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(21) International Application Number: PCT/US93/05797 (22) International Filing Date: 18 June 1993 (18.06.93) (30) Priority data: <table border="0"> <tr> <td>07/903,060</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> <tr> <td>07/903,061</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> <tr> <td>07/903,063</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> <tr> <td>07/903,064</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> <tr> <td>07/903,065</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> <tr> <td>07/903,066</td> <td>22 June 1992 (22.06.92)</td> <td>US</td> </tr> </table> (71) Applicant: UNITED TECHNOLOGIES CORPORATION [US/US]; Sikorsky Aircraft, Legal-Patents Mailstop Z209A, 6900 Main Street, Stratford, CT 06601-1381 (US). (72) Inventors: CYCON, James, P. ; 818 Robert Treat Drive, Orange, CT 06477 (US). HUNTER, David, H. ; 680 Country Wood Court, Cheshire, CT 06410 (US). KOHLHEPP, Fred, W. ; 468 Ridge Road, Hamden, CT 06517 (US). KRAUSS, Timothy, A. ; 711 Hill Road, Harwinton, CT 06791 (US). MILLEA, Vincent, F. ; 54 Tudor Ridge, Stratford, CT 06497 (US). FURNES, Kenneth, M. ; 30 Kimberly Drive, Monroe, CT 06468 (US). FARRELL, Marvin, D. ; 537 Burton Road, Beacon Falls, CT 06403 (US). SANDY, David, F. ; 350 Savin Avenue #37, West Haven, CT 06516 (US). BEATTY, Robert, D. ; 3000 Nicholas Avenue, Trumbull, CT 06611 (US). HANSEN, Bruce, D. ; 51 Ridgefield Terrace, Shelton, CT 06484 (US).		07/903,060	22 June 1992 (22.06.92)	US	07/903,061	22 June 1992 (22.06.92)	US	07/903,063	22 June 1992 (22.06.92)	US	07/903,064	22 June 1992 (22.06.92)	US	07/903,065	22 June 1992 (22.06.92)	US	07/903,066	22 June 1992 (22.06.92)	US	(74) Agent: RADKE, Terrance, J.; United Technologies Corporation, Sikorsky Aircraft, Legal-Patents Mailstop Z209A, 6900 Main Street, Stratford, CT 06601-1381 (US). (81) Designated States: AU, CA, DE, GB, JP, KP, RU, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>Without international search report and to be republished upon receipt of that report.</i>
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(54) Title: AN UNMANNED AERIAL VEHICLE HAVING DUCTED, COAXIAL COUNTER-ROTATING ROTORS																				
(57) Abstract An unmanned aerial vehicle (UAV) (10) has a composite toroidal fuselage structure (20) that surrounds a rotor assembly (100) that includes pair of coaxial, multi-bladed, counter-rotating rotors (200, 202). The toroidal fuselage structure (20) includes an annular C-shaped structure (430) that defines an internal cavity (436) and removable panel structures (464) mounted in combination with the annular C-shaped structure (430). The UAV has a drive train assembly (60) that includes a sprag clutch (62), an engine coupling subassembly (63), a transmission coupling subassembly (74), and a drive shaft (72) operative to couple torque between the UAV engine (54) and the rotor assembly (100) and configured to maximize allowable axial, angular, and/or parallel misalignments therebetween. The UAV further includes a coaxial transmission/center hub assembly (110), an integrated spline/cone seat subassembly (190), rotor blade subassemblies including pretwisted inner flexbeams (260), and snubber assemblies (230).																				

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**AN UNMANNED AERIAL VEHICLE
HAVING DUCTED, COAXIAL COUNTER-ROTATING ROTORS**

Related Application

The present application is related to

5 commonly-owned U.S. Patent No. 5,150,857 entitled
SHROUD GEOMETRY FOR UNMANNED AERIAL VEHICLES, to
commonly-owned U.S. Patent No. 5,152,478 entitled
AN UNMANNED FLIGHT VEHICLE INCLUDING COUNTER
ROTATING ROTORS POSITIONED WITHIN A TOROIDAL SHROUD
10 AND OPERABLE TO PROVIDE ALL REQUIRED VEHICLE FLIGHT
CONTROLS, to commonly-owned, co-pending U.S. patent
application Serial No. 07/903,061, filed 22 June
1992, entitled A ROTOR BLADE SUBASSEMBLY FOR A
ROTOR ASSEMBLY HAVING DUCTED, COAXIAL COUNTER-
15 ROTATING ROTORS, to commonly-owned, co-pending U.S.
patent application Serial No. 07/903,063, filed 22
June 1992, entitled A SNUBBER ASSEMBLY FOR A ROTOR
ASSEMBLY HAVING DUCTED, COAXIAL COUNTER-ROTATING
ROTORS (S-4544), to commonly-owned, co-pending U.S.
20 patent application Serial No. 07/903,064, filed 22
June 1992, entitled AN INTEGRATED SPLINE/CONE SEAT
SUBASSEMBLY FOR A ROTOR ASSEMBLY HAVING DUCTED,
COAXIAL COUNTER-ROTATING ROTORS, to commonly-owned,
co-pending U.S. patent application Serial
25 No. 07/903,066, filed 22 June 1992, entitled A
DRIVE TRAIN ASSEMBLY FOR A ROTOR ASSEMBLY HAVING
DUCTED, COAXIAL COUNTER-ROTATING ROTORS, and to
commonly-owned, co-pending U.S. patent application
Serial No. 07/903,060, entitled TOROIDAL AIRFRAME
30 STRUCTURE FOR SHROUDED ROTOR UNMANNED AERIAL
VEHICLES.

Technical Field

The present invention relates to unmanned aerial vehicles (UAVs), and more particularly, to an optimized coaxial transmission/center hub subassembly, an optimized snubber assembly, an optimized integrated spline/cone seat subassembly, an optimized rotor blade subassembly, and an optimized drive train assembly for a rotor assembly for a UAV having an optimized toroidal fuselage structure (shroud) and a pair of coaxial, counter-rotating, ducted, multi-bladed rotors.

Background of the Invention

There has been a recent resurgence in the interest in unmanned aerial vehicles (UAVs) for performing a variety of missions where the use of manned flight vehicles is not deemed appropriate, for whatever reason. Such missions include surveillance, reconnaissance, target acquisition and/or designation, data acquisition, communications datalink, decoy, jamming, harassment, or one-way supply flights. This interest has focused mainly on UAVs having the archetypical airplane configuration, i.e., a fuselage, wings having horizontally mounted engines for translational flight, and an empennage, as opposed to "rotor-type" UAVs, for several reasons.

First, the design, fabrication, and operation of "winged" UAVs is but an extrapolation of the manned vehicle flight art, and therefore, may be accomplished in a relatively straightforward and cost effective manner. In particular, the aerodynamic characteristics of such UAVs are well

documented such that the pilotage (flight operation) of such vehicles, whether by remote communications datalink of commands to the UAV and/or software programming of an on-board flight computer, is relatively simple.

In addition, the range and speed of such UAVs is generally superior to rotor-type UAVs. Moreover, the weight-carrying capacity of such UAVs is generally greater than rotor-type UAVs such that winged UAVs may carry a larger mission payload and/or a larger fuel supply, thereby increasing the vehicle's mission efficiency. These characteristics make winged UAVs more suitable than rotor-type UAVs for certain mission profiles involving endurance, distance, and load capability. Winged UAVs, however, have one glaring deficiency that severely limits their utility.

More specifically, winged UAVs do not have a fixed spatial point "loiter" capability. For optimal performance of many of the typical mission profiles described hereinabove, it is desirable that the UAV have the capability to maintain a fixed spatial frame of reference with respect to static ground points for extended periods of time, e.g., target acquisition. One skilled in the art will appreciate that the flight characteristics of winged UAVs are such that winged UAVs cannot maintain a fixed spatial frame of reference with respect to static ground points, i.e., loiter. Therefore, mission equipment for winged UAVs must include complex, sensitive, and costly motion-compensating means to suitably perform such mission profiles, i.e., maintenance of a constant viewing

azimuth for a static ground points.

Rotor-type UAVs, in contrast, are aerodynamically suited for such loiter-type mission profiles. The rotors of the main rotor assembly of such UAVs may be operated so that the UAV hovers at a fixed spatial frame of reference with respect to static ground points.

A need exists for rotary-type UAVs for a wide variety of reconnaissance and/or communication missions, especially tactical reconnaissance missions. Such UAVs may include a rotor assembly having ducted, coaxial counter-rotating rotors mounted within a toroidal composite structure. The UAV should be design optimized to provide a UAV airframe structure that is structurally and aerodynamically compact and lightweight. The UAV should be further design optimized to provide an optimal performance capability.

Summary of the Invention

One object of the present invention is to provide an unmanned aerial vehicle (UAV) having ducted, coaxial counter-rotating rotors mounted within a toroidal composite structure that is designed optimized to provide an optimal performance capability while minimizing overall vehicle weight.

Another object of the present invention is to provide the UAV with an optimized toroidal fuselage structure including removable panel structures for providing accessibility to mission equipment.

A further object of the present invention is to provide a toroidal fuselage structure with

improved bending stiffness to minimize structural distortion and with substantially rigid strut attachment points to minimize motion of the rotor assembly with respect to the fuselage structure.

5 Still another object of the present invention is to incorporate a sacrificial element in the toroidal fuselage structure that protects the fuselage duct wall from rotor blade strikes.

10 Yet a further object of the present invention is to provide a drive train assembly for the UAV that is design optimized to maximize allowable axial, angular, and/or parallel misalignments between the UAV engine and rotor assembly as a result of mechanical interconnections of the engine
15 drive shaft to the external crown spline coupling, internal spline coupling combination of the engine coupling assembly and the external crown spline coupling, gear spline coupling combination of the transmission coupling subassembly.

20 Still a further object of the present invention is to provide a drive shaft for the drive train subassembly that is configured as a torque tube having inside and outside diameters sized to provide a torsionally soft drive shaft wherein the
25 drive shaft functions as a torsional spring to isolate the spline coupling teeth, the sprag clutch, the transmission gearing, and the rotor assembly from vibratory torque generated by the UAV engine.

30 Yet another object of the present invention is to provide a coaxial transmission/center hub subassembly for the UAV that includes a single stage transmission, a transmission housing, and a

center hub support structure that are structurally and functionally interactive to provide enhanced power transfer efficiency between the UAV engine and the counter-rotating rotors.

5 One more object of the present invention is to provide a single stage transmission comprising an input pinion gear rotatably mounted in combination with the transmission housing, and upper and lower bevel gears, having
10 integral rotor shafts rotatably mounted in combination with the transmission housing, coupled in combination with the input pinion gear to provide counter-rotation of the rotor shafts.

15 Yet one more object of the present invention is to provide a transmission housing having external surfaces that function as sliding surfaces for rotor swashplate subassemblies to minimize the separation between the counter-rotating rotors wherein the airframe structure has a compact
20 aerodynamic and structural envelope.

25 Still one more object of the present invention is to provide a center hub support structure configured for mounting the coaxial transmission/center hub support subassembly in fixed coaxial relation to the UAV airframe structure and which is operative to couple dynamic loads of the counter-rotating rotors and thermal loads to the airframe structure and to cancel bending moments of the counter-
30 rotating rotors.

 Another object of the present invention is to provide a transmission housing for the UAV that is internally configured to provide a splash

lubrication subsystem.

Yet another object of the present invention is to provide an integrated spline/cone seat subassembly for the UAV rotor assembly that is design optimized to minimize the radial dimensions of the UAV rotor shafts, rotor shaft bearings, the transmission housing, and the swashplate subassemblies thereof.

Still a further object of the present invention is to provide a rotor blade subassembly for the UAV having reduced weight, low inertia, a high chordwise frequency, an improved aerodynamic profile, low static droop, and which eliminates high chordwise stresses and the need for blade damping mechanisms.

One further object of the present invention is to provide a laminated composite flexbeam for the rotor blade subassembly having a predetermined spanwise linear twist wherein the pretwisted flexbeam is unstrained during predetermined forward flight cruise conditions.

Yet one further object of the present invention is to provide a continuous, composite filament wound tubular integrated torque tube/spar member for the rotor blade subassembly having high torsional and bending stiffness that provides a continuous torsional load path and facilitates load coupling between the rotor blade and the pretwisted flexbeam.

Still one further object of the present invention is to provide a rotor blade for the rotor blade subassembly fabricated from a high modulus composite material and configured to having a high

5 aerodynamic taper to provide low outboard mass and high inboard stiffness, a high chordwise frequency such that the rotor blade subassembly operates over a weaker modal response zone, and a triangularly shaped trailing edge segment.

10 Yet one more object of the present invention is to provide a snubber assembly for the UAV rotor assembly that is configured for installation inboard of flexbeam-to-rotor hub attachment joint and to utilize self-aligning bearings.

15 These and other objects are achieved by an unmanned aerial vehicles (UAVs) having a rotor assembly with ducted, coaxial counter-rotating rotors. One embodiment of a UAV comprises a toroidal fuselage or shroud having an aerodynamic profile, flight/mission equipment, a powerplant subsystem, and a rotor assembly. The toroidal fuselage is fabricated from a composite material as a closed toroid to provide maximal structural strength. The toroidal fuselage has a plurality of support struts integrally formed with and extending radially outwardly from the inner periphery of the toroidal fuselage which are operative to support the rotor assembly in a fixed coaxial relation with respect to the toroidal fuselage. The toroidal fuselage structure is fabricated as a closed toroid to provide maximum structural strength. The toroidal fuselage structure is partially hollow, and fabricated as an open-faced annular structure having a C-shaped configuration that defines an internal cavity that defines the internal bays of the toroidal fuselage structure. Removable panel structures are disposed in combination with the C-

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30

shaped annular structure to provide access to the internal bays.

5 Pairs of bulkhead structures are disposed within and equally about the C-shaped annular structure. Each bulkhead pair is affixed to the toroidal fuselage structure at the attachment point of a support strut, and in concert with duct stiffening structures, form substantially rigid box structures for reacting the propulsive rotor loads imposed on the toroidal fuselage structure through the support struts. Horizontal mounting plates disposed between and affixed to the bulkhead structures further stiffen the rigid box structures, while additionally providing mounting surfaces for vehicle subsystems and mission equipment.

10 The duct wall of the toroidal fuselage structure has circumferential stiffening structures formed thereon to provide increased bending stiffness and to enhance the overall rigidity of the toroidal fuselage structure to minimize distortion or "egging" of the duct wall. The duct wall includes a plurality of vertical stiffening structures to further stiffen the overall toroidal fuselage structure, thereby causing the toroidal fuselage structure to act as a complete structure in bending. The vertical stiffening structures are further operative to stabilize the duct wall against deformation due to suction loads induced by downwash from the rotor assembly. Vertically orientated mounting plates are affixed to the vertical stiffening structures for mounting mission equipment.

Rub strip members are disposed within pockets formed by the circumferential stiffening structures and are disposed in the tip path planes defined by the rotation of the tip ends of the rotor blade assemblies. The rub strip members act as sacrificial elements to protect the duct wall from blade contact.

The removable panel structures are mounted to the ends of the C-shaped annular structure to complete the toroidal fuselage structure, while providing means for accessing the internal bays provided by the toroidal fuselage structure. The edges of the removable panel structures have a mating interface at the attachment region with the bulkhead structures. The mating interface has a sawtooth configuration which minimizes the number of fasteners required to attach the removable panels.

Forward located internal bays are typically utilized for sundry flight/mission equipment. Distribution of the various flight/mission equipment is optimized in conjunction with the placement of the powerplant subsystem. The powerplant subsystem includes the fuel tank(s), an engine, and a drive train assembly. The fuel tanks and engine are disposed within appropriate internal bays. The embodiment of the UAV described herein utilizes a Norton Motors rotary engine, Model NR801T (modified as described hereinbelow), which provides a high power to weight ratio and good partial power fuel consumption. The NR801T engine is an air/liquid cooled engine that produces 45 HP at 6,000 RPM. Operation of the engine is

controlled and monitored by the flight computer.

5 The standard Norton engine was modified by
combining the functional features of the flywheel
and the Plessey generator in an integrated
flywheel/generator subassembly. The integrated
flywheel/generator subassembly includes a large
diameter, thin rotor having a plurality of magnets
internally mounted therein, and a plurality of
rigidly mounted stators. The drive train assembly
10 of the described embodiment includes a sprag
clutch, an engine coupling subassembly, a drive
shaft, and a transmission coupling subassembly.
The drive train assembly is operative to transfer
the power developed by the engine to the rotor
15 assembly.

 The rotor assembly comprises an electronic
control servo subsystem, upper and lower stationary
swashplate subassemblies, a plurality of pitch
control rods, a coaxial transmission/center hub
20 subassembly, upper and lower integrated spline/cone
seat subassemblies, and upper and lower multi-
bladed, counter-rotating rotors integrated in
combination with the transmission/center hub
subassembly. The rotors are aerodynamically
25 "shrouded" by the toroidal fuselage. Blade pitch
changes induced in the counter-rotating rotors are
utilized to generate all required lift, pitch,
roll, and yaw control of the UAV. Such pitch
changes are also utilized to regulate the pattern
30 and velocity of airflow over the toroidal shroud
and into the rotor assembly. Such control of the
airflow creates a lifting component on the toroidal
shroud that augments the lift provided by the

counter-rotating rotors.

5 The electronic control servo subsystem is
operative to control the functioning of the upper
and lower stationary swashplate subassemblies by
coupling inputs from the flight computer to the
respective swashplate subassemblies. The upper and
lower stationary swashplate subassemblies are
operative, in response to mechanical inputs from
the linear actuators of the electronic control
10 servo subsystem, to selectively mechanically couple
cyclic pitch inputs and/or collective pitch inputs
to the respective counter-rotating rotors by means
of the pitch control rods, which are mechanically
secured at the ends thereof to the swashplate
15 subassemblies and rotor blade assemblies of the
counter-rotating rotors. The swashplate
subassembly is design optimized for effective
utilization in combination with the configuration
of the coaxial transmission/center hub subassembly.

20 The configuration of the transmission/center
hub subassembly is design optimized to provide an
integrated, low component part system that is
lightweight, compact, and structurally and
thermally efficient. The transmission/center hub
25 subassembly includes a single stage transmission
subsystem, a multi-member transmission housing, and
a center hub support structure. The configuration
of the transmission/center hub subassembly provides
enhanced power transfer efficiency between the
30 powerplant subsystem and the counter-rotating
rotors, thereby increasing the operational
capability and efficacy of the UAV. Further, the
transmission/center hub subassembly configuration

minimizes the separation between the upper and lower counter-rotating rotors, thereby providing a UAV having a compact structural and aerodynamic envelope. The configuration of the transmission/center hub subassembly also facilitates the transfer of the dynamic loads developed by the counter-rotating rotors, and reduces airframe vibration levels by providing a direct load path between the upper and lower counter-rotating rotors so that canceling of bending moments produced by the rotors during flight operations occurs. In addition, the transmission/center hub subassembly configuration according to the present invention eliminates the need for transmission mounting brackets.

The single stage transmission subsystem comprises an input pinion gear having a splined end portion, bearings for mounting the input pinion gear in rotatable combination with the transmission housing, and upper and lower spiral bevel gears. The upper and lower spiral bevel gears have upper and lower rotor shafts, respectively, integrally formed therewith, thereby eliminating the need for separate rotor shaft connection means. The transmission subsystem further includes standpipe bearings for rotatably mounting the respective upper and lower rotor shafts in combination with the transmission housing.

The input pinion gear is mechanically coupled to the drive shaft by means of the gear spline coupling (the gear spline coupling mechanically engages the splined end portion of the pinion gear), and operative to transmit torque from the

engine to the upper and lower spiral bevel gears. The placement of the bevel gears vis-a-vis the spiral gear portion of the input pinion gear causes counter rotation of the upper and lower rotor shafts with respect to one another. The splined end portion of the input pinion gear facilitates quick disconnection of the single stage transmission from the center hub support structure.

5 The multi-member transmission housing includes an upper standpipe housing, a lower standpipe housing, and a middle housing. The upper and lower standpipe housings are secured in combination with the middle housing by means of screws. By mounting the upper and lower standpipe housings in combination with the middle housing, direct load paths are provided for the dynamic and static longitudinal, lateral, vertical, and torsional loads developed by the upper and lower counter-rotating rotors into the middle housing. This functional feature allows the operating moments of the upper and lower rotors to cancel each other out in the middle housing. The cancellation function provided by the configuration of the transmission housing significantly reduces vibratory loads that would normally be transmitted to the toroidal fuselage.

10 The standpipe bearings are mounted against the internal surface of the upper and lower standpipe housings and are operative to facilitate rotary motion of the respective rotor shafts while transmitting rotor bending loads to the upper and lower standpipe housings. The respective standpipe bearings are separated to minimize shear reaction.

The coaxial transmission/center hub subassembly utilizes the external surfaces of the upper and lower standpipe housings as sliding surfaces for the bidirectional translational movement of the respective stationary swashplate subassemblies. The range of such bidirectional linear motion is sufficient to couple the requisite collective pitch inputs to respective blades of the counter-rotating rotors for flight operations of the UAV. By utilizing the external surfaces for swashplate motion, a minimum separation between the upper and lower counter-rotating rotors is achieved, thus providing the UAV with a compact structural and aerodynamic envelope.

The described embodiment of the coaxial transmission/center hub subassembly includes a separate center hub support structure comprising a cylindrical body having three equidistantly spaced integral support arms extending radially outwardly therefrom. The support arms function as the rigid attachment points for the support struts to mount the coaxial transmission/center hub subassembly in fixed coaxial relation to the toroidal fuselage.

The center hub support structure is configured so that the middle housing may be slidably inserted therein such that external surfaces of the middle housing abuttingly engage internal surfaces of the center hub support structure. The abuttingly engaged surfaces in combination function as mounting and load bearing surfaces that are operative to transfer the dynamic and static loads developed by the counter-rotating rotors to the center hub support structure. The middle housing

is secured in combination with the center hub support structure by means of pins and screws. Dynamic lift loads developed by the counter-rotating rotors are transmitted from the middle housing to the central hub support structure via the pins and screws. All other dynamic rotor loads, as well as thermal loads generated by operation of the single stage transmission, are coupled from the middle housing to the center hub support structure via the abuttingly engaged surfaces thereof.

The dynamic and static rotor loads and the thermal loads coupled into the center hub support structure are transmitted into the toroidal fuselage, via the support struts, by means of the integral support arms. Cooling of the coaxial transmission/center hub subassembly, and in particular the middle housing, is facilitated by the structural arrangement wherein the center hub support structure, the support arms, and the support struts lie directly in the downwash generated by the upper rotor, thereby facilitating convective cooling of such structural elements.

