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KNUCKLE-STYLE PDM TRANSMISSION WITH ARTICULATED TORQUE TRANSFER

Abstract

A knuckle-style ball-CV style transmission suitable for use in a Positive Displacement Motor (PDM). A knuckle head provides knuckle wings received into shaft cavity receptacles on a shaft. Each shaft cavity receptacle provides a shaft cavity recess. A Torque Transfer Element (TTE) and a ball is received into each shaft cavity receptacle, such that the TTE and ball are interposed between each knuckle wing and a corresponding shaft cavity recess within the shaft cavity recess. The TTEs float within their corresponding shaft cavity receptacles so as to maintain torque transfer contact between all thrust surfaces during articulated rotation of the shaft with respect to the knuckle head. The TTEs preferably float generally radially towards the shaft centerline as angular deflection increases during articulated rotation.

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Background/Summary

PRIORITY CLAIM [0001] This application is a continuation-in-part of co-pending, commonly-invented and commonly-assigned U.S. patent application Ser. No. 18/322,980 filed May 24, 2023 (U.S. Pat. No. 12,292,089). Ser. No. 18/322,980 is a continuation of commonly-invented and commonly-assigned U.S. patent application Ser. No. 16/797,178 filed Feb. 21, 2020 (U.S. Pat. No. 11,661,972). Ser. No. 16/797,178 claims the benefit of and priority to commonly-owned and commonly-invented U.S. Provisional Patent Application Ser. No. 62/808,709 filed Feb. 21, 2019. The entire disclosures of Ser. Nos. 18/322,980, 16/797,178 and 62/808,709 are incorporated herein by reference as if fully set forth herein.

FIELD OF THE DISCLOSURE
[0002] This disclosure is directed generally to rotary power transmission assemblies particularly adapted for use in bottom hole assemblies ("BHAs") in order to transfer torque generated by a subterranean positive displacement motor ("PDM") to, for example, a rotary drill bit. This disclosure is directed more specifically to such a transmission assembly transmitting torque via a ball and recessed torque transfer element ("TTE") in the style of a constant velocity ("CV") joint.
BACKGROUND
[0003] It is well understood that bottom hole assemblies ("BHAs") include rotating power shafts that are necessarily misaligned by virtue of the BHA's design. For example, the rotation of the rotor in the PDM is eccentric and not concentric. This eccentric rotation of the rotor must be resolved into concentric rotation that will ultimately rotate the bit. Further, directional drilling in deviated wellbores necessarily causes misalignment of rotating power shafts in interconnected BHA components. Directional misalignment in deviated wellbores can be as high as 3.0 degrees.
[0004] Specialized transmission sections designed for downhole applications (hereafter, "transmissions") transfer torque between such misaligned shafts. The development of increasingly high power output PDM power sections has led to the need for bearing and transmission components with higher strength and load bearing capability. A number of attempts have been made to improve the torque capability of PDM transmissions.
[0005] Woodruff key designs generally provide comparatively large Torque Transfer Elements (TTEs) whose aspect ratio is longer in the circumferential direction than in the radial or longitudinal direction. As a result, the TTEs have difficulty remaining stable within their torque transfer assembly pockets during misaligned rotation/articulation. Lack of stability, particularly in the radial direction, can unseat TTEs from their torque transfer contact during misaligned rotation. Even when in contact, such instability can cause high stress concentrations on the TTEs, similar to point loads, at locations along the contact/bearing surfaces during torque transfer. These effects are known to lead to high wear on the contact/bearing surfaces.
[0006] Bridge designs offer more stability to the TTEs by providing an aspect ratio that is shorter in the circumferential direction than in the radial or longitudinal direction. Ball/CV designs may

further stabilize the TTEs by building on the bridge design concept. A plurality of balls or similar arcuate components may be interposed between the transmission shaft head and cooperating housing (in which the shaft head is received). The ball, at least in theory, provides additional freedom to allow the shaft head to "tilt" with respect to shaft head during misaligned rotation. Various such ball/CV designs are disclosed, for example, in U.S. Pat. No. 8,915,788 to Foote et al. (hereafter "Foote"). Foote discloses a ball interposed to engage a partial spherical receptacle on the drive shaft head on one side of the ball, and a partial spherical receptacle in a TTE on the other side of the ball. The TTE slides within a groove formed in the housing. The drive shaft head is further shaped in the general form of a sphere, so that the assembly imitates a general spherical/retained-sliding-ball-in-groove CV design. This design limits potential torque transfer capability.

[0007] The design compels a torque transfer angle from the ball to the TTE receptacle that is less than optimal. Movement of the sliding TTE is constrained by the sides of the radial groove. The geometrical arrangement as constrained thus limits the potential mechanical advantage otherwise available to maximize the torque capability of the TTEs. Further, the Foote ball design, with its sliding TTE constrained by a radial groove in the housing, virtually ensures that at least one ball will physically disengage (unseat) from its TTE as the ball rotates off-center during misaligned rotation. Disproportional stress is then placed on the remaining engaged balls and TTEs to transfer torque. An improved design will transfer torque through the ball and TTE at a much more efficient transfer angle than is disclosed in Foote. An improved design will also reorient the sliding TTE of Foote in order to retain engagement of all balls in their respective TTEs during misaligned rotation. Reorientation of the sliding TTE will further allow the diameter of the ball to be optimized with respect to the size of its corresponding TTE. An optimized ball/TTE interface will reduce contact stress during torque transfer, allowing the improved design to transfer higher torque loads.

[0008] Other ball/CV designs are disclosed in U.S. Pat. No. 10,267,366 to LaGrange et al. (hereafter "LaGrange"). FIG. **1** is a simplified schematic illustrating articulated deflection in LaGrange. FIGS. **1**A and **1**B are sections as shown on FIG. **1**. FIGS. **1**, **1**A and **1**B are derived from drawings and disclosure in LaGrange. FIGS. **1**A and **1**B are simplified versions of FIG. 6 in LaGrange. It will be appreciated that FIGS. **1**A and **1**B are "mirror images" of LaGrange's FIG. 6, necessitated by the directions from which the sections are taken in FIG. **1**. Where feasible, part numbers and their part names on FIGS. **1**, **1**A and **1**B are carried over from corresponding part numbers and part names in LaGrange. Part numbers on FIGS. **1**, **1**A and **1**B further include the prefix "L" to denote reference to LaGrange, and in distinction to part numbers referring to embodiments of new transfer technology described in this disclosure on FIGS. **2** through **11**.

[0009] FIGS. **1**, **1**A and **1**B further adopt a part number "prime" convention, where a part number without a prime notation is in an unarticulated state, and a part number with a prime notation is in an articulated state. In an unarticulated state, the part is positioned according to coaxial alignment of a shaft axis and a housing axis. In an articulated state, the part's position is deflected as a result of articulated (or misaligned) rotation of the shaft axis with respect to the housing axis.

