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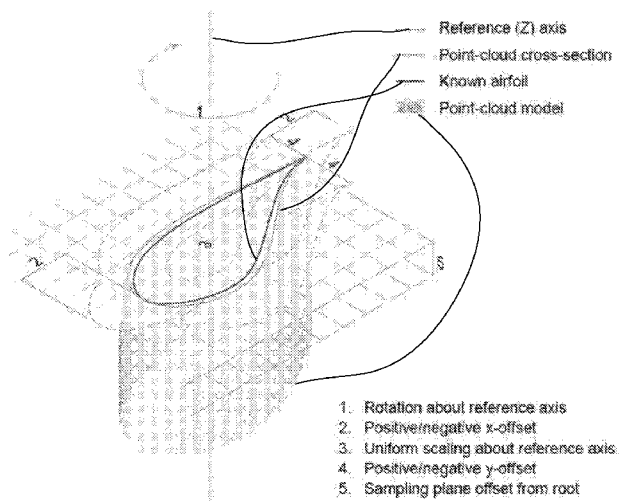


Fig. 3

(57) Abstract: An exemplary embodiment provides a method of predicting a geometry of a turbine blade, comprising: obtaining a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations on an external contour of the turbine blade; generating an external mesh for the turbine blade based on point cloud; defining a reference axis along the length of the blade; generating a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by portions of the mesh intersecting the sampling plane; for each of the plurality of sampling planes, matching the sampling plane to an airfoil profile in a database of known airfoil profiles; and creating a geometrical representation of the turbine blade by placing the airfoils on the reference axis and connecting the perimeter of each of the airfoils.

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SYSTEMS AND METHODS FOR PREDICTING THE GEOMETRY AND INTERNAL STRUCTURE OF TURBINE BLADES

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Serial No. 62/811,681, filed on 28 February 2019, which is incorporated herein by reference in its entirety as if fully set forth below.

FEDERALLY SPONSORED RESEARCH STATEMENT

[0002] This invention was made with government support under Grant No. 1701413, awarded by the National Science Foundation. The government has certain rights in the invention.

TECHNICAL FIELD OF THE INVENTION

[0003] The various embodiments of the present disclosure relate generally to predictions systems and methods. More particularly, the various embodiments of the present invention are directed to systems and methods for predicting the geometry and internal structure of turbine blades.

BACKGROUND OF THE INVENTION

[0004] The production of wind energy worldwide has increased twenty-fold since 2001. Almost all of this energy is generated by three-bladed wind turbines with fiber reinforced polymer (FRP) (e.g., plastic) composite wind blades. Blades for turbines installed in the early 2000s are nearing the end of their 20-year design lives, and the need to recycle the blades has become a well-recognized problem. In addition, many wind farm sites are being re-powered with new and more powerful turbines and blade sets being installed even through the current turbines have not reached their design lives. Advancements in turbine technology have rendered these turbines functionally obsolete. Recycling of the steel and copper that make up most of the turbine mass is well understood, but the potential for recycling or re-purposing the composite materials has not been addressed.

Most blades are constructed from thermoset composites using mostly glass but some carbon fibers. Currently material is recycled by shredding the blades, and the shredded polymer composite material is utilized as partial replacement for coal or natural gas in fossil power

plants and the ash for feedstock in cement kilns. Efforts to use the ground waste in the production of new FRP composites shows that the inclusion of recycled materials dramatically decreases the mechanical properties of the material. Chemical and thermal methods are also being investigated. Given this context, there is a need for reuse applications for wind blades, aiming to use entire blades or large parts of blades in architectural and civil infrastructure applications, taking advantage of their structural properties.

[0005] Wind blades often range from 9m to 90m in length. They are essentially large propellers, whose exterior surface is created by a series of successively more aerodynamic profiles placed along a reference axis. Beginning at the root, a circular section (above 10% of the total length) blends into a series of airfoil sections which taper along their length (about 90% of the total length). As shown in Fig. 1, each profile is located at a specific point away from the start point of the reference axis and provides material information regarding the layering of the composites and cores as well as geometric information that describes the shape of the blade at that point. Structural loading and aerodynamic performance have an inverse relationship along the length of the blade where the root and transitional region have poor aerodynamic performance but carry the highest structural loads while the mid-span and tip have a maximized lift-to-drag ratio and carry less structural loads. Wind blades behave as huge cantilevers, with the primary bending moments carried by a tapering and twisting box beam consistent of spar caps (i.e., flanges) bounded by internal structural webs that are also composed of sandwich panels.

