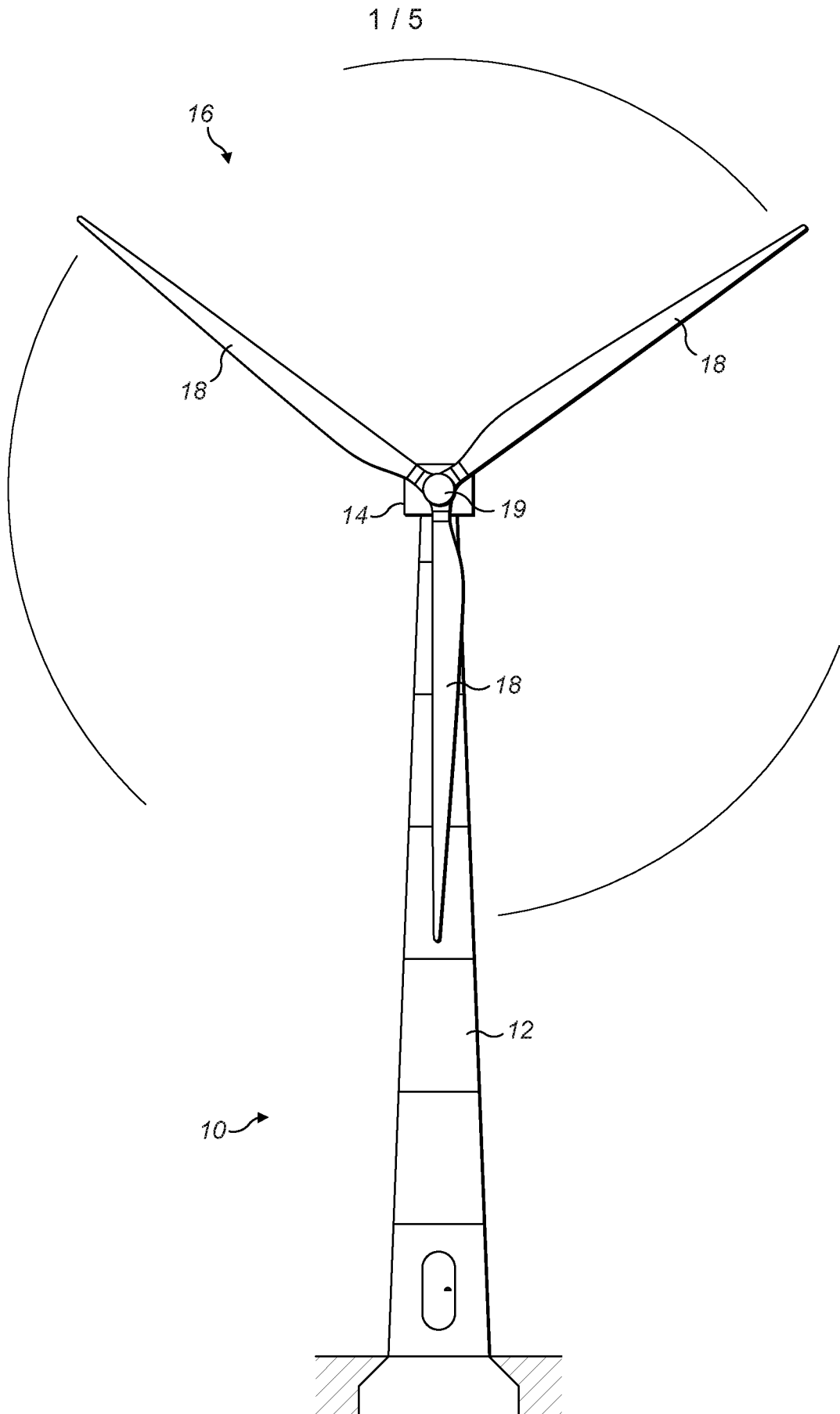
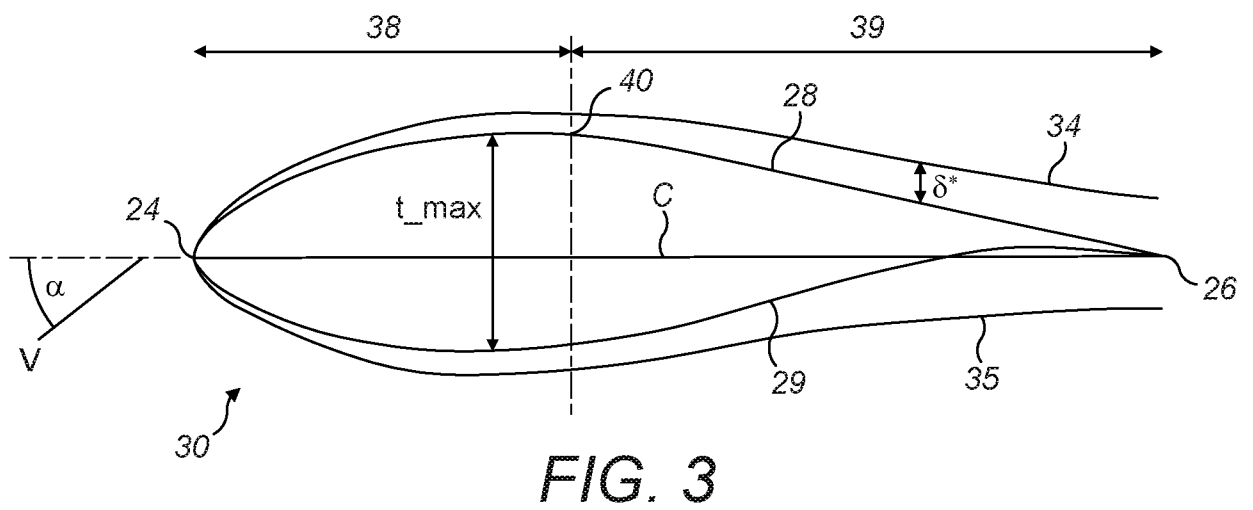