[0010] FIG. **1** compares the relative position of force transfer element L**60** with respect to socket housing L**50** in an unarticulated state (per FIG. **1**A) and an articulated state (per FIG. **1**B). FIG. **1** depicts force transfer element L**60** when crown ball centerline **34** is unarticulated, and force transfer element L**60′** when crown ball centerline **34′** is articulated.

[0011] FIG. **1**A depicts force transfer element L**60** retained in socket housing relief space L**58** between crown ball L**40** and socket housing L**50** in the unarticulated state. Socket ridge L**57** on socket housing L**50** cooperates with the shape of crown ball L**40** to restrict force transfer element L**60** from floating in socket housing relief space L**58**. Contact zone LC by socket housing L**50** on force transfer element L**60** is as illustrated on FIG. **1**A in the unarticulated state.

[0012] FIG. **1**B is as FIG. **1**A, except in the articulated state on FIG. **1**B. FIG. **1**B depicts gap LG′ opening between force transfer element L**60′** and socket housing L**50** as articulation progresses. Gap LG′ reduces contact zone LC on FIG. **1**A to a much smaller contact zone LC′ on FIG. **1**B.

Thus, while force transfer element L**60**′ is likely quite stable on FIG. **1**B (by virtue of physical retention by socket ridge L**57**, socket housing L**50**, and crown ball L**40**), the substantially reduced contact zone LC′ is likely to cause high stress concentrations on force transfer element L**60**′ and on socket housing L**50** at points of contact. This will likely lead to high wear, high heat concentrations, cracking, fretting and galling on the contact/bearing surfaces.

SUMMARY OF DISCLOSED TECHNOLOGY AND TECHNICAL ADVANTAGES

[0013] Ball/CV designs consistent with this disclosure improve upon prior art ball/CV designs such as are disclosed in LaGrange. A shaft head provides shaft wings. The shaft head is disposed to be received in to a housing during misaligned rotation of the shaft with respect to the housing. A ball is interposed between a TTE and a shaft wing. The TTE is interposed between the ball and the housing. The interoperation of ball and TTE provides an additional degree of freedom in the TTE assembly. Thus, according to the position of misaligned rotation at any moment in time, the TTE may rotate and tilt about the ball in multiple axes with respect to the shaft wing during torque transfer. Components in the torque transfer flow retain a high degree of contact with one another during misaligned rotation. A smooth and predictable torque transfer results.

[0014] FIG. **2** is a simplified schematic illustrating articulated deflection in one embodiment of the transmission technology described in this disclosure. FIGS. **2**A and **2**B are sections as shown on FIG. **2**. FIG. **2** should be viewed together with FIG. **1** in order to compare the articulated deflection illustrated on FIG. **2** with the prior art LaGrange articulated deflection illustrated on FIG. **1**.

[0015] Similar to FIGS. **1**, **1**A and **1**B, FIGS. **2**, **2**A and **2**B adopt a part number “prime” convention, where a part number without a prime notation is in the unarticulated state, and a part number with a prime notation is in the articulated state. FIG. **2** compares the relative position of ball **320** as received into Torque Transfer Element (TTE) **310** with respect to housing **205** and housing receptacle **207** in the unarticulated state (per FIG. **2**A) and the articulated state (per FIG. **2**B). FIG. **2** depicts ball **320** as received into TTE **310** when shaft centerline **10** is unarticulated, and ball **320**′ as received into TTE **310**′ when shaft centerline **10**′ is articulated.

[0016] FIG. **2**A depicts ball **320** and TTE **310** retained in housing receptacle **207** between shaft wing **106** and housing **205** in the unarticulated state. By contrast, FIG. **2**B depicts ball **320**′ and TTE **310**′ retained in housing receptacle **207** between shaft wing **106** and housing **205** in the articulated state. Comparison of FIGS. **2**A and **2**B shows that responsive to misaligned rotation of shaft centerline **10**′, TTE **310** floats position to TTE **310**′ within housing receptacle **207**/**207**′ during articulation. TTE **310**'s freedom to float within housing receptacle **207**/**207**′ enables substantial torque transfer contact to be maintained between all thrust surfaces (shaft wing **106**, ball **320**/**320**′, TTE **310**/**310**′ and housing **205**) during the misaligned rotation. In the embodiments of FIGS. **2**, **2**A and **2**B, TTE **310**/**310**′ tends to float generally radially towards the shaft centerline **10**/**10**′ as angular deflection increases during articulated rotation, although the scope of this disclosure is not limited in this regard. Thus, responsive to articulated rotation of the shaft centerline **10**/**10**′ and regardless of amount of angular deflection during an articulated revolution of the shaft, TTE **310**/**310**′ is free to slidably displace within housing receptacle **207**/**207**′ so as to maintain substantial torque transfer contact between shaft wing **106**, ball **320**/**320**′, TTE **310**/**310**′ and housing **205**. Such substantial torque transfer contact reduces the potential for high stress concentrations on the thrust surfaces.

[0017] Currently preferred embodiments of ball/CV designs consistent with this disclosure thus provide a degree of encapsulation of the ball by the TTE and by the shaft wing that may vary according to the embodiment. The selected depths and locations of spherically-shaped recesses provided in the TTEs and in the shaft wings for receiving the interposed ball will determine the degree of encapsulation of the ball, and the ball's relative position on the shaft. Different embodiments may provide different degrees of encapsulation, and different ball locations on the shaft, to suit particular design applications. Various considerations will affect precise details of the design, such as, for example, (1) size of ball; (2) amount of TTE and/or shaft material desired to retain the ball in the corresponding TTE/shaft wing recesses; (3) degree of encapsulation desired; and (4) shaft radius at which to position the ball. The foregoing considerations are not exhaustive. Note that with respect to item (4), ball/CV designs consistent with this disclosure will direct torque to transfer through the ball, and so the shaft radius at which to position the ball becomes of interest.

[0018] It is therefore a technical advantage of the disclosed transmission to be capable of transferring high torque loads while discouraging wear on the interfacing components. Ball/CV designs consistent with this disclosure remain seated, engaged and in torque transfer contact through all positions of misaligned rotation in one articulated revolution.

[0019] Another technical advantage of the disclosed transmission is that the geometry allows full mechanical advantage in the torque transfer angle through the ball and TTE. As noted above, a ball is interposed between a shaft wing and the TTE. The extra degree of freedom given to TTE to rotate about the surface of the ball during articulation allows the torque vector to be transferred accurately through the interfacing components. This reduces wear and optimizes torque transfer.

[0020] In some embodiments, TTE designs consistent with this disclosure may use a larger ball. A larger ball can be advantageous to increase interface surface area to reduce contact stresses. Wear may thus be reduced in such larger ball embodiments, and particularly wear manifesting itself as cracking, galling or fretting.