[0006] A problem exists, however, in that the specific geometrical structure of these turbines are unknown. The blades are proprietary, that is, the geometry and material structure were created by the original designers and manufacturers of the blades and is not public information. Therefore, there is a desire for systems and methods for determining the geometry of turbine blades. Various embodiments of the present invention address this desire.

BRIEF SUMMARY OF THE INVENTION

[0007] The present invention relates to systems and methods for predicting the external geometry of a turbine blade. An exemplary embodiment of the present invention provides a method of predicting a geometry of a turbine blade, comprising: obtaining a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations

on an external contour of the turbine blade; generating an external mesh for the turbine blade based on point cloud; defining a reference axis along the length of the blade; generating a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by portions of the mesh intersecting the sampling plane; for each of the plurality of sampling planes, matching the sampling plane to an airfoil profile in a database of known airfoil profiles; and creating a geometrical representation of the turbine blade by placing the airfoils on the reference axis and connecting the perimeter of each of the airfoils.

[0008] In any of the embodiments disclosed herein, the point cloud can include between 50 and 1,000,000 data points.

[0009] In any of the embodiments disclosed herein, matching the sampling plane to an airfoil profile in a database of known airfoil profiles can comprise determining a fitness score for the matched airfoil, the fitness score being a mean distance between corresponding points on the airfoil and the sampling plane.

[0010] In any of the embodiments disclosed herein, the method can further comprise iteratively altering one or more parameters of the airfoil to reduce the fitness score.

[0011] In any of the embodiments disclosed herein, the one or more parameters can comprise a rotation of the airfoil about the reference axis.

[0012] In any of the embodiments disclosed herein, the one or more parameters can comprise an offset of the airfoil along a first axis perpendicular to the reference axis.

[0013] In any of the embodiments disclosed herein, the one or more parameters can comprise an offset of the airfoil along a second axis perpendicular to the reference axis and first axis.

[0014] In any of the embodiments disclosed herein, the one or more parameters can comprise a uniform size scaling factor of the airfoil.

[0015] In any of the embodiments disclosed herein, a first axis can be perpendicular to the reference axis and a second axis can be perpendicular to the first axis and reference axis, wherein each airfoil profile in the database of airfoil profiles can be represented by a plurality of points having a first coordinate value on the first axis and a second coordinate value on the second axis.

[0016] In any of the embodiments disclosed herein, the method can further comprise stopping the iteratively altering the one or more parameters to reduce the fitness score when successive iterations reduce the fitness score less than a predetermined threshold amount.

[0017] turbine blade can be based on the matched airfoil profiles and the altered one or more parameters.

[0018] In any of the embodiments disclosed herein, the method can further comprise displaying the geometrical representation of the turbine blade.

[0019] Another embodiment of the present invention provides a system for predicting a geometry of a turbine blade. The system can comprise a processor and a memory. The memory can comprise instructions, that when executed by the processor, cause the system to: obtain a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations on an external contour of the turbine blade; generate an external mesh for the turbine blade based on point cloud; define a reference axis along the length of the blade; generate a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by portions of the mesh intersecting the sampling plane; for each of the plurality of sampling planes, match the sampling plane to an airfoil profile in a database of known airfoil profiles; and create a geometrical representation of the turbine blade by placing the airfoils on the reference axis and connecting the perimeter of each of the airfoils.

[0020] In any of the embodiments described herein, the instructions, when executed by the processor, can further cause the system to iteratively alter one or more parameters of the airfoil to reduce the fitness score.

[0021] In any of the embodiments described herein, the instructions, when executed by the processor, can further cause the system to stop iteratively altering the one or more parameters to reduce the fitness score when successive iterations reduce the fitness score less than a predetermined threshold amount.

[0022] In any of the embodiments described herein, the instructions, when executed by the processor, can further cause the system to display the geometrical representation of the turbine blade.

[0023] These and other aspects of the present invention are described in the Detailed Description of the Invention below and the accompanying figures. Other aspects and features of embodiments of the present invention will become apparent to those of ordinary skill in the art upon reviewing the following description of specific, exemplary embodiments of the

present invention in concert with the figures. While features of the present invention may be discussed relative to certain embodiments and figures, all embodiments of the present invention can include one or more of the features discussed herein. Further, while one or more embodiments may be discussed as having certain advantageous features, one or more of such features may also be used with the various embodiments of the invention discussed herein. In similar fashion, while exemplary embodiments may be discussed below as device, system, or method embodiments, it is to be understood that such exemplary embodiments can be implemented in various devices, systems, and methods of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0024] The following Detailed Description of the Invention is better understood when read in conjunction with the appended drawings. For the purposes of illustration, there is shown in the drawings exemplary embodiments, but the subject matter is not limited to the specific elements and instrumentalities disclosed.