The cylindrical body further includes six mounting lugs extending radially outwardly therefrom. The mounting lugs are utilized to mount the electronic control servo subsystem (more specifically, the three linear actuators thereof) in combination with the rotor assembly.

The coaxial transmission/center hub subassembly further includes a splash lubrication subsystem that provides oil lubrication for the input pinion gear, the transmission bearings, the

upper and lower spiral bevel gears, and the standpipe bearings. The upper standpipe bearing is grease lubricated due to its location vis-a-vis the splash lubrication subsystem. The splash lubrication subsystem includes a pinion chamber, cored passages, and standpipe chambers formed in the upper and lower standpipe housings, respectively, which are fluidically interconnected by means of a central reservoir.

The standpipe bearings, the transmission bearings, and the gear teeth of the input pinion gear, and the upper and lower spiral bevel gears are oil lubricated by means of the splash lubrication subsystem. Oil from the central reservoir is circulated, due to the rotary motion of the upper and lower spiral bevel gears, throughout the fluid flow pathways of the splash lubrication subsystem to lubricate the aforescribed components. Since no lubrication pumps are required for the splash lubrication subsystem, the overall system weight and complexity of the UAV is reduced.

The middle housing may be fabricated as an integral element of the center hub support structure to provide an alternative structural embodiment of the coaxial transmission/center hub subassembly. The integrated center hub support structure provides the functions of the middle housing in addition to the functions of the center hub support structure. In this embodiment, however, the securing pins and screws are not required.

The upper and lower integrated spline/cone

seat subassemblies are operative to secure the upper and lower counter-rotating rotors, respectively, in combination with the coaxial transmission/center hub subassembly. The integrated spline/cone seat subassembly is design optimized to reduce the size/radial dimensions of the upper and lower rotor shafts, the standpipe bearings, the standpipe housings, and the upper and lower stationary swashplate subassemblies. The downsizing of these components provides a significant savings in the overall system weight of the UAV.

The integrated spline/cone seat subassembly includes a primary shaft portion having a first diameter, an end shaft portion having a second diameter, and a truncated conic transition portion intermediate the primary, end shaft portions. Each end shaft portion has a plurality of shaft spines extending radially outwardly therefrom. Each counter-rotating rotor includes a rotor hub that functions as part of the respective integrated spline/cone seat subassembly. Each rotor hub includes a shaft aperture having a plurality of hub splines extending radially inwardly from the wall defining the shaft aperture. The lower portion of each hub spline has an outwardly tapered portion. The tapered portions of the hub splines abuttingly engage and are mechanically supported by the truncated conic transition portion of the respective rotor shafts. The diameter of the primary shaft portion defines the radial dimensions of the respective rotor shafts, and, in consequence, the sizing of the standpipe bearings,

the multi-member transmission housing, and the stationary swashplate subassemblies.

Each counter-rotating rotor includes the rotor hub, four snubber assemblies, and four rotor blade assemblies. The rotor hub additionally comprises four outwardly extending arms having ends forming a clevis. Each clevis provides the means for securing the rotor blade assembly in combination with the rotor hub. The rotor hub also functions as an element of the snubber assembly. Each outwardly extending arm is further configured to provide the means for securing the respective snubber assembly in combination with the rotor hub.

The snubber assembly comprises a spherical bearing, a bearing bolt, a locking nut, a snubber bracket secured in combination with the spherical bearing, and securing bolts. The spherical bearing, snubber bracket combination is rotatably mounted within the rotor hub by means of the bearing bolt, and secured in combination in the rotor hub by means of the locking nut.

Each counter-rotating rotor includes four rotor blade assemblies. Each rotor blade assembly comprises an inner flexbeam, an integrated torque tube/spar member, an outer aerodynamic fairing or rotor blade, an optimized blade joint and an optimized pitch control rod mounting scheme. Each rotor blade assembly has a tapered configuration that provides reduced weight, low inertia, a high chord frequency, an improved aerodynamic profile, low static droop, and eliminates high chordwise stresses and the need for blade damping mechanisms.

The flexbeam of the rotor blade assembly is a

laminated composite structure that is operative to react the centrifugal loads and a majority of the bending loads developed during operation of the counter-rotating rotors. The flexbeam is secured
5 in combination with the rotor hub and the respective integrated torque tube/spar member and tapered rotor blade. To compensate for the variable strains induced along the span of the flexbeam, the flexbeam has a predetermined linear
10 twist, i.e., built-in twist, along the span thereof (inboard end to outboard end). As a result of such pretwist, the pretwisted flexbeam makes an angle with respect to a horizontal plane that varies linearly from about 0° at the inboard end (root
15 section) of the pretwisted flexbeam to about 22° at the outboard end (tip section) of the pretwisted flexbeam.

The integrated torque tube/spar member of the rotor blade subassembly is formed as a continuous,
20 single piece, low cost tubular composite structure that provides high torsional and bending stiffness and facilitates the utilization of the efficient blade joint. The integrated torque tube/spar structure is formed as a continuous filament wound
25 piece that provides a continuous torsion load path and facilitates load coupling from the tapered rotor blade into the respective pretwisted flexbeam. The integrated torque tube/spar member includes an inboard torque tube segment and a
30 outboard spar segment. The spar segment functions as the primary structural member of the rotor blade subassembly and is operative to react all bending, torsional, shear, and centrifugal dynamic loads

developed during operation of the counter-rotating rotors. The torque tube segment is operative to react all torsional loads and some of the bending loads developed during operation of the counter-rotating rotors.

The configuration of the rotor blade of each rotor blade subassembly is design optimized for reduced weight utilizing composite materials, e.g., high modulus graphite, which results in a tapered rotor blade having a high chordwise frequency. Each outboard segment of the rotor blades is configured to have an aerodynamic taper of about 2:1, which results in a tapered rotor blade having a low outboard mass and a high inboard stiffness. The aerodynamic taper of the outer rotor blades results in a low moment of inertia about the hub centerline and the mass centroid of each tapered rotor blade being closer to the rotor hub. The high chordwise frequency of the tapered rotor blades provides the benefit of rotor operation over a weaker modal response zone.

The optimized blade joint is operative to secure the pretwisted flexbeam in combination with the respective integrated torque tube/spar member and tapered rotor blade. The blade joint includes an innovative bolt layout that is optimally positioned to eliminate the moment reaction at the blade joint due to the steady chordwise loading experienced by the rotor blade assembly, thereby allowing the utilization of smaller bolts and reduced joint thicknesses. The rotor blade subassembly further includes an optimized pitch control rod mounting scheme that results in

pressure forces acting on the strongest part of the control rod bearing such that longer effective lifetimes are achieved for the control rod bearings.

5 **Brief Description of the Drawings**

 A more complete understanding of the present invention and the attendant features and advantages thereof may be had by reference to the following detailed description of the invention when
10 considered in conjunction with the accompanying drawings wherein:

 Figure 1 is a perspective, partially broken away view of one embodiment of an unmanned aerial vehicle (UAV) according to the present invention.

15 Figure 2 is a cross-sectional view illustrating a preferred aerodynamic profile for the toroidal fuselage of the UAV of Figure 1.

 Figure 3 is a cross-sectional view illustrating a drive train assembly for the UAV
20 according to the present invention.

 Figure 3A is an expanded cross-sectional view of one portion of the drive train assembly of Figure 3.

25 Figure 4 is a partial plan view illustrating one embodiment of a rotor assembly for the UAV according to the present invention.

 Figure 5A is a top plan view of one preferred embodiment of a swashplate subassembly for the rotor assembly of Figure 4.

30 Figure 5B is a side plan view of the swashplate subassembly of Figure 5A.

 Figure 6 is a cross-sectional view of one

preferred embodiment of a coaxial transmission/center hub subassembly portion for the rotor assembly of Figure 4.

5 Figure 7 is a top plan view of the center hub support structure of the coaxial transmission/center hub subassembly of Figure 6.

Figure 8 is a schematic representation of a prior art spline/cone seat arrangement for a rotor assembly.

10 Figure 9 is a schematic representation of an integrated spline/cone seat subassembly for the rotor assembly according to the present invention.

Figure 9A is a top plan view of the rotor hub of the integrated spline/cone seat subassembly according to the present invention.

15 Figure 9B is a cross-sectional view of the rotor hub of Figure 9A.

Figure 10A is a top plan view of the top rotor assembly for the UAV of the present invention.

20 Figure 10B is a partially broken away side plan view of the rotor assembly of Figure 10A.

Figure 10C is a partial, enlarged view of Figure 10B illustrating the snubber assembly of the present invention.

25 Figure 10D is a cross-sectional view of the snubber assembly taken along line 10D-10D of Figure 10C.

Figure 11 is a graph depicting the operating curve for the UAV of the present invention vis-a-vis rotor assembly resonance mode conditions.

30 Figure 12A is a cross-sectional view of the spar segment of the integrated torque tube/spar member of the rotor blade assembly of the present

invention.

Figure 12B is a cross-sectional view of the torque tube segment of the integrated torque tube/spar member of the rotor blade assembly of the present invention.

Figure 13 is a graph defining the pretwist for the flexbeam of the rotor blade assembly according to the present invention.

Figure 14 is a partial plan view depicting the optimal positioning of the blade joint of rotor blade assembly for the UAV of the present invention.

Figure 15 is a graph showing the offset of the optimal blade joint position with respect to the outboard mass centroid of the rotor blade assembly of the present invention.

Figure 16 is a schematic representation of a prior art pitch control rod bearing mounting scheme for a conventional rotor assembly.

Figure 17 is a schematic representation of a pitch control rod bearing mounting scheme for the rotor assembly according to the present invention.

Figure 18 is a top plan view of the embodiment of the toroidal fuselage structure of the UAV of Figure 1.

Figure 19 is a profile view of the C-shaped annular structure of the toroidal fuselage structure of the UAV according to the present invention.

Figure 20A is a cross-sectional view taken along line 20a-20a of Figure 18.

Figure 20B is a cross-sectional view taken along line 20b-20b of Figure 18.

Figure 20C is a cross-sectional view taken along line 20c-20c of Figure 20B.

Figure 20D is a cross-sectional view taken along line 20d-20d of Figure 18.

5 Figure 21 is an enlarged view of the mating interface of the toroidal fuselage structure according to the present invention, taken along line 21-21 of Figure 18.

Detailed Description of Preferred Embodiments

10 Referring now to the drawings wherein like reference numerals identify corresponding or similar elements throughout the several views, Figures 1 and 2 illustrate one embodiment of an unmanned aerial vehicle (UAV) 10 according to the
15 present invention. The illustrated embodiment of the UAV 10 comprises a toroidal fuselage or shroud 20 having an aerodynamic profile 22, flight/mission equipment 30, a powerplant subsystem 50, and a rotor assembly 100. The
20 aerodynamic profile 22 of the toroidal fuselage 20 of the described embodiment may be optimized to minimize nose-up pitching moments during forward translational flight. One preferred aerodynamic profile 22 for the illustrated UAV 10 is described
25 in further detail in commonly-owned U.S. Patent No. 5,150,857 entitled SHROUD GEOMETRY FOR UNMANNED AERIAL VEHICLES. Another embodiment of the UAV 10 according to the present invention, which includes a toroidal fuselage or shroud having a
30 hemicylindrical aerodynamic profile, is described in commonly-owned U.S. Patent No. 5,152,478 entitled AN UNMANNED FLIGHT VEHICLE INCLUDING

COUNTER ROTATING ROTORS POSITIONED WITHIN A
TOROIDAL SHROUD AND OPERABLE TO PROVIDE ALL
REQUIRED VEHICLE FLIGHT CONTROLS. This embodiment
utilizes cyclic pitch to compensate for the
fuselage-induced nose-up pitching moments
experienced during forward translational flight.

The embodiment of the UAV 10 described herein
has a toroidal fuselage 20 diameter of about 6.5
feet, a toroidal fuselage 20 envelope height of
about 1.6 feet, an empty vehicle weight of about
175 pounds, and a gross vehicle weight of about 250
pounds. Reference numeral 12 illustrated in
Figure 1 defines the fuselage axis of the UAV 10.
The toroidal fuselage 20 has a plurality of support
struts 24 (three for the described embodiment)
integrally formed with and extending radially
outwardly from the inner periphery of the toroidal
fuselage 20 to the rotor assembly 100. The support
struts 24, which are rigidly attached to the rotor
assembly 100 as described hereinbelow in further
detail, are operative to support the rotor
assembly 100 in a fixed coaxial relation with
respect to the toroidal fuselage 20, i.e., the
rotational axis of the rotor assembly 100 coincides
with the fuselage axis 12. The support struts 24
are hollow structures to minimize the overall
weight of the UAV 10, and to provide conduits for
interconnecting operating elements of the UAV 10.
For example, the engine drive shaft (see
description hereinbelow) is routed through one of
the support struts 24, as illustrated in Figure 2.
In addition, the electrical interface wiring for
the electronic control servo subsystem (see

description hereinbelow) is routed through another support strut 24.

5 The toroidal fuselage 20 and the plurality of support struts 24 are preferably fabricated from composite material to provide a high strength structure of minimal weight. The various types of high tensile strength fibrous materials and resins having utility in the formation of aerospace composite structures are well known to those skilled in the art. The toroidal fuselage 20 is fabricated as a closed toroid to provide maximal structural strength. The toroidal fuselage 20 is a partially hollow structure, and fabricated so as to provide a plurality of accessible internal bays 26.

10 Forward located internal bays 26 are typically utilized for sundry flight/mission equipment 30 as described hereinbelow. The mission payload equipment 32 is preferably located, but not limited to, the internal bay 26 at the 180° azimuthal station (the forward station). Generally, the mission payload equipment 32 will consist of some type of passive sensor(s), e.g., infrared detector(s), television camera(s), etc., and/or active device(s), e.g., laser(s), radio communications gear, radar, etc., and the associated processing equipment, and the forward internal bay 26 provides a good field-of-view for such mission payload equipment 32. Other flight/mission equipment 30 such as avionics 34, navigation equipment 36, flight computer 38, communications gear 40 (for relaying real time sensor data and receiving real time command input signals), antennae, etc., are distributed in the

various internal bays 26 as exemplarily illustrated in Figure 1. Distribution of the various flight/mission equipment 30 is optimized in conjunction with the placement of the powerplant subsystem 50 as described hereinbelow.

5 With reference to Figure 18, the rotor assembly 100 includes two counter-rotating propulsive rotors 200, 202 (see also Figure 4, rotor 202 being obscured by rotor 200 in Figure 18)
10 coaxially mounted within a duct 402 formed by the toroidal fuselage 20 which are operative to direct airflow downward through the duct 402. Each rotor 200, 202 includes four rotor blade
15 assemblies 250 having tip end portions 284 in close proximity to the duct wall 402, the tip end portions 284 defining a tip path plane 404 when the rotors are turning. The close proximity of the tip end portions 284 to the duct wall 402 minimizes or suppresses rotor blade tip vortices, which improves
20 the propulsive efficiency of the UAV 10.

 As shown in Figure 18, the rotor assembly 100 is supported by a plurality of support strut members 24 which mount to the inner periphery or duct wall portion 402 of the toroidal fuselage
25 structure 20. The longitudinal axis 24A of each strut member is radially aligned with respect to the rotor axis 12, and the longitudinal axes 24A form 120° sectors therebetween. Also illustrated in Figure 18 are three pairs of bulkhead
30 structures 410 which are equally spaced about and located within the toroidal fuselage structure 20.

 Each pair of bulkhead structures 410 defines a first region 418 therebetween which is intersected

by the longitudinal axis 24A of the corresponding support strut 24. A second region 420 is defined between adjacent pairs of bulkhead structures 410. The first region 418 preferably defines a sector of the toroidal fuselage structure 20 not greater than about 45°, and more preferably, defines a sector less than about 30°. Such spacing for each pair of bulkhead structures 410 creates a substantially rigid structural box section for reacting lift loads from the rotor assembly 100, which loads are transferred to the toroidal fuselage 20 through the corresponding support strut 24. Since the rigidity of the first region 418 is dependent on the sector size, a relatively small sector size, as compared to the second region 420, is preferable. For a toroidal fuselage structure 20 having three pairs of bulkhead structures 410, each second region 420 will preferably form a sector greater than about 75°. It will be apparent that the larger the number of bulkhead pairs, the smaller the sector size encompassed by each second region 420.

The infrastructure of the toroidal fuselage structure 20 is illustrated in Figures 19, 20A, 20B, 20D and comprises an annular structure 430 having a C-shaped configuration in cross section. The first and second ends of the C-shaped structure 430 are identified in Figures 19, 20A by reference numerals 432, 434, respectively. The C-shaped structure 430 forms the duct wall 402 of the toroidal fuselage structure 20, and defines an internal cavity 436 for the toroidal fuselage structure 20. The annular structure 430, in combination with the pairs of bulkhead

structures 410, comprise the primary structural elements of the toroidal fuselage structure 20. The internal cavity 436 of the toroidal fuselage structure 20 delimited by the pairs of bulkhead structures 410 comprises the internal bays 26 described hereinabove.

The duct wall 402 formed by the C-shaped structure 430 preferably includes upper and lower circumferential stiffening structures 438, 440 integrally formed thereon and disposed within the internal cavity 436. The stiffening structures 438, 440 provide a continuous, stiff load path around the circumference of the duct wall 402, thus providing additional bending strength for the toroidal fuselage structure 20. A plurality of equally spaced vertical stiffening structures 442 are integrally formed on the duct wall 402 in facing relationship with the internal cavity 436. The vertical stiffening structures 442 are formed only in the second regions 420 of the toroidal fuselage structure 20. Adjacent vertical stiffening structures 442 are preferably spaced apart by about 15° with respect to the fuselage axis 12.

The duct wall 402 additionally includes integral duct stiffening structures 444 in facing relationship with the internal cavity 436. The duct stiffening structures 444 are formed only in the first regions 418 of the toroidal fuselage structure 20 between the upper and lower circumferential stiffening members 438, 440. Each duct stiffening structure 444 preferably extends between and serves as a mounting surface for the

corresponding pair of bulkhead structures 410. The duct stiffening structures 444, in combination with the corresponding pair of bulkhead structures 410, provide a substantially rigid box structure for reacting the propulsive rotor loads transferred into the toroidal fuselage structure 20 through the support struts 24.

A horizontal support plate 414 is affixed to the corresponding side walls 412 of the respective bulkhead structures 410 to provide enhanced box structure stiffness (see also Figure 18). Moreover, the horizontal support plates 414 provide a structural load path for transferring the weight of the vehicle subassemblies and mission payload equipment to the box structure defined by the duct stiffening structures in combination with the bulkhead structures 410.

Vertically orientated mounting plates 446 may be utilized to attach additional vehicle subassemblies, e.g., sundry flight/mission equipment 30, powerplant subsystem 50, etc., within the internal cavity 436 in one or more of the second regions 420. Each mounting plate 446 is preferably affixed to at least two adjacent vertical stiffening structures 442, thereby providing a suitable means for reacting the weight of the attached subassembly. It should be understood that the powerplant subsystem 50 and flight/mission equipment 30 may also be mounted directly to the vertical stiffening structures 442.

A cross section along line 20a-20a of Figure 18 of the toroidal fuselage structure 20 is shown in Figure 20A and identifies three structural

segments of the toroidal fuselage structure 20: the duct wall 402; a lower dorsal segment 450; and a closure segment 452 interconnecting the dorsal segment 450 to the duct wall 402. The duct wall 402 comprises a substantially cylindrical main segment 454 that has the longitudinal axis coaxial with the rotor axis 12, and an upper lip segment 456 that extends from an upper end 458 of the cylindrical main segment 454. The dorsal segment 450 extends radially outboard from a lower end 460 of the cylindrical main segment 454 of the duct wall 402. The duct wall 402 and the dorsal segment 450 of the toroidal fuselage structure 20 comprise the C-shaped annular structure 430 described hereinabove.

The closure segment 452 of the toroidal fuselage structure 20 is defined by two points of tangency T1 and T2 where horizontal and vertical lines XX and YY intersect the uppermost and radially outermost segments of the toroidal fuselage structure 20, respectively. Preferably an upper segment 462 of the closure segment 452 is integral with and smoothly transitions from the upper lip segment 456 of the duct wall 402. The C-shaped structure 430 includes the upper segment 462 of the closure segment 452, which provides added bending stiffness and positions the first end 432 of the C-shaped structure 430 away from the suction profile developed over the toroidal fuselage structure 20 during operation of the UAV 10. The structural stiffness of the annular C-shaped structure 430 may further be enhanced by extending the lower dorsal segment 450. However fabrication

of the C-shaped structure 430 may be adversely affected.

5 The closure segment 452 includes removable panel structures 464 that provide access to the internal cavity 436 of the toroidal fuselage structure 20. Each panel structure 464 is of sufficient size to facilitate the placement and removal of flight mission equipment 30 and the powerplant subsystem 50 within the various internal
10 bays 26.

 In one preferred embodiment of the C-shaped annular structure 430 described herein, the cylindrical main segment 454 of the duct wall 402 is fabricated from a continuous layup of six plies
15 of graphite/epoxy material having a total thickness (identified by reference numeral 470 in Figure 20A) of about 0.030 inches. The cylindrical main segment 454 includes the upper and lower circumferential stiffening structures 438, 440
20 located within the internal cavity 436, which form respective pockets 472, 474 on the inboard surface 476 of the cylindrical main segment 454. Each pocket 472, 474 has an average width dimension (exemplarily identified by reference numeral 478)
25 of about 1.5 inches and an average depth dimension (exemplarily identified by reference numeral 480) of about 0.50 inches. Tapering of the pockets 472, 474 in the depth 112 dimension is provided to facilitate manufacture.

30 Upper and lower rub strip members 482, 484 are disposed within the respective pocket 472, 474. The rub strip members 482, 484 are preferably formed of a conventional foam material. Each of

the rub strip members 482, 484 have a thickness and shape so as to fill the respective pocket 472, 474 completely. Accordingly, respective inboard surfaces 486, 488 defined by the rub strip members 482, 484 lie substantially flush with the inboard surface 476 of the cylindrical main segment 454. The rub strip members 482, 483 act as a sacrificial element to protect the duct wall 402 from contact by the tips 284 of the rotor blade assemblies 250. The rub strip members 482, 484 lie in the tip path plane 404 defined by the blade tip end portions 284 as the counter-rotating rotors 200, 202 rotate. In the preferred embodiment described herein, the rotor assembly 100 includes two counter-rotating rotors 200, 202 that define upper and lower tip path planes 404 that are separated by a vertical distance (reference numeral 490 in Figure 20A) of approximately 11.0 inches. Preferably the blade tip ends 284 are in close proximity to the inboard surface 476 of the cylindrical main segment 454 to minimize or suppress rotor blade tip vortices for improved propulsive efficiency.