[0021] According to a first aspect, therefore, this disclosure describes embodiments of an articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate; a plurality of knuckle recesses, each knuckle recess formed in a corresponding knuckle wing extending radially from the knuckle centerline; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; a plurality of torque transfer elements (TTEs), each TTE providing a TTE recess and a TTE bearing surface; and a plurality of balls; wherein each shaft cavity receptacle provides a shaft cavity bearing surface; wherein a knuckle wing, a TTE, and a ball are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the ball is received into the knuckle recess and the TTE recess, and the TTE bearing surface opposes the shaft cavity bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the TTE bearing surfaces are free to slidably displace against corresponding shaft cavity bearing surfaces; (2) the knuckle recesses restrain the balls from movement in at least a radial direction with respect to the knuckle centerline; and (3) the TTEs are free to tilt about the balls.

[0022] The first aspect includes embodiments in which the TTEs float at least generally radially with respect to the shaft centerline when the TTE bearing surfaces slidably displace against corresponding shaft cavity bearing surfaces.

[0023] The first aspect further includes embodiments in which each knuckle wing further provides a knuckle bearing surface and a knuckle backlash surface such that each knuckle bearing surface opposes a knuckle backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle backlash surface and shaft cavity backlash surface.

[0024] The first aspect further includes embodiments in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.

[0025] The first aspect further includes embodiments in which the backlash energizer assembly includes a puck. In some embodiments, the puck includes a laminate of metal and elastomer layers.

[0026] The first aspect further includes embodiments in which at least one knuckle wing further includes a knuckle release channel, and in which knuckle release channels extend knuckle recesses such that balls may float within knuckle release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.

[0027] The first aspect further includes embodiments in which at least one TTE further includes a TTE release channel, and in which TTE release channels extend TTE recesses such that balls may float within TTE release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.

[0028] The first aspect further includes embodiments in which at least one TTE comprises a TTE bearing cup contacting a TTE Belleville washer, such that the TTE bearing cup acts as the TTE recess and the TTE Belleville washer acts as the TTE bearing surface.

[0029] According to a second aspect, this disclosure describes an articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate; a plurality of knuckle recesses, each knuckle recess formed in a corresponding knuckle wing extending radially from the knuckle centerline; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; and a plurality of unitary torque transfer elements (UTTEs), each UTTE providing a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE; wherein each shaft cavity receptacle provides a shaft cavity bearing surface; wherein a knuckle wing and a UTTE are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the UTTE spherical surface is received into the knuckle recess, and the UTTE bearing surface opposes the shaft cavity bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the UTTE bearing surfaces are free to slidably displace against corresponding shaft cavity bearing surfaces; (2) the knuckle recesses restrain the UTTEs from movement in at least a radial direction with respect to the knuckle centerline; and (3) the UTTEs are free to tilt within the knuckle recesses.

[0030] The second aspect includes embodiments in which the UTTEs float at least generally radially with respect to the shaft centerline when the UTTE bearing surfaces slidably displace against corresponding shaft cavity bearing surfaces.

[0031] The second aspect further includes embodiments in which each knuckle wing further provides a knuckle bearing surface and a knuckle backlash surface such that each knuckle bearing surface opposes a knuckle backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle backlash surface and shaft cavity backlash surface.

[0032] The second aspect further includes embodiments in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.

[0033] The second aspect further includes embodiments in which the backlash energizer assembly includes a puck. In some embodiments, the puck includes a laminate of metal and elastomer layers.

[0034] The second aspect further includes embodiments in which at least one knuckle wing further includes a knuckle release channel, and in which knuckle release channels extend knuckle recesses such that UTTE spherical surfaces may float within knuckle release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.

[0035] According to a third aspect, this disclosure describes an articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate, the knuckle head providing a plurality of knuckle wings, each knuckle wing extending radially from the knuckle centerline and providing a knuckle wing bearing surface thereon; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; a plurality of torque transfer elements (TTEs), each TTE providing a TTE recess and a TTE bearing surface; and a plurality of balls; wherein each shaft cavity receptacle provides a shaft cavity bearing surface with a shaft cavity recess formed therein; wherein a knuckle wing, a TTE, and a ball are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the ball is received into the shaft cavity recess and the TTE recess, and the TTE bearing surface opposes the knuckle wing bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the TTE bearing surfaces are free to slidably displace against corresponding knuckle wing bearing surfaces; (2) the shaft cavity recesses restrain the balls from movement in at least a radial direction with respect to the knuckle centerline; and (3) the TTEs are free to tilt about the balls.

[0036] The third aspect includes embodiments in which the TTEs float at least generally radially with respect to the shaft centerline when the TTE bearing surfaces slidably displace against corresponding knuckle wing bearing surfaces.

[0037] The third aspect further includes embodiments in which each knuckle wing further provides a knuckle wing backlash surface such that each knuckle wing bearing surface opposes a knuckle wing backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle wing backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle wing backlash surface and shaft cavity backlash surface.

[0038] The third aspect further includes embodiments in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.

[0039] The third aspect further includes embodiments in which the backlash energizer assembly includes a puck. In some embodiments, the puck includes a laminate of metal and elastomer layers.

[0040] The third aspect further includes embodiments in which at least one TTE comprises a TTE bearing cup contacting a TTE Belleville washer, such that the TTE bearing cup acts as the TTE recess and the TTE Belleville washer acts as the TTE bearing surface.

[0041] According to a fourth aspect, this disclosure describes an articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate, the knuckle head providing a plurality of knuckle wings, each knuckle wing extending radially from the knuckle centerline and providing a knuckle wing bearing surface thereon; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; and a plurality of unitary torque transfer elements (UTTEs), each UTTE providing a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE; wherein each shaft cavity receptacle provides a shaft cavity bearing surface with a shaft cavity recess formed therein; wherein a knuckle wing and a UTTE are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the UTTE spherical surface is received into the shaft cavity recess and the UTTE bearing surface opposes the knuckle wing bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the UTTE bearing surfaces are free to slidably displace against corresponding knuckle wing bearing surfaces; (2) the shaft cavity recesses restrain the UTTEs from movement in at least a