[0025] Figure 1 illustrates a cross-sectional view of a turbine blade.

[0026] Figure 2 illustrates a plot of a point cloud of a turbine blade, in accordance with an exemplary embodiment of the present invention.

[0027] Figure 3 illustrates a method for predicting the external geometry of a turbine blade, in accordance with an exemplary embodiment of the present invention.

[0028] Figure 4 illustrates a method for predicting the external geometry of a turbine blade, in accordance with an exemplary embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0029] To facilitate an understanding of the principles and features of the present invention, various illustrative embodiments are explained below. To simplify and clarify explanation, the invention is described below as applied to predicting the geometry of a wind turbine blade. One skilled in the art will recognize, however, that the invention is not so limited. Instead, as those skilled in the art would understand, the various embodiments of the present invention also find application in other areas, including, but not limited to, hydro turbine blades, propellers, impellers, and the like.

[0030] The components, steps, and materials described hereinafter as making up various elements of the invention are intended to be illustrative and not restrictive. Many suitable

components, steps, and materials that would perform the same or similar functions as the components, steps, and materials described herein are intended to be embraced within the scope of the invention. Such other components, steps, and materials not described herein can include, but are not limited to, similar components or steps that are developed after development of the invention.

[0031] As discussed above, turbine blades contain a tremendous quantity of high-quality composite materials, which might be reused in structural architectural, or infrastructural applications, the current problem is that the external geometry of these blades are unknown, and the specific geometry is proprietary information of the blade manufacturers. Accordingly, the present invention provides systems and methods for accurately predicting the external geometry of a given turbine blade.

[0032] An exemplary embodiment of the present invention provides a method of predicting a geometry of a turbine blade. The method can begin by obtaining a point cloud of the turbine blade. The point cloud can comprise at least one data point representing a three-dimensional position of an external location of the turbine blade (i.e., the external contour of the blade). Fig. 2 provides an illustration of a point cloud of a turbine blade, in accordance with some embodiments of the present invention. The point cloud can comprise any number of data points. In some embodiments, the point cloud comprises a single data point, but in some embodiments the point cloud comprises more than 1,000,000 data points. As those of skill in the art would appreciate in view of the present disclosure, the accuracy of the geometrical prediction can be directly proportional with the number of data points in the point cloud. The point cloud can be generated using many different techniques known in the art, including, but not limited to, with the use of photogrammetry, laser scanning, LIDAR, and the like. In some embodiments, the method obtaining the point cloud can comprise generating the point cloud. In some embodiments, obtaining the point cloud can comprise accessing a point cloud previously generated, e.g., by another entity.

[0033] After obtaining the point cloud, the method can further comprise generating an external mesh for the turbine blade based on the point cloud. The mesh can be generated such that it intersects with the points forming the point cloud.

[0034] The method can further comprise defining a reference axis along the length of the blade. For example, the reference axis can span along the center point of the length of the blade. The reference axis is shown in Fig. 3.

[0035] The method further comprises generating a plurality of sampling planes along the length of the reference axis. Each sampling plane is normal to the reference axis and has a shape defined by portions of the mesh intersecting the sampling plane. Accordingly, as shown in Fig. 3, each sampling plane or point-cloud cross-section can have the shape of an airfoil.

[0036] Some exemplary methods also make use of a database of publicly available airfoil profiles. The database can contain a selection of normalized coordinate that describe airfoil profiles. Each of these airfoil shapes can be stored in the database as a set of XY points with, for example, 50-200 points for each airfoil. The X, Y, and Z axes can be described as follows. As shown in Fig. 3, the 3-D representation can be broken down into a z-axis (the reference axis), a first axis (X-axis) perpendicular to the reference axis and a second axis (y-axis) perpendicular to the first axis and reference axis. Each airfoil profile in the database of airfoil profiles can be represented by a plurality of points having a first coordinate value on the first axis and a second coordinate value on the second axis.

[0037] For each sampling plane, the sampling plane (or cross section of the point cloud) can be compared to airfoil shapes in the database. The airfoil shape that is a best match to the sampling plane can be selected. For example, an airfoil profile is selected from the database and is compared to a point-cloud section in a 2D XY plane. Given the density of the 3D point cloud (e.g., 500,000 points), the process generally identifies a subset of points, e.g., 500-700 points, with essentially equivalent Z coordinates. The airfoil and point-cloud section curves can be sampled at 100 points equidistant from each other.

