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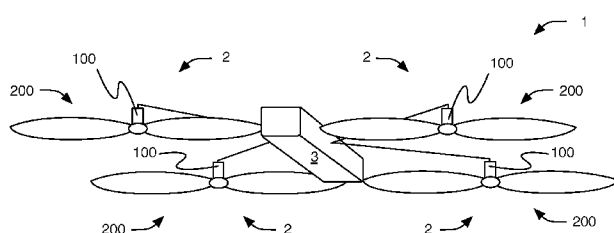


FIGURE 1A

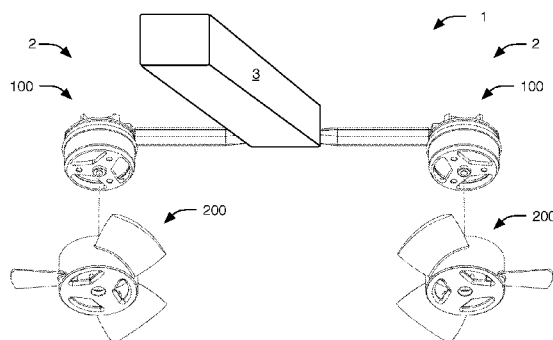


FIGURE 1B

(57) Abstract: An aerial vehicle including a housing, an outrunner motor including a stator mechanically coupled to the housing and a rotor rotationally coupled to the stator, and a propeller removably coupled to the rotor, the propeller including a hub and a plurality of propeller blades. A rotor, a propeller including a hub and a propeller blade, a radial alignment mechanism, a rotational retention mechanism, and an axial retention mechanism.

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AERIAL SYSTEM PROPULSION ASSEMBLY AND METHOD OF USE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application serial number 62/326,794, filed on 24-APR-2016, U.S. Provisional Application serial number 62/326,795, filed on 24-APR-2016, and U.S. Provisional Application serial number 62/412,408, filed on 25-OCT-2016, all of which are incorporated in their entirety by this reference.

TECHNICAL FIELD

[0002] This invention relates generally to the aerial system field, and more specifically to a new and useful aerial system propulsion assembly and method of use.

BACKGROUND

[0003] Aerial system propellers can be awkward and/or difficult to install and remove, and typical propellers often operate with poor aerodynamic performance. Thus, there is a need in the aerial system field to create an improved aerial system propulsion assembly and method for use.

BRIEF DESCRIPTION OF THE FIGURES

[0004] FIGURE 1A is a perspective view of an embodiment of the system;

[0005] FIGURE 1B is a partial perspective view of a variation of the embodiment;

[0006] FIGURE 2 is a perspective view of a first example of a propulsion assembly, in an unmated configuration;

[0007] FIGURE 3 is a plan view of the first example, in a mated configuration;

[0008] FIGURE 4A is a cross-sectional view taken along the line C-C in FIGURE 3;

[0009] FIGURE 4B is a detailed view of a region of FIGURE 4A;

[0010] FIGURE 5A is a detailed view of region I in FIGURE 4A;

- [0011] FIGURE 5B is a detailed view of an axial retention mechanism of the first example, transitioning between the unmated and mated configurations;
- [0012] FIGURE 6 is a detailed view of region II in FIGURE 4A;
- [0013] FIGURE 7A is a cross-sectional view taken along the line F–F in FIGURE 3;
- [0014] FIGURE 7B is a plan view of the motor and a portion of the mating mechanisms of the first example;
- [0015] FIGURE 7C is a plan view of the propeller and a portion of the mating mechanisms of the first example;
- [0016] FIGURE 8A is a perspective view of a second example of the propulsion assembly, in a mated configuration;
- [0017] FIGURE 8B is a cross-sectional perspective view of the second example, transitioning between the unmated and mated configurations;
- [0018] FIGURE 9A is a perspective view of a portion of a third example of the propulsion assembly;
- [0019] FIGURE 9B is a cross-sectional view of the third example, in a mated configuration;
- [0020] FIGURE 10A is a perspective view of a propeller of a fourth example of the propulsion assembly;
- [0021] FIGURE 10B is a cross-sectional view of a propeller blade of the fourth example;
- [0022] FIGURE 11 depicts the power loading curve of a specific example of the propeller during aerial system hovering;
- [0023] FIGURES 12A and 12B depict the twist angle and chord length, respectively, along the length of the specific example of the propeller;
- [0024] FIGURE 13 is a schematic representation of the method;
- [0025] FIGURE 14 is a schematic representation of a specific example of the method;
- [0026] FIGURE 15 is a cross-sectional view of a second example of a propulsion assembly, in the mated configuration;
- [0027] FIGURE 16 is a perspective view of a first specific example of the propeller of the second example;

[0028] FIGURE 17 is a perspective view of a second specific example of the propeller of the second example; and

[0029] FIGURES 18A–18C are perspective views of the second specific example of the propeller.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0030] The following description of the preferred embodiments of the invention is not intended to limit the invention to these preferred embodiments, but rather to enable any person skilled in the art to make and use this invention.

1. Overview.

[0031] As shown in FIGURES 1A–1B, the aerial system 1 preferably includes a housing 3 and one or more propulsion assemblies 2 (e.g., as described in U.S. Application serial number 15/349,749, filed on 11-NOV-2016, which is incorporated in its entirety by this reference). However, the aerial system 1 can additionally or alternatively include any other suitable elements.

[0032] Each propulsion assembly 2 is preferably a motorized propeller assembly (e.g., the rotor described in U.S. Application serial number 15/349,749, filed on 11-NOV-2016, which is incorporated in its entirety by this reference). As shown in FIGURES 2 and 15, the propulsion assembly 2 preferably includes a motor 100, a propeller 200, and one or more mating mechanisms. However, the propulsion assembly 2 can additionally or alternatively include any other suitable elements.

2. Benefits.

[0033] The aerial system 1 and method 400 can confer several benefits over conventional aerial systems 1 and methods of use. First, the propulsion assembly 2 can enable facile installation and removal of the propeller 200 using few tools or no tools (e.g., manual removal). The propulsion assembly 2 can be configured to provide feedback (e.g., haptic feedback, acoustic feedback such as clicking, etc.) during the propeller installation process (e.g., mating the propeller 200 to the motor 100) and/or removal process (e.g., unmating the propeller 200 from the motor 100), which can function to aid performance of the method 400 (e.g., by providing confirmation of correct

installation and/or removal). The propulsion assembly 2 can aid propeller installation by including alignment features (e.g., elements of the mating mechanisms), which can help achieve and/or maintain alignment between the motor 100 and propeller 200 during installation. Additionally or alternatively, the propulsion assembly 2 can enable facile propeller installation by being radially symmetric (or including elements with radial symmetry, such as elements of the mating mechanisms), which can allow propeller installation in a plurality of rotational alignments.

[0034] Second, during aerial system flight (and/or during other propulsion assembly operation), the force generated by the propeller 200 (e.g., reaction force caused by air displaced by the propeller 200) can help retain the propulsion assembly 2 in a mated configuration (e.g., keep the propeller 200 mated to the motor 100). This retention force can function to counteract forces that otherwise might cause the propeller 200 to become unmated from the motor 100 (e.g., centrifugal forces experienced during flight maneuvers). For example, the propeller 200 can be arranged below (e.g., relative to a typical aerial system orientation, relative to a gravity vector, etc.) the motor 100, and can be mated to the motor 100 by an upward force and unmated by a downward force. In this example, when the propulsion assembly 2 is operated (e.g., to provide propulsion to maintain an aerial system hover or otherwise counteract gravitational forces, to perform flight maneuvers, etc.), the propeller 200 is retained against the motor 100 by a force substantially opposing the unmating force direction (and substantially aligned with the mating force direction).

[0035] Third, the propulsion assembly 2 can be compatible with a plurality of mating mechanisms, which can enable additional versatility. For example, the system can include a first propeller 200 configured to mate with the motor 100 using snap-fit mating mechanisms and a second propeller 200 configured to mate with the motor 100 using screw-based mating mechanisms. In this example, the first and second propellers can be easily swapped into and out of the system, despite their use of different mating mechanisms.

[0036] Fourth, the propeller 200 can operate with good aerodynamic performance and/or generate little noise during operation. This benefit can be enabled by the design of the propeller blades 220. For example, the propeller 200 can include blades 220 defining airfoils with large camber, small thickness, high lift coefficient, and/or high lift-to-drag ratio under low Reynolds

number conditions. However, the aerial system 1 and method 400 can additionally or alternatively confer any other suitable benefits.

3. *Aerial system.*

3.1 *Motor.*

[0037] The motor 100 preferably functions to drive and/or control rotation of the propeller 200 and to mount the propeller 200 to the aerial system housing 3. The motor 100 preferably includes a stator 110 and a rotor 120, and can additionally or alternatively include any other suitable elements.

[0038] The motor 100 preferably has a low profile (e.g., to facilitate attachment to and/or containment within the aerial system housing). The motor 100 preferably has a high torque output, which can enable the motor 100 to directly drive the propeller 200 (e.g., without intervening gearing) in some embodiments; however, the motor 100 can have a low torque output, variable torque output, or any other suitable set of output parameters. The motor 100 is preferably a DC electric motor, more preferably a brushless DC electric motor, but can additionally or alternatively be powered by AC electricity, by internal combustion, and/or in any other suitable manner. The motor 100 is preferably an outrunner motor, but can alternatively be an inrunner motor, ferrite motor, and/or any other suitable motor. The motor 100 preferably includes an electrical connector (e.g., connected to the stator 110), which can function to provide power to the motor 100 and/or to control motor operation. However, the motor can be otherwise powered and/or controlled.

[0039] The stator 110 can be mechanically coupled to the aerial system 1. The stator 110 is preferably mechanically coupled to the aerial system housing, more preferably connected to and/or fixed with respect to the housing or a portion of the housing (e.g., by one or more mechanical fasteners). The stator 110 is preferably mounted to the housing from above (e.g., relative to a typical aerial system orientation, relative to a gravity vector, etc.), such as by mounting an upper portion of the stator 110 to an upper portion of the housing (e.g., in systems in which the housing surrounds the propulsion assembly 2), which can enable mounting the propeller 200 to the stator 110 from below. However, the stator 110 can include any other suitable elements, and can be arranged in any other suitable manner.

[0040] The rotor 120 is preferably rotationally coupled to the stator 110 about a rotor axis 123. The rotor 120 can define a rotor body (e.g., a rotor body defining and/or including a cylindrical body or body segment; polygonal prismatic body or body segment, such as one defining a regular polygonal cross-section; rounded body such as a spherical, spheroidal, or hemispherical body; etc.). The rotor body preferably extends along an axis (e.g., cylindrical body axis), more preferably the rotor axis 123, and can define a first end 121, a second end 122 (e.g., opposing the first end 121), and/or a rotor width such as a rotor diameter 124 (e.g., as shown in FIGURES 4A and 7A).

[0041] However, the motor 100 can additionally or alternatively include any other suitable elements in any suitable arrangement.

3.2 *Propeller.*

[0042] The propeller 200 can function to propel the aerial system 1 and/or control aerial system flight. The propeller 200 preferably includes a hub 210 and one or more blades 220, and can additionally or alternatively include any other suitable elements (e.g., as shown in FIGURES 3 and 10A).

3.2.1 *Hub.*

[0043] The hub 210 can define a hub body (e.g., a hub body defining and/or including a cylindrical body or body segment; polygonal prismatic body or body segment, such as one defining a regular polygonal cross-section; rounded body such as a spherical, spheroidal, or hemispherical body; etc.). The hub body preferably extends along an axis (e.g., cylindrical body axis), such as a hub axis 211. The hub body preferably defines a void (e.g., cylindrical void; void complementary to the rotor body, such that the rotor body can be inserted into the void; etc.). The void can define a void width such as a hub inner diameter 212.

[0044] The hub 210 is preferably configured to mate with the rotor 120 (e.g., removably, permanently, etc.). In a first embodiment, one of the rotor 120 and hub 210 (inner element) is configured to insert into the other (outer element). In this embodiment, a gap is preferably defined between the rotor 120 and hub 210. The gap can function to decrease vibration transfer and/or amplification between the motor 100 and propeller 200 (e.g., thereby reducing audible noise

generated during propulsion assembly operation). For example, a diameter (e.g., largest diameter) of the inner element can be less than an inner diameter of the outer element, and the gap can be defined by the difference in diameters. The gap can be greater and/or less than a threshold value, such as an absolute distance (e.g., 10 mm, 5 mm, 2 mm, 1 mm, 0.5 mm, 0.2 mm, 0.1 mm, etc.), a relative distance (e.g., a percentage of a rotor and/or hub diameter, such as 0.1%, 0.2%, 0.5%, 1%, 2%, 5%, 10%, etc.), and/or any other suitable value.

[0045] In this embodiment, the outer element preferably does not detach from the inner element in response to an applied torque (e.g., about an axis perpendicular to the rotor axis 123 and/or hub axis 211). Preferably, the inner element restricts removal of the outer element along directions that are not substantially aligned with the inner element axis. For example, the outer element can define an outer element end plane normal the outer element axis, the outer element end plane and inner element axis can define an intersection point, and a distance from the intersection point to a region of the inner element within the outer element can be greater than half the outer element inner diameter (e.g., such that the region of the inner element interferes with the outer element during removal along a direction that is not substantially aligned with the inner element axis). In a specific example (e.g., as shown in FIGURE 4B), the inner diameter of the outer element can be less than twice an inner element diagonal length (e.g., distance from the intersection point to an extremal region of the inner element within the outer element).

[0046] In a first variation of this embodiment, the rotor 120 is the inner element and the hub 210 is the outer element. In this variation, the rotor 120 is configured to be inserted into the hub 210 (e.g., rotor body insertable into a void defined by the hub 210), and the rotor diameter 124 is less than a hub inner diameter 212 to accommodate such insertion (e.g., wherein the gap is defined by the difference between the diameters). In this variation, the rotor 120 is preferably inserted into the hub void (e.g., into an opening of the void at a hub end, such as one defining a hub end plane normal to the hub axis 211) beginning with the first end 121 (e.g., wherein the second end 122 is inserted following the first end 121, wherein the second end 122 remains outside the void, etc.). In a second variation, the rotor 120 is the outer element and the hub 210 is the inner element. In this variation, the hub 210 is configured to be inserted into the rotor 120 (e.g., into a

void defined by the rotor 120), and a hub outer diameter is less than a rotor inner diameter (e.g., defined by the void).

[0047] However, the rotor 120 can additionally or alternatively abut the hub 210, interdigitate with the hub 210, and/or be otherwise coupled (e.g., attached) to the hub 210 (e.g., by one or more elements of the mating mechanisms, such as an axial retention mechanism 310).

3.2.2 *Blades.*

[0048] The blades 220 are preferably statically connected to the hub 210, but can additionally or alternatively be coupled to the hub 210 in any other suitable manner. The blades 220 can be arranged radially outward of the hub axis 211. The blades 220 preferably each radiate out from the hub 210, but alternatively the hub can surround the blades 220 (e.g., surround circumferentially), can be coupled to the blades 220 along their length (e.g., wherein the hub 210 defines ribs between the blades 220), and/or have any other suitable arrangement.