radial direction with respect to the knuckle centerline; and (3) the UTTEs are free to tilt within the shaft cavity recesses.
[0042] The fourth aspect includes embodiments in which the UTTEs float at least generally radially with respect to the shaft centerline when the UTTE bearing surfaces slidably displace against corresponding knuckle wing bearing surfaces.
[0043] The fourth aspect further includes embodiments in which each knuckle wing further provides a knuckle wing backlash surface such that each knuckle wing bearing surface opposes a knuckle wing backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle wing backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle wing backlash surface and shaft cavity backlash surface.
[0044] The foregoing has rather broadly outlined some features and technical advantages of the disclosed transmission designs, in order that the following detailed description may be better understood. Additional features and advantages of the disclosed technology may be described further below. It should be appreciated by those skilled in the art that the conception and the specific embodiments disclosed may be readily utilized as a basis for modifying or designing other structures for carrying out the same inventive purposes of the disclosed technology, and that these equivalent constructions do not depart from the spirit and scope of the technology as described.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
[0045] For a more complete understanding of the embodiments described in this disclosure, and their advantages, reference is made to the following detailed description taken in conjunction with the accompanying drawings, in which:
[0046] FIG. **1** is a simplified schematic illustrating articulated deflection in a prior art transmission;
[0047] FIG. **1**A is a section as shown on FIG. **1**;
[0048] FIG. **1**B is a section as also shown on FIG. **1**;
[0049] FIG. **2** is a simplified schematic illustrating articulated deflection in one embodiment of the transmission technology described in this disclosure;
[0050] FIG. **2**A is a section as shown on FIG. **2**;
[0051] FIG. **2**B is a section as also shown on FIG. **2**;
[0052] FIG. **3**A is partial cutaway and exploded view of a first transmission design according to this disclosure;
[0053] FIG. **3**B is a perspective view of lower housing **205**L on FIG. **3**A in isolation;
[0054] FIG. **3**C is a section as shown on FIG. **3**B;
[0055] FIG. **4**A is a section as shown on FIG. **3**A, and FIG. **4**B is a section as shown on **4**A;
[0056] FIG. **4**C depicts an alternative transmission embodiment including unitary TTEs **315** similar to those depicted on FIGS. **5**H and **5**I, and FIG. **4**D is a section as shown on FIG. **4**C;
[0057] FIG. **5**A illustrates TTE assembly **300**A, which for reference is the same TTE embodiment as TTE assembly **300** depicted on FIGS. **3**A and **6**;
[0058] FIGS. **5**B through **5**G illustrate TTE assemblies **300**B through **300**G respectively (in which TTE assemblies **300**B through **300**G are alternative embodiments to TTE assembly **300**A on FIG. **5**A);
[0059] FIG. **5**H illustrates unitary TTE **315** as an alternative embodiment to TTE assembly **300**A on FIG. **5**A;
[0060] FIG. **5**I is a section as shown on FIG. **5**H;
[0061] FIG. **5**J illustrates spheroidal TTE **316** as a further alternative embodiment to TTE assembly **300**A on FIG. **5**A;

[0062] FIG. **5**K is a section as shown on FIG. **5**J;
[0063] FIG. **6** is a fully exploded view of the transmission embodiment shown on FIG. **3**A;
[0064] FIGS. **7**A and **7**B are “faux section” views of shaft assembly **100** substantially assembled at lower housing assembly **200**L per FIGS. **3**A, **4**A and **4**B, in which FIGS. **7**A and **7**B combine to schematically depict articulation during misaligned rotation;
[0065] FIG. **8**A is a section similar to FIG. **4**A, except depicting Bellville TTE assembly **330** as a further alternative embodiment to TTE assembly **300** as shown on FIGS. **3**A and **6**, for example;
[0066] FIG. **8**B is an exploded view of Belleville TTE assembly **330** from FIG. **8**A in isolation;
[0067] FIG. **9**A is a section similar to FIG. **4**A, except depicting an alternative embodiment including backlash energizer assembly **400**;
[0068] FIG. **9**B is an exploded view of backlash energizer assembly **400** from FIG. **9**A in isolation;
[0069] FIGS. **9**C and **9**D, FIGS. **9**E and **9**F, and FIGS. **9**G and **9**H are matched pairs of cutaway section views and corresponding exploded isolation views of alternative backlash energizer embodiments;
[0070] FIG. **10**A is a section as shown on FIG. **10**B, and FIG. **10**B illustrates an alternative embodiment of shaft head **102** in which shaft release channels **107** are provided in shaft wings **106**A;
[0071] FIG. **10**C is a section as shown on FIG. **10**D, and FIG. **10**D illustrates a further alternative TTE embodiment in which TTE release channel **311** is provided in TTE embodiment **310**Y;
[0072] FIG. **11** is a section similar to FIG. **4**A, except depicting an alternative “angled” TTE embodiment **310**Z bearing upon corresponding “angled” housing bearing surface **203**X;
[0073] FIG. **12**A depicts an alternative transmission embodiment “reversed” from the embodiment shown on FIG. **4**A, and FIG. **12**B is a section as shown on FIG. **12**A;
[0074] FIG. **12**C depicts an alternative transmission embodiment “reversed” from the embodiment shown on FIG. **4**C, and FIG. **12**D is a section as shown on FIG. **12**C;
[0075] FIG. **13**A is partial cutaway and exploded view of a “knuckle-style” transmission design according to this disclosure;
[0076] FIG. **13**B is a perspective view of lower housing **2205**L on FIG. **13**A in isolation;
[0077] FIG. **13**C is a section as shown on FIG. **13**B;
[0078] FIG. **14**A is a section as shown on FIG. **13**A;
[0079] FIG. **14**B is a section as shown on FIG. **14**A;
[0080] FIG. **15** is a fully exploded view of the transmission embodiment shown on FIG. **13**A;
[0081] FIG. **16**A is a section similar to FIG. **14**A, except depicting Bellville TTE assembly **2330** as a further alternative embodiment to TTE assembly **2300** as shown on FIGS. **13**A and **15**, for example;
[0082] FIG. **16**B is an exploded view of Belleville TTE assembly **2330** from FIG. **16**A in isolation;
[0083] FIG. **17**A is a section as shown on FIG. **17**B;
[0084] FIG. **17**B illustrates an alternative embodiment of shaft head **2102** in which shaft release channels **2107** are provided in shaft wings **2106**A;
[0085] FIG. **17**C is a section as shown on FIG. **17**D; and
[0086] FIG. **17**D illustrates a further alternative TTE embodiment in which TTE release channel **2311** is provided in TTE embodiment **2310**Y.

DETAILED DESCRIPTION

[0087] The following description of embodiments provides non-limiting representative examples using Figures, diagrams, schematics, flow charts, etc. with part numbers and other notation to describe features and teachings of different aspects of the disclosed technology in more detail. The embodiments described should be recognized as capable of implementation separately, or in combination, with other embodiments from the description of the embodiments. A person of ordinary skill in the art reviewing the description of embodiments will be capable of learning and understanding the different described aspects of the technology. The description of embodiments should facilitate understanding of the technology to such an extent that other implementations and embodiments, although not specifically covered but within the understanding of a person of skill in the art having read the description of embodiments, would be understood to be consistent with an application of the disclosed technology.