[0038] The matching process seeks to minimize a “fitness score,” representative of how close of a match an airfoil is to the sampling plane. The fitness score can be determined by a least squares minimization as the mean distance between corresponding points on the airfoil and point-cloud section (sampling plane). The process can minimize the fitness score by altering the airfoil selected from the database, in addition to one or more other parameters as shown in Fig. 3, including, but not limited to, the rotation of the selected airfoil about the reference axis, offset in the X-Y direction, uniform size scaling of the selected airfoil, and offset of the

sampling plane from the root. The minimization of the fitness score can proceed through an iterative process, such that the fitness of each iteration progressively increases. The iterative process can continue until a change in the fitness score from a previous iteration is less than a predetermined threshold.

[0039] Once the airfoil shape and associated parameter values are determined for each position along the reference axis, a geometrical representation of the turbine blade can be created by placing the airfoils (with corresponding parameter values) on the reference axis and connective the perimeters of each of the airfoils to create an external surface, as shown in Fig. 4. This geometrical representation can be created on the display of a computer.

[0040] The process can also include outputting the selected airfoils and associated parameters, together defining the predicted external geometry of the turbine blade.

[0041] Embodiments of the present invention also provide systems for predicting the external geometry of a turbine blade. An exemplary system comprises a computing device having a processor and memory. The memory includes instructions stored thereon that can carry out one or more of the methods disclosed herein. The computing device may comprise, for example, a desktop or laptop computer, a server, bank of servers, or cloud-based server bank. The computing device may also comprise one or more processors, which may include a central processing unit (CPU), a graphics processing unit (GPU), or both CPU and GPU, or any other sort of processing unit. The memory may comprise non-transitory computer-readable media, such as volatile and nonvolatile, removable and non-removable tangible, physical media implemented in technology for storage of information, such as computer readable instructions, data structures, program modules, or other data.

[0042] In some embodiments, the system can comprise one or more one or more output devices. The output device(s) can include any sort of output devices known in the art, such as a display (e.g., a liquid crystal or thin-film transistor (TFT) display). As discussed above, the display can be used to display the predicted external geometry of the turbine blade.

[0043] It is to be understood that the embodiments and claims disclosed herein are not limited in their application to the details of construction and arrangement of the components set forth in the description and illustrated in the drawings. Rather, the description and the drawings provide examples of the embodiments envisioned. The embodiments and claims disclosed herein are further capable of other embodiments and of being practiced and carried

out in various ways. Also, it is to be understood that the phraseology and terminology employed herein are for the purposes of description and should not be regarded as limiting the claims.

[0044] Accordingly, those skilled in the art will appreciate that the conception upon which the application and claims are based may be readily utilized as a basis for the design of other structures, methods, and systems for carrying out the several purposes of the embodiments and claims presented in this application. It is important, therefore, that the claims be regarded as including such equivalent constructions.

[0045] Furthermore, the purpose of the foregoing Abstract is to enable the United States Patent and Trademark Office and the public generally, and especially including the practitioners in the art who are not familiar with patent and legal terms or phraseology, to determine quickly from a cursory inspection the nature and essence of the technical disclosure of the application. The Abstract is neither intended to define the claims of the application, nor is it intended to be limiting to the scope of the claims in any way. Instead, it is intended that the invention is defined by the claims appended hereto.

What is claimed is:

1. A method of predicting a geometry of a turbine blade, comprising:
 - obtaining a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations on an external contour of the turbine blade;
 - generating an external mesh for the turbine blade based on point cloud;
 - defining a reference axis along the length of the blade;
 - generating a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by portions of the mesh intersecting the sampling plane;
 - for each of the plurality of sampling planes, matching the sampling plane to an airfoil profile in a database of known airfoil profiles; and
 - creating a geometrical representation of the turbine blade by placing the airfoils on the reference axis and connecting the perimeter of each of the airfoils.
2. The method of claim 1, wherein the point cloud includes between 50 and 1,000,000 data points.
3. The method of claim 1, wherein matching the sampling plane to an airfoil profile in a database of known airfoil profiles, comprises determining a fitness score for the matched airfoil, the fitness score being a mean distance between corresponding points on the airfoil and the sampling plane.
4. The method of claim 3, further comprising iteratively altering one or more parameters of the airfoil to reduce the fitness score.
5. The method of claim 4, wherein the one or more parameters comprises a rotation of the airfoil about the reference axis.
6. The method of claim 4, wherein the one or more parameters comprise an offset of the airfoil along a first axis perpendicular to the reference axis.