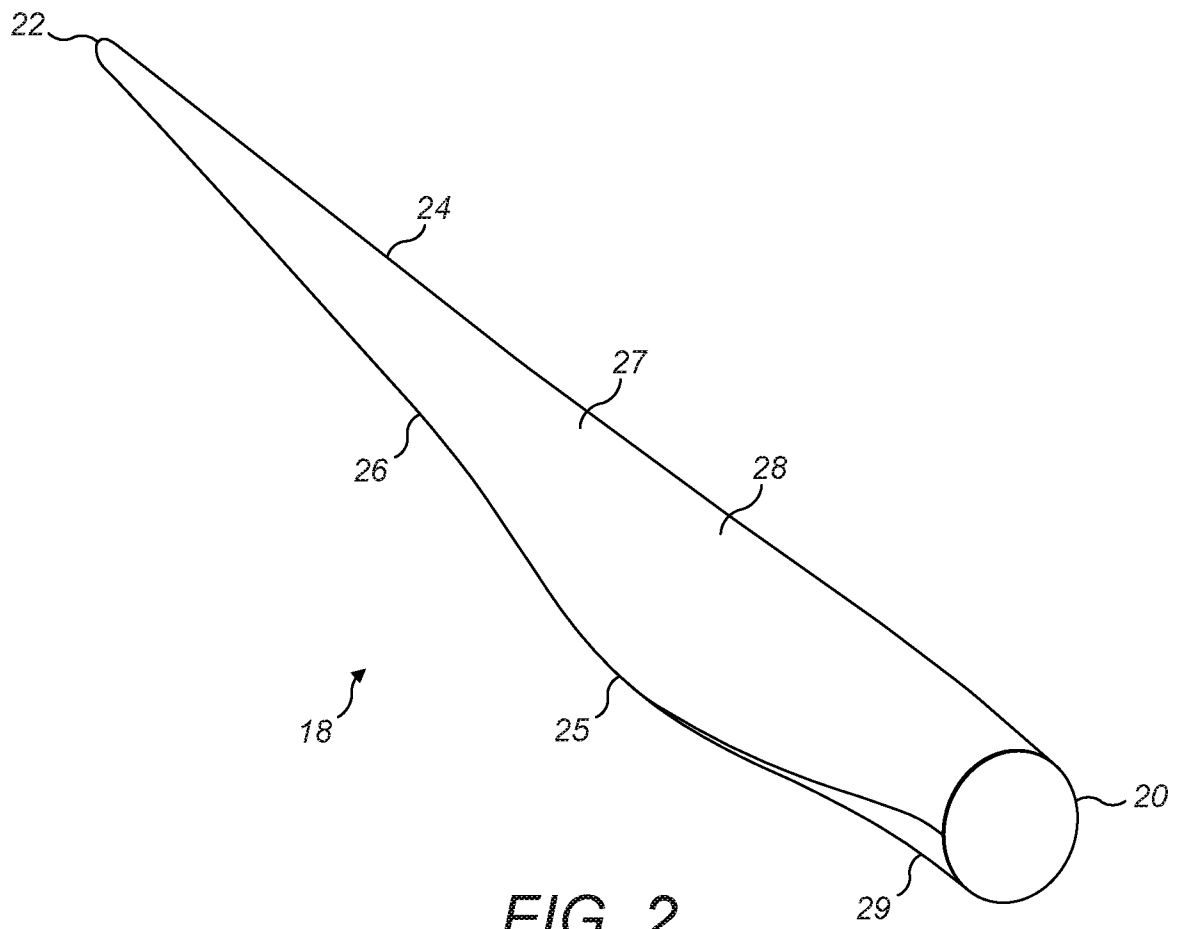