[0049] In a first embodiment, the propeller 200 can operate with high efficiency and/or at a low Reynolds number. In this embodiment, the propeller 200 preferably enables low power consumption for aerial system flight (e.g., in low altitude rotary wing drone applications). The propeller 200 can include a plurality of blades 220, with evenly or un-evenly distributed angle separation between blades (e.g., about the hub axis 211). The blades 220 can optionally include one or more proplets (e.g., upward, downward, bi-directional, etc.), preferably arranged at or near the blade tip. The proplets preferably define a proplet height of 2%–6% of the propeller blade radius (e.g., distance from the hub cylinder axis to the outer propeller blade end). The propeller 200 of this embodiment typically works under $6.0 \times 10^3 - 1.0 \times 10^5$ Re flow condition, with power loading typically greater than 8 g/W (e.g., as shown in FIGURE 11) and/or figure of merit typically above 65%. The blades 220 can optionally define a symmetric profile along some or all of a propeller blade central axis (e.g., within 20%–80% of the distance along the length of the blade 220).

[0050] In this embodiment, for one or more points on the propeller blade central axis (e.g., for each point on the axis between an inner and outer propeller blade end), one or more of the blades 220 preferably define a chord on a propeller blade cross-section including the point, the chord defining a normalized chord length C_r substantially defined by the equation:

$$C_r = a_1 \times \left(1 - \frac{r}{R}\right)^3 + 3 \times a_2 \times \left(\frac{r}{R}\right) \times \left(1 - \frac{r}{R}\right)^2 + 3 \times a_3 \times \left(\frac{r}{R}\right)^2 \times \left(1 - \frac{r}{R}\right) + a_4 \times \left(\frac{r}{R}\right)^3$$

and/or defining a twist angle β_r (e.g., angle between the chord and a reference plane such as a plane normal the hub axis 211) substantially defined by the following equation:

$$\beta_r = b_1 \times \left(1 - \frac{r}{R}\right)^3 + 3 \times b_2 \times \left(\frac{r}{R}\right) \times \left(1 - \frac{r}{R}\right)^2 + 3 \times b_3 \times \left(\frac{r}{R}\right)^2 \times \left(1 - \frac{r}{R}\right) + b_4 \times \left(\frac{r}{R}\right)^3$$

wherein r is a distance from the hub cylinder axis to the point and R is the propeller blade radius. Preferably, a_1 is a constant greater than 8 and less than 30, a_2 is a constant greater than 15 and less than 60, a_3 is a constant greater than 15 and less than 60, a_4 is a constant greater than 5 and less than 25, b_1 is a constant greater than 40 and less than 70, b_2 is a constant greater than 30 and less than 60, b_3 is a constant greater than 15 and less than 40, and b_4 is a constant greater than 30 and less than 70 (e.g., as shown in FIGURES 12A–12B).

[0051] In a first variation of this embodiment, the propeller diameter (e.g., twice the distance from the hub axis 211 to a propeller blade tip) can be 40–200 mm and a widest chord length can be 10–60 mm, preferably located 30%–50% of the distance along the length of the blade 220 (e.g., measured from the axis of rotation). In one example of this variation, the propeller diameter is between 60 mm and 120 mm and the widest chord length is between 10 mm and 60 mm. The point on the leading edge that is used to define the chord can be defined as the surface point of minimum radius, the surface point that will yield maximum chord length, or any other suitable point. The blades 220 preferably define airfoils with large camber, small thickness, high lift coefficient, and high lift-to-drag ratio under low Reynolds number condition (e.g., as shown in FIGURE 10B). The blades 220 can include sweep features (e.g., within the range of 75%–95% of the length of the blade from the hub axis 211), preferably with the magnitude of sweep smaller than 5% of the blade radius (e.g., 2.5% of the propeller diameter).

[0052] The propeller 200 is preferably of unitary construction. Alternatively, the blades 220 can be inserted in to the hub 210 (e.g., retained within the hub by friction), otherwise fastened or affixed to the hub (e.g., by mechanical fasteners, by adhesive, etc.), and/or coupled to the hub in any other suitable manner. The propeller 200 can additionally or alternatively include any other suitable elements in any suitable arrangement.

3.3 *Mating mechanisms.*

[0053] The mating mechanisms can function to couple the propeller 200 to the rotor 120 and to align and/or retain the propeller 200 with respect to the rotor 120. The aerial system 1 preferably includes one or more mating mechanisms, and each of the mating mechanisms can preferably retain and/or align the propeller 200 and rotor 120 along one or more directions. The directions can include an axial translation direction (e.g., directed substantially along the rotor axis 123 and/or hub axis 211), a yaw direction (e.g., rotation about the axial translation direction), radial translation directions (e.g., directed perpendicular to the axial translation direction), radial rotation directions (e.g., rotations about axes perpendicular to the axial translation direction), and/or any other suitable directions. Each mating mechanism preferably includes complementary elements on (e.g., of unitary construction with, affixed to, etc.) each of the rotor 120 and hub 210, but can alternatively include only elements on one of the rotor 120 and hub 210, elements separate from both the rotor and hub, and/or elements in any other suitable arrangement.

3.3.1 *Axial retention mechanism.*

[0054] The axial retention mechanism 310 functions to retain the hub 210 at the rotor 120 in the axial translation direction, and can optionally retain the hub in one or more other directions. The axial retention mechanism 310 can fix the relative positions of the hub and rotor along the axis (e.g., rotor axis, hub axis), can limit the hub and rotor to a range of relative positions (e.g., wherein the hub and rotor are free to translate with respect to each other within the range but are restricted from exiting the range), or axially retain the hub and rotor in any other suitable manner. The axial retention mechanism 310 preferably retains the rotor within the void of the hub (e.g., as described above), but can additionally or alternatively retain the hub within a void of the rotor, or retain the hub and rotor in any other suitable arrangement.

[0055] The axial retention mechanism 310 is preferably configured to engage (thereby retaining the hub and rotor axially) in response to application of an insertion force (e.g., inward axial force) above a threshold value (e.g., 5 N, 8 N, 10 N, 12 N, 15 N, 20 N, 25 N, 30 N, 15–20 N, etc.). The axial retention mechanism 310 is preferably configured to disengage (thereby no longer retaining the hub and rotor axially) in response to application of a removal force (e.g., outward axial force) above a threshold value (e.g., 10 N, 15 N, 20 N, 25 N, 30 N, 35 N, 40 N, 25–35 N,

etc.). However, the axial retention mechanism 310 can operate using any suitable insertion and/or removal force thresholds, and/or engage in response to application of any other suitable force applied in any other suitable manner (e.g., torque).

[0056] The axial retention mechanism 310 preferably includes a first and second axial retention element (or a first and second set of axial retention elements). One of the first and second axial retention elements is preferably on the hub, and the other is preferably on the rotor. The first and second axial retention elements are preferably complementary (e.g., wherein they cooperatively retain the hub and rotor axially). For example, the first and second axial retention elements can be configured to fit together (e.g., abut, interdigitate, one retained within the other, etc.). However, the first and second axial retention elements can be non-complementary or otherwise configured.

[0057] The axial retention mechanism 310 preferably includes a snap-fit retention mechanism, but can additionally or alternatively include a latch mechanism, friction fit mount, interference fit, bayonet mount, threaded mount, magnetic mechanism, and/or any other suitable retention mechanism. The snap-fit retention mechanism preferably includes a protrusion 311 (e.g., as the first axial retention element) and a complementary recess 312 (e.g., as the second axial retention element), and can additionally or alternatively include any other suitable elements.

[0058] The protrusion 311 is preferably fixed to one of the hub or the rotor (captive element), but can alternatively be fixed to the stator or to any other suitable component. The protrusion 311 defines a protrusion depth 317 (e.g., protrusion height) by which it protrudes from the captive element. The recess 312 is preferably fixed to the other of the hub or the rotor (i.e. capturing element; the element to which the protrusion is not fixed). The recess 312 is preferably complementary to the protrusion 311 (e.g., configured to fit around the protrusion). When the axial retention mechanism 310 is engaged, the protrusion 311 is preferably retained within the recess 312, and when the axial retention mechanism 310 is not engaged, the protrusion 311 is preferably not within the recess 312.

[0059] The capturing element preferably includes additional elements arranged near the recess 312 such that the protrusion 311 interacts with one or more of the additional elements during engagement and/or disengagement. The additional elements can include a retention flange 313

(e.g., flange including a wall of the recess), which can define a retention angle 316 (e.g., between an axis such as the hub axis 211 and a tangent plane, such as a plane tangent to the wall at a point at which the protrusion 311 contacts it during retention and/or removal). The additional elements can include a lead-in surface 314 (e.g., a second wall of the retention flange, opposing the wall shared by the retention flange and the recess), which can define an insertion angle 315 (e.g., between an axis such as the hub axis 211 and a tangent plane of the lead-in surface 314, such as a plane tangent to the lead-in surface 314 at a point at which the protrusion 311 contacts it during insertion). The insertion angle 315 can be 10°, 20°, 25°, 30°, 35°, 40°, 50°, 60°, 25°–35°, 20°–40°, 10°–50°, less than 10°, greater than 50°, or any other suitable angle. The retention angle 316 can be 10°, 20°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, 80°, 90°, 40°–50°, 35°–55°, 30°–60°, less than 30°, greater than 60°, or any other suitable angle. During insertion and/or removal, the rotor strain and/or hub strain is preferably less than a threshold value (e.g., 5%, 4%, 3%, 2.5%, 2%, 1.5%, etc.), and the friction coefficient between the axial retention mechanism elements is preferably within a target range (e.g., 0.45–0.55, 0.4–0.6, 0.3–0.7, 0.1–1.0, etc.). The axial retention mechanism 310 (and/or any other suitable element of the system) can additionally or alternatively include one or more strain-relief elements 318 (e.g., notches, flexible members, etc.). The strain-relief elements 318 can function to reduce the mechanical strain needed during mating and/or unmating, can allow regions of an element to strain (e.g., during mating and/or unmating) while other (e.g., adjacent) regions remain unstrained or less strained, and/or can function in any other suitable manner.

[0060] In a first example, the rotor is the outer element and the hub is the inner element. In this example, a cylindrical segment of the hub fits within a cylindrical void of the rotor, the hub includes an annular protrusion, and the rotor includes a complementary recess, retention flange, and lead-in surface.

[0061] In a second example (e.g., as shown in FIGURES 5A–5B), the rotor is the inner element and includes a cylindrical segment that fits within a cylindrical void of the hub, which is the outer element. The rotor includes an annular (e.g., circumferential) protrusion 311, preferably defining a curved profile but additionally or alternatively defining an angular profile and/or other suitable profile. The hub defines a complementary (e.g., annular, circumferential) recess 312. The

recess 312 is preferably arranged near an open end of the hub (e.g., wherein, when the hub and rotor are in the mated configuration, the rotor second end 122 is near the open end of the hub). The retention flange 313 (e.g., annular retention flange, circumferential retention flange, retention flange following substantially the same path as the recess 312, etc.) is preferably arranged between the open end and the recess 312 (e.g., in the mated configuration, arranged between the second end 122 and the recess 312). The retention flange 313 can define an inner diameter equal to, less than, or greater than the hub inner diameter 212. The lead-in surface 314 is preferably arranged between the open end and the retention flange 313 (e.g., in the mated configuration, arranged between the second end 122 and the retention flange 313). The lead-in surface 314 can be defined by a chamfer, bevel, round, and/or any other suitable feature.

[0062] The elements of the axial retention mechanism (e.g., in the first and second examples) can be defined along the entire cylinder circumference, defined along portions of the circumference, and/or defined along any other suitable paths and/or in any other suitable regions. The complementary elements (e.g., protrusion 311, recess 312, retention flange 313, lead-in surface 314, etc.) can be defined in substantially the same regions and/or in different regions (e.g., one element defined in only a subset of the regions of another element, elements having both overlapping and non-overlapping regions, etc.). The regions of definition along the circumference can be unequally or equally distributed (e.g., a number of regions, such as 2, 3, 4, 5, 6, or 7 or more regions, regularly or irregularly spaced around the circumference), can be of equal or unequal sizes (e.g., each covering an angular segment such as 5°, 10°, 15°, 20°, 30°, 40°, 2–10°, 10–20°, 20–40°, etc.) and can be in a common or different plane (e.g., have offset locations along the hub axis). For example, the protrusion 311 can be defined along the entire circumference, and the retention flange 313 and lead-in surface 314 can be defined only in a subset of the circumference (e.g., as shown in FIGURE 16). The axial retention mechanism can optionally include strain-relief elements 318. Examples of strain-relief elements 318 that can be used include: notches, springs, strain conversion mechanisms (e.g., that convert the strain to heat), interleaved flexible material, and/or any other suitable strain-relief element. In a specific example (e.g., as shown in FIGURES 17 and 18A–18C), a subset of regions of the propeller 200 and/or motor 100 (e.g., the regions in which all elements of the axial retention mechanism 310 are defined) can include strain-relief elements 318

(e.g., notches), which can allow the subset of regions to strain (e.g., during mating and/or unmating) while reducing the strain in other regions.

[0063] However, the axial retention mechanism 310 can additionally or alternatively include any other suitable elements in any other suitable arrangement.

3.3.2 *Rotational retention mechanism.*

[0064] The rotational retention mechanism 320 functions to retain the hub 210 at the rotor 120 in the yaw direction, and can optionally retain the hub in one or more other directions. The rotational retention mechanism 320 can fix the relative positions of the hub and rotor about the axis, can limit the hub and rotor to a range of relative positions (e.g., wherein the hub and rotor are free to rotate with respect to each other within the range but are restricted from exiting the range), or retain the hub and rotor about the axis in any other suitable manner.

[0065] The rotational retention mechanism 320 preferably includes a first and second rotational retention element or a first and second set of rotational retention elements. The elements of the first and second sets can have a one-to-one relationship, a many-to-one relationship (e.g., the first set can include two elements for each element of the second set, one element of the first set arranged on each of two opposing sides of each element of the second set), or any other suitable relationship. One of the first and second rotational retention elements is preferably on the hub, and the other is preferably on the rotor. The first and second rotational retention elements are preferably complementary (e.g., wherein they cooperatively retain the hub and rotor in the yaw direction). For example, the first and second rotational retention elements can be configured to fit together (e.g., abut, interdigitate, one retained within the other, etc.). However, the rotational retention elements can be otherwise arranged and configured. The first and second rotational retention elements can contact at a surface defining a normal vector, preferably wherein the inner product of the normal vector and a rotation tangent vector (e.g., tangent to the yaw direction at a point radially aligned with the contact surface) is substantially non-zero, more preferably wherein the normal and tangent vectors are substantially parallel (e.g., defining an angle less than a threshold angle, such as 1°, 3°, 10°, etc.).

[0066] In a first variation, the rotational retention mechanism 320 includes at least one radial member 321 fixed to one of the hub or rotor, and at least one limit member 322 (e.g., member

extending substantially parallel the rotor axis 123 and/or hub axis 211) fixed to the other of the hub or rotor. The limit member 322 can be configured to contact the radial member 321 (e.g., thereby preventing rotation of the radial member past the limit member). The radial members can radiate inward and/or outward (e.g., from a body or void, such as a cylindrical body or void; from a central member; from an axial retention element, etc.).