7. The method of claim 6, wherein the one or more parameters comprise an offset of the airfoil along a second axis perpendicular to the reference axis and first axis.
8. The method of claim 4, wherein the one or more parameters comprises a uniform size scaling factor of the airfoil.
9. The method of claim 1, wherein a first axis is perpendicular to the reference axis and a second axis is perpendicular to the first axis and reference axis, wherein each airfoil profile in the database of airfoil profiles is represented by a plurality of points having a first coordinate value on the first axis and a second coordinate value on the second axis.
10. The method of claim 3, further comprising stopping the iteratively altering the one or more parameters to reduce the fitness score when successive iterations reduce the fitness score less than a predetermined threshold amount.
11. The method of claim 10, wherein the geometrical representation of the turbine blade is based on the matched airfoil profiles and the altered one or more parameters.
12. The method of claim 1, further comprising displaying the geometrical representation of the turbine blade.
13. A system for predicting a geometry of a turbine blade, comprising:
 - a processor; and
 - a memory comprising instructions that, when executed by the processor, cause the system to:
 - obtain a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations on an external contour of the turbine blade;
 - generate an external mesh for the turbine blade based on point cloud
 - defining a reference axis along the length of the blade;
 - generate a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by portions of the mesh intersecting the sampling plane;

for each of the plurality of sampling planes, match the sampling plane to an airfoil profile in a database of known airfoil profiles; and

create a geometrical representation of the turbine blade by placing the airfoils on the reference axis and connecting the perimeter of each of the airfoils.

14. The system of claim 13, wherein the point cloud includes between 50 and 1,000,000 data points.

15. The system of claim 13, wherein matching the sampling plane to an airfoil profile in a database of known airfoil profiles, comprises determining a fitness score for the matched airfoil, the fitness score being a mean distance between corresponding points on the airfoil and the sampling plane.

16. The system of claim 15, wherein the instructions, when executed by the processor, further cause the system to iteratively alter one or more parameters of the airfoil to reduce the fitness score.

17. The system of claim 16, wherein the one or more parameters comprises a rotation of the airfoil about the reference axis.

18. The system of claim 16, wherein the one or more parameters comprise an offset of the airfoil along a first axis perpendicular to the reference axis.

19. The system of claim 18, wherein the one or more parameters comprise an offset of the airfoil along a second axis perpendicular to the reference axis and first axis.

20. The system of claim 16, wherein the one or more parameters comprises a uniform size scaling factor of the airfoil.

21. The system of claim 13, wherein a first axis is perpendicular to the reference axis and a second axis is perpendicular to the first axis and reference axis, wherein each airfoil profile in the database of airfoil profiles is represented by a plurality of points having a first coordinate value on the first axis and a second coordinate value on the second axis.

22. The system of claim 15, wherein the instructions, when executed by the processor, further cause the system to stop iteratively altering the one or more parameters to reduce the fitness score when successive iterations reduce the fitness score less than a predetermined threshold amount.

23. The system of claim 22, wherein the geometrical representation of the turbine blade is based on the matched airfoil profiles and the altered one or more parameters.

24. The system of claim 13, wherein the instructions, when executed by the processor, further cause the system to display the geometrical representation of the turbine blade.

25. A method of predicting a geometry of a turbine blade, comprising:
obtaining a point cloud of the turbine blade, the point cloud comprising a plurality of points corresponding to locations on an external contour of the turbine blade;
defining a reference axis in the point cloud along the length of the blade;
generating a plurality of sampling planes along the length of the reference axis, each sampling plane being normal to the reference axis and having a shape defined by a cross-section of the point cloud;
for each of the plurality of sampling planes, matching the sampling plane to an airfoil profile in a database of known airfoil profiles; and
creating a geometrical representation of the turbine blade by placing the matched airfoil profiles on the reference axis and connecting the perimeter of each of the matched airfoil profiles.

26. The method of claim 25, wherein the point cloud includes between 50 and 1,000,000 data points.

27. The method of any of claims 25-26, wherein matching the sampling plane to an airfoil profile in a database of known airfoil profiles, comprises determining a fitness score for the matched airfoil profile, the fitness score being a mean distance between corresponding points on the airfoil profile and the sampling plane.