The upper lip segment 456 is preferably fabricated from six plies of graphite/epoxy material with a total thickness (reference numeral 492 in Figure 20a) of approximately 0.030 inches, providing sufficient strength to react the suction loads applied to the upper lip segment 456 during flight operations. The lower dorsal segment 450 is preferably fabricated from six plies of graphite/epoxy material with a total thickness (reference numeral 494 in Figure 20A) of

approximately 0.030 inches.

In the preferred embodiment described herein, the closure segment 452 is fabricated from graphite/epoxy material, with the upper segment 462 thereof being fabricated with six plies having a thickness (reference numeral 496 in Figure 20A) of about 0.030 inches. The removal panel structures 464 are fabricated from three plies having a thickness (reference numeral 498 in Figure 20A) of approximately 0.015 inches. The attachment of the removable panel structures 464 of the closure segment 452 to the first and second ends 432, 434 of the C-shaped annular structure 430 may be accomplished through the any number of methods known to those skilled in the art.

The first and second ends 432, 434 of the C-shaped annular structure 430 have integral reverse flanges 500, 502, respectively, which provide increased buckling and crippling strength for the first and second ends 432, 434, and which also assist in transferring the loads applied thereto from the removable panel structures 464 of the closure segment 452. The reverse flanges 500, 502 include an additional ply buildup so as to result in a total thickness (reference numeral 504 in Figure 20A) of approximately 0.045 inches.

A cross section along section 20b-20b of Figure 18 is shown in Figure 20B and illustrates the toroidal fuselage structure 20 at the location of one vertical stiffening structure 442 in the second region 420. The vertical stiffening structure 442 extends between the upper and lower

circumferential stiffening structures 438, 440 and is integrally formed on the duct wall 402 facing the internal cavity 436. The vertical stiffening structures 442 serve to stiffen the overall toroidal fuselage structure 20, thereby forcing the structure 20 to act as a complete structure in bending. Furthermore, the vertical stiffening structures 443 stabilize the duct wall 402 to prevent deformation due to suction forces induced by rotor downwash. The vertical stiffening structure 442 is preferably fabricated to include a core 510 of conventional foam material. The core 510 has a stiffener height (reference numeral 512 in Figure 20B) sufficient to meet the upper and lower circumferential stiffening structures 438, 440. The stiffener depth (reference numeral 514 in Figure 20B) of the vertical stiffening structure 442 is preferably about 0.50 inches so as to smoothly transition from the upper and lower circumferential stiffening structures 438, 440 to the vertical stiffening structure 442.

Figure 20C depicts a cross section of the duct wall 402 along line 20c-20c of Figure 20B at the location of a vertical stiffening structure 442. The vertical stiffening structure 442 has a trapezoidal configuration with a base width (reference numeral 516) of approximately 2.0 inches and a top width (reference numeral 518) of approximately 1.0 inches. The vertical stiffening structure 442 is tapered along the depth for ease of manufacture. The core 510 of the vertical stiffening structure 442 is disposed within the ply layup that forms the duct wall 402 so as to form an

integral stiffening structure for transferring loads. During manufacture of the toroidal fuselage structure 20, the core 510 is placed within the ply layup, and preferably has three of the six duct wall plies on both sides of the core 510.

A cross section along line 20d-20d of Figure 18 is shown in Figure 20D and depicts the toroidal fuselage structure 20 at the location of the duct stiffening structure 444 located within one first region 418 of the internal cavity 436. The duct stiffening structure 444 extends between the upper and lower circumferential stiffening structures 438, 440 and is integrally formed on the cylindrical main segment 454 of the duct wall 402. The duct stiffening structure 444 increases the bending stiffness of the overall toroidal fuselage structure 20, and acting working in combination with the corresponding pair of bulkhead structures 410, provides a substantially rigid box structure for the attachment of the respective support strut 24. The rigid attachment of the support strut 24 to the toroidal fuselage structure 20 minimizes the relative motion of the propulsive rotor assembly 100 with respect to the toroidal fuselage structure 20 and provides a structural load path for transferring loads from the propulsive rotor assembly 100.

The duct stiffening structure 444 is preferably fabricated from a honeycomb sandwich structure having one face sheet 520 comprising three plies of graphite/epoxy having a thickness of about 0.015 inches. The duct stiffening structure 444 has a height (reference

numeral 522) sufficient to meet the upper and lower circumferential stiffening structures 438, 440.

5 The width (reference numeral 524) of the duct stiffening structure 444 is preferably about 0.50 inches so as to form a smooth transition between the upper and lower circumferential stiffening structures 438, 440 and the duct stiffening structure 444. The duct stiffening structure 444 is placed atop and bonded to the six ply layup
10 comprising the duct wall 402 with the face sheet 520 facing outboard.

Each pair of bulkhead structures 410 (only one is shown in Figure 20D) is bonded in combination with the C-shaped annular structure 430 within the
15 internal cavity 436. The bulkhead pairs 410 act in concert with the duct stiffening structure 444 and the C-shaped annular structure 430 form a substantially rigid box structure for attachment of the support strut 24. The bulkheads 410 are
20 preferably formed from nine plies of graphite/epoxy having a thickness of about 0.045 inches. The shape of the bulkheads 410 approximately defines the shape of the toroidal fuselage structure 20. The bulkheads 410 include flanged portions 530,
25 532, 534 corresponding to the duct wall 402, the dorsal segment 450, and the closure segment 452, respectively. Flange portions 530, 532 serve the purpose of attaching the bulkheads 410 to the C-shaped annular structure 430 in the internal
30 cavity 436. The flange portion 534 provides a means for attaching the removable panel structure 464 to the toroidal fuselage structure 20. The flange portions 530, 532, 534

are fabricated from graphite/epoxy ply layups and are preferably formed integral with bulkhead structure.

5 Also shown in Figure 20D is the horizontal support plate 414, which is utilized for mounting the heaviest vehicle subsystems and mission payload equipment 30 so that the loads thereof are transferred to the bulkhead structures 410. The horizontal support plate 414 also acts as an
10 additional stiffening member in rigidizing the box structure formed by the bulkhead structures 410 and associated structural elements as described hereinabove. The horizontal support plates 414 are preferably fabricated from graphite/epoxy material
15 and affixed to the side walls 412 of the corresponding bulkhead structures 410. Within the first region 418, it is preferable to add three additional plies to the duct wall 402 and dorsal segment 450 to increase the local stiffness of the
20 region.

Figure 21 shows an enlargement of the attachment of the removable panel structures 464 of the closure segment 452 to the corresponding bulkhead structure 410. For the purpose of
25 minimizing the aircraft weight, adjacent removable panel structures 464 form a corresponding mating interface 540 for attaching the same to the flange portion 534 of the bulkhead structure 410. The mating interface 540 has a generally sawtooth
30 configuration wherein each tooth segment 542 of one removable panel structure 464 mates with a corresponding valley region 544 of the adjacent removable panel structure 464. Each tooth

segment 542 of the removable panel structure 464 is secured to the underlying flange portion 543 preferably by a screw or other fastening means. The base width (reference numeral 546) of the tooth segment 542 is approximately 2.0 inches, and the tip width (reference numeral 548) thereof is approximately 1.0 inches. The corresponding valley region 544 is necessarily larger in size than the mating tooth segment 542 so as to provide a tight interface therebetween.

The powerplant subsystem 50 includes the fuel tank(s) 52, an engine 54, and a drive train assembly 60. The fuel tanks 52 are disposed within appropriate internal bays 26, preferably in opposed equipment bays 26 at the 90°, 270° azimuthal stations (the lateral stations) to maintain a constant center of gravity for the UAV 10 during flight operations. The engine 54 is mounted within an internal bay 26. The positioning of the engine 54 is selected to counterbalance the weight of the flight/mission equipment 30, which is disposed in the opposite portion of the toroidal fuselage 20 as described hereinabove. The embodiment of the UAV 10 described herein utilizes a Norton Motors rotary engine, Model NR801T (modified as described hereinbelow), which provides a high power to weight ratio and good partial power fuel consumption. The NR801T engine is an air/liquid cooled engine that produces 45 HP at 6,000 RPM. Operation of the engine 54 is controlled and monitored by the flight computer 38.

The standard Norton engine described in the preceding paragraph was determined to be deficient

in several respects for utilization in the embodiment of the UAV 10 described herein. The standard Norton engine includes a separate flywheel that is operative to store/release torque energy as required so that the Norton engine provides a relatively steady torque output. The standard Norton engine further includes a separate Plessey generator that is driven by the engine to provide electrical power. The Plessey generator of the standard Norton engine is a heavy device having outsized dimensions.

As a result of these features and characteristics of the standard Norton engine, the overall dimensional envelope of the standard Norton engine was not compatible with the structural contours of the toroidal fuselage described hereinabove. More specifically, the standard Norton engine could not be mounted within the internal bays 26 defined by the toroidal fuselage 20. Furthermore, the weight of the standard Norton engine would have significantly increased the overall gross weight of the UAV. The weight of the standard Norton engine would have also resulted in an outboard shift in the center of gravity of the UAV, which would have presented weight and balance distribution problems with the flight/mission equipment 30.

The standard Norton engine was modified by combining the functional features of the flywheel and the Plessey generator in an integrated flywheel/generator subassembly 55 as illustrated in Figure 3. The integrated flywheel/generator subassembly 55 is operative to store/release torque

energy as required so that the modified Norton engine 54 provides a relatively steady torque output while concomitantly providing electrical power. The integrated flywheel/generator subassembly 55 includes a large diameter, thin rotor 56 having a plurality of magnets 57 internally mounted therein, and a plurality of rigidly mounted stators 58. The rotor 56 is mechanically interconnected to the bundt pan of the drive train assembly (described hereinbelow in further detail) such that the modified Norton engine 54 provides the necessary torque for rotation of the rotor 56.

The integrated flywheel/generator subassembly 55 weighs less than the separate flywheel and Plessey generator of the standard Norton engine such that the overall gross weight of the UAV 10 is reduced. In addition, the dimensional envelope of the integrated flywheel/generator subassembly 55 permits the modified Norton engine 54 to be mounted within an internal bay 26 of the toroidal fuselage 20. Further, the dimensional envelope, relative positioning, and reduced weight of the integrated flywheel/generator subassembly 55 result in an inboard shift of the center of gravity of the modified Norton engine 54.

The drive train assembly 60 of the described embodiment of the UAV 10 includes an over-running clutch such as a Borg-Warner sprag clutch. Over-running clutches are included as functional elements of the drive trains of rotor assemblies to provide automatic decoupling between the drive

shaft and the engine when the engine is shut down. Such decoupling permits the kinetic energy stored in the rotor assembly to be efficaciously and safely dissipated. Over-running clutches, however, do not function efficiently if subjected to over-hung loads, i.e., large operating moments and/or vibratory torque loads, such over-hung loads inducing misalignments between the inner and outer races of the clutch housings. To ensure effective functioning of over-running clutches, vibratory torque coupled into the over-running clutch and/or operating moments coupled through the over-running clutch bearings should be minimized.

The Norton engine 54 utilized in the described embodiment of the UAV 10 produces a torque signature similar to a two-cycle internal combustion engine. Measurements taken during operation of such an engine revealed large torque irregularities of up to eight times the magnitude of the steady state torque produced by the engine 54. Such torque irregularities adversely affect the functional capabilities of over-running clutches as described in the preceding paragraph.

Furthermore, the Norton engine 54 is mounted on soft shock absorbers (not illustrated) to attenuate engine loads and moments generated during operation of the engine 54. Operation of the engine 54 (as well as the rotor assembly 100) can induce misalignments in the drive train drive shaft.

One preferred embodiment of the drive train assembly 60 for the embodiment of the UAV 10 described herein is illustrated in Figures 3, 3A

and includes a sprag clutch 62, an engine coupling subassembly 63, a drive shaft 72, and a transmission coupling subassembly 74. The drive train assembly 60 is operative to transfer the power developed by the engine 54 to the rotor assembly 100. The configuration of the drive train assembly 60 of the present invention is design optimized to maximize the functional capability of the sprag clutch 62, i.e., minimize/eliminate loads and/or moments that degrade clutch performance, and to accommodate maximum axial, angular, and parallel misalignment between the engine 54 and the rotor assembly 100. In addition, the configuration of the drive train assembly 60 is operative to effectuate cancellation of loads developed by the integrated flywheel/generator subassembly 55 of the engine 54 described hereinabove.

With reference to Figures 3, 3A, the engine coupling subassembly 63 includes a stud 64, a tapered adaptor or bundt pan 65, ball bearings 66, an external crown spline coupling 67, an internal spline coupling 68, and a pin-collar connector 69. The stud 64 provides a hard mount between the engine coupling subassembly 63 and the tapered output shaft 54S of the engine 54. The stud 64 is mechanically interconnected to the bundt pan 65. The sprag clutch 62 is rigidly centered intermediate the external crown spline coupling 67 and the bundt pan 65 by means of the ball bearings 66. The external crown spline coupling 67 is mechanically interconnected (via complementary spline teeth 67T, 68T as illustrated in Figure 3A) to the internal spline coupling 68.

One end of the drive shaft 72 is mechanically coupled to the engine coupling subassembly 63 (more specifically the internal spline coupling 68) by means of the pin-collar connector 69. The other
5 end of the drive shaft 72 is mechanically coupled to the transmission coupling subassembly 74 by means of a pin-collar connector 75. The transmission coupling subassembly 74 includes, in addition to the pin-collar connector 75, an
10 external crown spline coupling 76 and a gear spline coupling 77. The external crown spline coupling 76 is mechanically coupled (via complementary spline teeth) to the gear spline coupling 77. The gear
15 spline coupling 77 is configured for mechanical interconnection with the rotor assembly 100 as described in further detail hereinbelow.

The internal spline coupling 68 and the external crown spline coupling 76 include additional material masses 70, 78 as illustrated in
20 Figure 3. These material masses 70, 78 are machined as required to facilitate balancing of the drive shaft 72.

Torque from the engine 54 is transmitted to the engine coupling subassembly 63 by means of the
25 stud 64, tapered output shaft 54S combination. The stud 64 couples torque to the bundt pan 65. Torque from the bundt pan 65 is coupled through the sprag clutch 62 to the external crown spline coupling 67, which in turn couples torque to the internal spline
30 coupling 68 (via the complementary spline teeth 67T, 68T). The internal spline coupling 68 couples torque to the drive shaft 72, which transmits torque to the rotor assembly 100 via the

transmission coupling subassembly 74.

5 The drive shaft 72 of the drive train subassembly 60 is configured as a torque tube, having inside and outside diameters sized to provide torsional softness, i.e., the drive shaft 72 functions as a torsional spring to isolate the coupling spline teeth 67T, 68T, the sprag clutch 62, the transmission gearing (described hereinbelow in further detail), and the rotor
10 assembly 100 from vibratory torque generated by the engine. The configuration of the drive shaft 72 eliminates the need for any additional torsionally soft couplings. The drive shaft 72 is not supported by bearings, thereby reducing the
15 installation weight of the drive train subassembly 60. In addition, the configuration and coupling arrangements, i.e., internal spline coupling 68 and the external crown spline coupling 76, of the drive shaft 72 facilitate
20 maximum axial, angular, and/or parallel misalignments between the rotor assembly 100 and the engine 54 without degrading the functional capabilities thereof.

The mounting arrangement of the sprag
25 clutch 62 and the external crown spline coupling 67 eliminates undesirable loads that could adversely affect performance of the sprag clutch 62. Since the external crown spline coupling 67 cannot react a moment, loads transmitted through the external
30 crown spline coupling 67 react through the center of the sprag clutch 62 such that misaligning moments that could degrade clutch performance are not generated. Loads developed by the integrated

swashplate subassembly 80 has an in-line configuration wherein the stationary point for pitch inputs, i.e., the bearings 84 of the stationary swashplate 83, is outboard of the rotating point, i.e., the bearings 86 of the rotating swashplate 85, as illustrated in Figure 5B. The configuration of the swashplate subassembly 80 facilitates mounting of the pitch control rods 104 in combination with the multi-bladed, counter-rotating rotors 200, 202, as described hereinbelow in further detail, approximately in-line with respective snubber assemblies, thereby providing a rotor assembly 100 having a Delta 3 of approximately zero.

One embodiment of the coaxial transmission/center hub subassembly 110 is illustrated in further detail in Figures 4, 6-7. The configuration of the transmission/center hub subassembly 110 is design optimized to provide an integrated, low component part system that is lightweight, compact, and structurally and thermally efficient. The transmission/center hub subassembly 110 includes a single stage transmission subsystem 120, a multi-member transmission housing 140, and a center hub support structure 160. The configuration of the transmission/center hub subassembly 110 provides enhanced power transfer efficiency between the powerplant subsystem 50 and the counter-rotating rotors 200, 202, thereby increasing the operational capability and efficacy of the UAV 10.

Further, the transmission/center hub subassembly 110 configuration minimizes the

separation between the upper and lower counter-rotating rotors 200, 202, thereby providing a UAV 10 having a compact structural and aerodynamic envelope. The configuration of the

5 transmission/center hub subassembly 110 also facilitates the transfer of the dynamic loads developed by the counter-rotating rotors 200, 202, and reduces airframe vibration levels by providing a direct load path between the upper and lower

10 counter-rotating rotors 200, 202 so that canceling of bending moments produced by the rotors 200, 202 during flight operations occurs. In addition, the transmission/center hub subassembly 110 configuration according to the present invention

15 eliminates the need for transmission mounting brackets.

With reference to Figure 6, the single stage transmission subsystem 120 comprises an input pinion gear 122 having a splined end portion 124, bearings 126 for mounting the input pinion gear 122

20 in rotatable combination with the transmission housing 140, and upper and lower spiral bevel gears 128, 130. The upper and lower spiral bevel gears 128, 130 have upper and lower rotor

25 shafts 128R, 130R, respectively, integrally formed therewith, thereby eliminating the need for separate rotor shaft connection means. The transmission subsystem 120 further includes standpipe bearings 132, 134, 136, 138 for rotatably

30 mounting the respective upper and lower rotor shafts 128R, 130R in combination with the transmission housing 140. The integrated spline/cone seat subassembly 190 (upper and lower)

flywheel/generator subassembly 55 are coupled into the bundt pan 65 and are effectively canceled in the bundt pan 65 adjacent the stud 64.

5 Preferably, the UAV 10 of the present invention includes an inlet screen 14, disposed as partially illustrated in Figure 1, to protect the rotor assembly 100 from FOD. The UAV 10 may also include an outlet screen (not illustrated) to similarly protect the rotor assembly 100.

10 One embodiment of the rotor assembly 100 of the present invention is illustrated in Figure 4 and comprises an electronic control servo subsystem 102 that includes linear actuators 102LA, upper and lower stationary swashplate
15 subassemblies 80, a plurality of pitch control rods 104, a coaxial transmission/center hub subassembly 110, upper and lower integrated spline/cone seat subassemblies 190, and upper and lower multi-bladed, counter-rotating rotors 200,
20 202 integrated in combination with the transmission/center hub subassembly 110. The rotor assembly 100 has a rotational axis 101 (see Figure 6) that is coaxially aligned with the fuselage axis 12. The rotors 200, 202 are
25 aerodynamically "shrouded" by the toroidal fuselage 20. The rotors 200, 202 are preferably of the rigid rotor type (as opposed to articulated rotors) to reduce the complexity and weight of the rotor assembly 100. Blade pitch changes induced in
30 the counter-rotating rotors 200, 202 are utilized to generate all required lift, pitch, roll, and yaw control of the UAV 10. Such pitch changes are also utilized to regulate the pattern and velocity of

airflow over the toroidal shroud 20 and into the rotor assembly 100. Such control of the airflow creates a lifting component on the toroidal shroud 20 that augments the lift provided by the counter-rotating rotors 200, 202. Additional structural and functional features of the counter-rotating rotors 200, 202 are described in further detail hereinbelow.

The electronic control servo subsystem 102 is operative to control the functioning of the upper and lower stationary swashplate subassemblies 80 by coupling inputs from the flight computer 38 of the UAV 10 to the respective swashplate subassemblies 80. The upper and lower stationary swashplate subassemblies 80 are operative, in response to mechanical inputs from the linear actuators 102LA of the electronic control servo subsystem 102, to selectively mechanically couple cyclic pitch inputs and/or collective pitch inputs to the respective counter-rotating rotors 200, 202 by means of the pitch control rods 104, which are mechanically secured at the ends thereof to the swashplate subassemblies 80 and rotor blade assemblies of the counter-rotating rotors 200, 202, respectively.

An electronic control servo subsystem 102 especially designed for a UAV incorporating counter-rotating rotors is illustrated and described in U.S. Patent No. 5,058,824, entitled SERVO CONTROL SYSTEM FOR A CO-AXIAL ROTARY WINGED AIRCRAFT. Conventional swashplate subassemblies, such as those described in the '824 patent, include a rotating swashplate and a stationary swashplate

which are operative in combination, through attitude or displacement changes induced in the rotational plane of the rotating swashplate by the stationary swashplate, to provide pitch inputs to the blades of the rotor assembly. In addition, in conventional in-line swashplate subassemblies the rotating component thereof is located outboard with respect to the stationary component of the swashplate subassembly. Further, the rotor blade - rotor hub attachment joint is outboard of the pitch control rod (which interconnects with the swashplate assembly).

A preferred embodiment of the stationary swashplate subassembly 80 according to the present invention is illustrated in further detail in Figures 5A, 5B, and includes a central spherical ball bearing 82, a stationary swashplate 83 of triangular configuration (the star mechanism) having three bearings 84 mounted in combination therewith, a rotating swashplate 85 having four bearings 86 mounted in combination therewith, an annular bearing 87 intermediate the stationary and rotating swashplates 83, 85 to facilitate rotary motion therebetween, a rotating scissor hub plate 88, two rotating scissors 89 mechanically interconnecting the rotating swashplate 85 and the rotating scissor hub plate 88, and two stationary scissors 90 mechanically interconnecting the stationary swashplate 83 to respective stationary scissor supports 91 (see Figure 4) secured to the coaxial transmission/center hub subassembly 110.

The stationary swashplate 83 is mounted in combination with the central spherical ball 82 and

operative for pivotal movement with respect thereto to provide cyclic pitch inputs to the multi-bladed, counter-rotating rotors 200, 202. Such pivotal motion is induced in the stationary swashplate 83 by means of the linear actuators 102LA (see Figures 4, 5B) that are coupled to the stationary swashplate 83 by means of the bearings 84. Pivotal motion of the stationary swashplate 83 with respect to the central spherical ball 82 is facilitated by the mechanical interaction between the stationary scissors 90 and the respective scissor supports 91.