[0067] In a first example of this variation, the rotor 120 includes a plurality of ribs (radial members 321) extending radially inward from the rotor cylinder, preferably meeting at or near the rotor axis 123, and the hub 210 includes a plurality of limit members 322 (e.g., extending upward and/or downward from one or more radial ribs of the hub) arranged on both sides of each radial member 321 (e.g., as shown in FIGURES 7B–7C). In a specific example, the rotor and hub each include three radial ribs arranged with equal angular spacing about the rotor and hub axes, respectively, and the hub includes six limit members (two for each radial rib of the rotor).

[0068] In a second example, the hub includes protrusions (e.g., bosses, pins, dowels, etc.), preferably protruding substantially parallel the hub axis 211 but alternatively at any suitable angle to the hub axis 211, that align with complementary holes defined in the rotor (e.g., in the rotor cylinder, in one or more radial members of the rotor, etc.).

[0069] In a third example, the annular recess and protrusion of the axial retention mechanism 310 vary along their length (e.g., based on angular position). In a specific example, the recess and protrusion are only defined in some angular sections, and are absent from others (e.g., do not extend around the entire circumference of the cylindrical bodies). However, the rotational retention mechanism 320 can additionally or alternatively include any other suitable elements arranged in any other suitable manner.

3.3.3 *Radial alignment mechanism.*

[0070] The radial alignment mechanism 330 can function to retain the hub 210 at the rotor 120 in the radial translation and rotation directions, and can optionally retain the hub in one or more other directions. The radial alignment mechanism 330 preferably fixes the relative positions of the hub and rotor in the radial translation and rotation directions, but can alternatively limit the hub and rotor to a range of relative positions (e.g., wherein the hub and rotor are free to move in the radial translation and/or rotation directions with respect to each other within the range but are

restricted from exiting the range) or retain the hub and rotor about the axis in any other suitable manner. The radial alignment mechanism 330 preferably establishes and/or maintains a substantially coaxial alignment of the rotor axis 123 and hub axis 211 (e.g., establishing and/or maintaining parallelism and/or concentricity of cylindrical bodies defined by the rotor 120 and hub 210), but can additionally or alternatively establish and/or maintain any other suitable alignments.

[0071] The radial alignment mechanism 330 preferably includes a first and second radial alignment element (or a first and second set of radial alignment elements). One of the first and second radial alignment elements is preferably on the hub, and the other is preferably on the rotor. The first and second radial alignment elements are preferably complementary. For example, the first and second radial alignment elements can be configured to fit together (e.g., abut, interdigitate, one retained within the other, etc.). However, a radial alignment mechanism pair can be otherwise configured. The system can include one or more radial alignment mechanism pairs, which can be evenly arcuately and/or radially distributed or otherwise configured.

[0072] In a first variation, an axial protrusion 331 (e.g., boss, dowel, pin, shaft, etc.) on one of the hub or rotor is configured to fit into a hole 332 (e.g., pocket, through-hole, etc.) in the other of the hub or rotor (e.g., as shown in FIGURE 6). The axial protrusion 331 is preferably on the rotor and the hole 332 is preferably in the hub, but alternatively the axial protrusion 331 can be on the hub and the hole 332 can be in the rotor. The axial protrusion 331 and hole 332 are preferably circular and centered on the rotor axis 123 and/or hub axis 211. Alternatively, the axial protrusion 331 and/or hole 332 can be non-circular, the radial alignment mechanism 330 can include more than one axial protrusion 331 and/or hole 332, and/or the axial protrusion(s) 331 and hole(s) 332 can be arranged off-axis (e.g., with a rotationally symmetric or asymmetric distribution), which can enable the axial protrusion 331 and hole 332 to additionally function as a rotational retention mechanism 320. The axial protrusion 331 and hole 332 preferably have a clearance fit, but can alternatively have an interference fit, a snap fit, and/or any other suitable fit. The axial protrusion 331 and/or hole 332 can include features (e.g., chamfers, fillets, rounds, etc.) to help guide them into alignment (e.g., during mating of the hub and rotor). In a specific example, the hole 332 is defined in a central segment of the hub 210 and a boss (axial protrusion 331) is defined at the center of the rotor, each defined where a plurality of radial ribs (e.g., of the rotational

retention mechanism 320) meet. The interior surface of the hole and/or exterior surface of the boss can optionally define chamfers, rounds, and/or any other suitable lead-in features. In a second variation, one of the hub or rotor includes a pair of axial protrusions (e.g., fins) and the other of the hub or rotor includes a rib (e.g., radial rib), wherein the axial protrusions are separated by a distance substantially equal to or slightly larger than the rib width. However, the radial alignment mechanism 330 can include any other suitable elements in any other suitable arrangement.

3.3.4 *Damping mechanism.*

[0073] The damping mechanism 340 can function to reduce vibration transmission between the hub and rotor, and can optionally retain the hub and rotor with respect to each other (e.g., function as one or more of the retention and/or alignment mechanisms). The damping mechanism 340 can be arranged between the hub and rotor, preferably compressed between them (e.g., having an interference fit). The damping mechanism 340 is preferably affixed to and/or embedded in (e.g., glued to, retained within a groove of, etc.) one of the hub or rotor, but can alternatively be retained only by the interference fit and/or retained in any other suitable manner.

[0074] The damping mechanism 340 preferably includes (e.g., is made of) one or more flexible materials (e.g., rubber, silicone, etc.), but can additionally or alternatively include rigid materials and/or any other suitable materials. The damping mechanism 340 can define shapes such as dots, lines, and/or pads. The damping mechanism 340 can include one or more damping elements. The elements can be arranged circumferentially (e.g., around an entire circumference, around a portion of a circumference), axially (e.g., parallel the rotor axis 123 and/or hub axis 211), diagonally, and/or in any other suitable directions.

[0075] In a first example, the damping mechanism 340 includes an O-ring retained in a groove of the inner element (e.g., as shown in FIGURES 9A–9B). The O-ring can be arranged axially above or below the axial retention mechanism interface. Additionally or alternatively, the O-ring can optionally function as an axial retention mechanism 310 and/or rotational retention mechanism 320. In a second example, the damping mechanism 340 includes a plurality of axial ribs with equal angular spacing around the outside of the inner element and/or the inside of the outer element. However, the damping mechanism 340 can additionally or alternatively include any other suitable elements in any other suitable arrangement.

3.3.5 *Additional elements.*

[0076] The mating mechanisms can additionally or alternatively include fasteners (e.g., screws, latches, etc.). For example, the mating mechanisms can include self-locking low cap screws, threaded holes, and counterbored through-holes (e.g., as shown in FIGURES 8A–8B), which can function as secure and/or low-profile fasteners.

[0077] The mating mechanisms can additionally or alternatively include one or more grip-enhancing elements. The grip-enhancing elements can function to allow and/or facilitate manual gripping of the motor 100 and/or propeller 200 (e.g., to mate or unmate the hub 210 from the rotor 120). In a first variant, the propeller blades 220 can function as grip-enhancing elements. In a second variant, the grip-enhancing elements can include grooves defined in an outer surface of the hub. However, the mating mechanisms can additionally or alternatively include any other suitable elements in any other suitable arrangement.

4. *Method.*

[0078] A method 400 for aerial system use can include mating a motor and propeller S410, rotating the propeller S420, ceasing propeller rotation S430, and/or unmating the motor and propeller S440 (e.g., as shown in FIGURE 13). The method 400 is preferably performed using the aerial system 1 and/or propulsion assembly 2 described above, but can additionally or alternatively be performed using any other suitable aerial system.

[0079] Mating the motor and propeller S410 can include establishing alignments between the rotor and hub (e.g., approximate alignments, precise alignments, etc.), which can include coaxial alignment (e.g., in the radial translation and/or rotation directions) and/or rotational alignment (e.g., in the yaw direction), and applying inward axial force (e.g., greater than an insertion force threshold). Elements of the system (e.g., mating mechanisms) can guide the mating of the hub to the rotor (e.g., guiding from approximate alignment into more precise alignment) and subsequently maintain the desired arrangement.

[0080] A specific example of mating the motor and propeller S410 includes: establishing approximate coaxial alignment between the propeller and the rotor (e.g., manually, such as by holding the propeller in one hand and the motor or aerial system housing in the other hand); establishing approximate yaw alignment between the propeller hub and the rotor (e.g., aligning the

radial ribs of the hub and rotor), so that the chamfering of the limit members will cause the rotor ribs to align more precisely during mating; and pressing the propeller toward the rotor along the axial direction. In this specific example, if the propeller and the motor are not approximately aligned, the propeller hub cylinder will contact the top surface of the motor housing so that the propeller hub cannot be pressed into the mating configuration. In this specific example, when axial pressure is applied, the annular protrusion passes over the retention flange and the inner surface of the hub contacts the top surface of the motor housing. During this process, an audible sound is preferably emitted, which can indicate that the installation is complete. However, the motor and propeller can be otherwise mated.

[0081] Rotating the propeller S420 is preferably performed by the motor, and can function to propel the aerial system and/or to control aerial system flight. Rotation of the rotor preferably causes the propeller to rotate (e.g., due to the rotational retention mechanism). During propeller rotation, the force generated by the propeller (e.g., reaction force caused by air displaced by the propeller) preferably retains the propeller against the hub axially (e.g., the force is directed substantially along the axis in the inward or mating direction). In a specific example, in which the propeller is mounted to the rotor from below, when the propeller is driven by the motor, the propeller generates a propulsion force, so that the inner surface of the propeller hub and the top surface of the motor housing are retained against each other (e.g., as shown in FIGURE 14).

[0082] Ceasing propeller rotation S430 can function to cease aerial system flight. Ceasing propeller rotation S430 is preferably performed by the motor (e.g., by ceasing motor rotation, by ceasing powered motor rotation, etc.).

[0083] Unmating the motor and propeller S440 preferably includes applying outward axial force (e.g., greater than a removal force threshold), more preferably by holding the propeller (e.g., by a grip-enhancing element) in one hand, retaining the motor or aerial system housing (e.g., in a second hand, in a stand, pressed against a surface, etc.), and pulling the propeller away from the motor in the outward axial direction. In a specific example, S440 includes orienting the aerial system so that the propeller is above the motor, gently holding the propeller blades between the fingers of a hand, and pulling upward to unmate the propeller. S440 can be performed to remove a damaged propeller (e.g., for subsequent replacement by a functional propeller), to remove a first

type of propeller (e.g., for subsequent replacement by a second type of propeller), and/or for any other suitable purpose. However, the method 400 can include any other suitable elements performed in any other suitable manner.

[0084] Although omitted for conciseness, the preferred embodiments include every combination and permutation of the various system components and the various method processes. Furthermore, various processes of the preferred method can be embodied and/or implemented at least in part as a machine configured to receive a computer-readable medium storing computer-readable instructions. The instructions are preferably executed by computer-executable components preferably integrated with the system. The computer-readable medium can be stored on any suitable computer readable media such as RAMs, ROMs, flash memory, EEPROMs, optical devices (CD or DVD), hard drives, floppy drives, or any suitable device. The computer-executable component is preferably a general or application specific processing subsystem, but any suitable dedicated hardware device or hardware/firmware combination device can additionally or alternatively execute the instructions.

[0085] The FIGURES illustrate the architecture, functionality and operation of possible implementations of systems, methods and computer program products according to preferred embodiments, example configurations, and variations thereof. In this regard, each block in the flowchart or block diagrams may represent a module, segment, step, or portion of code, which comprises one or more executable instructions for implementing the specified logical function(s). It should also be noted that, in some alternative implementations, the functions noted in the block can occur out of the order noted in the FIGURES. For example, two blocks shown in succession may, in fact, be executed substantially concurrently, or the blocks may sometimes be executed in the reverse order, depending upon the functionality involved. It will also be noted that each block of the block diagrams and/or flowchart illustration, and combinations of blocks in the block diagrams and/or flowchart illustration, can be implemented by special purpose hardware-based systems that perform the specified functions or acts, or combinations of special purpose hardware and computer instructions.

[0086] As a person skilled in the art will recognize from the previous detailed description and from the figures and claims, modifications and changes can be made to the preferred

embodiments of the invention without departing from the scope of this invention defined in the following claims.

CLAIMS

We claim:

1. An aerial vehicle comprising:
 - a housing;
 - an outrunner motor comprising a stator mechanically coupled to the housing and a rotor rotationally coupled to the stator about a rotor axis, the rotor comprising:
 - a body centered around and extending parallel the rotor axis;
 - an outward protrusion from the body, the outward protrusion mechanically connected to the body and defined along an outer perimeter of a cross-section of the body, the cross-section normal the rotor axis;
 - a radial member mechanically connected to the body and extending radially inward from the body; and
 - a boss mechanically coupled to the body by the radial member, the boss centered around and extending parallel the rotor axis; and
 - a propeller removably coupled to the rotor, the propeller comprising a hub and a plurality of propeller blades mechanically coupled to the hub, the propeller defining a central propeller axis, the hub comprising:
 - an inner surface arranged around the body and defining a recess retaining the outward protrusion within the recess;
 - a limit member contacting the radial member and rotationally retaining the propeller about the rotor axis with respect to the rotor; and
 - a surface defining a hole centered around the central propeller axis, the boss arranged within the hole and retaining the central propeller axis substantially collinear with the rotor axis.
2. The aerial vehicle of Claim 1, wherein the hub is mounted below the rotor.
3. The aerial vehicle of Claim 1, wherein the body comprises a substantially cylindrical body segment.

4. The aerial vehicle of Claim 1, further comprising a set of radial members comprising the radial member, each radial member of the set mechanically connected to the body and to the boss.
5. The aerial vehicle of Claim 1, wherein the plurality of propeller blades define a regular angular spacing around the central propeller axis.
6. A system for an aerial vehicle, the system comprising:
 - a rotor defining a cylindrical body, the cylindrical body defining a first and second end, a rotor cylinder axis, and a rotor diameter;
 - a propeller comprising a hub and a propeller blade mechanically coupled to the hub, the hub defining a cylindrical void, the cylindrical void defining a hub cylinder axis and a hub inner diameter greater than the rotor diameter;
 - a radial alignment mechanism mechanically coupled to the rotor proximal the first end and to the hub, the radial alignment mechanism retaining the hub cylinder axis substantially collinear with the rotor cylinder axis, the radial alignment mechanism comprising:
 - a first surface defining a hole substantially centered on the rotor cylinder axis; and
 - a boss retained within the hole;
 - a rotational retention mechanism mechanically coupled to the rotor proximal the first end and to the hub, the rotational retention mechanism rotationally retaining the hub about the rotor axis with respect to the rotor, the rotational retention mechanism comprising:
 - a radial member extending radially inward of the cylindrical body; and
 - a limit member contacting the radial member; and
 - an axial retention mechanism mechanically coupled to the rotor proximal the second end and to the hub, the axial retention mechanism translationally retaining the hub with respect to the rotor along an axial direction parallel the rotor cylinder axis, the axial retention mechanism comprising:
 - a second surface defining a circumferential recess; and

- a circumferential protrusion defined along a third surface separate from the second surface, the circumferential protrusion retained within the circumferential recess.
7. The system of Claim 6, wherein:
- the second surface is defined by the hub;
 - the circumferential protrusion is attached to the rotor more proximal the second end than the first end; and
 - a protrusion radius from the rotor cylinder axis to the circumferential protrusion is greater than half the hub inner diameter.
8. The system of Claim 7, wherein the axial retention mechanism further comprises:
- a circumferential retention flange attached to the second surface, the circumferential retention flange arranged proximal the second end relative to the circumferential recess, wherein a flange radius from the hub cylinder axis to the circumferential retention flange is greater than the protrusion radius; and
 - a lead-in surface attached to the circumferential retention flange, the lead-in surface arranged proximal the second end relative to the circumferential retention flange, the lead-in surface defining a tangent plane at an oblique angle to the second end and to the hub cylinder axis.
9. The system of Claim 6, wherein the hub inner diameter exceeds the rotor diameter by more than 1 mm.
10. The system of Claim 6, wherein:
- the hub comprises a hub end proximal the second end, the hub end defining a hub end plane normal the hub cylinder axis;
 - the hub end plane and the rotor cylinder axis intersect at an intersection point; and
 - a distance from the intersection point to a region of the rotor within the hub is greater than half the hub inner diameter.
11. The system of Claim 6, wherein the limit member extends substantially parallel the rotor cylinder axis.