28. The method of claim 27, further comprising iteratively altering one or more parameters of the matched airfoil profile to reduce the fitness score.
29. The method of claim 27, wherein the one or more parameters comprises a rotation of the matched airfoil profile about the reference axis.
30. The method of any of claims 28-29, wherein the one or more parameters comprise an offset of the matched airfoil profile along a first axis perpendicular to the reference axis.
31. The method of any of claims 28-30, wherein the one or more parameters comprise an offset of the matched airfoil profile along a second axis perpendicular to the reference axis and first axis.
32. The method of any of claims 28-31, wherein the one or more parameters comprises a uniform size scaling factor of the matched airfoil profile.
33. The method of any of claims 25-32, wherein a first axis is perpendicular to the reference axis and a second axis is perpendicular to the first axis and reference axis, wherein each airfoil profile in the database of airfoil profiles is represented by a plurality of points having a first coordinate value on the first axis and a second coordinate value on the second axis.
34. The method of any of claims 25-33, further comprising stopping the iteratively altering the one or more parameters to reduce the fitness score when successive iterations reduce the fitness score less than a predetermined threshold amount.
35. The method of any of claims 25-34, wherein the geometrical representation of the turbine blade is based on the matched airfoil profiles and the altered one or more parameters.
36. The method of any of claims 25-35, further comprising displaying the geometrical representation of the turbine blade.