Collective pitch inputs to the multi-bladed, counter-rotating rotors 200, 202 are effectuated by bidirectional linear motion of the stationary swashplate 83, central spherical ball 82 combination in response to control inputs from the electronic control servo subsystem 102 (via the linear actuators 102LA). Collective and cyclic pitch inputs are coupled from the stationary swashplate 83 to the rotating swashplate 85. Such pitch inputs are coupled to the multi-bladed, counter-rotating rotors 200, 202 by means of the pitch control rods 104, which are mechanically connected to the rotating swashplate 85 by means of the bearings 86. Mechanical coupling of the pitch control rods 104 to the multi-bladed, counter-rotating rotors 200, 202 is described in further detail hereinbelow.

The swashplate subassembly 80 described hereinabove is design optimized for effective utilization in combination with the coaxial transmission/center hub subassembly 110 as described in further detail hereinbelow. The

for securing the upper and lower multi-bladed rotors 200, 202 in combination with respective rotor shafts 128R, 130R (see Figure 4) is described in further detail hereinbelow.

5 The input pinion gear 122 is mechanically coupled to the drive shaft 72 by means of the gear spline coupling 77 (the gear spline coupling 77 mechanically engages the splined end portion 124 of the pinion gear 122), and operative to transmit
10 torque from the engine 54 to the upper and lower spiral bevel gears 128, 130. The placement of the bevel gears 128, 130 vis-a-vis the spiral gear portion of the input pinion gear 122 causes counter
15 rotation of the upper and lower rotor shafts 128R, 130R with respect to one another. The splined end portion 124 of the input pinion gear 122 facilitates quick disconnection of the single stage transmission 120 from the center hub support structure 160.

20 The multi-member transmission housing 140 includes an upper standpipe housing 142, a lower standpipe housing 144, and a middle housing 146. The upper and lower standpipe housings 142, 144 are secured in combination with the middle housing 146
25 by means of screws 148 (twelve in number). By mounting the upper and lower standpipe housings 142, 144 in combination with the middle housing 146, direct load paths are provided for the dynamic and static longitudinal, lateral, vertical,
30 and torsional loads developed by the upper and lower counter-rotating rotors 200, 202 into the middle housing 146. This functional feature allows the operating moments of the upper and lower

rotors 200, 202 to cancel each other out in the middle housing 146. The cancellation function provided by the configuration of the transmission housing 140 described hereinabove significantly
5 reduces vibratory loads that would normally be transmitted to the toroidal fuselage 20.

The standpipe bearings 132, 134 and 136, 138 are mounted against the internal surface of the upper and lower standpipe housings 142, 144, as
10 illustrated in Figure 6. The standpipe bearings 132, 134, 136, 138 are operative to facilitate rotary motion of the respective rotor shafts 128R, 130R while transmitting rotor bending loads to the multi-member transmission housing 140,
15 i.e., the upper and lower standpipe housings 142, 144. The respective standpipe bearings 132, 134, and 136, 138 are separated to minimize shear reaction.

The coaxial transmission/center hub subassembly 110 of the present invention utilizes
20 the external surfaces 142E, 144E of the upper and lower standpipe housings 142, 144 as sliding surfaces for the bidirectional translational movement of the respective stationary swashplate subassemblies 80, as indicated by reference
25 numerals 150, 152 in Figure 4. The range of such bidirectional linear motion is sufficient to couple the requisite collective pitch inputs to respective blades of the counter-rotating rotors 200, 202 for
30 flight operations of the UAV 10. By utilizing the external surfaces 142E, 144E for swashplate motion, a minimum separation between the upper and lower counter-rotating rotors 200, 202 is achieved, thus

providing the UAV 10 with a compact structural and aerodynamic envelope.

5 The embodiment of the coaxial transmission/center hub subassembly 110 illustrated in Figures 4, 6-7 includes a separate center hub support structure 160. With reference to Figure 7, the center hub support structure 160 comprises a cylindrical body 162 having three equidistantly spaced integral support arms 164 extending radially
10 outwardly therefrom. The support arms 164 function as the rigid attachment points for the support struts 24 to mount the coaxial transmission/center hub subassembly 110 in fixed coaxial relation to the toroidal fuselage 20.

15 The center hub support structure 160 is configured so that the middle housing 146 of the multi-member transmission housing 140 may be slidably inserted therein such that external surfaces 146E of the middle housing 146 abuttingly
20 engage internal surfaces 162I of the center hub support structure 160. The abuttingly engaged surfaces 146E, 162I in combination function as mounting and load bearing surfaces that are operative to transfer the dynamic and static loads
25 developed by the counter-rotating rotors 200, 202 to the center hub support structure 160. The middle housing 146 is secured in combination with the center hub support structure 160 by means of pins 168 (eighteen total) and screws 170 (six
30 total) as exemplarily illustrated in Figure 6. Dynamic lift loads developed by the counter-rotating rotors 200, 202 are transmitted from the middle housing 146 to the central hub support

structure 160 via the pins 168 and screws 170. All other dynamic rotor loads, as well as thermal loads generated by operation of the single stage transmission 120, are coupled from the middle housing 146 to the center hub support structure 160 via the abuttingly engaged surfaces 146E, 162I thereof.

The dynamic and static rotor loads and the thermal loads coupled into the center hub support structure 160 are transmitted into the toroidal fuselage 20, via the support struts 24, by means of the integral support arms 164. Cooling of the coaxial transmission/center hub subassembly 110, and in particular the middle housing 146, is facilitated by the structural arrangement described hereinabove wherein the center hub support structure 160, the support arms 164, and the support struts 24 lie directly in the downwash generated by the upper rotor 200, thereby facilitating convective cooling of such structural elements.

The cylindrical body 162 further includes six mounting lugs 166 extending radially outwardly therefrom as illustrated in Figure 7. The mounting lugs 166 are utilized to mount the electronic control servo subsystem 102 (more specifically, the three linear actuators 102LA thereof) in combination with the rotor assembly 100.

The coaxial transmission/center hub subassembly 110 further includes a splash lubrication subsystem 174 that provides oil lubrication for the input pinion gear 122, the transmission bearings 126, the upper and lower

spiral bevel gears 128, 130, and the standpipe bearings 134, 136, 138. The upper standpipe bearing 132 is grease lubricated due to its location vis-a-vis the splash lubrication subsystem 174. The splash lubrication subsystem 174 includes a pinion chamber 176, cored passages 178, 180, and standpipe chambers 182, 184 formed in the upper and lower standpipe housings 142, 144, respectively, which are fluidically interconnected by means of a central reservoir 186. Access to the central reservoir 186 is provided by means of an oil plug 188. Reference numeral 189 represents the oil fill line for the central reservoir 186.

The standpipe bearings 134, 136, 138, the transmission bearings 126, and the gear teeth of the input pinion gear 122 and the upper and lower spiral bevel gears 128, 130 are oil lubricated by means of the splash lubrication subsystem 174. Oil from the central reservoir 186 is circulated, due to the rotary motion of the upper and lower spiral bevel gears 128, 130, throughout the fluid flow pathways of the splash lubrication subsystem 174 as described in the preceding paragraph to lubricate the aforescribed components. Since no lubrication pumps are required for the splash lubrication subsystem 174 described hereinabove, the overall system weight and complexity of the UAV 10 is reduced.

The middle housing 146 may be fabricated as an integral element of the center hub support structure 160 to provide an alternative structural embodiment of the coaxial transmission/center hub

subassembly 110 described hereinabove. The integrated center hub support structure provides the functions of the middle housing in addition to the functions of the center hub support structure. In this embodiment, however, the securing pins 168 and screws 170 described hereinabove are not required.

The upper and lower integrated spline/cone seat subassemblies 190 of the rotor assembly 100 are operative to secure the upper and lower counter-rotating rotors 200, 202, respectively, in combination with the coaxial transmission/center hub subassembly 110 as illustrated generally in Figure 4. The integrated spline/cone seat subassembly 190 of the present invention is design optimized to reduce the size/radial dimensions of the upper and lower rotor shafts 128R, 130R, the standpipe bearings 132, 134, 136, 138, the standpipe housings 142, 144, and the upper and lower stationary swashplate subassemblies 80 described hereinabove. The downsizing of these components provides a significant savings in the overall system weight of the UAV 10 according to the present invention.

Traditional rotary aircraft mount the rotor hub in combination with the rotor shaft by means of a spline and cone seat arrangement wherein the two elements are separate and distinct. With reference to Figure 8, the conventional spline/cone seat arrangement comprises a rotor hub RH having a shaft aperture SA that includes a plurality of spaced apart hub splines HS extending inwardly from the wall thereof, and a countersink CK contiguous with

the wall of the shaft aperture SA. The rotor shaft RS includes a complementary plurality of shaft splines SS and a complementary cone seat CS. The rotor hub RH slides downwardly onto the rotor shaft RS so that the hub splines HS are interleaved with the shaft splines SS and the countersink CK abuttingly engages the complementary cone seat CS.

The interleaved hub and shaft splines HS, SS are operative to provide a rotational interlock between the rotor hub RH and the rotor shaft RS while the complementary cone seat CS is operative to provide the mechanical support for the rotor hub RH. The aforescribed configuration of the conventional spline/cone seat arrangement requires that the shaft aperture SA be large enough to accommodate the shaft splines SS and that the diameter D of the rotor shaft RS be sufficient to provide the complementary cone seat CS support surface. The diameter D of the rotor shaft RS is, therefore, a critical dimension that significantly influences the dimensions of the transmission housing and the swashplate assembly. The conventional spline/cone seat arrangement generally results in a heavy rotor assembly having a large radial dimension.

The integrated spline/cone seat subassembly 190 of the present invention is schematically illustrated in Figure 9 and in further detail in Figures 9A, 9B. With reference to Figure 9, each rotor shaft 128R, 130R is formed to include a primary shaft portion 192 having a first diameter D_1 (the critical diameter), an end shaft portion 194 having a second diameter D_2 where

$D_1 > D_2$, and a truncated conic transition portion 196 intermediate the portions 192, 194 (see also Figure 6). The truncated portion 196 makes a predetermined angle β with respect to the rotational axis 101, i.e., with the axis of the respective rotor shaft. Each end shaft portion 194 has a plurality of shaft splines 198 extending radially outwardly therefrom. The diameter D_3 defined by the outboard, circumferential surfaces of the shaft splines 198 is equal to the critical diameter D_1 of the primary shaft portion 192.

Each counter-rotating rotor 200, 202 for the described embodiment of the UAV 10 includes a rotor hub 204 that functions as part of the respective integrated spline/cone seat subassembly 190. Referring to Figures 9A, 9B, each rotor hub 204 includes a shaft aperture 206 having a plurality of hub splines 208 extending radially inwardly from the wall defining the shaft aperture 206. The hub splines 208 and the shaft splines 198 are sized to accommodate the torque required by the counter-rotating rotors 200, 202. The specific number and individual thicknesses of the hub splines 208 complement the specific number and individual thicknesses of the shaft splines 198 so that the interleaved hub and shaft splines 208, 198 are operative to provide a rotational interlock between each rotor hub 204 and the corresponding rotor shaft 128R, 130R.

The lower portion of each hub spline 208 has an outwardly tapered portion 210 that makes a predetermined angle θ with respect to the hub centerline 212, i.e., with respect to the

rotational axis 101 (see Figure 9). The predetermined angle θ of the outwardly tapered portions 210 of the hub splines 208 is equal to the predetermined angle β of the truncated portion 196.

5 The tapered portions 210 of the hub splines 208, therefore, abuttingly engage and are mechanically supported by the truncated conic transition portion 196 of the respective rotor shafts 128R, 130R. Self-locking nuts 199 (see Figure 4) are
10 threaded onto the ends of the respective rotor shafts 128R, 130R to secure the rotor hubs 204 in interlocked, engaged combination with the respective rotor shafts 128R, 130R.

The critical diameter D_1 of the primary shaft
15 portion 192 of the respective rotor shafts 128R, 130R is less than the diameter D of a rotor shaft that incorporates the conventional spline/cone seat arrangement (compare first diameter D_1 of Figure 9 with diameter D of Figure 8). The critical
20 diameter D_1 defines the radial dimensions of the respective rotor shafts 128R, 130R, and, in consequence, the sizing of the standpipe bearings 132, 134, 136, 138, the multi-member transmission housing 140, and the stationary
25 swashplate subassemblies 80.

Each counter-rotating rotor 200, 202 includes the rotor hub 204, four snubber assemblies 230, and four rotor blade assemblies 250. The rotor hub 204 described in the preceding paragraphs additionally
30 comprises four outwardly extending arms 214, each arm 214 having bifurcated ends 216U, 216L having bolt holes 218U, 218L, respectively, formed therethrough as illustrated in Figures 9A, 9B. The

bifurcated ends 216U, 216L and the respective bolt holes 218U, 218L, in combination, form a clevis 220. Each clevis 220, in combination with a respective bolt, nut, washer set 222, is operative to provide the means for securing the rotor blade assembly 250 in combination with the rotor hub 204 as illustrated in Figures 10A, 10B, 10C and as described in further detail hereinbelow.

The rotor hub 204 also functions as an element of the snubber assembly 230. Each outwardly extending arm 214 of the rotor hub 204 further comprises an inboard internal bulkhead 223 and an outboard internal bulkhead 224, which in combination, define a bearing cavity 225, and an inboard cavity 226, as illustrated in Figures 9A, 9B. The inboard and outboard internal bulkheads 223, 224 have bolt holes 227, 228, respectively, formed therethrough. The foregoing elements are operative to provide the means for securing the respective snubber assembly 230 in combination with the rotor hub 204 as described in the following paragraphs.

Traditional "bearingless" rotor system designs have the snubber assembly installed outboard of the flexbeam-to-hub attachment joint to reduce the hub length. Such a mounting installation, however, does not facilitate assembly and maintenance of the snubber assembly, and to compensate for such a mounting installation, traditional rotor systems incorporate expensive elastomeric bearings that are more wear resistant than inexpensive self-aligning bearings to minimize maintenance requirements. To utilize an outboard mounting installation in a UAV

of the type described herein, the flexbeam of each rotor blade assembly 250 (described in further detail hereinbelow) would require a slotted configuration so that the respective snubber assembly passes through the flexbeam for securement to the upper and lower surfaces of the respective integrated torque tube/spar member. Since this inboard segment of the flexbeam is a highly loaded zone, the flexbeam configuration would have to be widened, which would require wider rotor hub arms, to accommodate the high loading. In addition, the flexbeam-to-hub bolts would have to be located closer to the center of the rotor hub, and would have to be larger to accommodate the corresponding high loading. These features would increase the overall weight of the rotor assembly for the UAV.

The rotor hub 204 configuration described hereinabove facilitates installation of the respective snubber assembly 230 of the present invention inboard of the flexbeam-to-hub attachment joint as illustrated in Figures 10A, 10B, 10C. The inboard installation eliminates the need for any structural modifications of the flexbeam, minimizes the width requirements of the hub arms 214, and allows the use of a self-aligning bearing that is less expensive than an elastomeric bearing. The inboard installed snubber assembly 230 is also more accessible for assembly and maintenance, resulting in reduced labor costs for such activities.

The snubber assembly 230 of the present invention is illustrated in further detail in Figures 10C, 10D and comprises a spherical bearing 232, a bearing bolt 234, a locking nut 236,

a snubber bracket 238 secured in combination with the spherical bearing 232, and securing bolts 240. The spherical bearing 232, snubber bracket 238 combination is rotatably mounted within the bearing cavity 225 by means of the bearing bolt 234 which is inserted through the bolt hole 227, the spherical bearing 232, and the bolt hole 228, respectively. The bearing bolt 234 is secured in combination in the rotor hub 204 by means of the locking nut 236 which is threaded onto the bearing bolt 234 to jam against the inboard bulkhead 223. The securing bolts 240 are utilized to secure the integrated torque tube/spar member 270 in combination with the snubber assembly 230 as described hereinbelow in further detail.

Each counter-rotating rotor 200, 202 includes four rotor blade assemblies 250. Each rotor blade assembly 250 comprises an inner flexbeam 260, an integrated torque tube/spar member 270, an outer aerodynamic fairing or rotor blade 280, and a blade joint 290, as illustrated in Figures 10A, 10B. Each rotor blade assembly 250 has a tapered configuration that provides reduced weight, low inertia, a high chord frequency, an improved aerodynamic profile, low static droop, and eliminates high chordwise stresses and the need for blade damping mechanisms.

The flexbeam 260 of the rotor blade assembly 250 is a laminated composite structure that is operative to react the centrifugal loads and a majority of the bending loads developed during operation of the counter-rotating rotors 200, 202. The inboard end 262 of the

flexbeam 260 is inserted into the clevis 220 and fastened in combination therewith by means of the bolt, washer, nut sets 222 (two in the illustrated embodiment) to secure the flexbeam 260 in
5 combination with the rotor hub 204 as illustrated in Figures 10A, 10B, 10C. The outboard end 264 of the flexbeam 260 is secured in combination with the respective integrated torque tube/spar member 270 and tapered rotor blade 280 by means of the blade
10 joint 290, as described in further detail hereinbelow.

One aspect of rotor blade design involves accounting for the spanwise variation of the resultant velocity vector, which is a combination
15 of the rotational velocity vector acting on the rotor blade and the air inflow velocity vector perpendicular to the rotor plane, acting on the rotor blade. The spanwise variation of the resultant velocity vector results in a variation in
20 the downwash angle, i.e., the angle between the resultant velocity vector and the rotor plane, along the span of tapered rotor blade 280. If the rotor blade has a constant pitch angle along the span, the angle of attack, i.e., the angle between
25 the resultant velocity vector and the airfoil chord, will be less than optimum, resulting in poor rotor blade performance.

To produce a near optimum angle of attack distribution along the span of the tapered rotor
30 blade 280, rotor blade airfoil sections are normally pretwisted. Pretwisted rotor blades are operative to pitch in flight as rigid bodies, i.e., uniformly along the span, in response to control

commands to adjust for variations in flight conditions. The spanwise uniform pitch angle can be either constant with respect to blade azimuth position (collective pitch) or sinusoidally
5 variable with respect to blade azimuth position (cyclic pitch).

Whatever the final pitch position of the rotor blade at the outboard joint with the flexbeam, the flexbeam must be twisted to the same angle so that
10 it fits inside the blade spar to form a clean, minimum thickness outside airfoil. If twisting of the flexbeam is all elastic, very high twisting strains are induced in the flexbeam. Generally, the outboard end of the flexbeam is locally
15 pretwisted to accommodate the blade collective pitch required during normal flight modes. For the UAV described herein, however, local pretwisting of only the outboard end of the flexbeam would create high kick loads in the flexbeam laminate, resulting
20 in possible delaminations between plies during operation of the rotor assembly 100.

To compensate for the variable strains induced along the span of the flexbeam, the flexbeam 260 of the present invention is fabricated to have a
25 predetermined linear twist, i.e., built-in twist, along the span thereof (inboard end 262 to outboard end 264). As a result of such pretwisting (which is not explicitly shown in Figures 10A, 10B, 10C for purposes of clarity), the pretwisted
30 flexbeam 260 makes an angle with respect to a horizontal plane HP (see Figure 10B) that varies linearly from about 0° at the inboard end 262 (root section) of the pretwisted flexbeam 260 to about

22° at the outboard end 264 (tip section) of the pretwisted flexbeam 260. The linear pretwist of the flexbeam 260 of the present invention is defined in the graph of Figure 13.

5 The angle of the pretwisted flexbeam 260 corresponds to the elastic twist that an untwisted flexbeam would normally experience during forward flight of the UAV 10, i.e., rotor blade tip speed of about 700 fps under normal thrust during cruise
10 conditions. As a result, the pretwisted flexbeam 260 is unstrained during such forward flight conditions. The pretwist of the flexbeam 260 also minimizes the flexbeam elastic twist required to accommodate the pitch motion of
15 the rotor blade 280 in all other normal flight modes, i.e., the induced strains are reduced due to the linear pretwist of the flexbeam 260 according to the present invention.

 The integrated torque tube/spar member 270 of
20 the rotor blade subassembly 250 is formed as a continuous, single piece, low cost tubular composite structure. The structural configuration of the integrated torque tube/spar member 270 provides high torsional and bending stiffness and
25 facilitates the utilization of the efficient blade joint 290 described in further detail hereinbelow.

 Conventional rotor blade design, in contrast, generally involves the combination of several structural and non-structural elements to form the
30 blade subassembly. For example, conventional blade subassemblies usually include separate members for reacting dynamic torsional and bending loads. This design philosophy is deficient inasmuch as it

requires separate members to react dynamic loads, and it results in inefficient joints.

5 The integrated torque tube/spar member 270 includes an inboard torque tube segment 272 and a
outboard spar segment 274, as illustrated in
Figure 10A. The integrated torque tube/spar
structure 270 is formed as a continuous filament
wound piece that provides a continuous torsion load
path and facilitates load coupling from the tapered
10 rotor blades 280 into the respective flexbeams 260.
The spar segment 274, which functions as the
primary structural member of the rotor blade
subassembly 250, has a truncated aerodynamic
profile as illustrated in Figure 12A and is
15 operative to react all bending, torsional, shear,
and centrifugal dynamic loads developed during
operation of the counter-rotating rotors 200, 202.
The torque tube segment 272 has a generally
elliptical profile as illustrated in Figure 12B and
20 is operative to react all torsional loads and some
of the bending loads developed during operation of
the counter-rotating rotors 200, 202. The inboard
end of the torque tube segment 272 is secured in
combination with the snubber bracket 238 of the
25 snubber assembly 230 by means of the securing
bolts 240 (see Figure 10C) which extend through the
inboard wall of the torque tube segment 274. Pitch
inputs from the swashplate subassemblies 80 are
coupled into the rotor blade subassemblies 250 of
30 the counter-rotating rotors 200, 202 by means of
the respective torque tube segments 272 which are
twistable about the bearing bolt 234 of the snubber
assembly 230 (Figure 10D illustrates a torque tube

segment 274 in a twisted condition, i.e., pitch input applied thereto).

5 Rotor systems for conventional rotorcraft are designed to provide an autorotation capability. To facilitate operation of the rotor system in the autorotation mode, conventional rotor blades generally incorporate ancillary mass near the blade tips to increase blade inertia. The relatively high inertia of such rotor blades presents a problem at start up inasmuch as greater engine torque must be provided to initiate rotor blade rotation. The high blade inertia of conventional rotor systems also creates an additional problem inasmuch as such systems result in chordwise natural frequencies near the 1/rev resonance frequency, which is the highest amplitude excitation frequency (see Figure 11). Operation of a rotor system near the 1/rev resonance mode is generally undesirable due to high induced loading, and in consequence, operation of conventional stiff, in-plane rotor systems is generally constrained to rotor speeds that fall between resonance mode conditions, as exemplarily represented by operating curve CRS in Figure 11.