[0088] Reference is now made to FIGS. **3**A through **17**D in describing embodiments of the disclosed transmission. For the purposes of the following disclosure: (1) FIGS. **3**A through **11** should be viewed together as illustrating embodiments of a first transmission design described herein; (2) FIGS. **12**A through **12**D should be viewed together as illustrating embodiments of a second ("reverse") transmission design described herein; and (3) FIGS. **13**A through **17**D should be viewed together as illustrating embodiments of a third ("knuckle-style") transmission design described herein. Any part, item, or feature that is identified by part number on one of FIGS. **3**A through **17**D will have the same part number when illustrated on another of FIGS. **3**A through **17**D. It will be understood that the embodiments as illustrated and described with respect to FIGS. **3**A through **17**D are exemplary, and the scope of the inventive material set forth in this disclosure is not limited to such illustrated and described embodiments.

[0089] FIG. **3**A is partial cutaway and exploded view of an embodiment of a first transmission design according to this disclosure. FIG. **6** is a fully exploded view of the transmission embodiment shown on FIG. **3**A. Generally on FIGS. **3**A and **6**, torque is shown transmitted from upper housing assembly **200**U into shaft assembly **100**, and then into lower housing assembly **200**L. A general convention is followed throughout the embodiments illustrated on FIGS. **3**A through **11**, in which clockwise torque is transmitted from an illustrated "high side" (see notation near upper housing assembly **200**U on FIGS. **3**A and **6**) to an illustrated "low side" (see notation near lower housing assembly **200**L). This convention follows the generally accepted subterranean drilling convention of "clockwise rotation looking downhole". In particular, this convention follows the general convention of configuring the rotor of a positive displacement motor ("PDM" or "mud motor") to rotate in a clockwise direction looking downhole.

[0090] It will be understood, however, that the scope of this disclosure is not limited to embodiments following the "clockwise looking downhole" convention for rotation and torque. Alternative embodiments, not illustrated, configured to transmit counterclockwise torque looking downhole are within the scope of this disclosure. Persons of ordinary skill in this art will require very little experimentation to adapt the embodiments illustrated on FIGS. **3**A through **11** of this disclosure to transfer torque in the opposite direction from the direction illustrated. In many cases, it will require no more than reversing orientations of illustrated components or creating "mirror images" of illustrated assemblies.

Torque Transfer

[0091] FIGS. **3**A and **6** should be viewed together for a more detailed understanding of torque transmission from upper housing assembly **200**U into shaft assembly **100**, and then into lower housing assembly **200**L, all according to a first illustrated transmission embodiment. Upper housing assembly **200**U includes upper housing **205**U, which in turn includes upper pin threads **201**U provided on one end thereof. Upper threads **201**U are preferably configured to mate with an adapter ultimately connected rotatably to a PDM rotor, although the scope of this disclosure is not limited any particular component with which upper threads **201**U may be configured to mate. Torque rotation direction R on FIGS. **3**A and **6** illustrates clockwise rotation of upper housing assembly **200**U looking downhole, consistent with the corresponding general convention of configuring a PDM rotor to rotate clockwise looking downhole, as described above.

[0092] Lower housing assembly **200**L includes lower housing **205**L, which in turn includes lower pin threads **201**L provided on one end thereof. Lower threads **201**L are preferably configured to mate with a motor bearing mandrel or drive shaft ultimately connected to a rotary bit, although the scope of this disclosure is not limited any particular component with which lower threads **201**L may be configured to mate. Torque rotation direction R on FIGS. **3**A and **6** further illustrates clockwise rotation of lower housing assembly **200**L looking downhole, consistent with the corresponding general convention of configuring a PDM rotor to rotate clockwise looking downhole, as described above.

[0093] FIGS. **3**A and **6** show upper and lower housings **205**U, **205**L as hollow, with internal receptacles and surfaces formed therein according to Figures and detailed description set forth below. FIGS. **3**A and **6** further show that shaft assembly **100** provides a shaft head **102** at each end of shaft **101**. As will be described in more detail further below, each shaft head **102** is configured to be received into a corresponding one of upper and lower housings **205**U, **205**L and, when received therein, to interface with receptacles and surfaces formed internally on upper and lower housings **205**U, **205**L. As seen on FIGS. **3**A and **6**, each shaft head **102** provides a preselected number of shaft wings **106**. Shaft wings **106** are preferably spaced equally in radial disposition around shaft head **102**, although the scope of this disclosure is not limited to equi-spaced radial disposition. Five (5) shaft wings **106** are provided on each shaft head **102** in the embodiments illustrated on FIGS. **3**A through **11**, although again the scope of this disclosure is not limited to any particular number of shaft wings **106** per shaft head **102**. Other embodiments (not illustrated) may provide shaft heads with other numbers of shaft wings, and/or with other than equi-spaced radial disposition. Other embodiments (not illustrated) may also provide a number and spacing configuration of shaft wings on a shaft head at one end of a shaft that differs from the number and spacing configuration of shaft wings at the other end of the shaft.

[0094] FIG. **6** illustrates each shaft wing **106** providing a shaft bearing surface **104** and a shaft backlash surface **105**. The shaft bearing surface **104** on one shaft wing **106** generally faces the shaft backlash surface **105** of a neighboring shaft wing **106**. FIGS. **3**A and **6** further depict each shaft bearing surface **104** providing a shaft recess **103** formed therein.

[0095] FIGS. **3**A and **6** further illustrate Torque Transfer Element (“TTE”) assemblies **300** interposed between shaft wings **106** and upper and lower housings **205**U, **205**L when shaft heads **102** are received into upper and lower housings **205**U, **205**L. TTE assemblies **300** each include TTE **310** and ball **320** in the embodiments illustrated on FIGS. **3**A and **6**. As shown on FIG. **3**A, balls **320** are received into shaft recesses **103** in shaft wings **106**. Preferably, one (1) TTE assembly **300** is provided for each shaft wing **106**, as depicted in the embodiments illustrated throughout FIGS. **3**A through **11** in this disclosure. It will nonetheless be appreciated that the scope of this disclosure is not limited in this regard, and other embodiments may provide some shaft wings without TTE assemblies.

[0096] Currently preferred embodiments further provide shaft webs **108**, as illustrated on FIGS. **3**A and **6**. In such currently preferred embodiments, shaft webs **108** connect shaft bearing surfaces **104** (on shaft wings **106**) and shaft backlash surfaces **105**. In such embodiments, shaft webs **108** thus combine to provide a circumferential “flange” connecting shaft wings **106**. This additional “flange” material strengthens shaft head **102** during torque transfer (and especially during articulation), and further provides a “pocket” for each TTE assembly **300** to assist with keeping TTE assemblies **300** from becoming contact-disengaged during articulation.

[0097] It will be nonetheless appreciated that the scope of this disclosure is not limited to embodiments providing shaft webs **108**. Referring momentarily to FIGS. **7**A and **7**B and imagining such views without shaft webs **108**, other embodiments (not illustrated herein) may provide near shaft distance A1 still greater than far shaft diameter A2 without the circumferential “flange” material described in the preceding paragraph. In yet further embodiments, again not illustrated herein, near shaft diameter A1 and far shaft diameter A2 as designated on FIGS. **7**A and **7**B may be substantially the same, with slots provided to retain torque-transferring balls (such as seen in some conventional designs).