12. The system of Claim 6, wherein:

- the radial member comprises a first side and a second side opposing the first side, the first and second sides substantially parallel the rotor cylinder axis;
- the limit member contacts the first side; and
- the rotational retention mechanism further comprises a second limit member contacting the second side.

13. The system of Claim 6, wherein the radial member is attached to the rotor and the limit member is attached to the hub.

14. The system of Claim 13, wherein the boss is attached to the radial member and the first surface is mechanically coupled to the hub.

15. The system of Claim 6, further comprising a damper arranged between the rotor and the hub.

16. The system of Claim 15, wherein the damper comprises a gasket arranged circumferentially around the rotor.

17. A propeller configured to couple to a motor for an aerial vehicle, the propeller comprising:

- a hub defining a hub central axis;
- a propeller blade mechanically coupled to the hub, wherein, for each point between an inner and outer propeller blade end on a propeller blade central axis, the propeller blade defines a chord on a propeller blade cross-section including the point, the chord defining a normalized chord length C_r substantially defined by the following equation:

$$C_r = a_1 \times \left(1 - \frac{r}{R}\right)^3 + 3 \times a_2 \times \left(\frac{r}{R}\right) \times \left(1 - \frac{r}{R}\right)^2 + 3 \times a_3 \times \left(\frac{r}{R}\right)^2 \times \left(1 - \frac{r}{R}\right) + a_4 \times \left(\frac{r}{R}\right)^3$$

and defining a twist angle β_r substantially defined by the following equation:

$$\beta_r = b_1 \times \left(1 - \frac{r}{R}\right)^3 + 3 \times b_2 \times \left(\frac{r}{R}\right) \times \left(1 - \frac{r}{R}\right)^2 + 3 \times b_3 \times \left(\frac{r}{R}\right)^2 \times \left(1 - \frac{r}{R}\right) + b_4 \times \left(\frac{r}{R}\right)^3$$

wherein r is a distance from the hub central axis to the point, R is a propeller blade radius from the hub central axis to the outer propeller blade end, a_1 is a constant greater than 8 and less than 30, a_2 is a constant greater than 15 and less than 60, a_3 is a constant greater than 15 and less than 60, a_4 is a constant greater than 5 and less than 25, b_1 is a constant

greater than 40 and less than 70, b_2 is a constant greater than 30 and less than 60, b_3 is a constant greater than 15 and less than 40, and b_4 is a constant greater than 30 and less than 70.

18. The propeller of Claim 17, wherein:

- the propeller blade radius is greater than 20 mm and less than 100 mm;
- a length of a longest chord of the chords is greater than 10 mm and less than 25 mm; and
- the longest chord is associated with a value of r greater than $0.3R$ and less than $0.5R$.

19. The propeller of Claim 17, wherein the propeller blade further comprises a proplet attached proximal the outer propeller blade end, the proplet defining a proplet height greater than 0.3 mm and less than 0.7 mm.

20. The propeller of Claim 17, wherein, for each point at which a value of r is greater than $0.2R$ and less than $0.8R$, the propeller blade cross-section including the point is substantially symmetric.