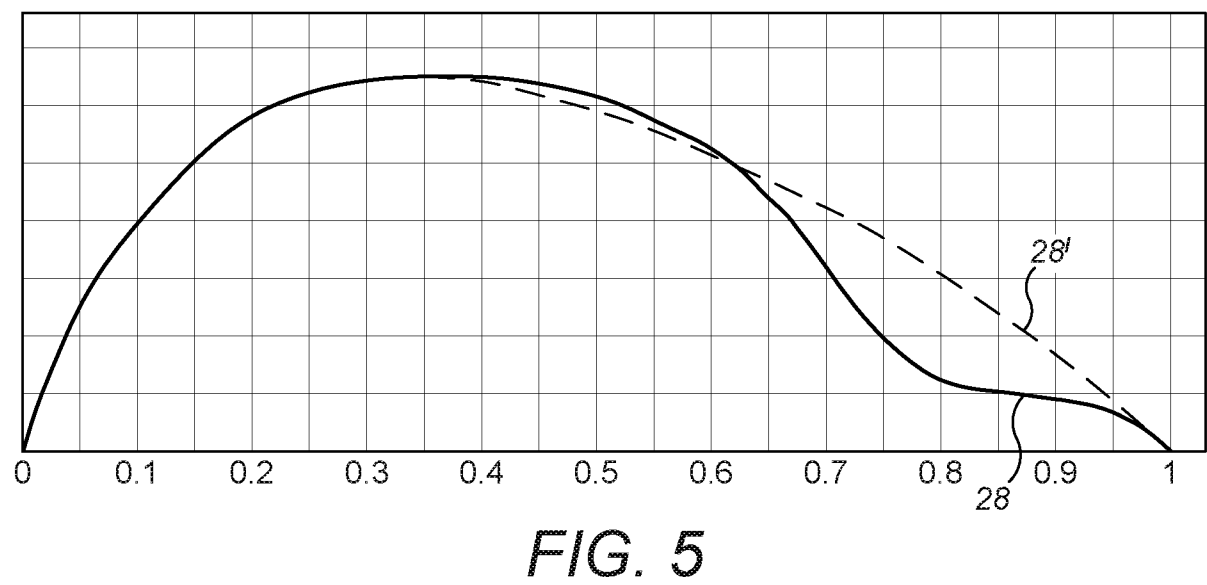
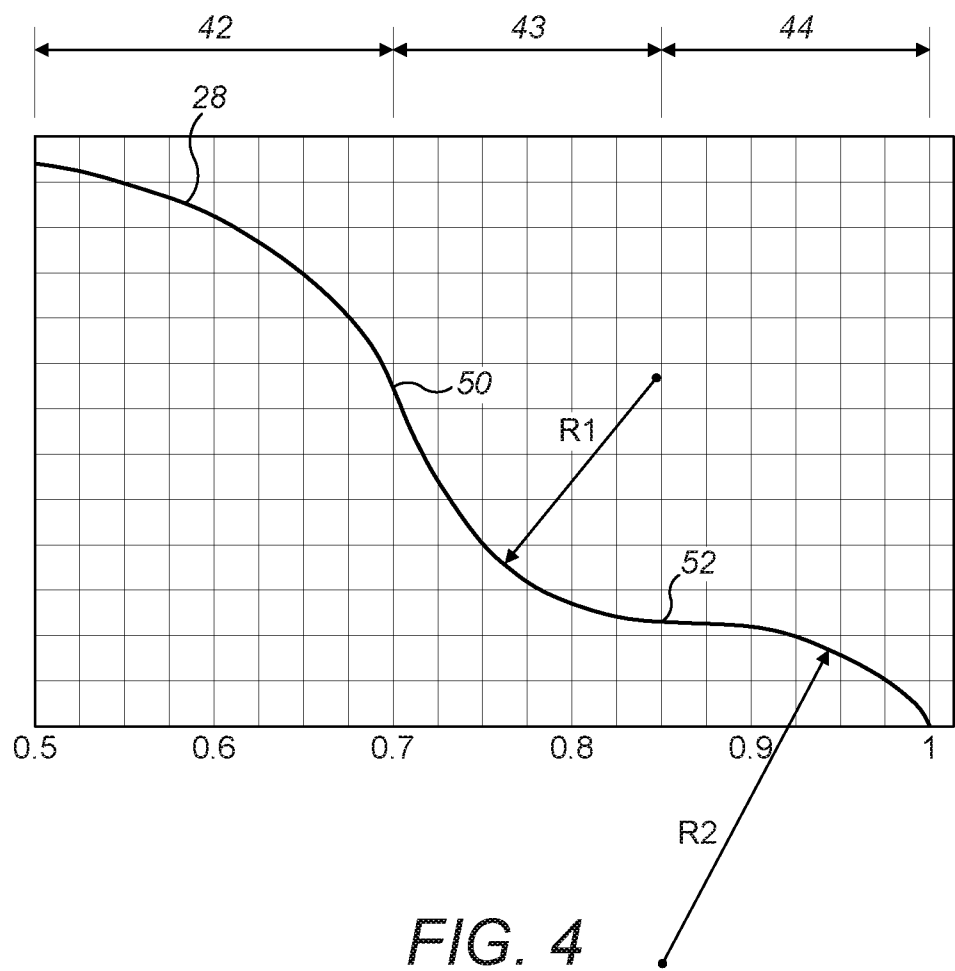