[0098] FIGS. **3**A and **6** further illustrate boots **210**U/L, boot retaining rings **211**U/L and split rings **212**U/L to seal the connection between shaft **101** and upper and lower housings **205**U, **205**L at either end of shaft **101**. Boots **210**U/L are preferably made of a rubber or elastomer material in order to provide seals while at the same time permitting independent articulation between shaft **101** and upper housing **205**U at one end of shaft **101**, and between shaft **101** and lower housing **205**L at the other end of shaft **101**.

[0099] From this point forward with reference to embodiments illustrated in FIGS. **3**A and **6**, the Figures and associated disclosure will describe features, aspects and alternative embodiments with reference to assemblies at the "low side" as drawn on FIGS. **3**A and **6**. That is, the Figures and associated disclosure will describe features, aspects and alternative embodiments in and around and associated with lower housing assembly **200**L as depicted on FIGS. **3**A and **6**. Persons of ordinary skill in this art will require very little experimentation to reverse the orientation of embodiments illustrated with reference to the "low side" on FIGS. **3**A and **6** in order to understand corresponding assemblies and features on the "high side".

[0100] FIG. **3**B is a perspective view of lower housing **205**L on FIG. **3**A in isolation. FIG. **3**C is a section as shown on FIG. **3**B. FIG. **3**C shows housing receptacles **207** provided in lower housing **205**L. With momentary reference to FIGS. **3**A and **6**, it will be appreciated that lower housing **205**L provides one (1) housing receptacle **207** each for receiving a corresponding shaft wing **106** on shaft head **102**. Thus, five (5) housing receptacles **207** are illustrated on FIG. **3**C, one each for receiving a corresponding one of the five (5) shaft wings **106** shown on FIG. **6**.

[0101] FIG. **3**C further illustrates that each housing receptacle **207** provides a housing bearing surface **203** and a housing backlash surface **202**. FIG. **3**B illustrates housing bearing surfaces **203** and housing backlash surfaces **202** in perspective view.

[0102] FIGS. **3**B and **3**C further illustrate optional hard facing **209** inside lower housing **205**L. In embodiments where provided, hard facing **209** assists reducing thrust wear between shaft head **102** and lower housing **205**L during articulated/misaligned rotation of shaft head **102** as received in/connected to lower housing **205**L. It will be understood that hard facing **209** may optionally also be provided in upper housing **205**U. In other non-illustrated embodiments, a thrust bearing may be provided instead of hard facing **209**.

[0103] FIG. **4**A is a section as shown on FIG. **3**A. FIG. **4**B is a section as shown on FIG. **4**A. FIGS. **4**A and **4**B show shaft wings **106** engaged with balls **320** and TTEs **310** in housing receptacles **207**. FIG. **4**B shows TTE recesses **301** formed in TTEs **310** for receiving balls **320**. FIG. **4**A illustrates torque transfer in a clockwise direction in the following sequence (A) through (C): (A) from shaft wings **106** on shaft head **102** into balls **320**; (B) through balls **320** and into TTEs **310**; and then (C) through TTEs **310** and into lower housing **205**L via housing bearing surfaces **203**. Such clockwise torque transfer on FIG. **4**A is consistent with clockwise rotation direction R as shown on FIG. **4**A. FIGS. **4**A and **4**B further illustrate that during such clockwise torque transfer, TTE bearing surfaces **302** bear upon housing bearing surfaces **203**. FIG. **4**B also shows that during such clockwise torque transfer, shaft recesses **103** formed in shaft bearing surfaces **104** bear upon balls **320**, and balls **320** bear upon TTE recesses **301**.

[0104] With reference now to FIG. **6**, it will be understood that an opposite transfer sequence enables clockwise torque transfer at upper housing assembly **200**U, in which torque is transferred in the following sequence (A) to (C): (A) from upper housing **205**U into TTEs **310**; (B) through TTEs **310** and into balls **320**; and then (C) through balls **320** and into shaft wings **106** on shaft head **102**. This opposite sequence is like imagining torque transfer on FIG. **4**A in the opposite direction (counterclockwise) to rotation direction R as illustrated on FIG. **4**A.

[0105] FIGS. **7**A and **7**B are "faux section" views of shaft assembly **100** substantially assembled at lower housing assembly **200**L per FIGS. **3**A, **4**A and **4**B, in which FIGS. **7**A and **7**B combine to schematically depict articulation during misaligned rotation. By "faux section" views, it will be understood from FIGS. **4**A and **6** that since the illustrated embodiments depict five (5) shaft wings **106** and associated TTE balls **320** distributed evenly around the periphery of shaft head **102**, a true straight line section through the assembly of shaft assembly **100** at lower housing assembly **200**L does not allow opposing shaft wings **106** to be seen on one view. Thus, FIGS. **7**A and **7**B depict more of a “pie-shaped” or “offset” section through the assembly of shaft assembly **100** at lower housing assembly **200**L, so that opposing shaft wings **106** can be seen on each of FIGS. **7**A and **7**B.

[0106] FIG. **7**A illustrates shaft assembly **100** substantially assembled at lower housing assembly **200**L without shaft misalignment. FIG. **7**B illustrates shaft assembly **100** substantially assembled at lower housing assembly **200**L with shaft misalignment as seen during articulation. Referring now to FIG. **3**A, TTE balls **320** are retained in shaft recesses **103** in shaft wings **106**. Thus, comparing FIG. **7**A to FIG. **7**B, it will be seen that TTE balls **320** retain their relative position with respect to shaft wings **106** during articulation, even as shaft wings **106** displace with respect to lower housing **205**L.

[0107] Now referring to FIGS. **4**A and **4**B, it will be further seen that TTEs **310** are given space within housing receptacles **207** to permit sliding displacement of TTEs during articulation. (Refer to FIGS. **3**B and **3**C for additional detail on housing receptacles **207**). Responsive to rotation and tilt of TTEs **310** around balls **320**, such sliding displacement of TTEs **310** further enables TTE bearing surfaces **302** and housing bearing surfaces **203** to remain in contact throughout articulation.

[0108] As a result, torque transfer occurs through all shaft wings **106** and corresponding TTE assemblies **300** around the periphery of shaft head **102** during articulation, regardless of the change of angular deflection experienced by a particular shaft wing/TTE assembly during one articulated revolution. This arrangement in turn enables smooth torque transfer, keeping torque transfer force directions normal to the direction of rotation and keeping TTE assemblies **300** stable and contact-engaged against shaft wings **106** within housing receptacles **207** throughout a complete articulated revolution. Point loads are avoided. This arrangement further limits stress and wear on the shaft wing/TTE assembly units by ensuring that all units remain contact-engaged and participate in torque transfer throughout a complete articulated revolution. Situations are avoided in which torque might be transferred through perhaps only one or two shaft wing/TTE assembly units at any moment in time because articulation has caused the other units to become contact-disengaged.