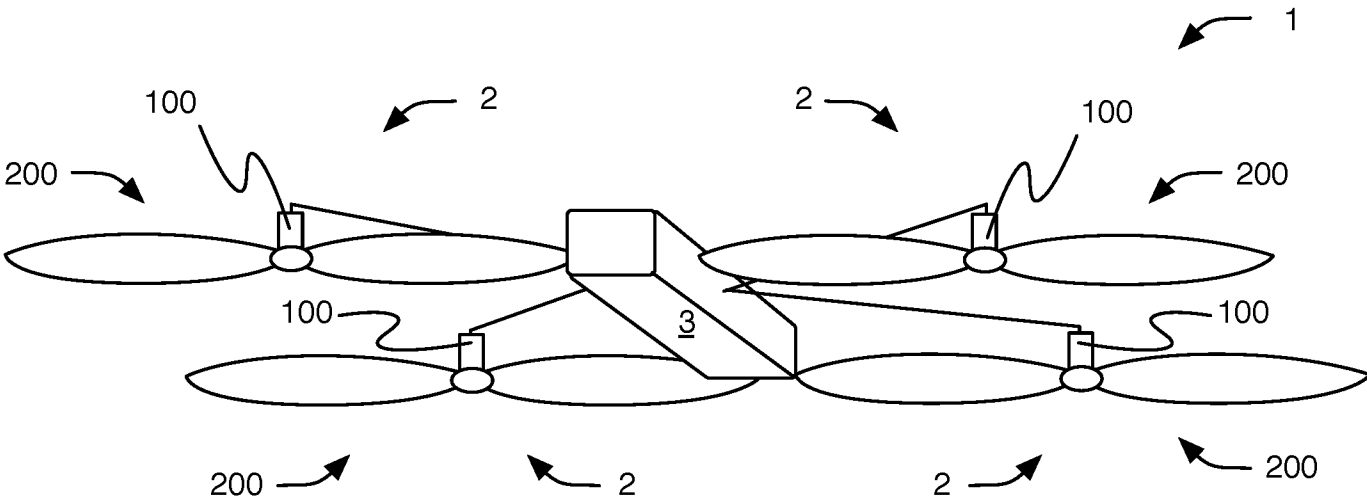


FIGURE 1A

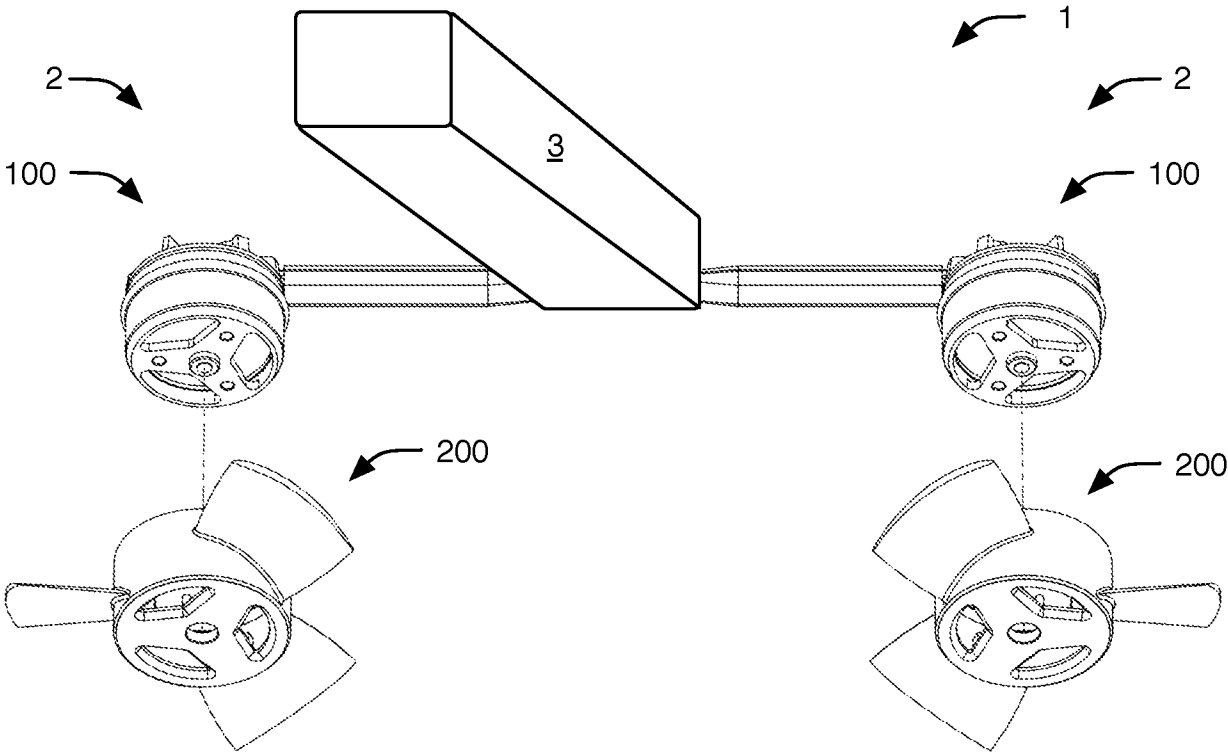


FIGURE 1B

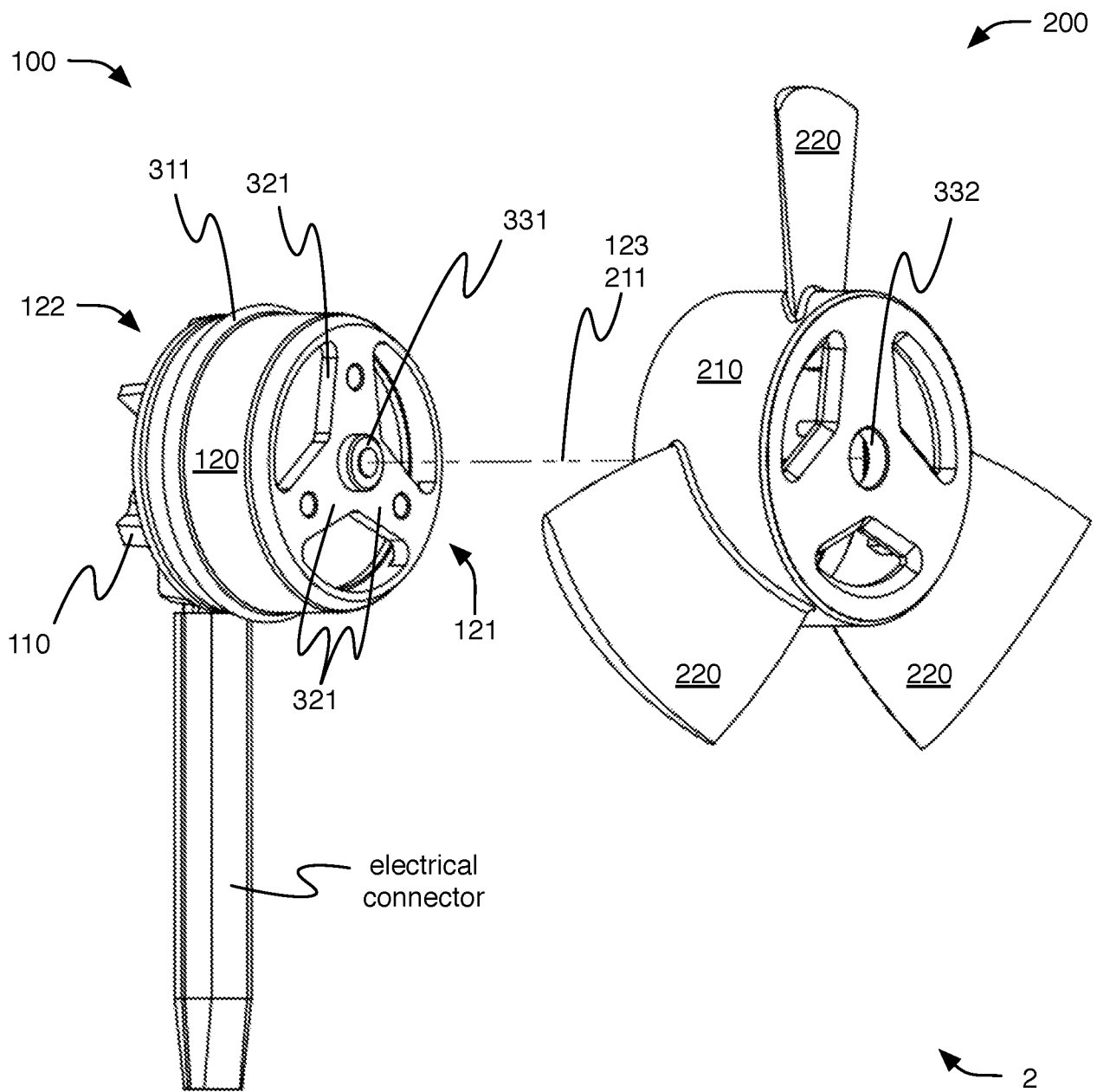


FIGURE 2

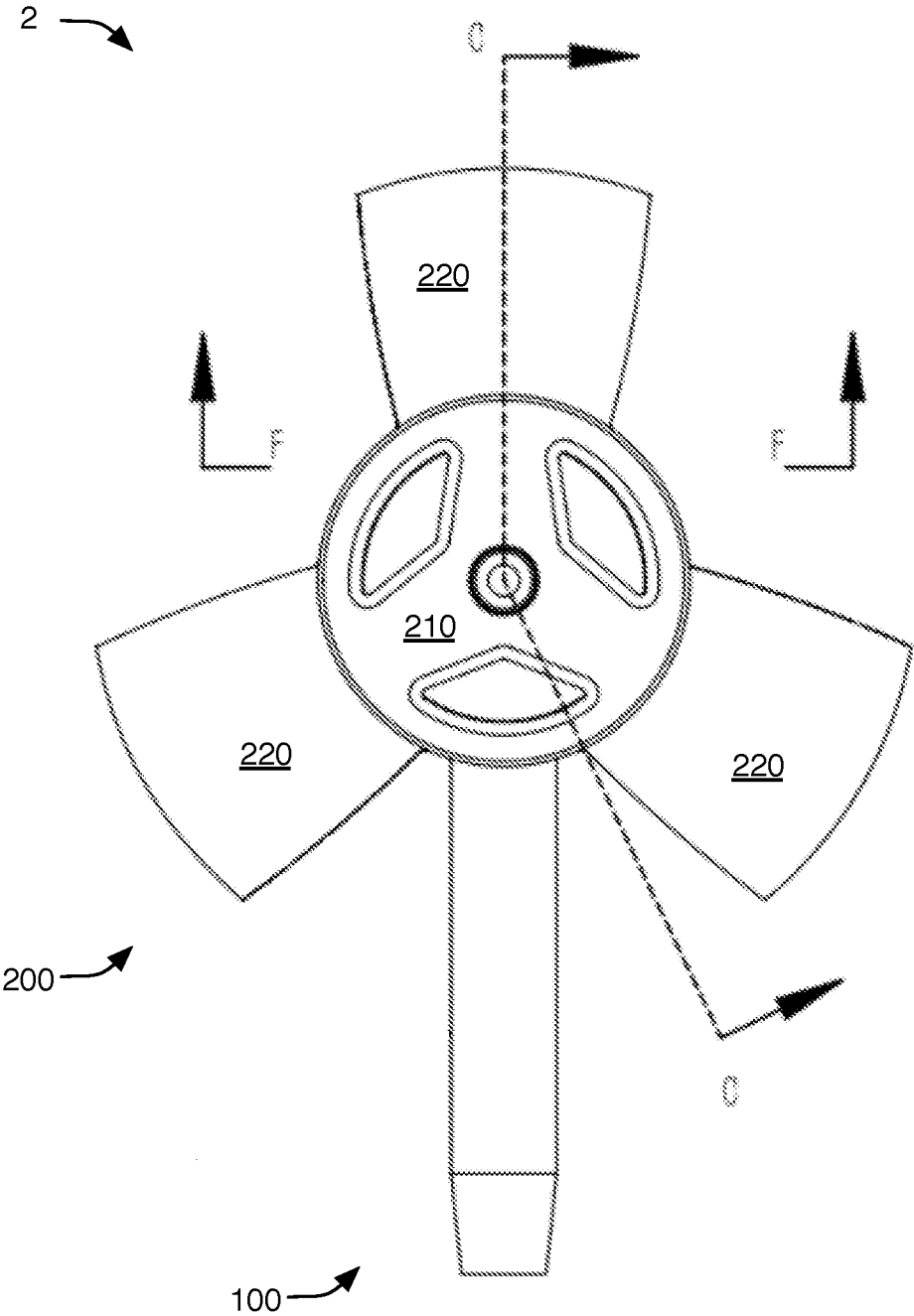


FIGURE 3

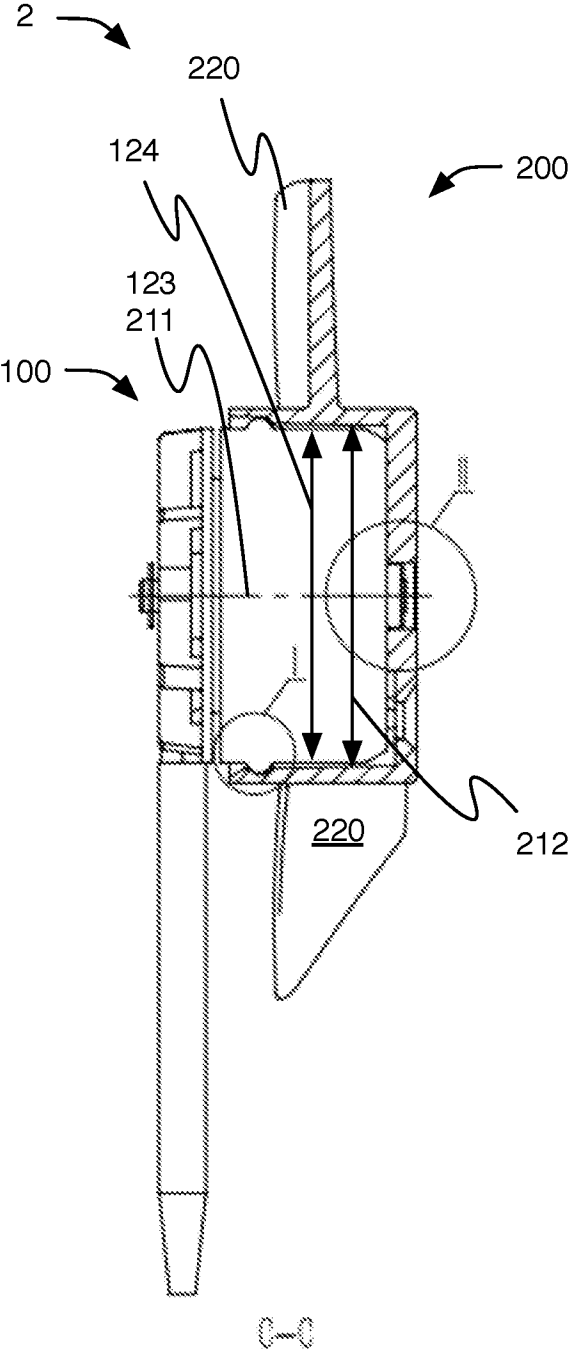


FIGURE 4A

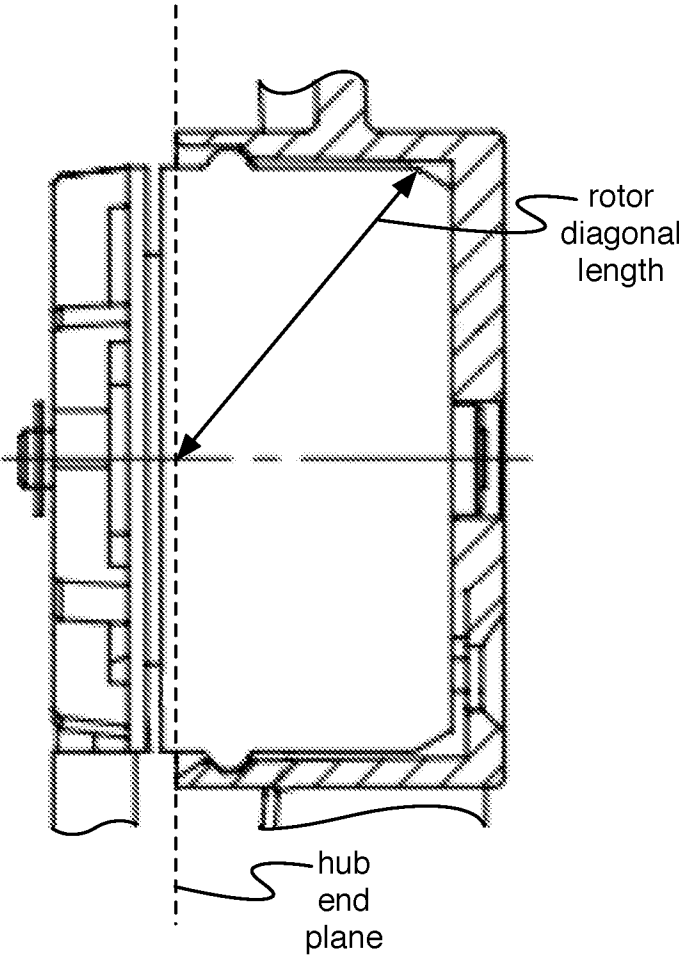


FIGURE 4B

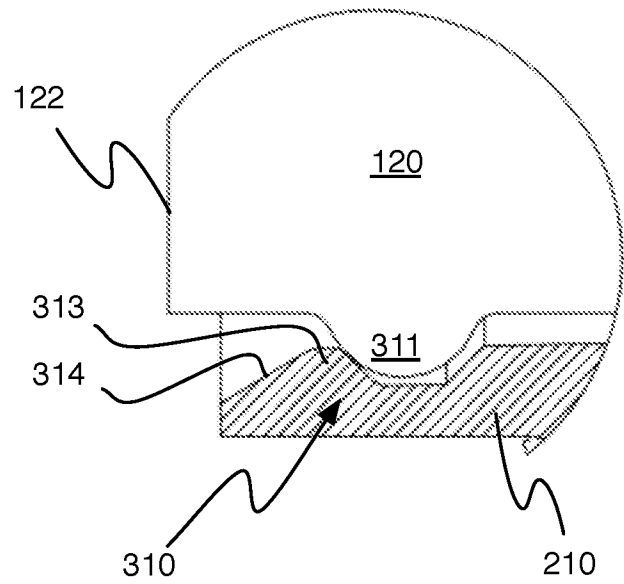


FIGURE 5A

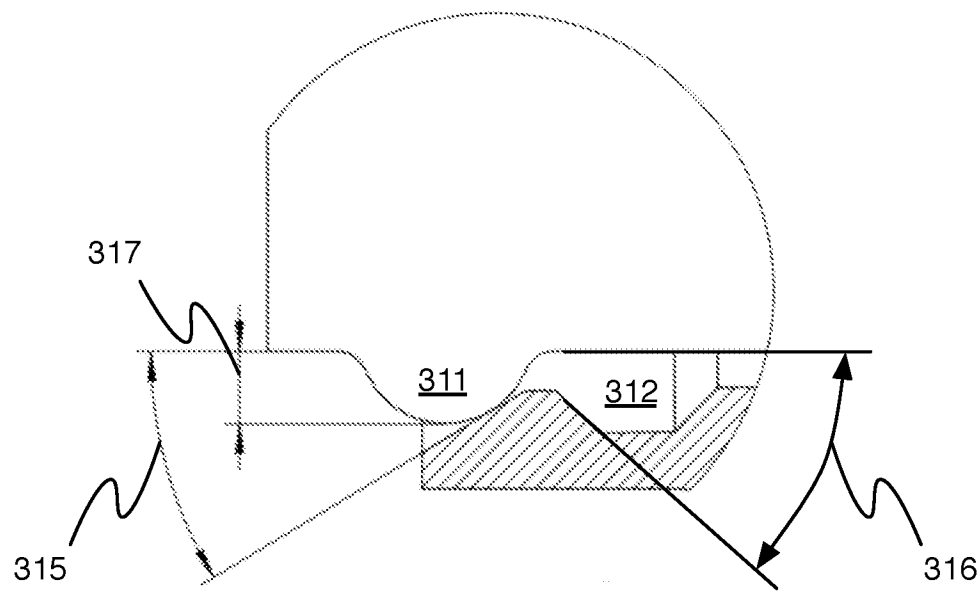


FIGURE 5B

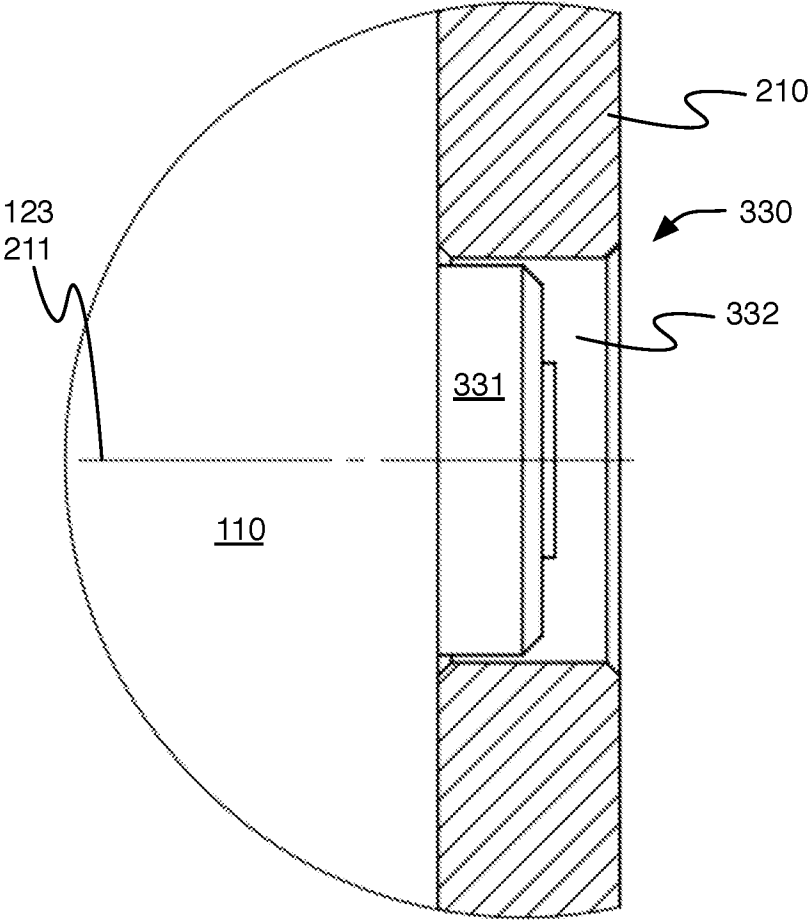


FIGURE 6

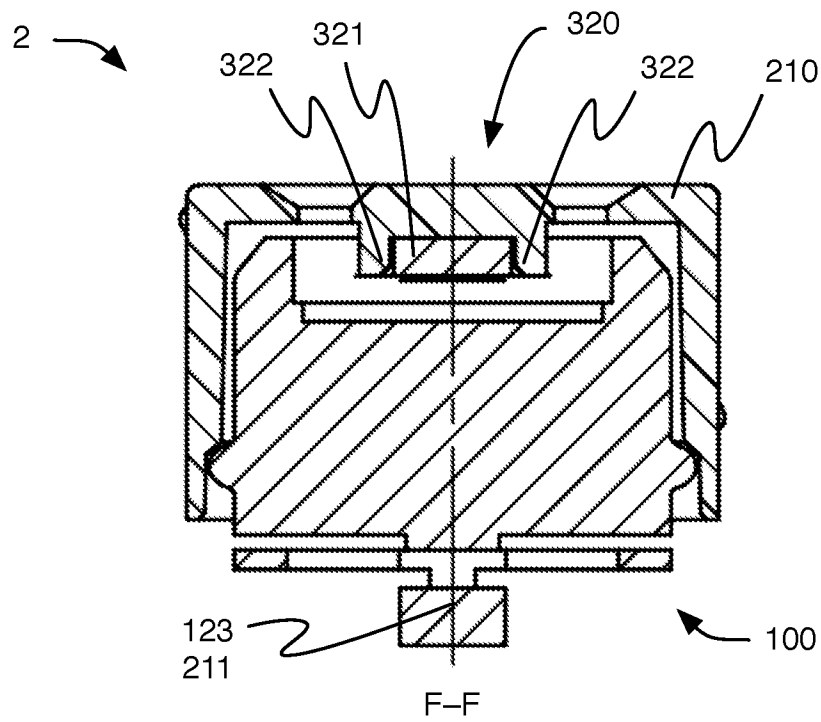