FIG. 1

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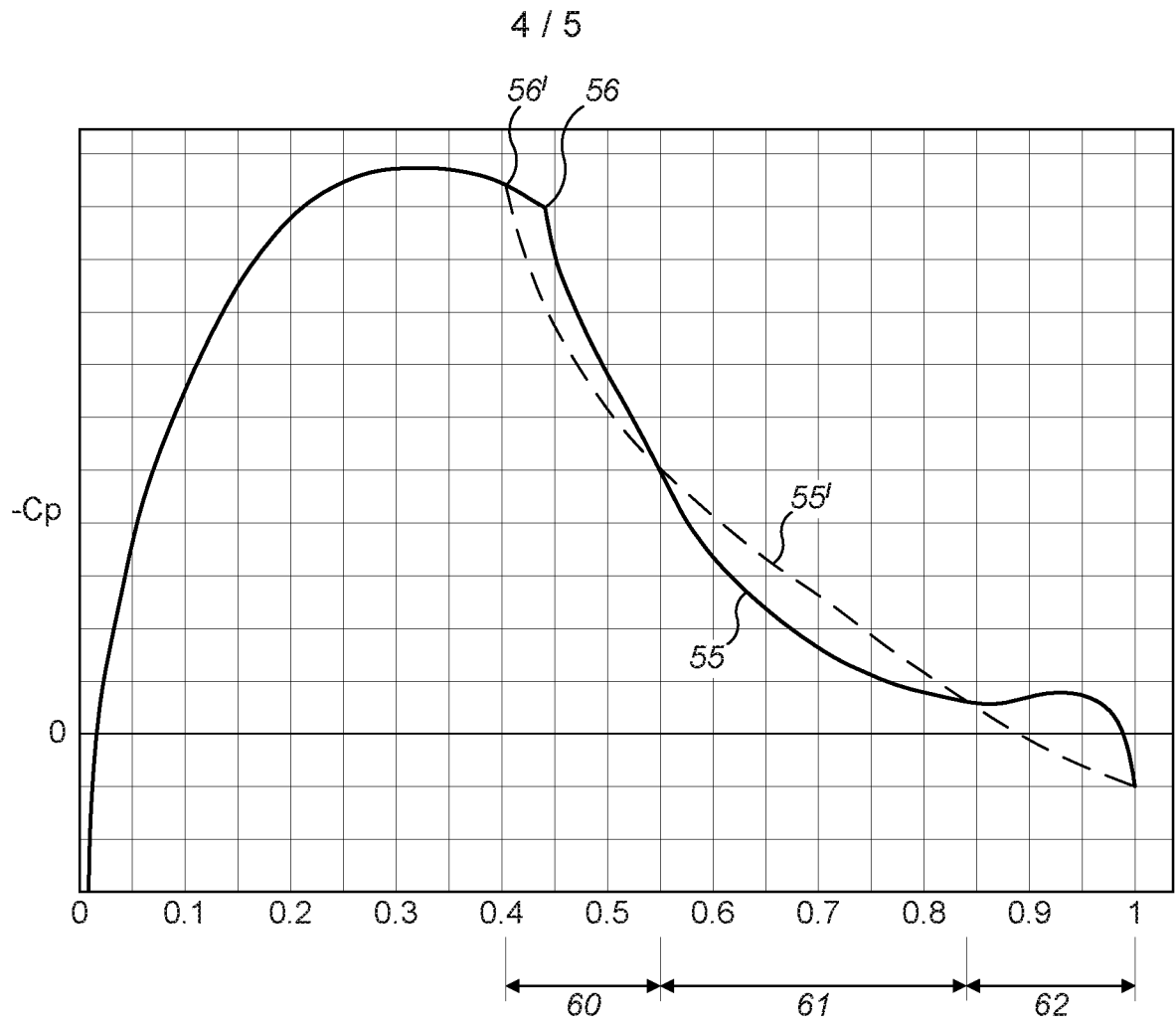