[0109] Although the foregoing torque transfer description has been made with reference to lower housing **205**L on FIGS. **3**A, **4**A, **4**B, **6**, **7**A and **7**B, it will be understood that such description applies equally at upper housing **205**U shown on FIGS. **3**A and **6**.

[0110] The foregoing description of torque transfer has been made with reference to embodiments in which ball **320** is interposed between and received in TTE recess **301** and shaft recess **103**. It will be nonetheless appreciated that, consistent with the broader scope of this disclosure, alternative embodiments may provide TTE **310** reversed within housing receptacle **207**, such that ball **320** is interposed between and received in TTE recess **301** and a new recess provided in housing bearing surface **203**. In such “reverse” embodiments, shaft bearing surface **104** may be plain (without shaft recess **103** formed therein) and disposed to contact TTE bearing surface **302** during torque transfer. FIGS. **12**A through **12**D illustrate an example of such a “reverse” embodiment. FIG. **12**A depicts an alternative transmission embodiment “reversed” from the embodiment shown on FIG. **4**A. FIG. **12**B is a section as shown on FIG. **12**A. FIGS. **12**A and **12**B show modified shaft wings **1106** engaged with TTEs **310** and balls **320** in modified housing receptacles **1207**. FIG. **12**B shows TTE recesses **301** formed in TTEs **310** for receiving balls **320**. FIG. **12**A illustrates torque transfer in a clockwise direction in the following sequence (A) through (C): (A) from modified shaft wings **1106** on modified shaft head **1102** into TTEs **310** via shaft bearing surfaces **1104**; (B) through TTEs **310** and into balls **320**; and then (C) through balls **320** and into modified lower housing **1205**L via housing recesses **1203** in modified lower housing **1205**L. Such clockwise torque transfer on FIG. **12**A is consistent with clockwise rotation direction R as shown on FIG. **12**A. FIGS. **12**A and **12**B further illustrate that during such clockwise torque transfer, shaft bearing surfaces **1104** bear upon TTE bearing surfaces **302**. FIG. **12**B also shows that during such clockwise torque transfer, TTE recesses **301** bear upon balls **320**, and balls **320** bear upon housing recesses **1203** formed in modified lower housings. Such “reverse” embodiments may provide a trade-off for advantages and disadvantages and may be suitable in appropriate deployments. As a potential advantage, shaft recess **103** shown on FIGS. **4**A and **4**B is obviated on modified shaft wing **1106** shown on FIGS. **12**A and **12**B, allowing modified shaft wing **1106** to be made thicker and thus stronger. Conversely, however, depending on geometry of a particular design, TTE **310** may have less freedom to float within modified housing receptacle **1207** in the "reverse" design of FIGS. **12**A and **12**B. FIGS. **12**C and **12**D illustrate a further example of "reversed" embodiments. FIG. **12**C depicts an alternative transmission embodiment "reversed" from the embodiment shown on FIG. **4**C. FIG. **12**D is a section as shown on FIG. **12**C.

[0111] FIGS. **12**C and **12**D are discussed in more detail further below under "Alternative TTE embodiments". The embodiments illustrated on FIGS. **12**C and **12**D are related to FIGS. **12**A and **12**B, however, in that UTTEs **315** on FIGS. **12**C and **12**D substitute for balls **320** and TTEs **310** on FIGS. **12**A and **12**B. UTTEs **315** are described in more detail below with reference to FIGS. **5**H and **5**I.

[0112] The foregoing description of torque transfer has been made with reference to (1) embodiments according to a first aspect in which ball **320** is interposed between and received in TTE recess **301** and shaft recess **103**; and (2) "reverse" embodiments according to a second aspect in which TTE **310** is reversed within housing receptacle **207**, such that ball **320** is interposed between and received in TTE recess **301** and a new recess provided in housing bearing surface **203**. Alternative "knuckle-style" embodiments will now be described in which, consistent with the broader scope of this disclosure, a knuckle assembly at each end provides a corresponding upper and lower knuckle for receiving TTEs.

[0113] FIG. **13**A is partial cutaway and exploded view of an embodiment of a "knuckle" transmission design according to this disclosure. FIG. **15** is a fully exploded view of the transmission embodiment shown on FIG. **13**A. Generally on FIGS. **13**A and **15**, torque is shown transmitted from upper knuckle assembly **2600**U into shaft assembly **2500**, and then into lower knuckle assembly **2600**L. As with other aspects and embodiments described in this disclosure, a general convention is followed throughout the embodiments illustrated on FIGS. **13**A through **17**D, in which clockwise torque is transmitted from an illustrated "high side" (see notation near upper knuckle assembly **2600**U on FIGS. **13**A and **15**) to an illustrated "low side" (see notation near lower knuckle assembly **2600**L). This convention follows the generally accepted subterranean drilling convention of "clockwise rotation looking downhole". In particular, this convention follows the general convention of configuring the rotor of a positive displacement motor ("PDM" or "mud motor") to rotate in a clockwise direction looking downhole.

[0114] It will be understood, however, that the scope of this disclosure is not limited to embodiments following the "clockwise looking downhole" convention for rotation and torque. Alternative embodiments, not illustrated, configured to transmit counterclockwise torque looking downhole are within the scope of this disclosure. Persons of ordinary skill in this art will require very little experimentation to adapt the embodiments illustrated on FIGS. **13**A through **17**D of this disclosure to transfer torque in the opposite direction from the direction illustrated. In many cases, it will require no more than reversing orientations of illustrated components or creating "mirror images" of illustrated assemblies.

[0115] FIGS. **13**A and **15** should be viewed together for a more detailed understanding of torque transmission from upper knuckle assembly **2600**U into shaft assembly **2500**, and then into lower knuckle assembly **2600**L, all according to a knuckle transmission design as illustrated. Upper knuckle assembly **2600**U includes upper knuckle **2605**U, which in turn includes upper pin threads **2601**U provided on one end thereof. Upper pin threads **2601**U are preferably configured to mate with an adapter ultimately connected rotatably to a PDM rotor, although the scope of this disclosure is not limited any particular component with which upper pin threads **2501**U may be configured to mate. Torque rotation direction R on FIGS. **13**A and **15** illustrates clockwise rotation of upper knuckle assembly **2600**U looking downhole, consistent with the corresponding general convention of configuring a PDM rotor to rotate clockwise looking downhole, as described above.

[0116] Lower knuckle assembly **2600**L includes lower knuckle **2605**L, which in turn includes lower pin threads **2601**L provided on one end thereof. Lower pin threads **2601**L are preferably configured to mate with a motor bearing mandrel or drive shaft ultimately connected to a rotary bit, although the scope of this disclosure is not limited any particular component with which lower pin threads **2601**L may be configured to mate. Torque rotation direction R on FIGS. **13**A and **15** further illustrates clockwise rotation of lower knuckle assembly **2600**L looking downhole, consistent with the corresponding general convention of configuring a PDM rotor to rotate clockwise looking downhole, as described above.