FIGURE 7A

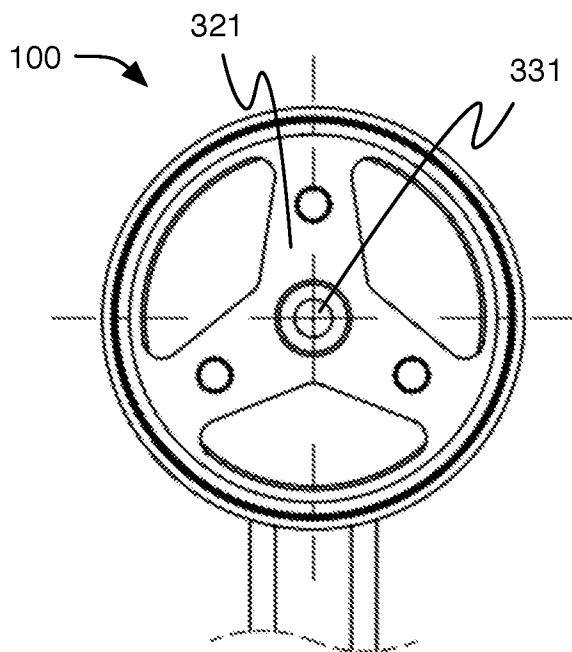


FIGURE 7B

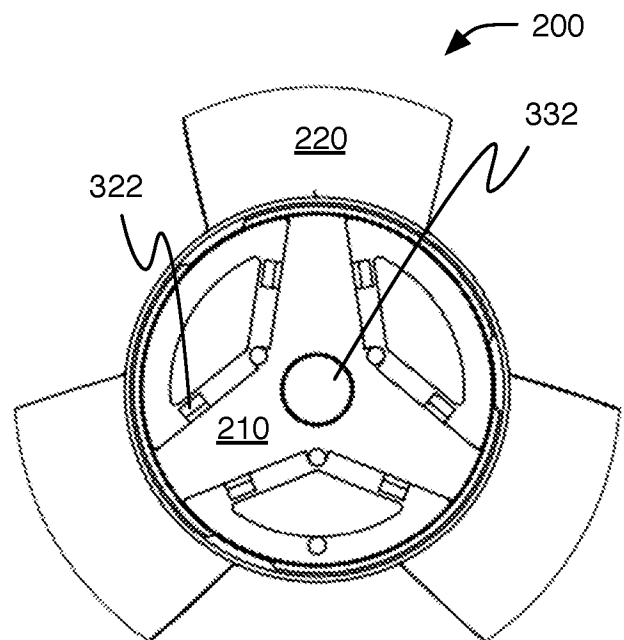


FIGURE 7C

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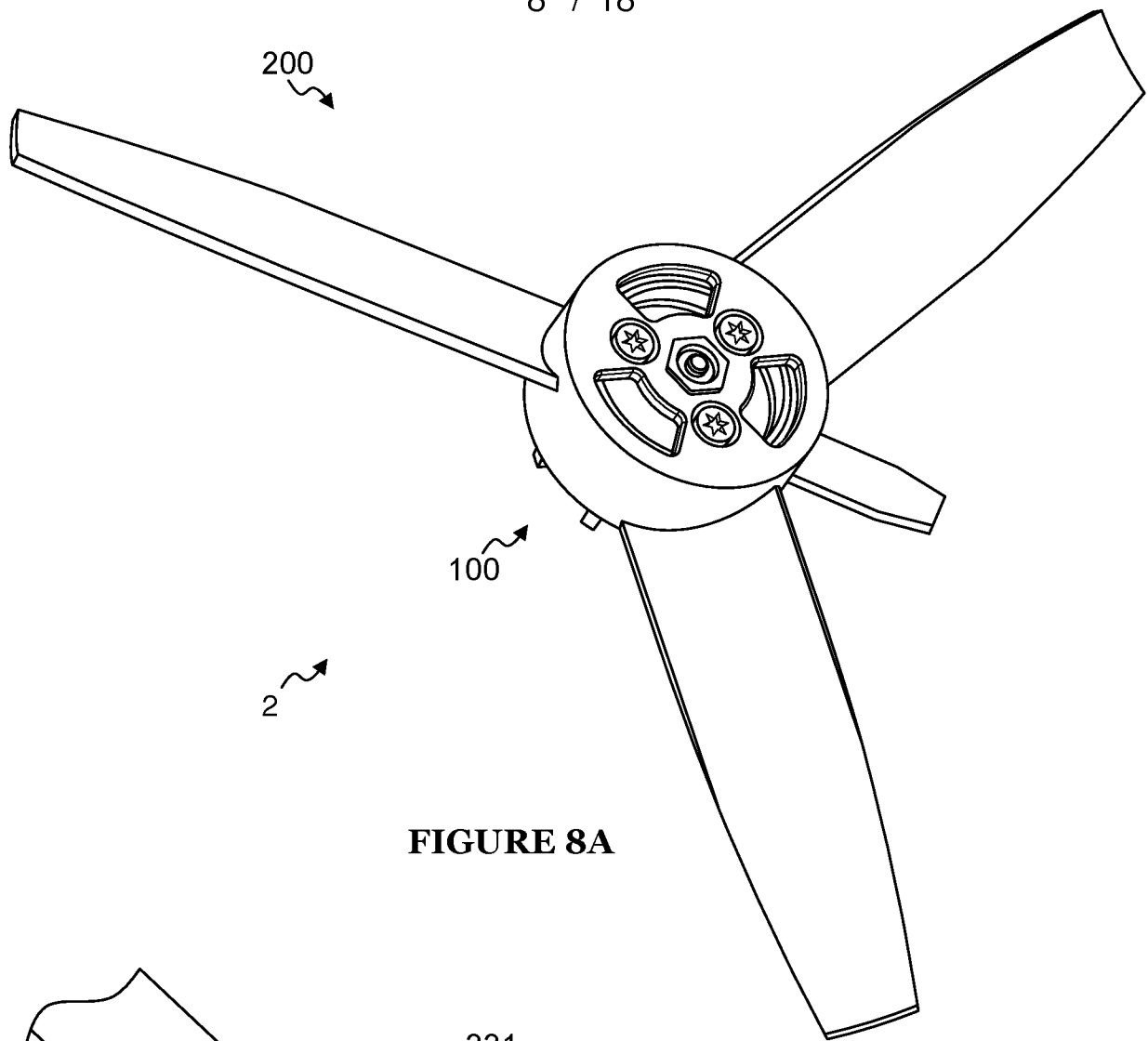


FIGURE 8A

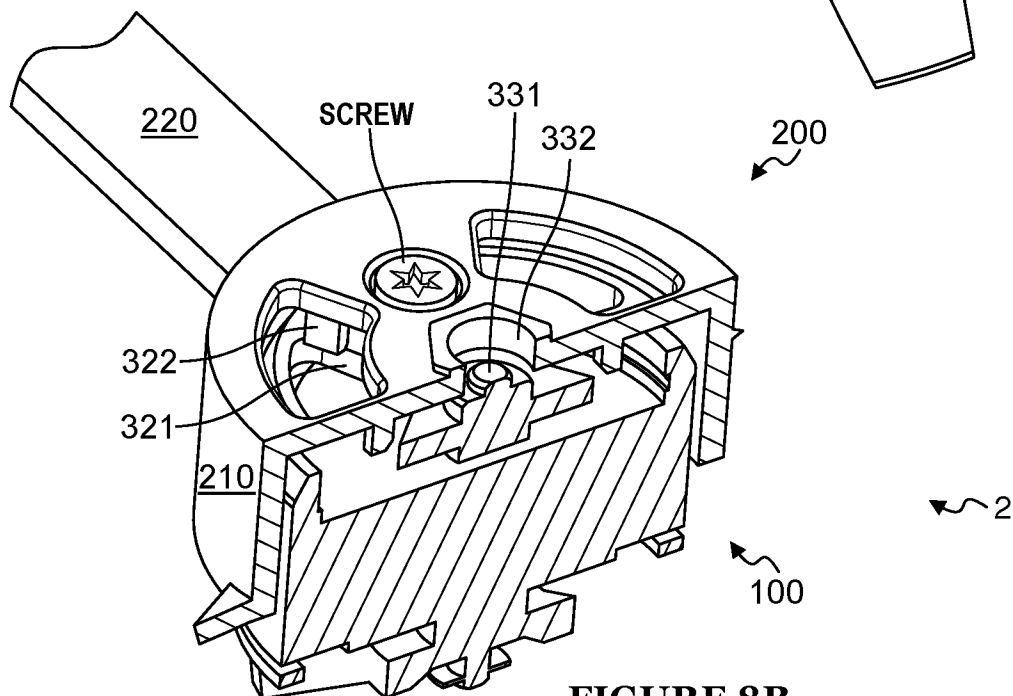


FIGURE 8B

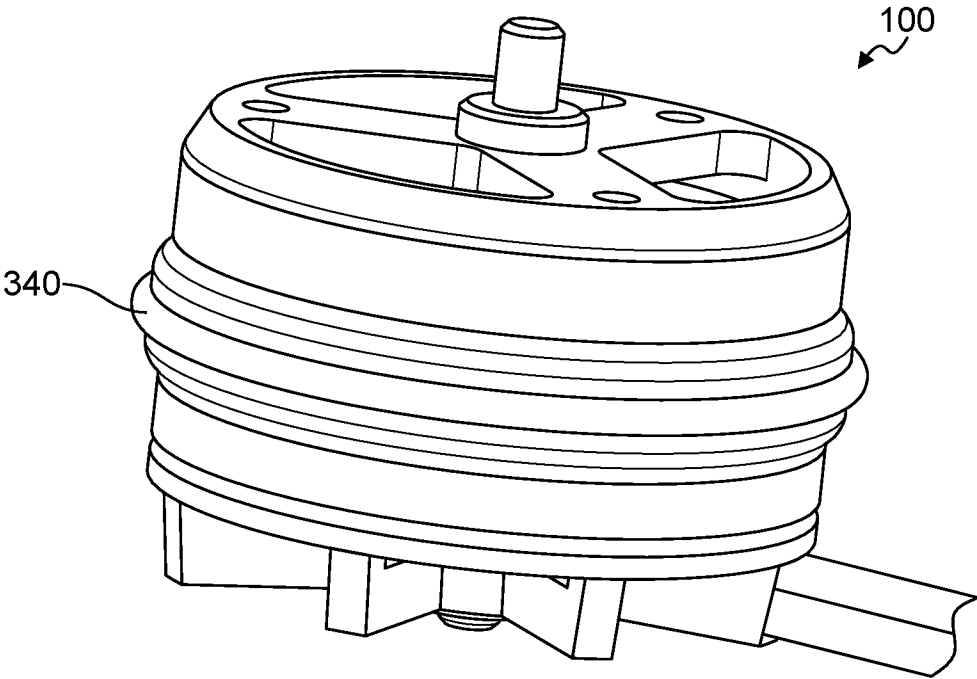


FIGURE 9A

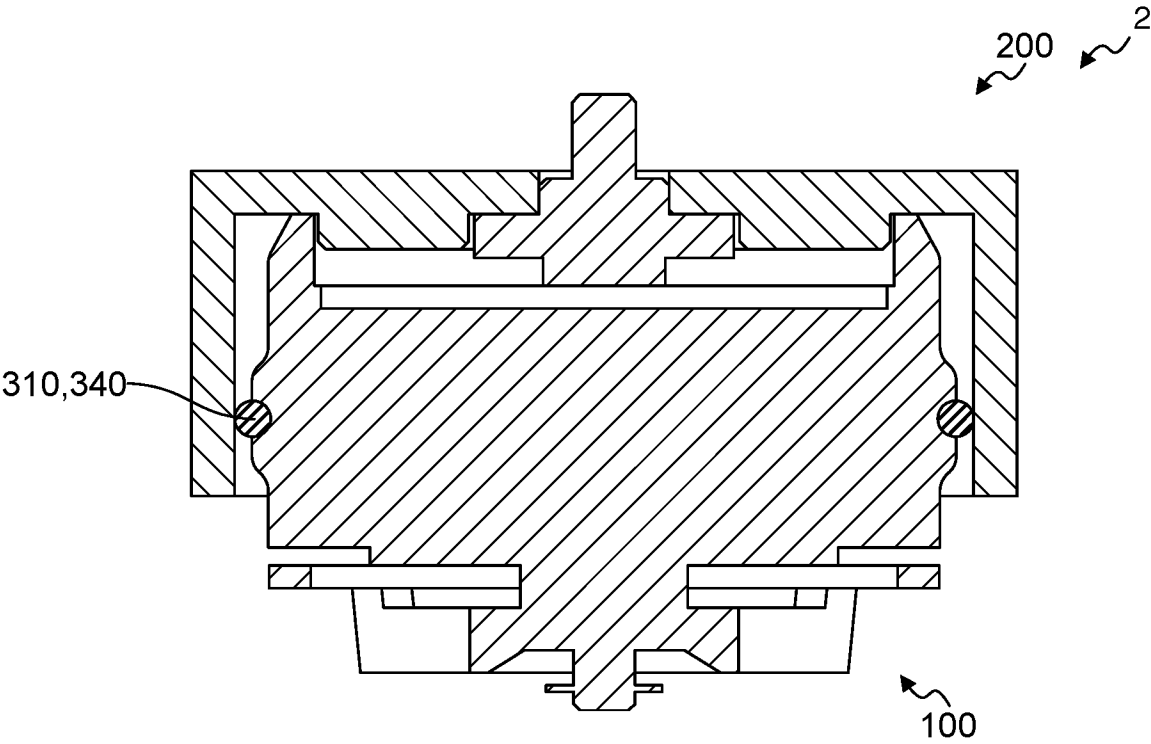


FIGURE 9B

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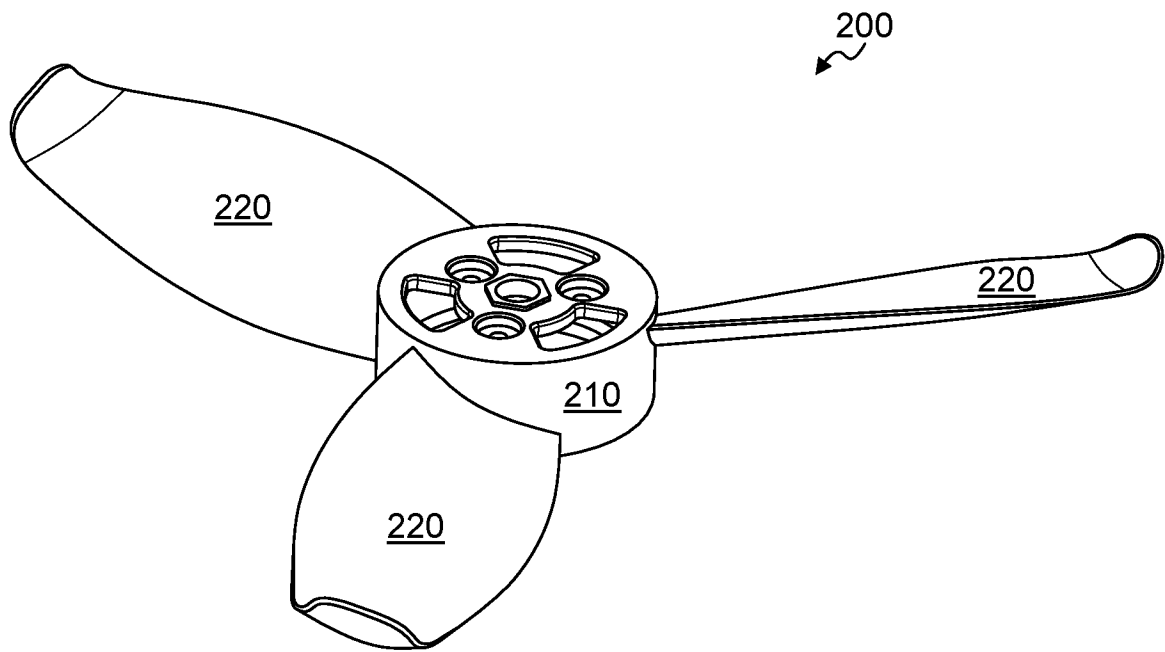
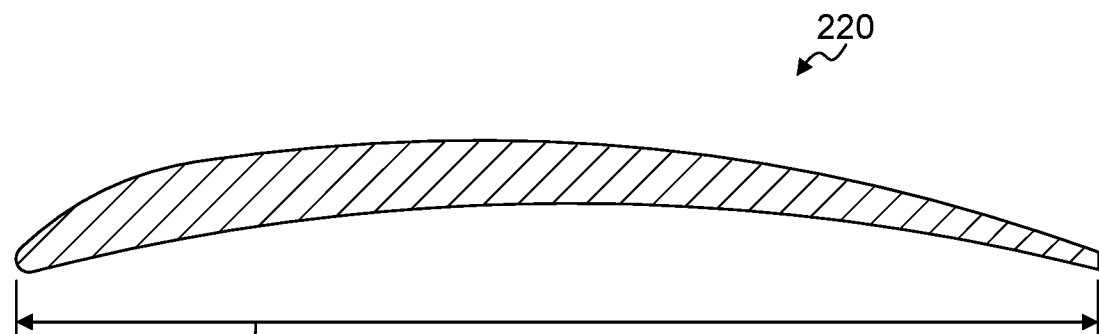