1/3

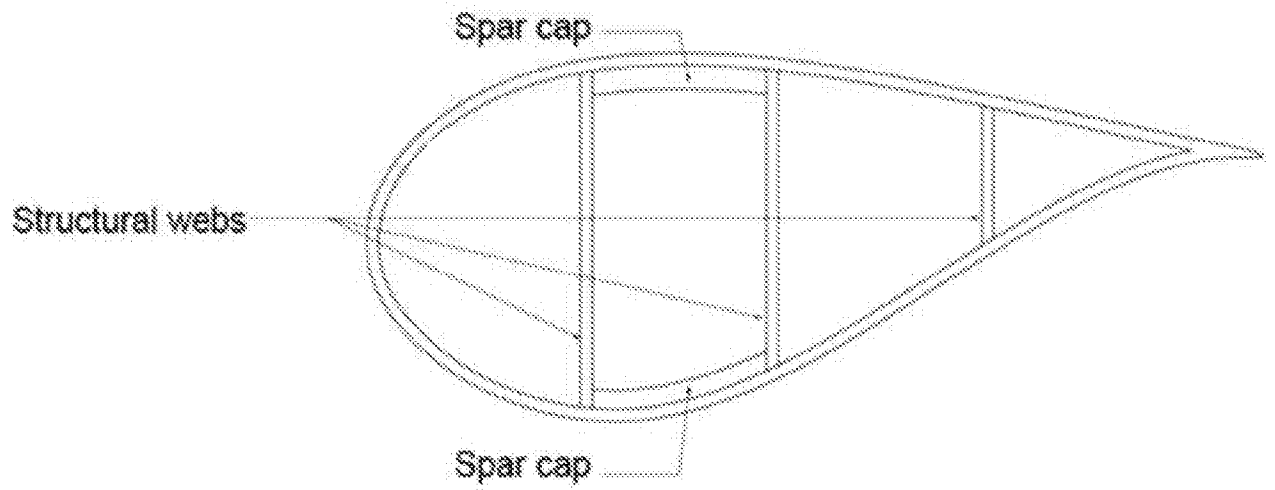


Fig. 1

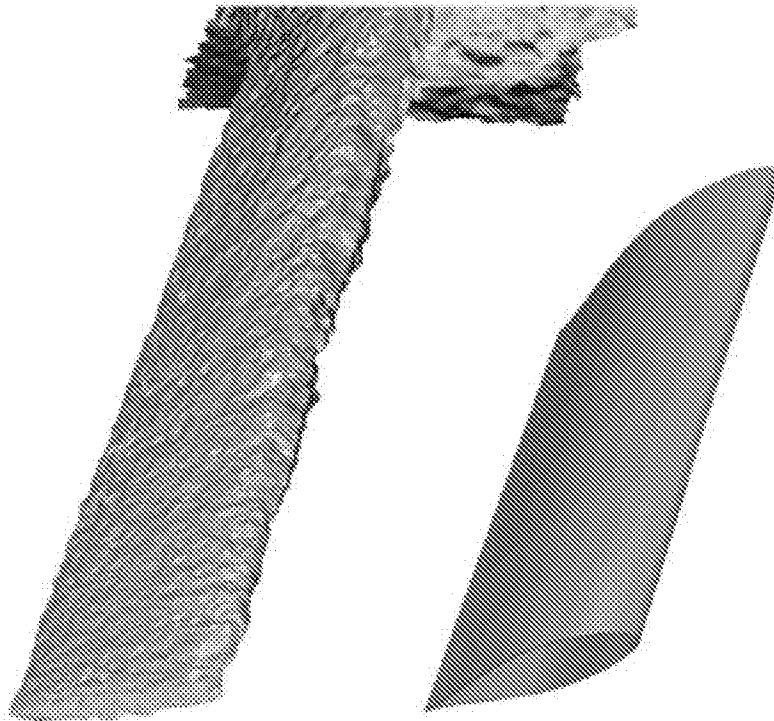
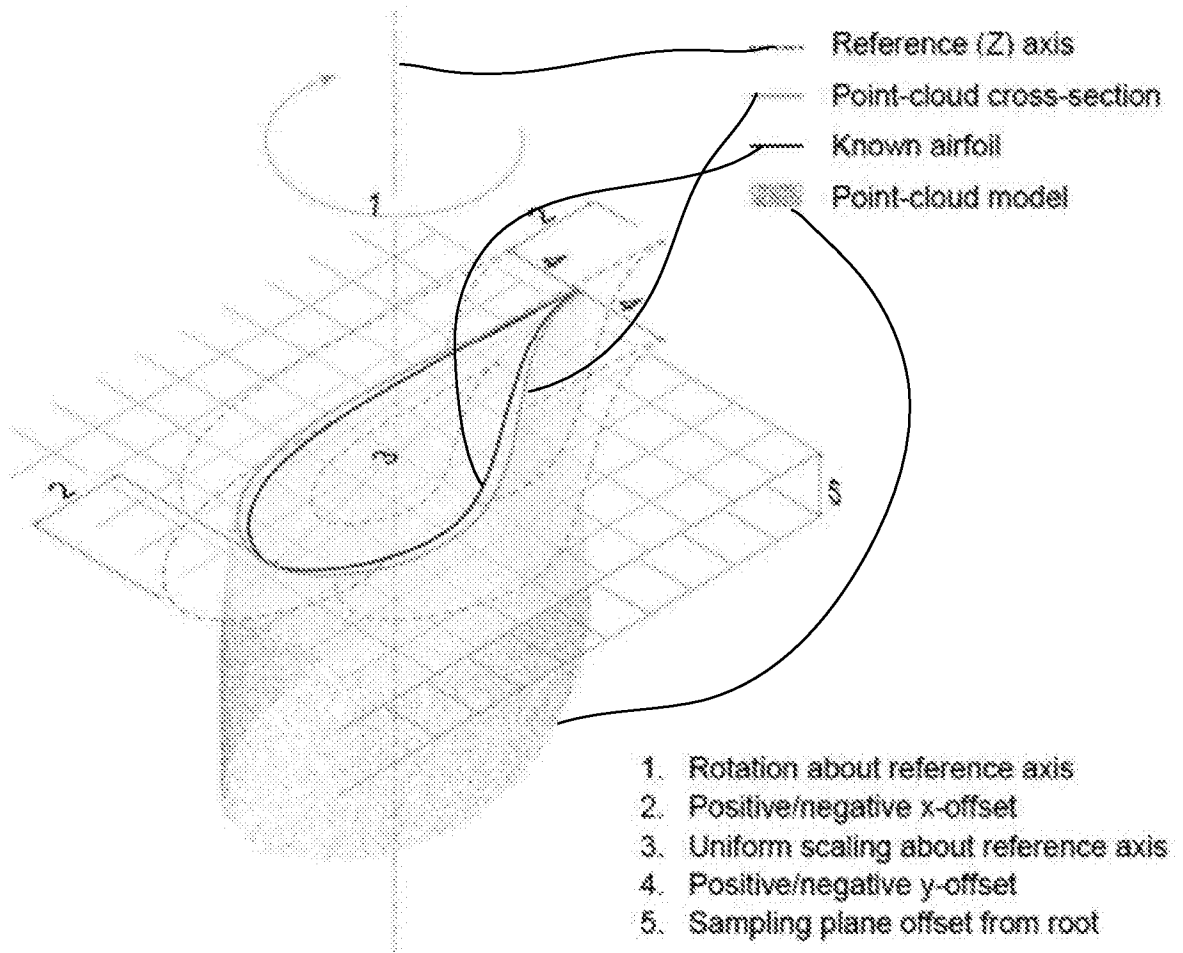