25 The UAV 10 of the present invention does not require an autorotation capability. In consequence, the configuration of the rotor blade 280 of each rotor blade subassembly 250 may be design optimized for reduced weight utilizing composite materials, e.g., high modulus graphite, which results in a tapered rotor blade 280 having a high chord frequency. Each outboard segment of the rotor blades 280 of the present invention is

configured to have an aerodynamic taper of about 2:1, which results in a tapered rotor blade 280 having a low outboard mass and a high inboard stiffness. With reference to Figure 10A where
5 reference numeral 282 defines the aerodynamic root of the rotor blade 280 and reference numeral 282 defines the aerodynamic tip of the rotor blade 280, aerodynamic taper is defined as the ratio of the effective chord at the aerodynamic root 282 to the
10 effective chord at the aerodynamic tip 284.

The aerodynamic taper of the outer rotor blades 280 results in a low moment of inertia about the hub centerline 212 and the mass centroid of each rotor blade 280 being closer to the rotor
15 hub 204. The high chordwise frequency of the tapered rotor blades 280 provides the benefit of rotor operation over a weaker modal response zone, i.e., the high frequency design provided by the tapered rotor blades 280 eliminates operation in
20 critical resonance mode conditions which may occur due to the wide RPM operating range of the UAV 10 of the present invention. Referring to Figure 11, reference numeral 286 identifies the operating curve of a UAV 10 incorporating rotor blade
25 assemblies 250 having the tapered rotor blade 280 configuration described hereinabove.

For the normal operating range of the UAV 10, i.e., between a 550 fps hover mode and a 700 fps cruise mode (wherein the fps values reflect blade
30 tip speeds), the counter-rotating rotors 200, 202 operate between the 2/rev and 3/rev resonance mode conditions, i.e., generally above 2.5/rev. These resonance mode conditions are lower load conditions

in comparison to the 1/rev resonance mode condition, which is the highest load condition (see Figure 11), such that induced loading of the rotor blade assemblies 250 is reduced. In addition, the high frequency design of the rotor blade assembly 250 eliminates ground and air resonance during UAV 10 operations, and thus eliminates requirements for lag dampers.

Each tapered rotor blade 280 is further configured to include a trailing edge segment 286 of generally triangular shape (see Figures 12A, 12B). The trailing edge segment 286 of the rotor blade 280 is a continuous structural member that extends aftwardly from the integrated torque tube/spar member 270 as illustrated in Figures 10A, 12A, 12B. The configuration of the trailing edge segment 286 provides a low weight blade configuration that is design optimized for the aerodynamic pressures encountered during operation of the "shrouded" counter-rotating rotors 200, 202.

The blade joint 290 of the rotor blade assembly 250 according to the present invention is illustrated generally in Figures 10A, 10B and in further detail in Figure 14. As disclosed hereinabove, the blade joint 290 is operative to secure the pretwisted flexbeam 260 in combination with the respective integrated torque tube/spar member 270 and tapered rotor blade 280. The blade joint 290 of the present invention includes an innovative bolt layout that is optimally positioned to eliminate the moment reaction at the blade joint 290 due to the steady chordwise loading experienced by the rotor blade assembly 250,

thereby allowing the utilization of smaller bolts 298 and reduced joint thicknesses.

5 A conventional rotor blade attachment joint is designed and positioned to react the axial loading resulting from the centrifugal force exerted on the rotor blade during operation thereof. A rotor blade assembly has an identifiable centroid for that portion of the rotor blade assembly mass outboard of the blade attachment joint. Such
10 outboard mass centroid lies on the centroidal axis of the rotor blade assembly. The centrifugal force vector acting on the rotor blade acts through the outboard mass centroid. The conventional attachment joint is designed and positioned such
15 that the center of the attachment joint lies near the centroidal axis such that the centrifugal force vector acts through the attachment joint center, i.e., the attachment joint is subjected to only axial loading due to the centrifugal force vector,
20 there is no in-plane reaction moment at the attachment joint due to the centrifugal force vector.

The conventional attachment joint is further designed to react an in-plane moment arising from
25 the chordwise aerodynamic and inertia loads experienced by the rotor blade assembly during operation thereof. Such a chordwise load vector causes a reaction moment at the attachment joint center. The effect of the chordwise bending moment
30 is to induce large steady stresses in the attachment joint, which reduces the fatigue allowable therein. To compensate for the foregoing effects, a conventional rotor blade attachment

joint utilizes heavy bolts and enhanced joint thicknesses.

Referring to Figure 14, each rotor blade assembly 250 of the present invention has an identifiable outboard mass centroid 292 that lies on the blade centroidal axis 294. The centrifugal force vector CFV acts through the outboard mass centroid 292 as shown. The steady chordwise load vector CLV, which includes aerodynamic as well as inertia loads, acts generally perpendicular to the centroidal axis 294 as illustrated. Since the chordwise load vector CLV includes an aerodynamic load component, the chordwise load vector CLV of the rotor blade assembly 250 does not act through the outboard mass centroid 292.

The blade joint 290 includes a bolt pattern 296 comprised of a plurality of bolts 298 (four in the illustrated embodiment) arranged to define a structural center 300 for the bolt pattern 296. Extending through the bolt pattern structural center 300, parallel to the blade centroidal axis 294, is a bolt pattern center axis 302.

According to the present invention, the bolt pattern 296 of the blade joint 290 is disposed in combination with the rotor blade assembly 250 so that the bolt pattern center axis 302 is spaced apart a predetermined distance D from the blade centroidal axis 294. Further, the blade joint 290 is disposed in combination with the rotor blade assembly 250 so that the bolt pattern structural center 300 is spaced apart a predetermined distance X from the steady chordwise load

vector CLV (one skilled in aerodynamics, based upon the configuration of the rotor blade assembly 250 and nominal cruise condition of the UAV 10, can compute the predetermined distance X). The location of the bolt pattern 296 with respect to the outboard mass centroid 292 and the chordwise load vector CLV, as defined by the predetermined distances D, X, respectively is such that the reaction moments M_{CLV} , M_{CFV} at the blade joint 290 due to the chordwise load vector CLV and the centrifugal force vector CFV, respectively, cancel out, i.e., $M_{CLV} = M_{CFV}$, at the nominal cruise condition of the UAV 10, e.g., blade tip speed of about 700 fps. An examination of Figure 14 shows that

$$(CFV) \times (D) = (CLV) \times (X)$$

since $M_{CLV} = M_{CFV}$. Figure 15 is a graphical depiction of the predetermined distance D in terms of the moments produced by the centrifugal force vector CFV and the chordwise load vector CLV.

A further examination of Figure 14 shows that the structural center 300 of the bolt pattern 296 lies forward of the outboard mass centroid 292, i.e., forward of the centroidal axis 292. The functional results described hereinabove could not be achieved by moving the outboard mass centroid 292 aft since the forward position of the outboard mass centroid 292 is required for stability of the rotor blade assembly 250. Positioning of the blade joint 290 as described hereinabove does not affect stability and will only result in a local moment change. Moments at other span locations will remain unaffected.

The blade joint 290 described hereinabove was a bolt pattern 296 formed by four bolts 298. Those skilled in the art will appreciate that other bolt patterns, i.e., more or less than four bolts, may be utilized for the blade joint 290 of the present invention. Any such other bolt pattern must define a bolt pattern structural center and a bolt pattern center axis that provides the predetermined distances D, X described hereinabove.

Conventional rotor assemblies include a plurality of pitch control rods secured in combination with respective torque tubes of the rotor blade subassemblies. The pitch control rods are operative to couple collective and/or cyclic pitch inputs to individual rotor blades via the respective torque tubes. A conventional mounting scheme for pitch control rods is illustrated in Figure 16. A control rod bearing CRB is mounted to an end of the pitch control rod (not shown). The control rod bearing CRB is mounted within a bearing mount BM, by means of a bearing attachment bolt BAB, that is rigidly secured to the torque tube TT of the respective rotor blade subassembly. The conventional mounting scheme results in the weak axis WA of the control rod bearing CRB facing outboard, i.e., approximately parallel to the rotor blade centerline CL.

The conventional mounting scheme described in the preceding paragraph is necessary so that the pitch control rods have the required range of motion to impart the full range of pitch inputs to the rotor blades. This mounting scheme is deficient in that the high centrifugal load F_{cl} of

the pitch control rod acts in the direction where the control rod bearing CRB is weakest. This causes high pressure forces HPF to be exerted against the bearing liner, which causes the control rod bearing CRB to wear out rather quickly. The replacement frequency for such control rod bearings CRB, due to the effects of centrifugal loading, results in increased maintenance costs and system downtime.

The rotor assembly 100 of the present invention does not require the full range of pitch inputs required by conventional rotor assemblies. As a result, the range of motion for the pitch control rods 104 (see Figure 4) is less than the range of motion required by conventional rotor assemblies. In consequence, the rotor assembly 100 of the present invention utilizes an optimized pitch control rod mounting scheme 310 as illustrated generally in Figure 4 and in further detail in Figure 17.

A control rod bearing 312 is mounted to the end of a respective pitch control rod 104 (see Figure 4). The control rod bearing 312 is mounted within a bearing mount 314 having a clevis configuration by means of a bearing attachment bolt 316. The bearing mount is rigidly secured to the torque tube segment 272 of the respective rotor blade subassembly 250. The bearing mount 314 is configured so that the axis 316A of the bearing attachment bolt 316 makes an angle β with respect to the centerline 318 of the rotor blade subassembly 250. The angle β corresponds to the direction of centrifugal loading F_{cl} such that the

pressure forces 320 acting on the control rod bearing 312 as a result of centrifugal loading F_{cl} are exerted against the strongest part of the control rod bearing 312.

5 The optimized pitch control rod mounting scheme 310 described hereinabove results in the pressure forces 320 acting on the strongest part of the control rod bearing 312. As a result, the optimized pitch control rod mounting scheme 310
10 results in longer effective lifetimes for the control rod bearings 312.

 A variety of modifications and variations of the present invention are possible in light of the above teachings. It is therefore to be understood
15 that, within the scope of the appended claims, the present invention may be practiced otherwise than as specifically described hereinabove.

What is claimed is:

Claims

1. A toroidal fuselage structure for an unmanned aerial vehicle having a rotor assembly including counter-rotating rotors defining at least one tip path plane, the rotor assembly being supported by
5 radially oriented strut members coaxially within said toroidal fuselage structure, each strut member having a longitudinal axis, comprising:
an annular structure having a generally C-
10 shaped configuration in cross-section and including a duct wall that forms a duct for said toroidal fuselage structure, said C-shaped annular structure having first and second ends defining an internal cavity for said toroidal fuselage structure, and
15 wherein the rotor assembly is coaxially mounted within said duct by means of the radially oriented strut members;
at least three pairs of bulkhead structures disposed and equally spaced within said internal cavity of said C-shaped annular structure, each
20 pair of said bulkhead structures defining a first region and adjacent pairs of said bulkhead structures defining a second region, said second region being larger than said first region, and
25 wherein said first regions are intersected respectively by the longitudinal axes of the strut members; and
means for forming a closure segment between
said first and second ends of said C-shaped annular
30 structure.

2. The toroidal fuselage structure of claim 1

wherein each said first region forms a sector of about 30 to about 45 degrees.

5 3. The toroidal fuselage structure of claim 1 wherein each said first region forms a sector of about 30 degrees and each said second region forms a sector of about 90 degrees.

10 4. The toroidal fuselage structure of claim 1 further comprising a plurality of vertical stiffening structures integrally formed on said duct wall in facing relation to said internal cavity.

15 5. The toroidal fuselage structure of claim 4 wherein said vertical stiffening structures are located in said second region of said internal cavity and further wherein adjacent vertical stiffening structures are separated by about 15 degrees.

20 6. The toroidal fuselage structure of claim 4 further comprising at least one vertically oriented mounting plate affixed to adjacent vertical stiffening members.

25 7. The toroidal fuselage structure of claim 4 further comprising upper and lower circumferential stiffening structures integrally formed on said duct wall in facing relation to said internal cavity, and wherein said vertical stiffening structures are disposed between said upper and lower circumferential stiffening structures.

8. The toroidal fuselage structure of claim 1 further comprising at least one circumferential stiffening structure integrally formed on said duct wall in facing relation to said internal cavity.
- 5 9. The toroidal fuselage structure of claim 8 further comprising at least one rub strip member, and wherein said at least one circumferential stiffening structure forms a pocket in said duct wall for forming said rub strip member.
- 10 10. The toroidal fuselage structure of claim 9 wherein said rub strip member coincides with the at least one tip path plane defined by the counter-rotating rotors.
- 15 11. The toroidal fuselage structure of claim 1 further comprising a duct stiffening structure formed on said duct wall in facing relation to said internal cavity in said first region.
- 20 12. The toroidal fuselage structure of claim 1 wherein said closure segment further comprises at least one removable panel structure operative to provide access to said internal cavity.
- 25 13. The toroidal fuselage structure of claim 12 wherein said closure segment comprises adjacent removable panel structures, said adjacent removable panel structures forming a corresponding mating interface therebetween, said mating interface aligning with at least one of said bulkhead structures.

14. The toroidal fuselage structure of claim 13 wherein said mating interface has a generally sawtooth configuration.

5 15. A drive train assembly for an unmanned aerial vehicle for coupling torque from an engine to a transmission of a rotor assembly having ducted, coaxial counter-rotating rotors, comprising:

10 engine coupling subassembly means for coupling the torque from the engine, said engine coupling subassembly means including an over-running clutch and means for eliminating misaligning moments that could degrade performance of said over-running clutch;

15 drive shaft means coaxially and mechanically interconnected to said engine coupling subassembly for functioning as a torsional spring to isolate the transmission and the rotor assembly from vibratory torque developed by the engine; and

20 transmission coupling subassembly means coaxially and mechanically interconnected to said drive shaft means for coupling the torque from said drive shaft means to the transmission;

25 said misalignment moment eliminating means and said transmission coupling subassembly means in combination being operative to accommodate maximal misalignments between the transmission and the engine.

30 16. The drive train assembly of claim 15 wherein said drive shaft means is configured as a torque tube having outer and inner diameters sized to provide torsional softness for said torque tube,

said torsionally soft torque tube functioning as said torsional spring to isolate the transmission and the rotor assembly from vibratory torque developed by the engine.

5 17. The drive train assembly of claim 15 wherein
said misalignment moment eliminating means
comprises an external crown spline coupling having
spline coupling teeth, and wherein said over-
10 running clutch is rigidly centered with respect to
said external crown spline coupling such that loads
transmitted through said external crown spline
coupling react through the center of said over-
running clutch.

15 18. The drive train assembly of claim 17 wherein
said misalignment moment eliminating means further
comprises an internal spline coupling having spline
coupling teeth, said internal spline coupling being
disposed in combination with said external crown
20 spline coupling with said spline coupling teeth
thereof in meshing engagement with said spline
coupling teeth of said external crown spline
coupling.

25 19. The drive train assembly of claim 18 wherein
said internal spline coupling is mechanically
interconnected to said drive shaft means.

20. The drive train assembly of claim 15 wherein
said transmission coupling subassembly means
comprises an external crown spline coupling having
spline coupling teeth and a gear spline coupling

having spline coupling teeth, said external crown spline coupling being disposed in combination with said gear spline coupling with said spline coupling teeth thereof in meshing engagement with said spline coupling teeth of said gear spline coupling.

21. The drive train assembly of claim 20 wherein said external crown spline coupling is mechanically interconnected to said drive shaft means, and wherein said gear spline coupling is configured for mechanical interconnection with the transmission of the rotor assembly.

22. The drive train assembly of claim 15 wherein said misalignment moment eliminating means comprises an external crown spline coupling having spline coupling teeth and an internal spline coupling having spline coupling teeth, said internal spline coupling being disposed in combination with said external crown spline coupling with said spline coupling teeth thereof in meshing engagement with said spline coupling teeth of said external crown spline coupling, said over-running clutch being rigidly centered with respect to said external crown spline coupling such that loads transmitted through said external crown spline coupling react through the center of said over-running clutch; and wherein

said transmission coupling subassembly means comprises an external crown spline coupling having spline coupling teeth and a gear spline coupling having spline coupling teeth, said external crown spline coupling being disposed in combination with

said gear spline coupling with said spline coupling teeth thereof in meshing engagement with said spline coupling teeth of said gear spline coupling;
said meshingly engaged external crown spline coupling and said internal spline coupling and said meshingly engage external crown spline coupling and gear spline coupling of said transmission coupling subassembly means in combination being operative to accommodate maximal misalignments between the transmission and the engine.

23. The drive train assembly of claim 17 wherein said engine coupling subassembly means includes a bundt pan, and wherein said over-running clutch is rigidly centered intermediate said bundt pan and said external crown spline coupling.

24. The drive train assembly of claim 23 wherein said engine coupling subassembly means further includes a stud configured to provide a hard mount with the engine such that the torque of the engine is coupled to said stud, and wherein said stud is mechanically interconnected to said bundt pan.

25. A coaxial transmission/center hub subassembly for a rotor assembly having ducted counter-rotating rotors for an unmanned aerial vehicle having an engine and a toroidal fuselage, the rotor assembly including upper and lower swashplate subassemblies and the toroidal fuselage including a plurality of inwardly extending radial support struts, comprising:

single stage transmission means for coupling torque from the engine of the aerial vehicle to the ducted counter-rotating rotors;

means for housing said single stage
5 transmission means in rotatable combination therewith;

means for providing direct load paths for dynamic loads developed by the ducted counter-rotating rotors;

10 means for canceling bending moments produced by the ducted counter-rotating rotors; and

means for coaxially mounting the ducted counter-rotating rotors, said single stage transmission means, said housing means, said direct
15 load paths providing means, and said bending moments canceling means in combination with the plurality of inwardly extending radial support struts.

26. The coaxial transmission/center hub
20 subassembly of claim 25 wherein said housing means, said direct load paths providing means, and said bending moments canceling means comprises a multi-member transmission housing, said multi-member transmission housing including an upper standpipe
25 housing, a lower standpipe housing, and middle housing, said upper and lower standpipe housings being secured in combination with said middle housing.

27. The coaxial transmission/center hub
30 subassembly of claim 26 wherein said coaxial mounting means comprises a center hub support

structure, said center hub support structure including a cylindrical body having a configuration for mounting said middle housing internally therein, said cylindrical body having a plurality
5 of integral, outwardly extending radial support arms for coaxially mounting the ducted counter-rotating rotors and said multi-member transmission housing in combination with the plurality of inwardly extending radial support struts.

10 28. The coaxial transmission/center hub subassembly of claim 26 wherein external surfaces of said upper and lower standpipe housings provide sliding surfaces for bidirectional linear movement of the upper and lower swashplate subassemblies,
15 respectively.

29. The coaxial transmission/center hub subassembly of claim 26 wherein said single stage transmission means comprises an input pinion gear rotatably mounted in combination with said middle
20 housing and operative to couple the torque from the engine, and upper and lower spiral bevel gears disposed in rotatable combination with said input pinion gear to couple the torque to the counter-rotating rotors, said upper and lower bevel gears
25 including integral upper and lower rotor shafts, respectively, rotatably mounted in said upper and lower standpipe housings, respectively.

30. The coaxial transmission/center hub subassembly of claim 26 wherein said multi-member
30 transmission housing is internally configured to

provide a splash lubrication subsystem for said single stage transmission means.

31. An integrated spline/cone seat subassembly for a rotor assembly having ducted counter-rotating
5 rotors for an unmanned aerial vehicle, comprising:
a rotor shaft having an axis, said rotor shaft including
- a primary shaft portion having a first diameter,
 - 10 an end shaft portion having a second diameter and having a plurality of shaft splines extending radially outwardly therefrom, and
 - a conic transition portion intermediate
15 said primary and end shaft portions, said conic transition portion making a predetermined angle with respect to said axis of said rotor shaft; and
 - a rotor hub having a centerline, said rotor
20 hub having a shaft aperture having a plurality of hub splines extending radially inwardly therefrom, each of said hub splines having an outwardly tapered lower portion that makes a predetermined angle with respect to said centerline;
 - 25 said predetermined angle of said outwardly tapered lower portion of each of said hub splines being equal to said predetermined angle of said conic transition portion of said rotor shaft wherein said tapered lower portions of said hub
30 splines abuttingly engage and are mechanically supported by said conic transition portion of said rotor shaft in the rotor assembly;

5 said plurality of hub splines and said plurality of shaft splines being interleaved in combination to provide a rotational interlock between said rotor hub and said rotor shaft in the rotor assembly.

10 32. The integrated spline/cone seat subassembly of claim 31 wherein said plurality of shaft splines have outboard surfaces defining a circumference having a third diameter, and wherein said third diameter is equal to said first diameter of said rotor shaft.

15 33. A snubber assembly for a rotor assembly having ducted counter-rotating rotors for an unmanned aerial vehicle, the rotor assembly including a rotor shaft, a torque tube having an inboard end, and a flexbeam having an inboard end, comprising:

20 a bracket configured to be secured in combination with the inboard end of the torque tube;

25 a bearing secured in combination with said bracket; and

30 a rotor hub, configured for securement in interlocked, engaged combination with the rotor shaft, having a plurality of radially extending arms, each said radially extending arm having an outboard end configured for securing the inboard end of the flexbeam in combination with said rotor hub, each said radially extending arm of said rotor hub including means for rotatably mounting said bearing, bracket combination internally in said rotor hub;

said internally rotatably mounted bearing, bracket combination being positioned inboard of said outboard end of said radially extending arm and inboard of the inboard end of the flexbeam.

5 34. The snubber assembly of claim 33 wherein said bearing is a spherical bearing.

35. The snubber assembly of claim 33 wherein said internal mounting means of each said radially extending arm comprises an outboard internal
10 bulkhead and an inboard internal bulkhead, said outboard and inboard internal bulkheads in combination defining a bearing cavity for rotatably mounting said bearing, bracket combination internally in said radially extending arm.

15 36. The snubber assembly of claim 35 wherein said internal mounting means further comprises a bearing bolt disposed in combination with said outboard internal bulkhead, said bearing, and said inboard internal bulkhead for rotatably mounting said
20 bearing, bracket combination in said bearing cavity.

37. The snubber assembly of claim 36 wherein said internal mounting means further comprises a locking nut threaded in combination with said bearing bolt
25 to jam against said inboard internal bulkhead to secure said bearing bolt in said rotor hub.

38. The snubber assembly of claim 33 where said rotor hub has four radially extending arms.

39. The snubber assembly of claim 38 wherein said outboard end of each said radially extending arm is configured as a clevis.

5 40. A rotor blade subassembly for a rotor assembly having ducted, coaxial counter-rotating rotors for an unmanned aerial vehicle, the rotor assembly including a rotor hub, comprising:

flexbeam means configured for reacting centrifugal and bending loads of one of the ducted, coaxial counter-rotating rotors, said flexbeams means having an inboard end and an outboard end, said inboard end being configured for securing said flexbeam means in combination with the rotor hub, said flexbeam means having a predetermined linear twist along the span thereof from said inboard end to said outboard end;

spar means for reacting bending, torsional, shear, and centrifugal loads of the one ducted, coaxial counter-rotating rotor, said spar means functioning as a primary structural member of said rotor blade subassembly;

torque tube means for reacting torsional and bending loads of the one ducted, coaxial counter-rotating rotor; and

25 a rotor blade;

said rotor blade, said torque tube means, said spar means, and said flexbeam means being secured in combination at said outboard end of said flexbeam means.