FIGURE 10A



CORD LENGTH

FIGURE 10B

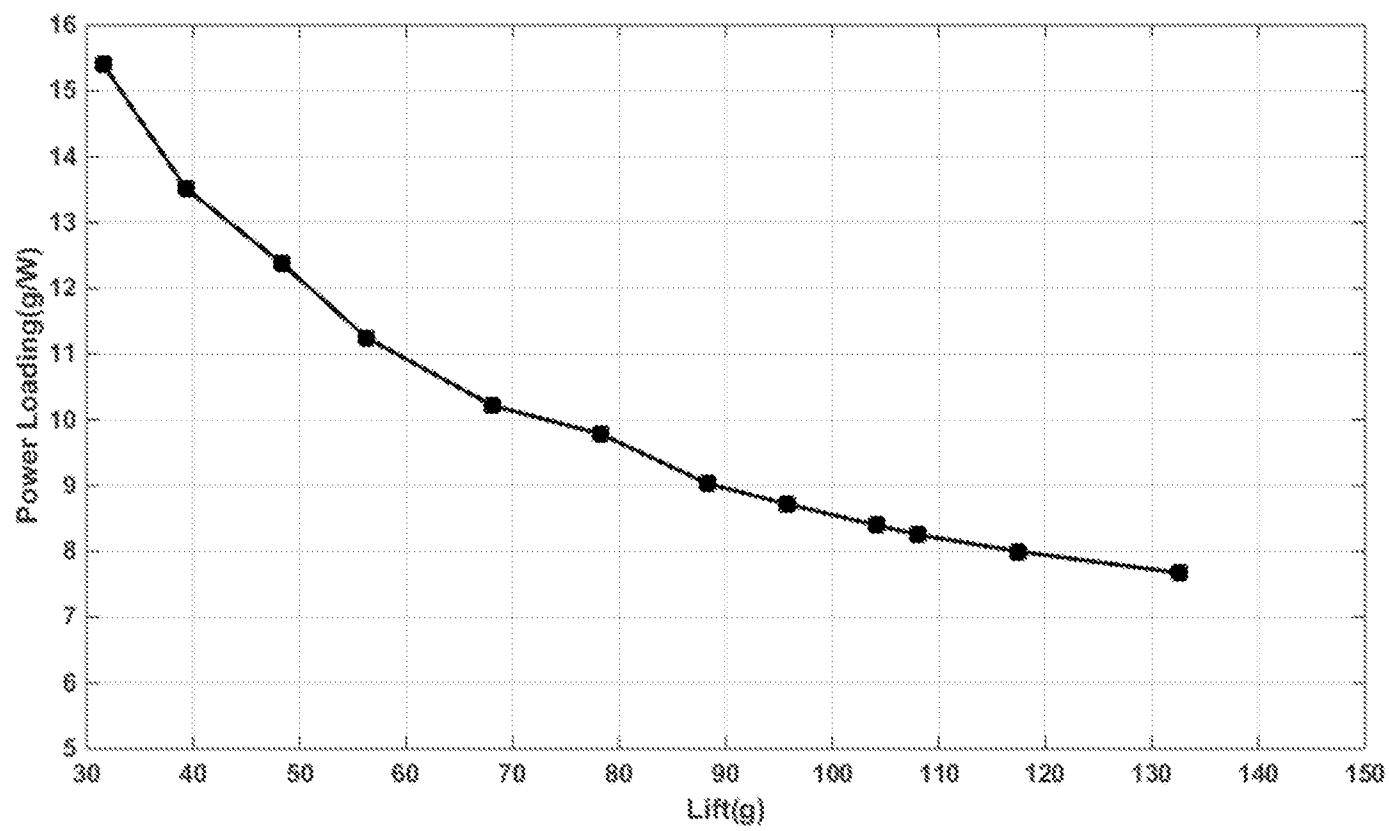


FIGURE 11

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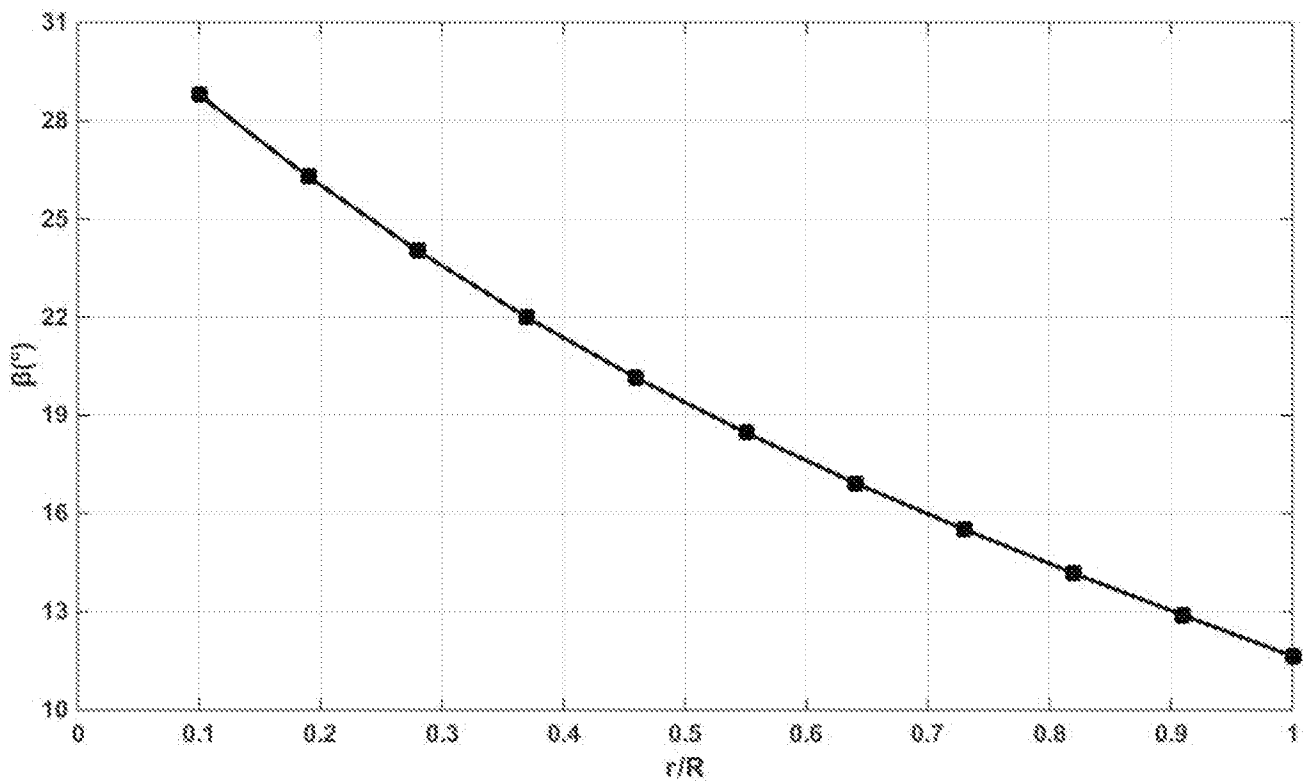


FIGURE 12A

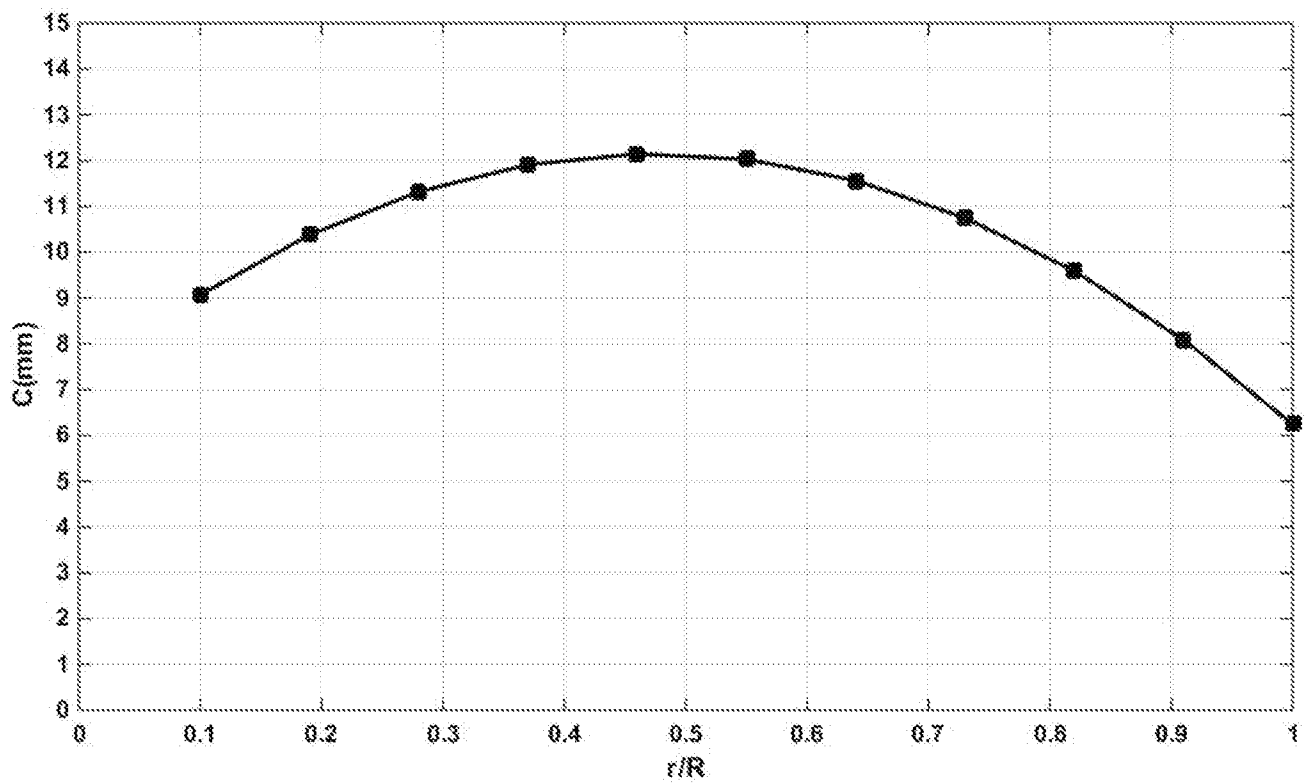
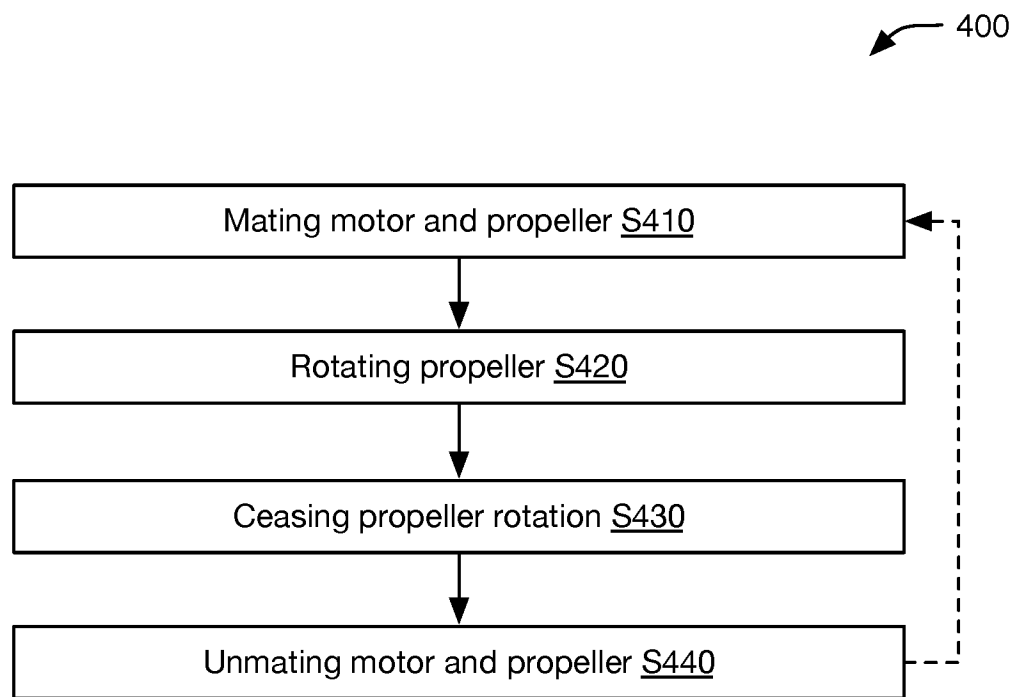