Fig. 2

2/3

**Fig. 3**

3/3

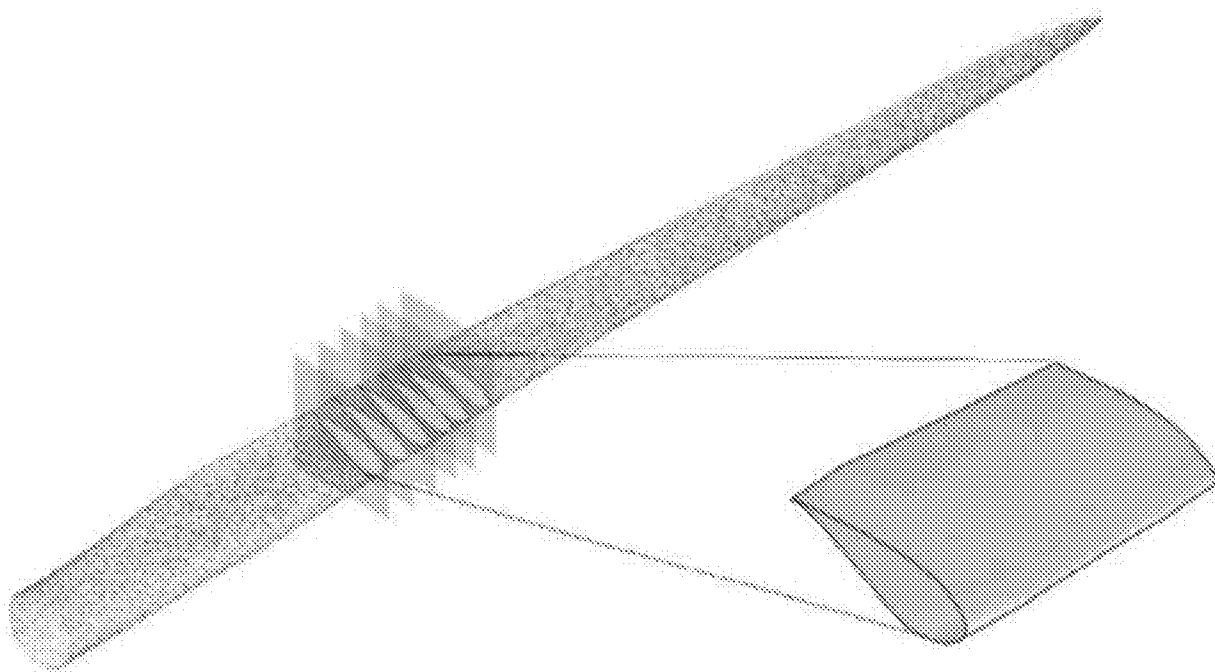


Fig. 4

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US20/20330

A. CLASSIFICATION OF SUBJECT MATTER

IPC - F01D 5/14; G06T 17/20; G06F 17/15 (2020.01)

CPC - F01D 5/141, 5/143; G06T 17/20, 17/205; G06F 17/153

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)

See Search History document

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

See Search History document

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.
A	US 9,542,739 B1 (GENERAL ELECTRIC COMPANY) 10 January 2017; abstract; figures 2-4; column 1; lines 9-28; column 4, line 43 to column 6, line 12	1-29
A	US 2009/0089020A1 (BOYER, J. et al.) 02 April 2009; figures 1-2; paragraphs [0010-0011, 0014, 0017]	1-29
A	US 2010/0095526 A1 (DERRIEN, G. et al.) 22 April 2010; figures 1-3; paragraph [0005-0008, 0012-0013]	1-29
P/X	TASISTRO-HART, B. et al. "Reconstruction of Wind Turbine Blade Geometry and Internal Structure from Point Cloud Data" Computing in Civil Engineering; Publication [online]. June 13, 2019 [retrieved 22 April 2020]. Retrieved from the Internet: <URL: https://ascelibrary.org/doi/10.1061/9780784482438.017 >; pages 130-136	1, 13, 25

☐ Further documents are listed in the continuation of Box C.☐ See patent family annex.

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"D" document cited by the applicant in the international application

"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

23 April 2020 (23.04.2020)

Date of mailing of the international search report

21 MAY 2020

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-8300

Authorized officer

Shane Thomas

Telephone No. PCT Helpdesk: 571-272-4300

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US20/20330

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:
2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
3. ☒ Claims Nos.: 30-36
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:
4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.