30 41. The rotor blade subassembly of claim 40 wherein said predetermined linear twist of said

flexbeam means varies linearly along the span thereof from about 0° at said inboard end thereof to about 22° at said outboard end thereof.

5 42. The rotor blade subassembly of claim 40 wherein said spar means and said torque tube means comprise a single continuous tubular composite structure.

10 43. The rotor blade subassembly of claim 42 wherein said torque tube means of said continuous tubular composite structure is an inboard segment thereof configured to react the torsional and bending loads of the one ducted, coaxial counter-rotating rotor and wherein said spar means of said continuous tubular composite structure is an
15 outboard segment thereof configured to react the bending, torsional, shear, and centrifugal loads of the one ducted, coaxial, counter-rotating rotor.

20 44. The rotor blade subassembly of claim 43 wherein said inboard torque tube segment of said continuous tubular composite structure has a generally elliptical profile.

25 45. The rotor blade subassembly of claim 44 wherein said outboard spar segment of said continuous tubular composite structure has a truncated aerodynamic profile.

46. The rotor blade subassembly of claim 40 wherein said rotor blade is configured to have a high aerodynamic taper such that said tapered rotor

blade has a low outboard mass, a high inboard stiffness, and a high chordwise frequency.

5 47. The rotor blade subassembly of claim 46 wherein said tapered rotor blade has an aerodynamic root having an effective chord and an aerodynamic tip having an effective chord, said high aerodynamic taper being defined as a ratio of said effective chord at said aerodynamic root to said effective chord at said aerodynamic tip.

10 48. The rotor blade subassembly of claim 47 wherein said ratio defining said high aerodynamic taper is about 2:1.

15 49. The rotor blade subassembly of claim 46 wherein said high chordwise frequency of said tapered rotor blade provides for operation of the rotor assembly over a weaker modal response zone, said weaker modal response zone for said unmanned aerial vehicle being between about a 2/rev resonance mode condition and a 3/rev resonance mode
20 condition.

FIG. 1

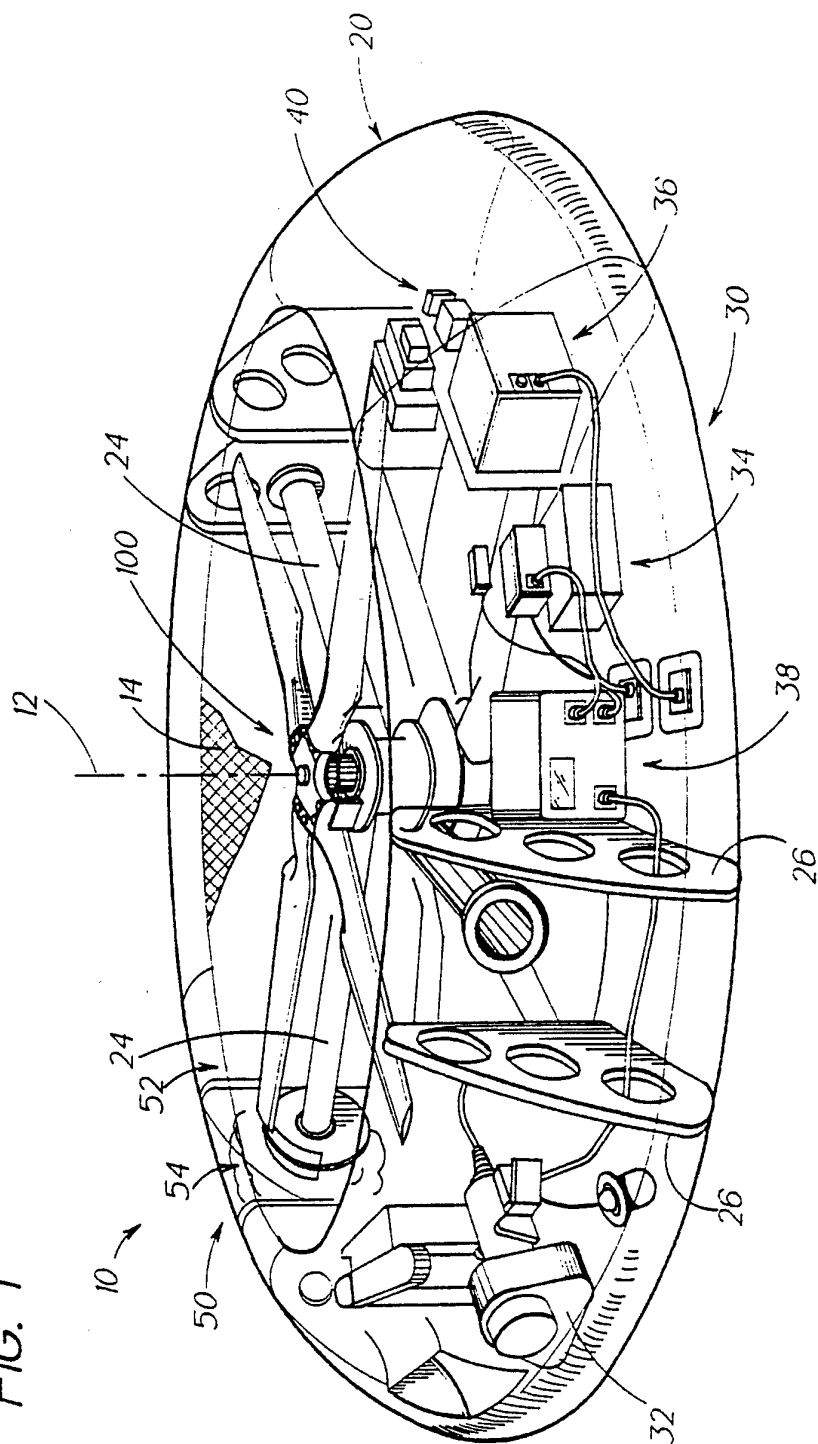
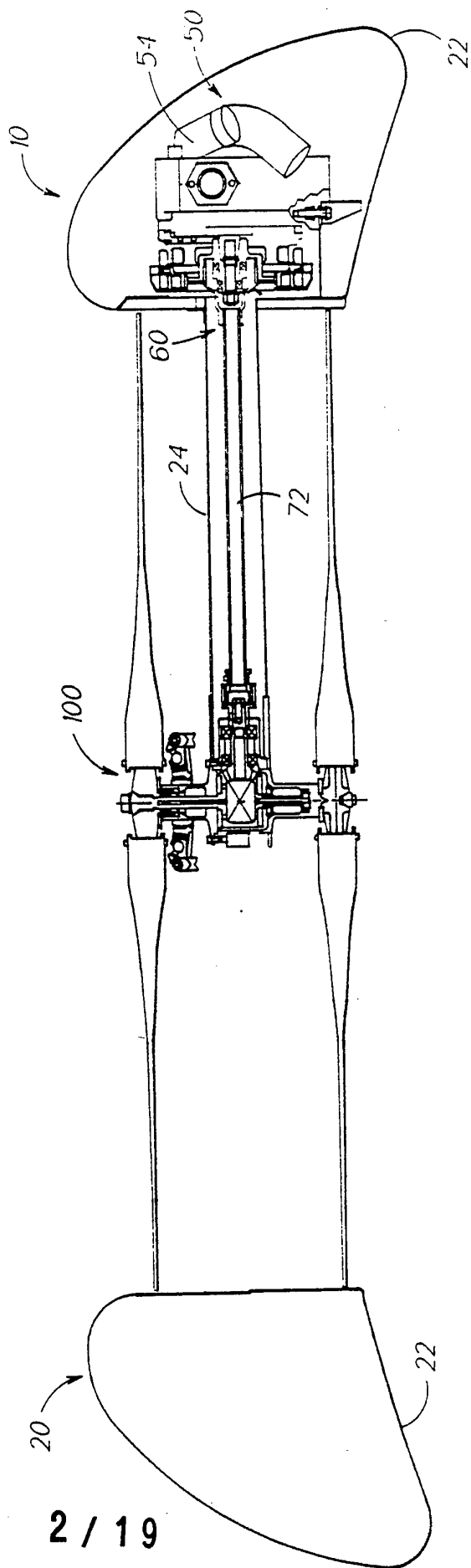