FIGURE 12B

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**FIGURE 13**

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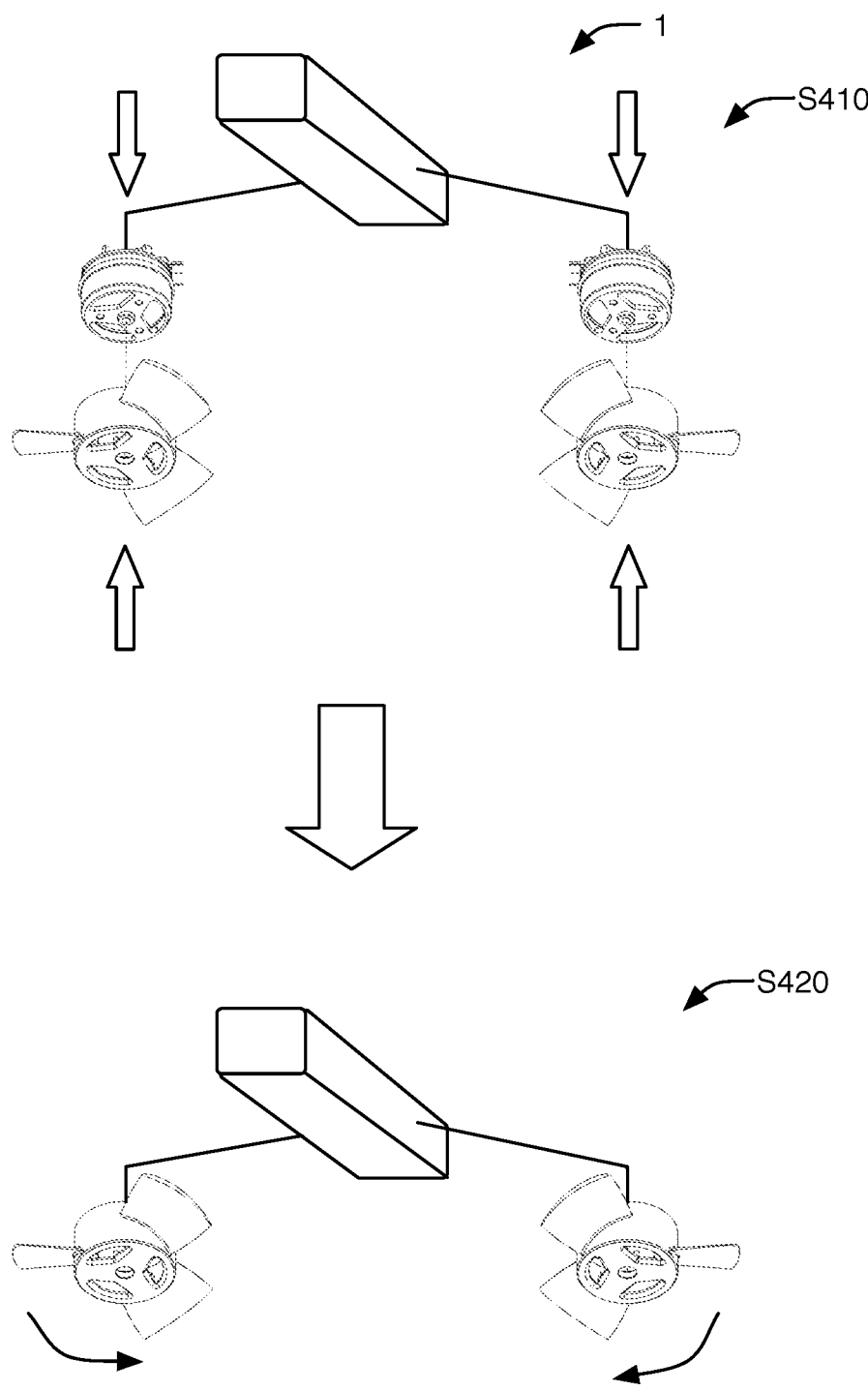


FIGURE 14

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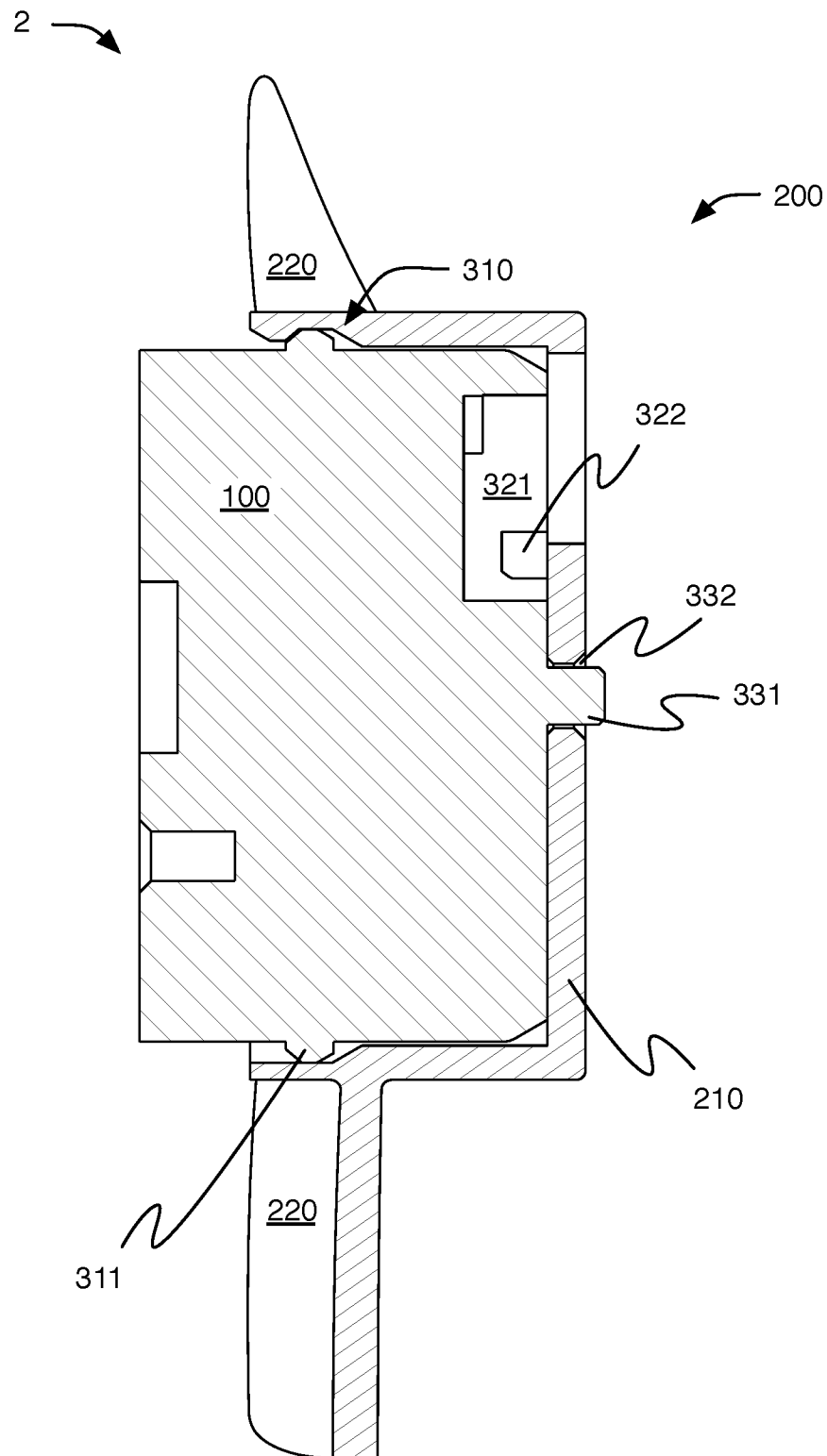


FIGURE 15

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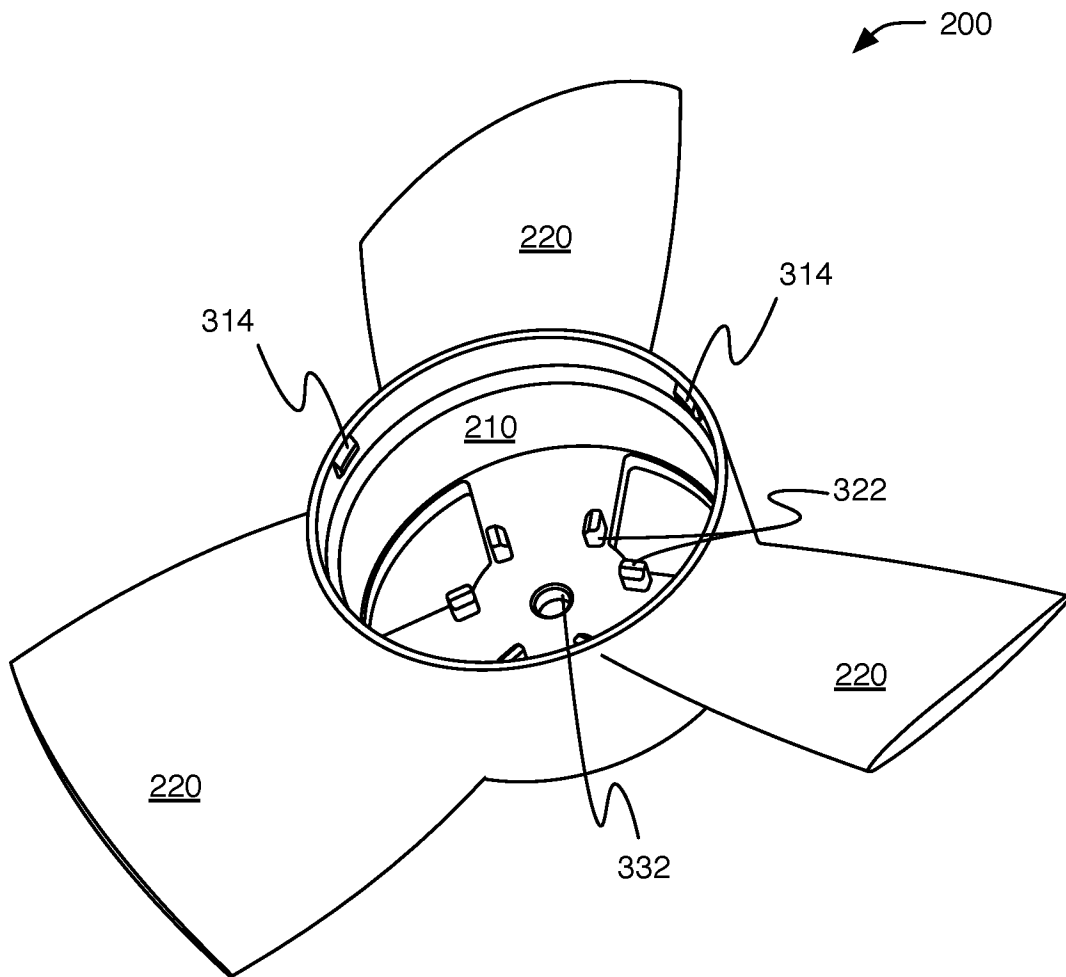


FIGURE 16

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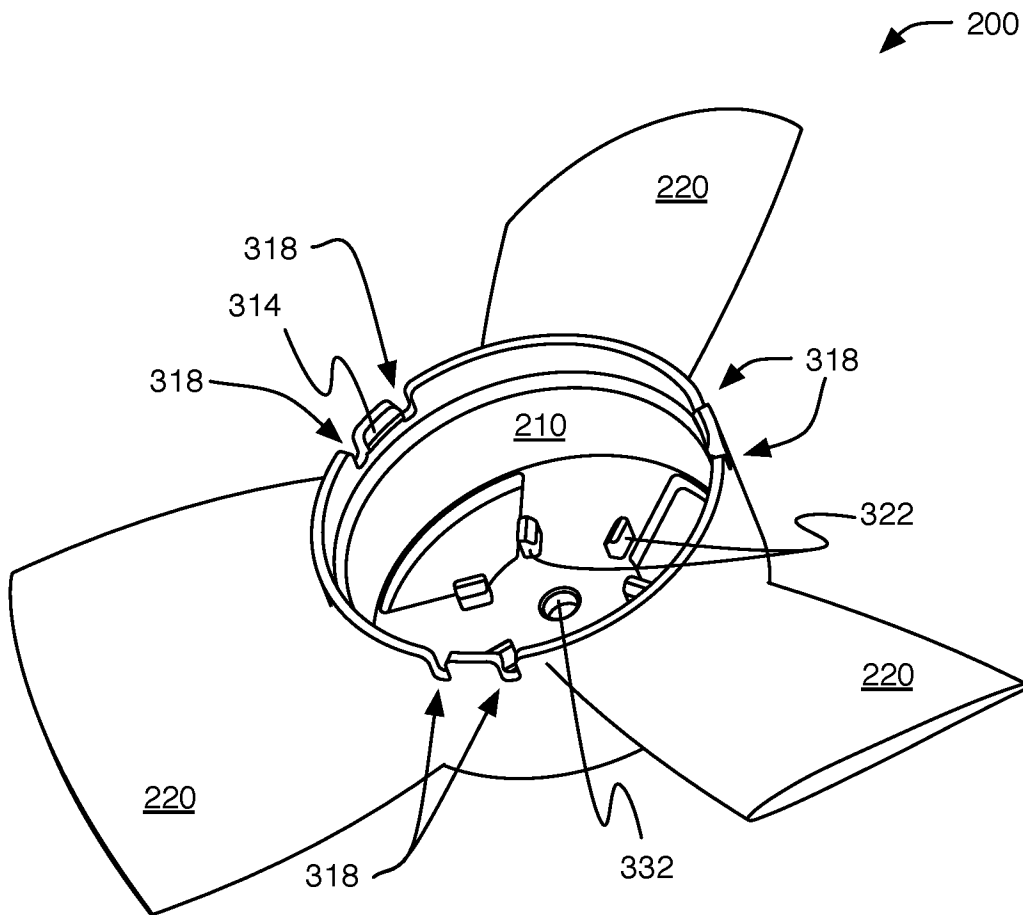


FIGURE 17

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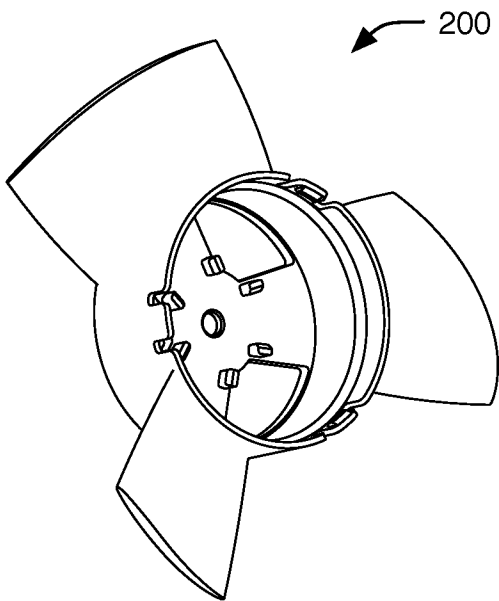


FIGURE 18A

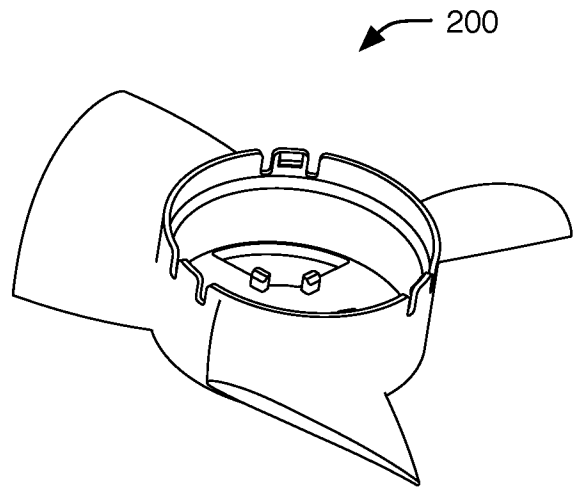


FIGURE 18B

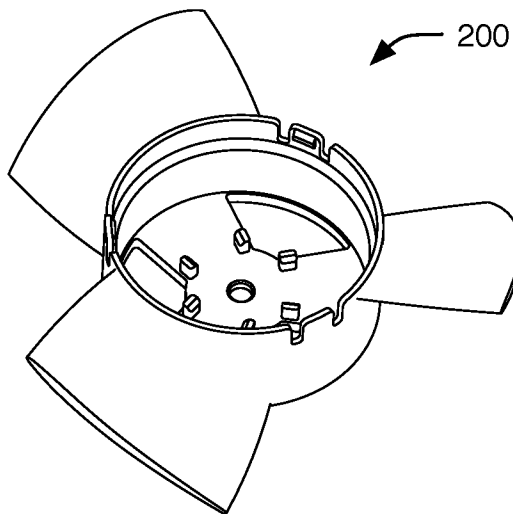


FIGURE 18C