FIG. 6

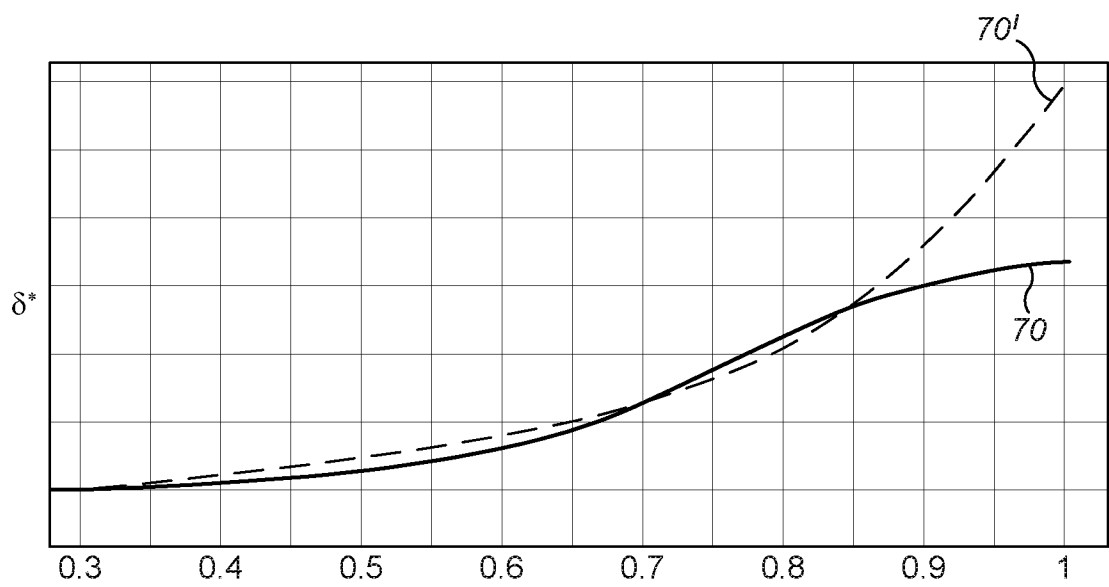


FIG. 7

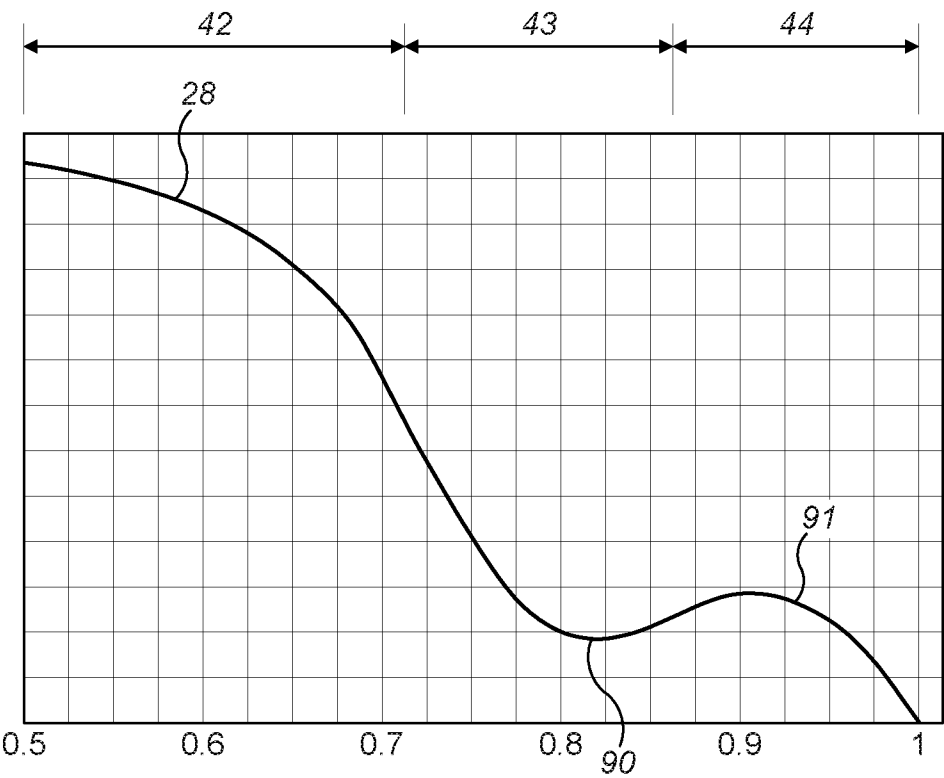


FIG. 8

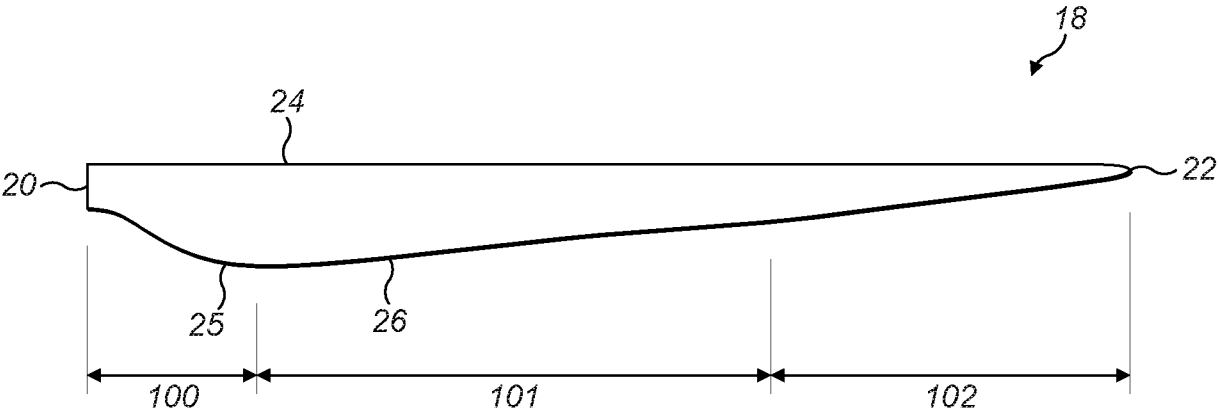


FIG. 9

INTERNATIONAL SEARCH REPORT

International application No
PCT/DK2017/050280

A. CLASSIFICATION OF SUBJECT MATTER
INV. F03D1/06 F03D7/02
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)
F03D

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)

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C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 395 071 A (FELIX FREDERICK L [US]) 7 March 1995 (1995-03-07) figure 1 column 1, lines 7,8 column 6, line 65 - column 6, line 15 -----	1-11



Further documents are listed in the continuation of Box C.



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Date of the actual completion of the international search

15 November 2017

Date of mailing of the international search report

23/11/2017

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/DK2017/050280

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5395071	A	07-03-1995	NONE