FIG. 2



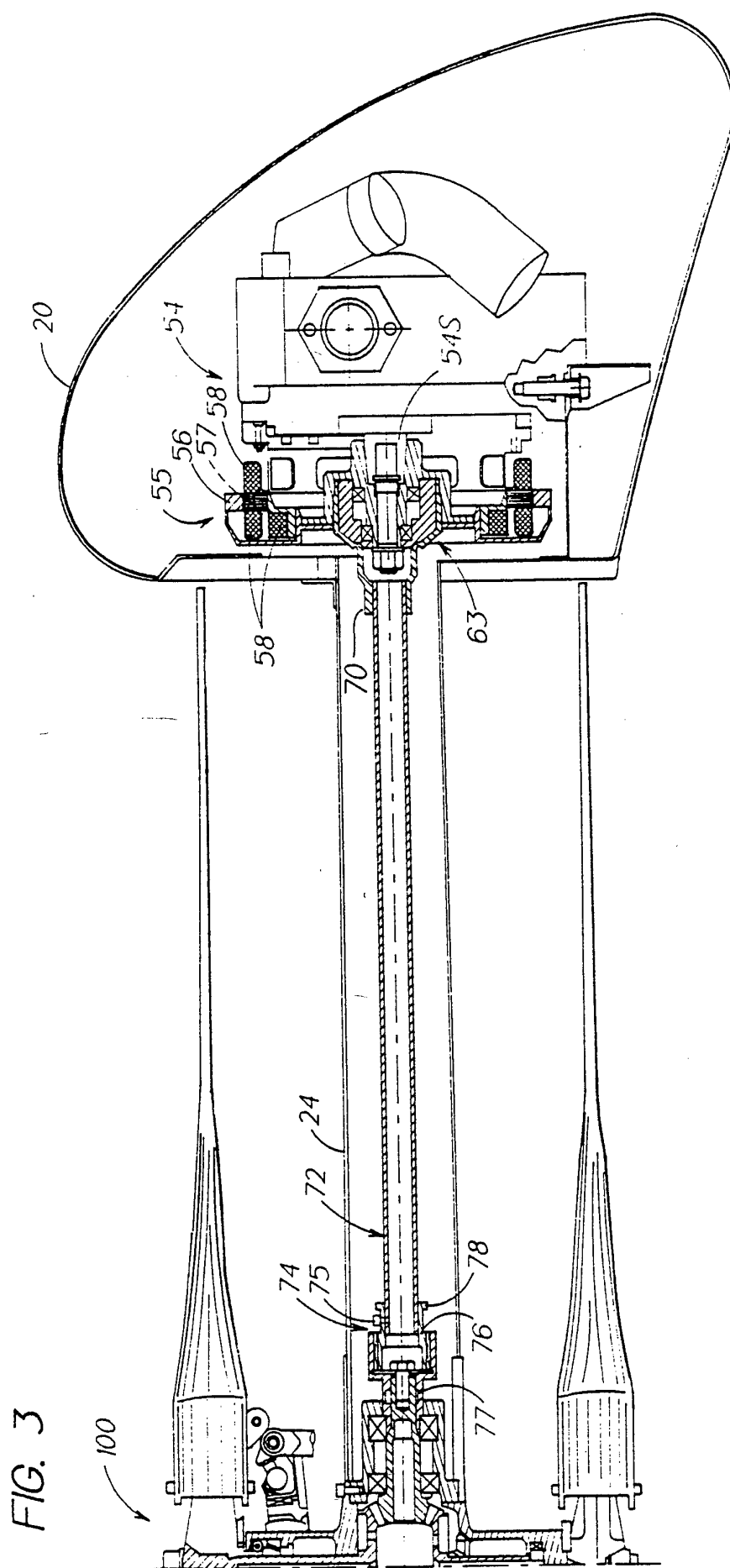


FIG. 3A

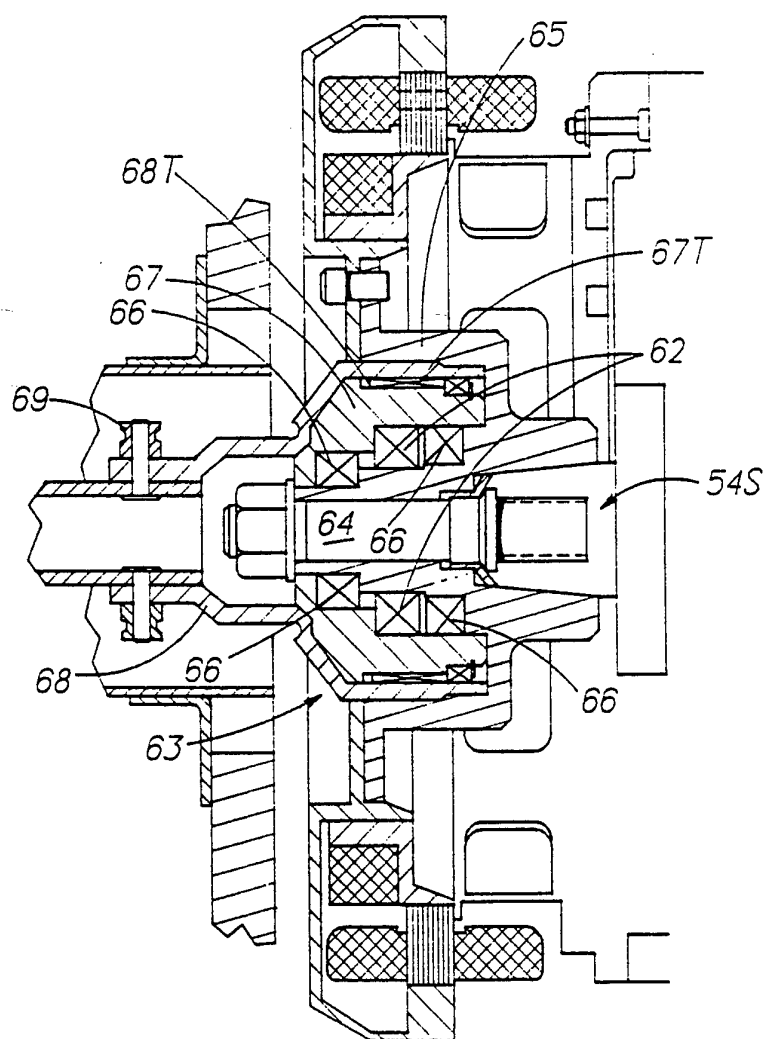


FIG. 4

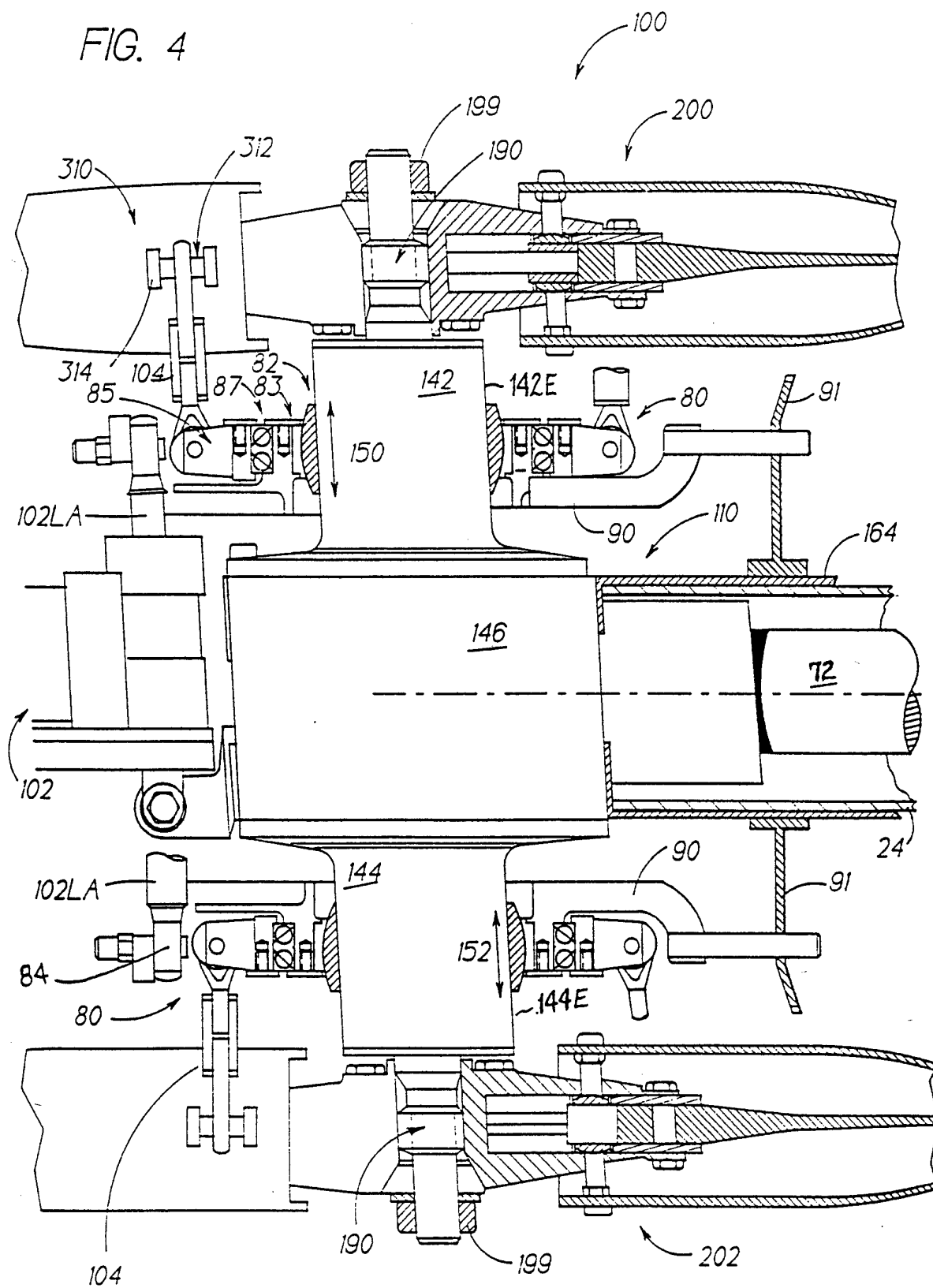


FIG. 5A

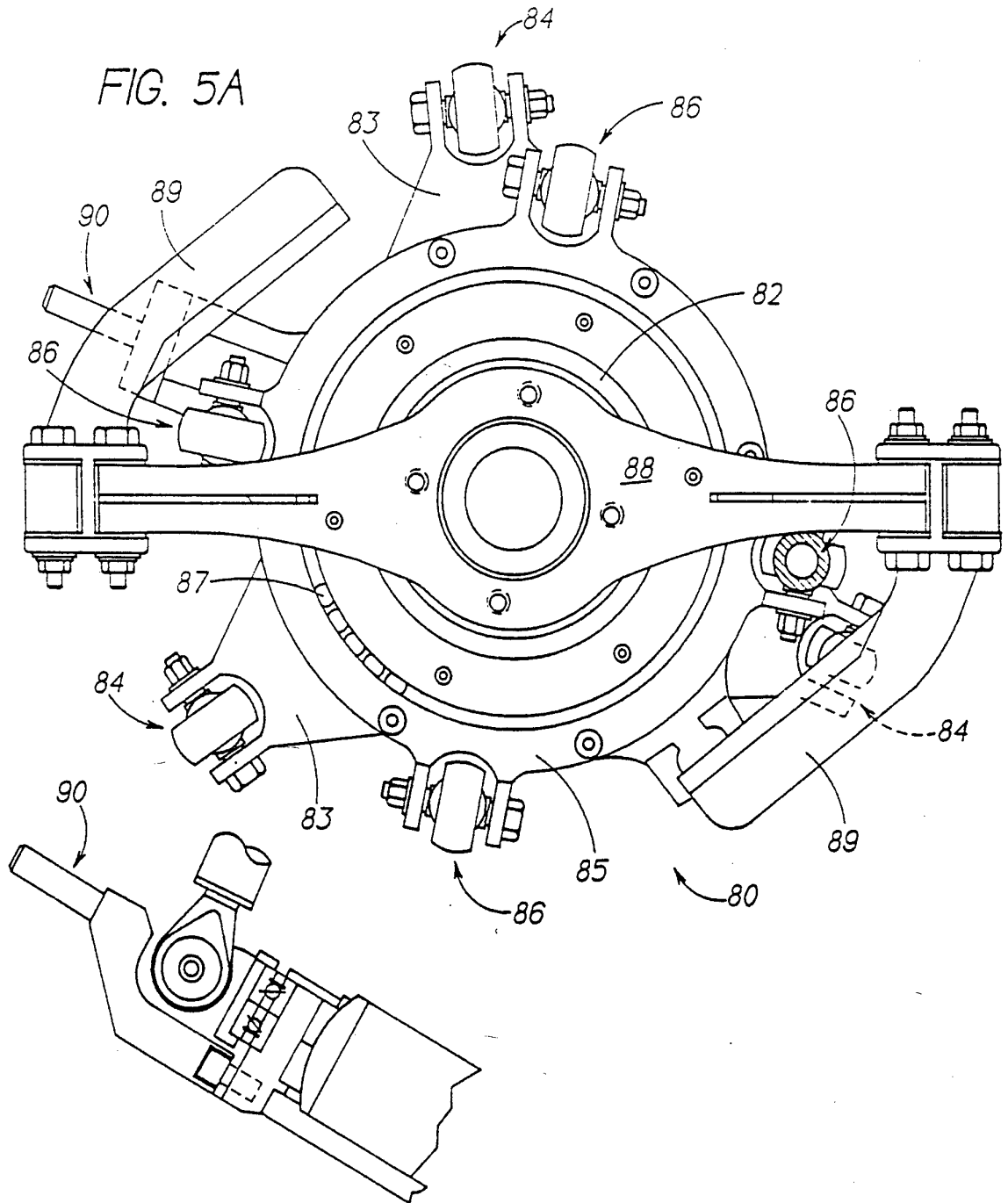


FIG. 5B

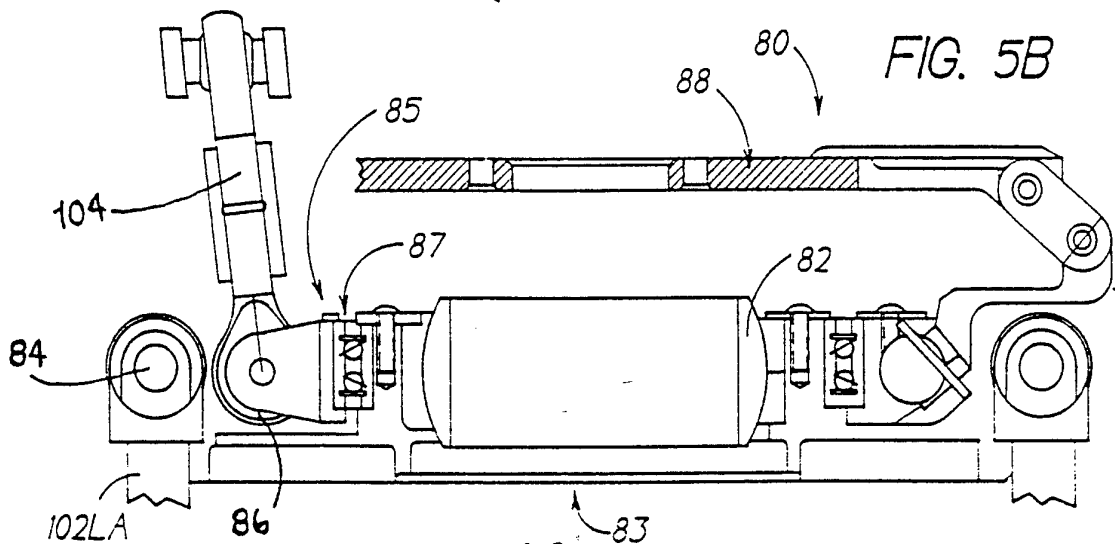


FIG. 6

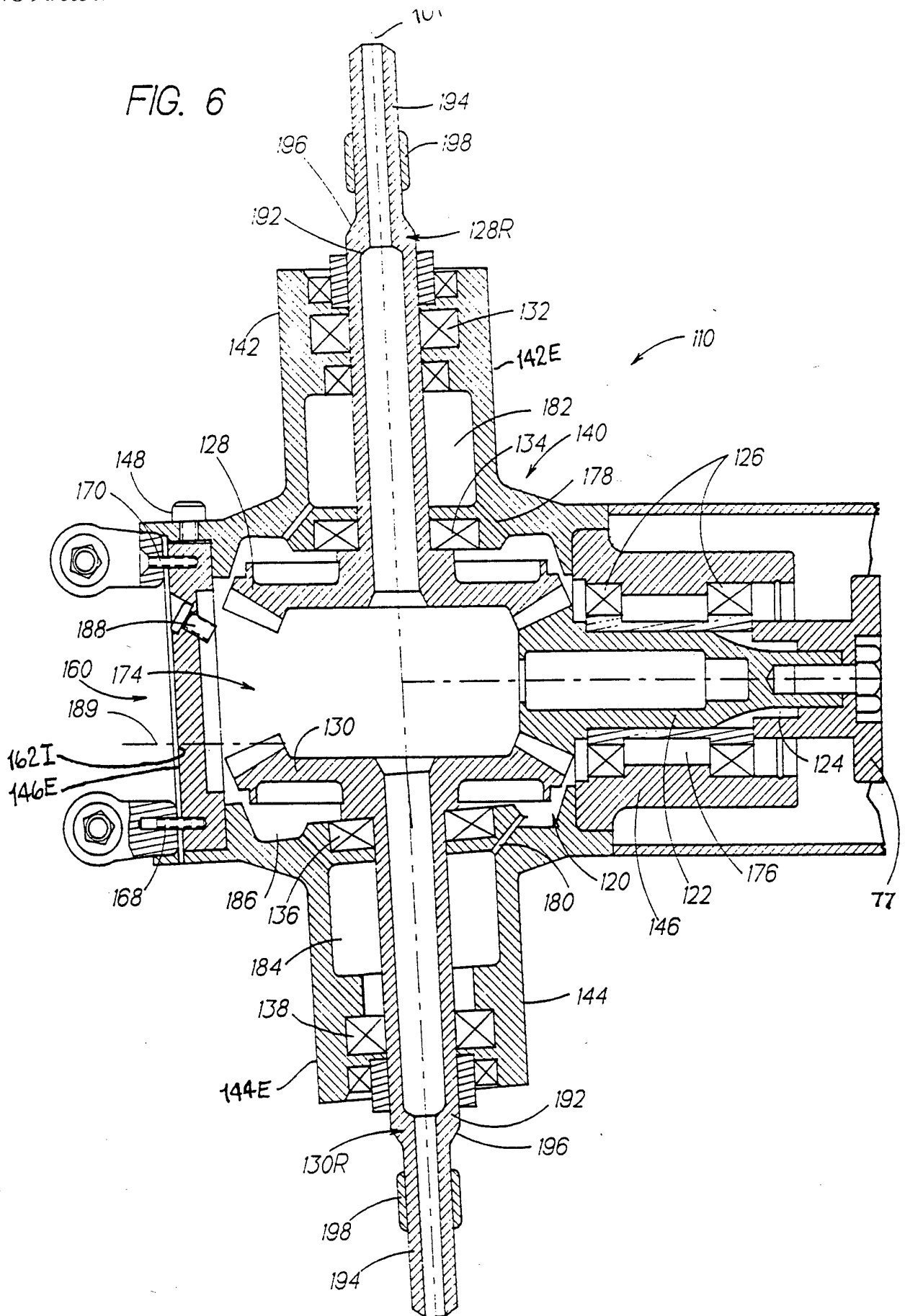
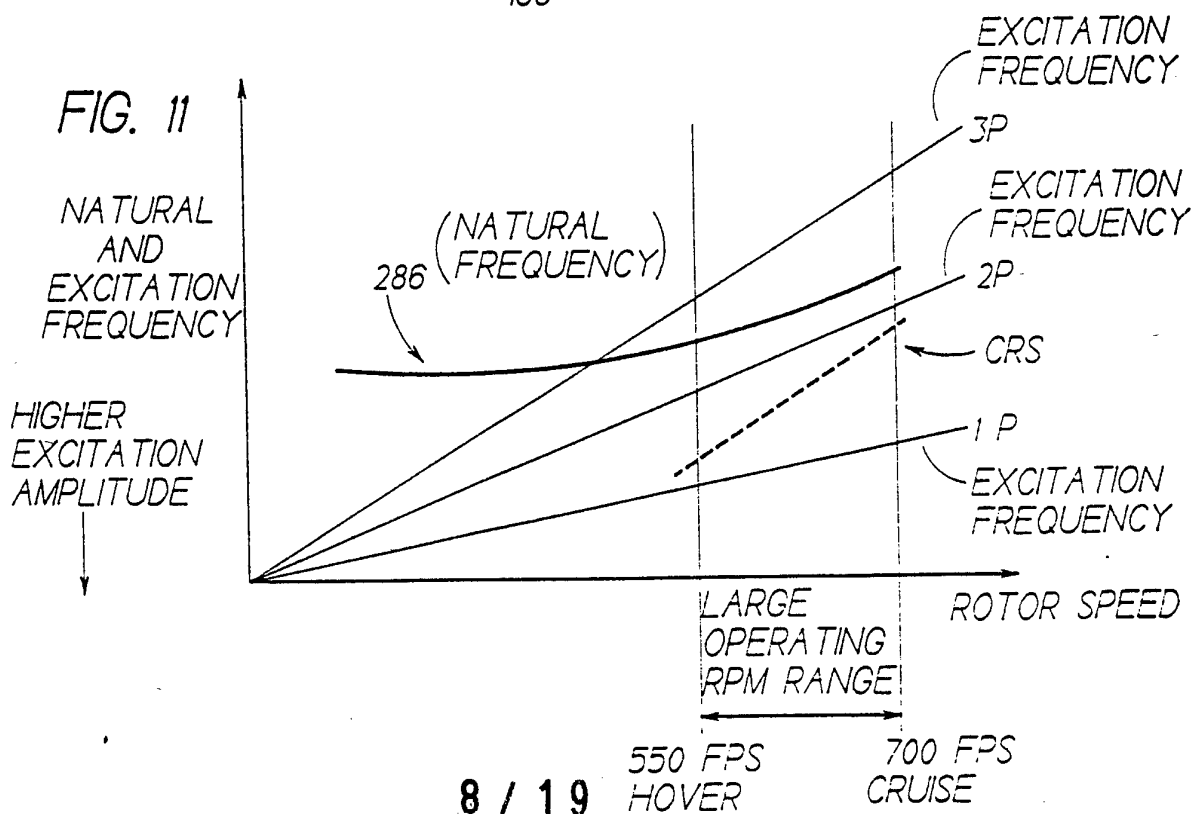
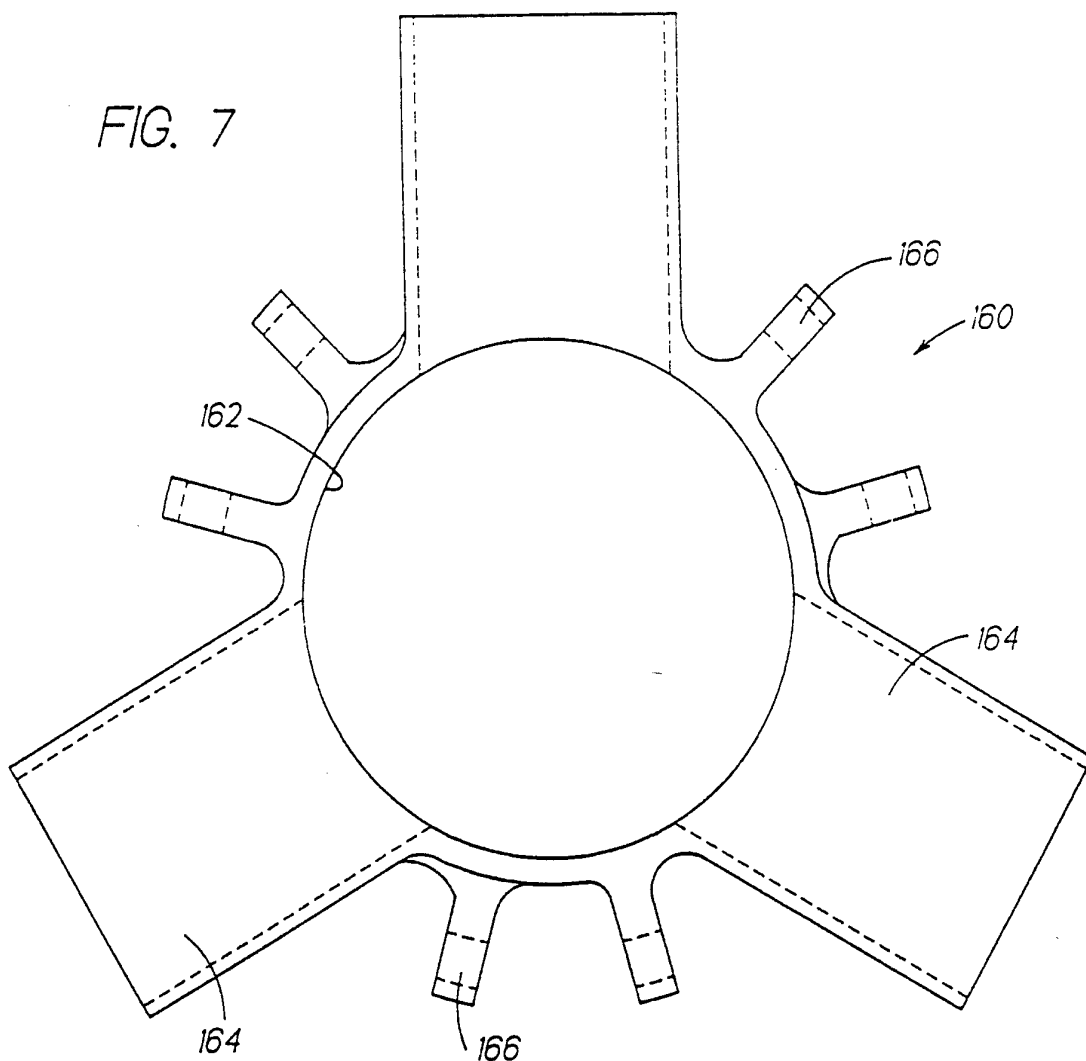


FIG. 7



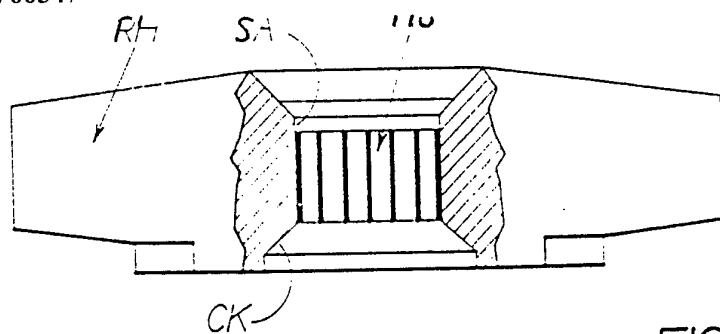
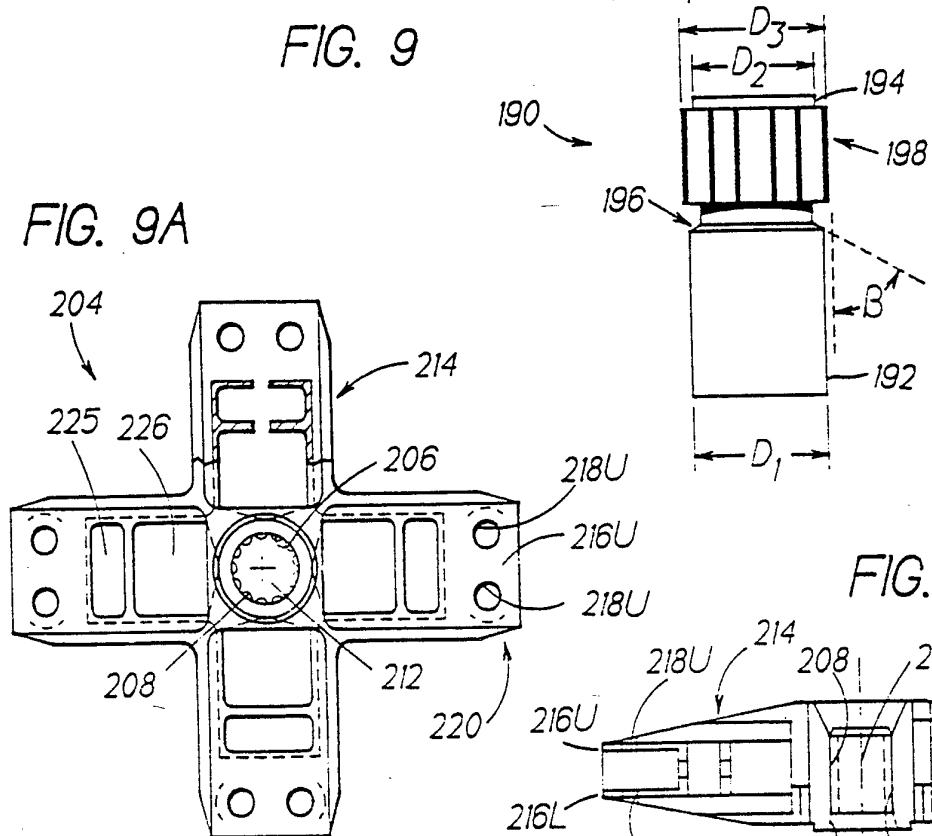
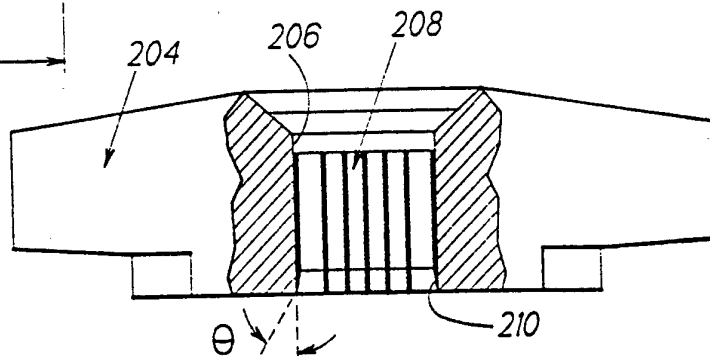
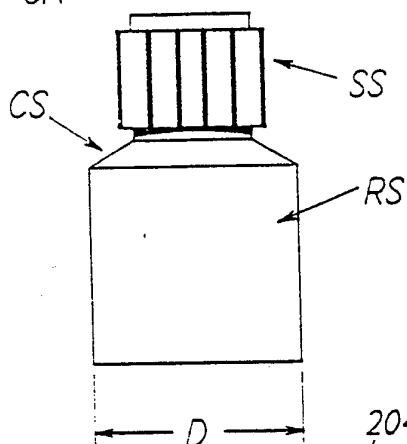
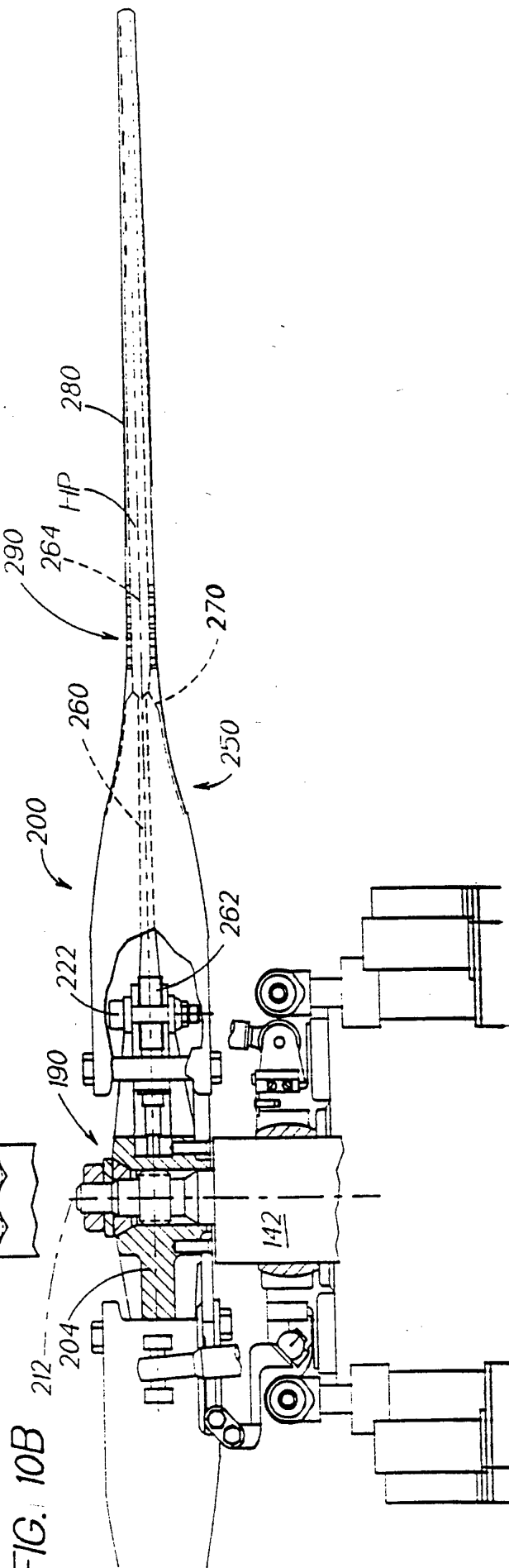
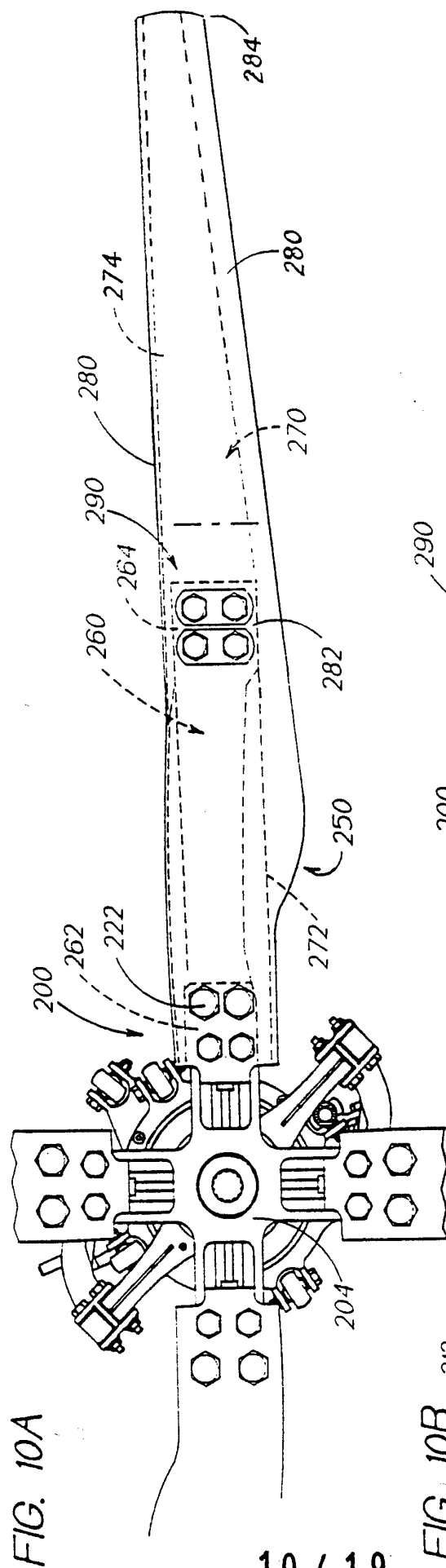


FIG. 8
PRIOR ART





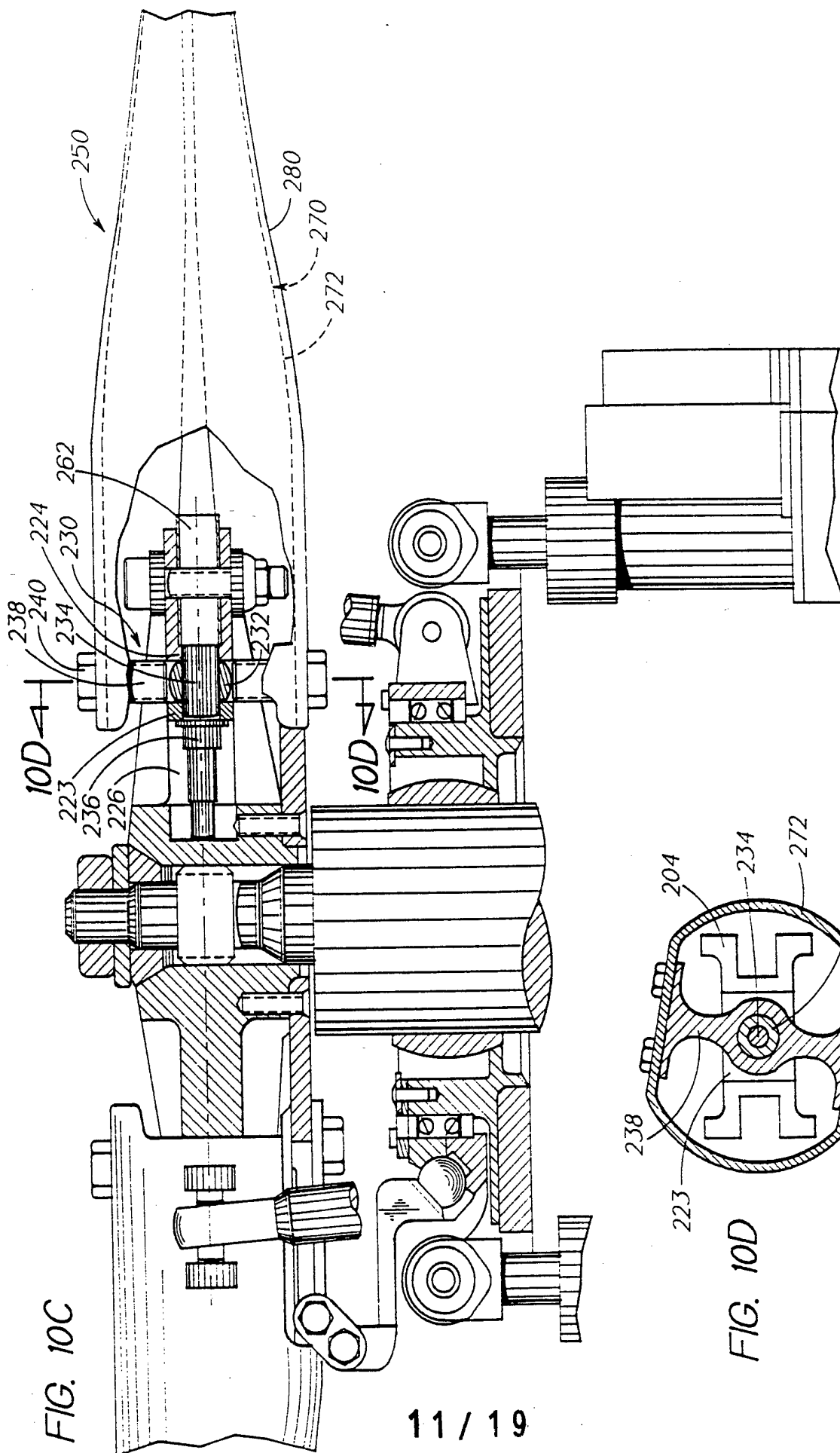


FIG. 12A

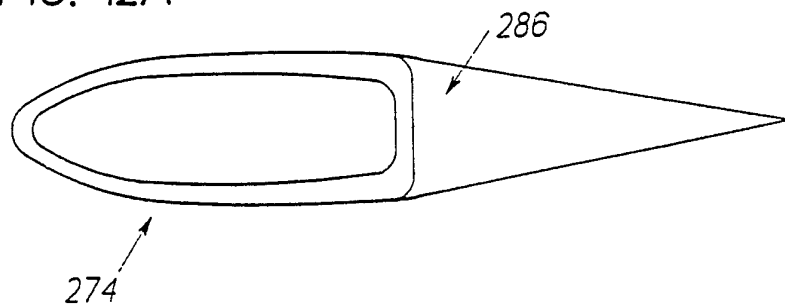


FIG. 12B

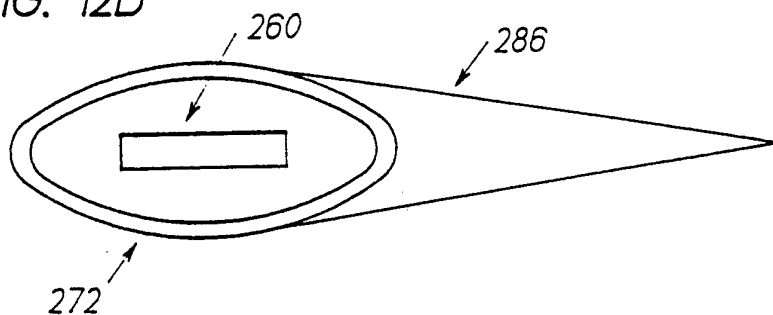
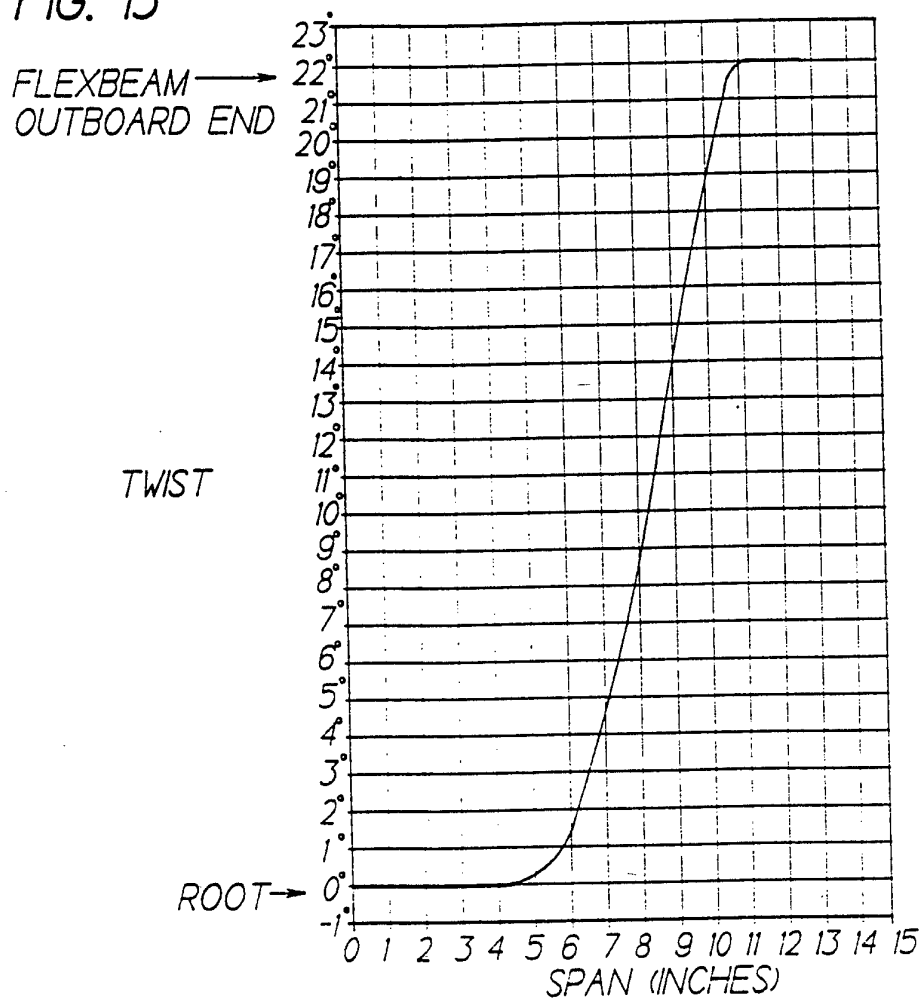


FIG. 13



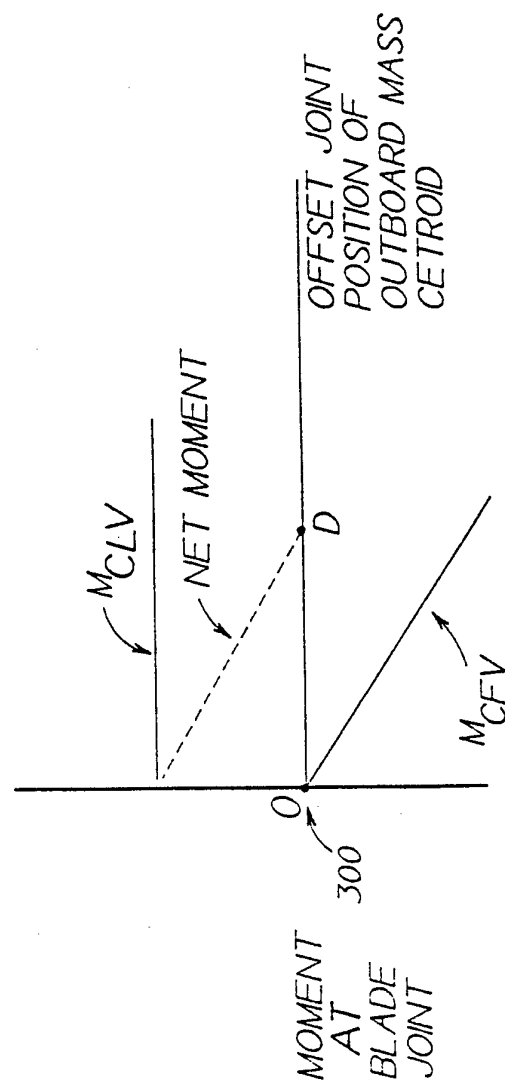
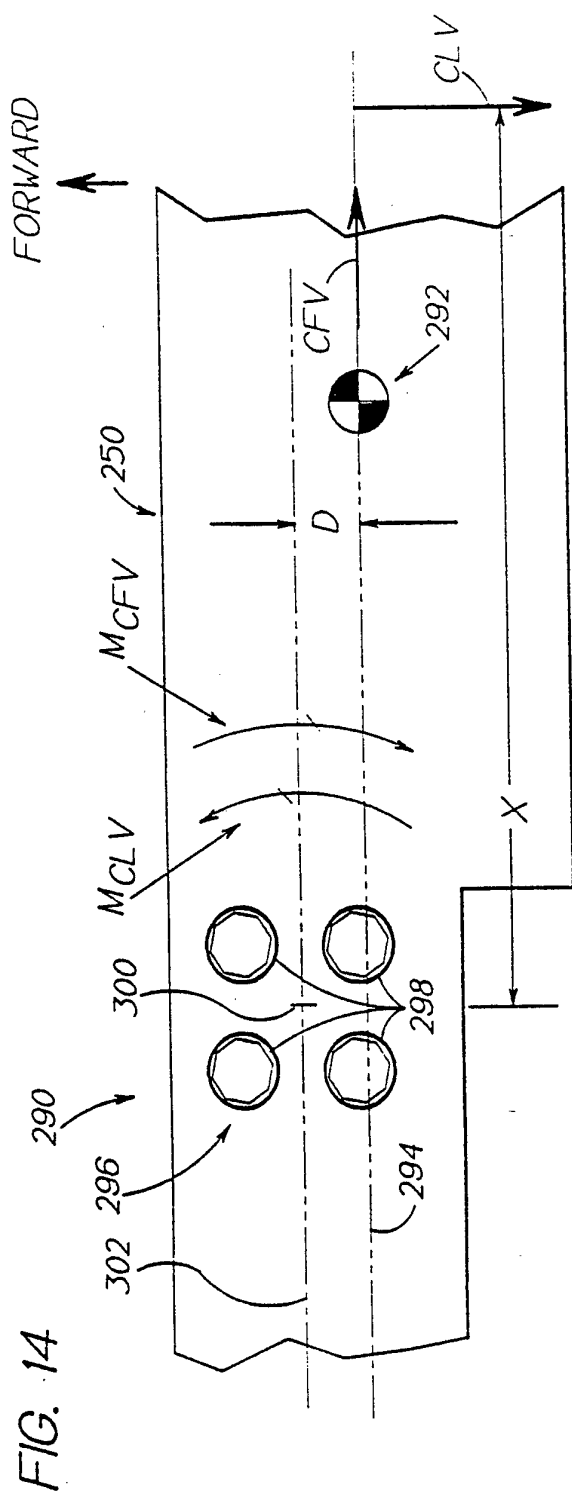


FIG. 16
PRIOR ART

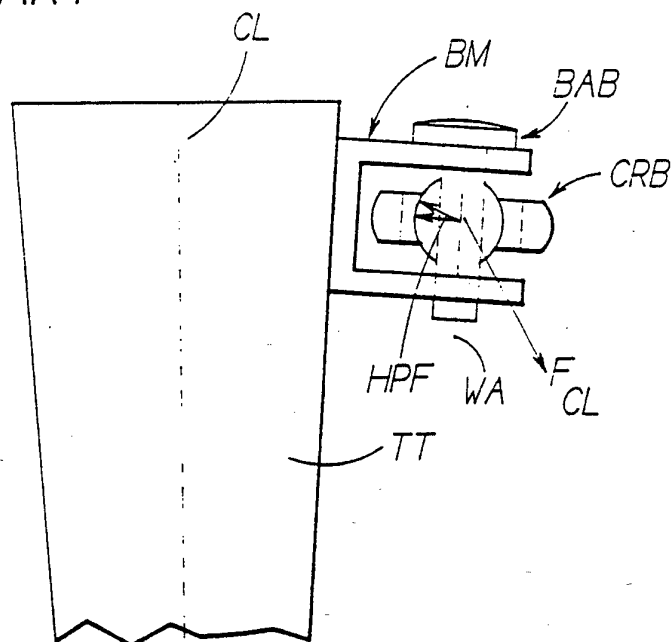


FIG. 17

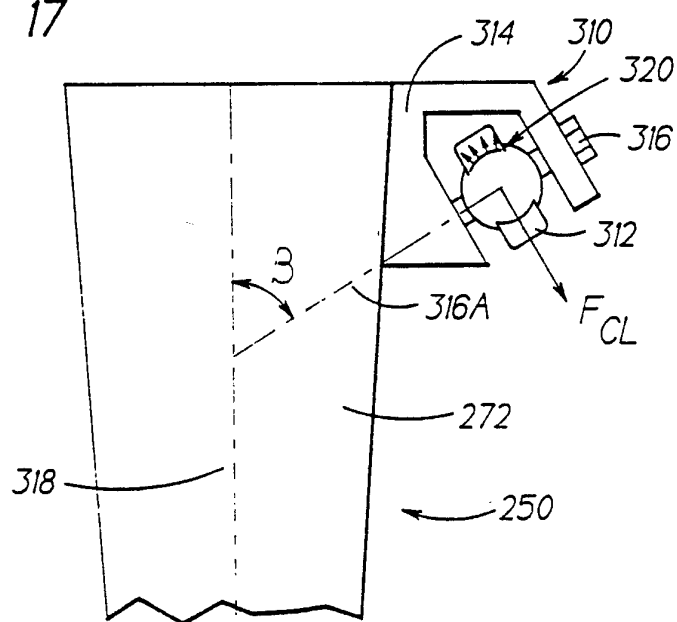


FIG. 18

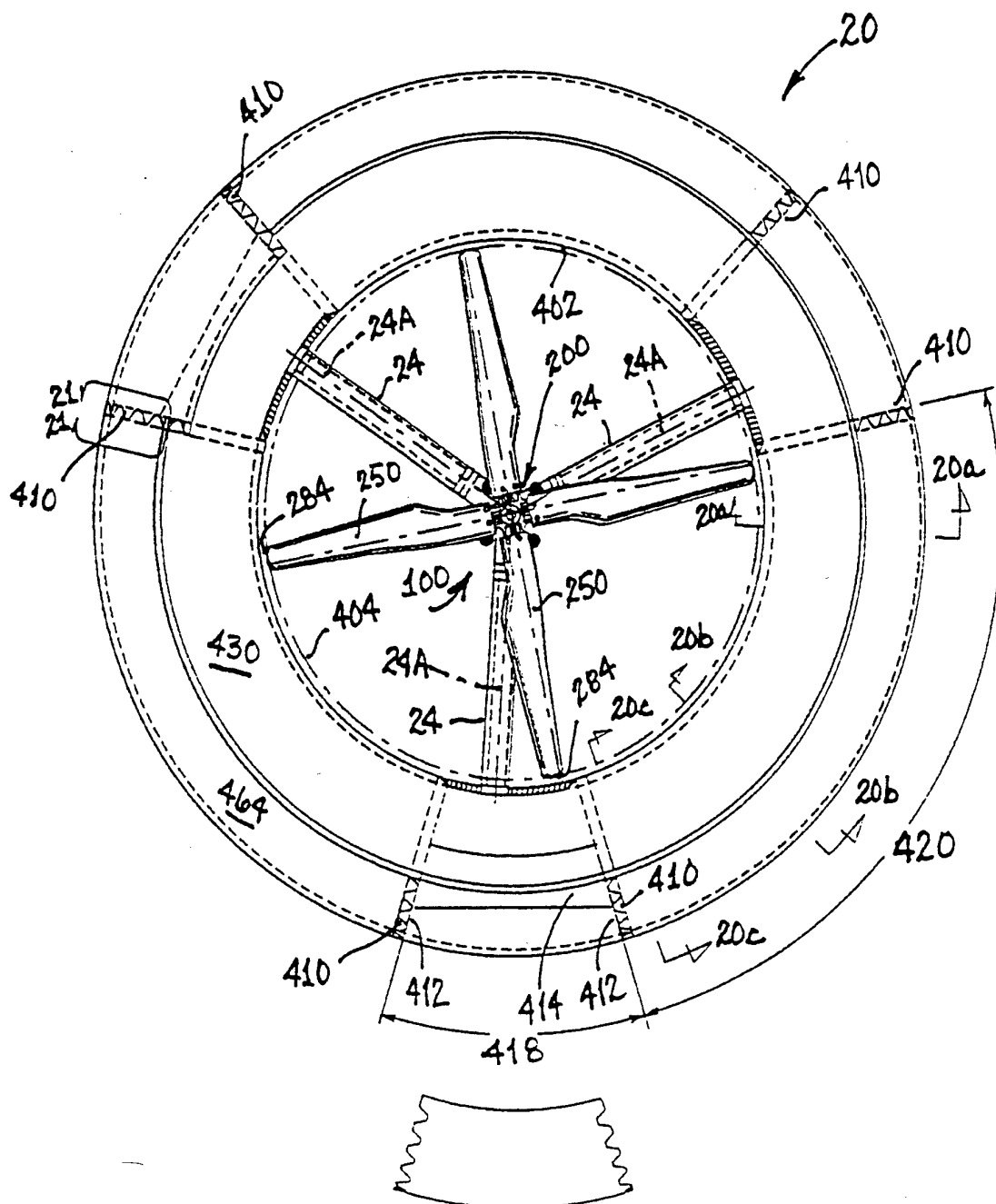


FIG. 19

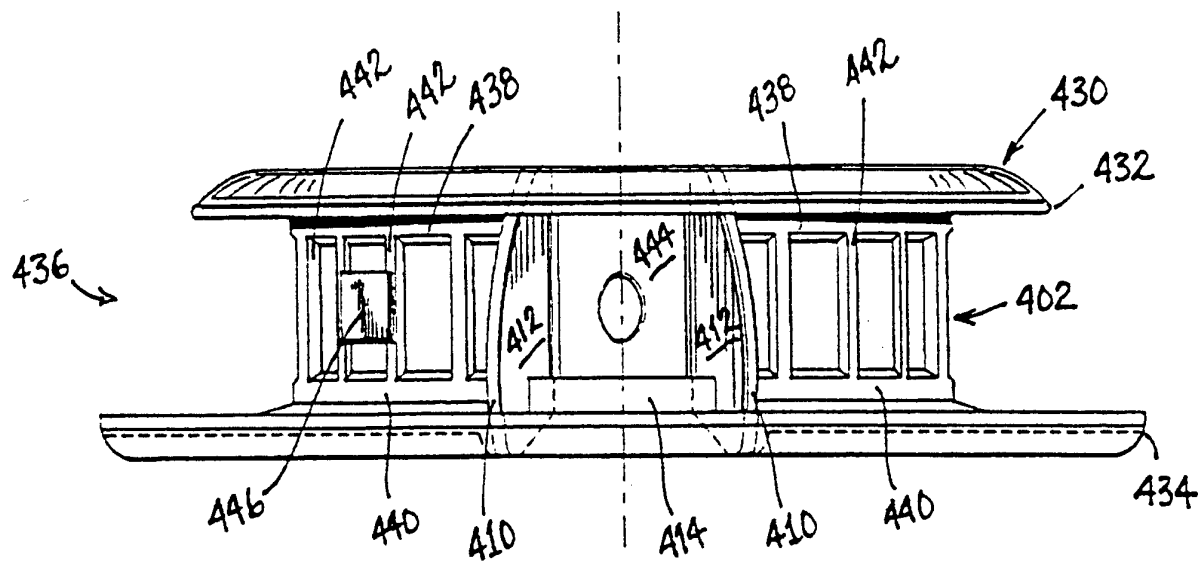


FIG. 21

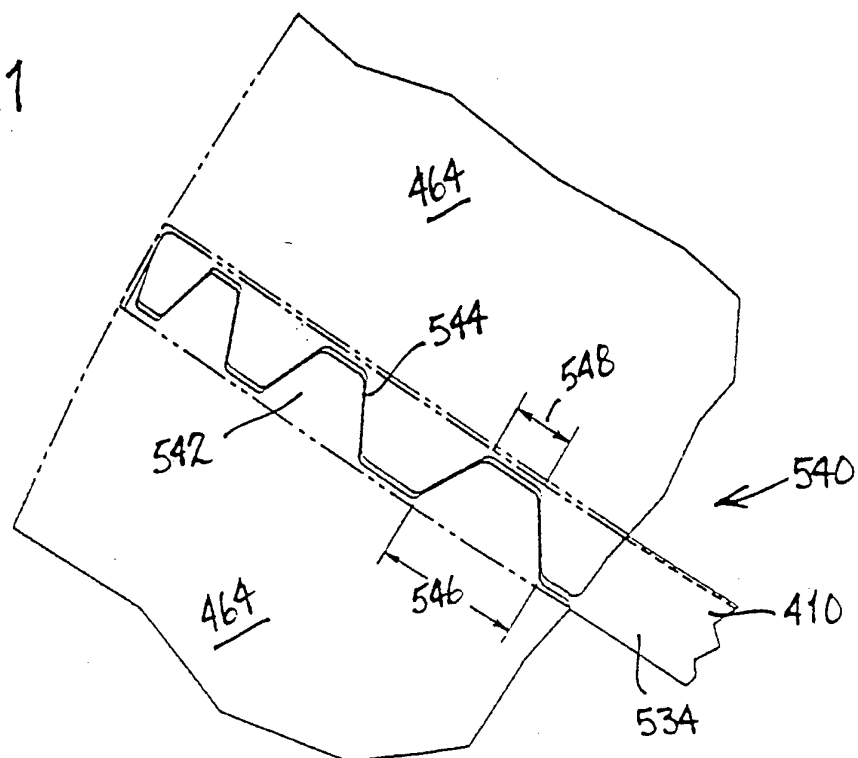


FIG. 20A