[0117] FIGS. **13**A and **15** further show that shaft assembly **2500** provides upper and lower shaft cavities **2502**U, **2502**L at upper and lower ends of shaft **2501** respectively, in which upper and lower shaft cavities **2502**U, **2502**L are depicted as hollow, with internal receptacles and surfaces formed therein according to Figures and detailed description set forth below. FIGS. **13**A and **15** further show that each knuckle assembly **2600**U, **2600**L provides a corresponding upper and lower knuckle **2605**U, **2605**L. Each upper and lower knuckle **2605**U, **2605**L in turn provides a knuckle head **2602**. As will be described in more detail further below, each knuckle head **2602** is configured to be received into a corresponding one of upper and lower shaft cavities **2502**U, **2502**L and, when received therein, to interface with receptacles and surfaces formed internally on upper and lower shaft cavities **2502**U, **2502**L. As seen on FIGS. **13**A and **15**, each knuckle head **2602** provides a preselected number of knuckle wings **2606**. Knuckle wings **2606** are preferably spaced equally in radial disposition around knuckle head **2602**, although the scope of this disclosure is not limited to equi-spaced radial disposition. Five (5) knuckle wings **2606** are provided on each knuckle head **2602** in the embodiments illustrated on FIGS. **13**A through **17**D, although again the scope of this disclosure is not limited to any particular number of knuckle wings **2606** per knuckle head **2602**. Other embodiments (not illustrated) may provide knuckle heads with other numbers of knuckle wings, and/or with other than equi-spaced radial disposition. Other embodiments (not illustrated) may also provide a number and spacing configuration of knuckle wings on a knuckle head disposed at one end of shaft **2500** that differs from the number and spacing configuration of knuckle wings on a knuckle head disposed at the other end of shaft **2500**.

[0118] FIG. **15** illustrates each knuckle wing **2606** providing a knuckle bearing surface **2604** and a knuckle backlash surface **2609**. The knuckle bearing surface **2604** on one knuckle wing **2606** generally faces the knuckle backlash surface **2609** of a neighboring knuckle wing **2606**. FIGS. **13**A and **15** further depict each knuckle bearing surface **2604** providing a knuckle recess **2603** formed therein.

[0119] FIGS. **13**A and **15** further illustrate Torque Transfer Element ("TTE") assemblies **300** interposed between knuckle wings **2606** and upper and lower shaft cavities **2502**U, **2502**L when knuckle heads **2602** are received into upper and lower shaft cavities **2502**U, **2502**L. TTE assemblies **300** each include TTE **310** and ball **320** in the embodiments illustrated on FIGS. **13**A and **15**. As shown on FIG. **13**A, balls **320** are received into knuckle recesses **2603** in knuckle wings **2606**. Preferably, one (1) TTE assembly **300** is provided for each knuckle wing **2606**, as depicted in the embodiments illustrated throughout FIGS. **13**A through **17**D in this disclosure. It will nonetheless be appreciated that the scope of this disclosure is not limited in this regard, and other embodiments may provide some knuckle wings without TTE assemblies.

[0120] Illustrated embodiments on FIGS. **13**A and **15** provide knuckle webs **2608**. In such illustrated embodiments, knuckle webs **2608** connect knuckle bearing surfaces **2604** (on knuckle wings **2606**) and knuckle backlash surfaces **2609**. In such embodiments, knuckle webs **2608** thus combine to provide a circumferential "flange" connecting knuckle wings **2606**. This additional "flange" material strengthens knuckle head **2602** during torque transfer (and especially during articulation), and further provides a "pocket" for each TTE assembly **300** to assist with keeping TTE assemblies **300** from becoming contact-disengaged during articulation. It will be nonetheless appreciated that the scope of this disclosure is not limited to embodiments providing knuckle webs

2608.

[0121] FIGS. **13**A and **15** further illustrate boots **2610**U/L, boot retaining rings **2611**U/L and split rings **2612**U/L to seal the connection between upper and lower knuckles **2605**U, **2605**L and upper and lower shaft cavities **2502**U, **2502**L respectively at either end of shaft **2501**. Boots **2610**U/L are preferably made of a rubber or elastomer material in order to provide seals while at the same time permitting independent articulation between upper knuckle **2605**U as received in upper shaft cavity **2502**U at one end of shaft **2501**, and between lower knuckle **2605**L as received in lower shaft cavity **2502**L at the other end of shaft **2501**.

[0122] From this point forward with reference to knuckle-style embodiments, the Figures and associated disclosure will describe features, aspects and alternative embodiments with reference to assemblies at the “low side” as drawn on FIGS. **13**A and **15**. That is, the Figures and associated disclosure will describe features, aspects and alternative embodiments in and around and associated with lower knuckle assembly **2600**L as depicted on FIGS. **13**A and **15**. Persons of ordinary skill in this art will require very little experimentation to reverse the orientation of embodiments illustrated with reference to the “low side” on FIGS. **13**A and **15** in order to understand corresponding assemblies and features on the “high side”.

[0123] FIG. **13**B is a perspective view of lower shaft cavity **2502**L on FIG. **13**A in isolation. FIG. **13**C is a section as shown on FIG. **13**B. FIG. **13**C shows shaft cavity receptacles **2507** provided in lower shaft cavity **2502**L. With momentary reference to FIGS. **13**A and **15**, it will be appreciated that lower shaft cavity **2502**L provides one (1) shaft cavity receptacle **2507** each for receiving a corresponding knuckle wing **2606** on knuckle head **2602**. Thus, five (5) shaft cavity receptacles **2507** are illustrated on FIG. **13**C, one each for receiving a corresponding one of the five (5) knuckle wings **2506** shown on FIG. **15**.

[0124] FIG. **13**C further illustrates that each shaft receptacle **2507** provides a shaft cavity bearing surface **2504** and a shaft cavity backlash surface **2505**. FIG. **16**B illustrates shaft cavity bearing surfaces **2504** and shaft cavity backlash surfaces **2505** in perspective view.

[0125] FIGS. **13**B and **13**C further illustrate optional hard facing **2509** inside lower shaft cavity **2502**L. In embodiments where provided, hard facing **2509** assists reducing thrust wear between knuckle head **2602** and lower shaft cavity **2502**L during articulated/misaligned rotation of knuckle head **2602** as received in/connected to lower shaft cavity **2502**L. It will be understood that hard facing **2509** may optionally also be provided in upper shaft cavity **2502**U. In other non-illustrated embodiments, a thrust bearing may be provided instead of hard facing **2509**.

[0126] FIG. **14**A is a section as shown on FIG. **13**A. FIG. **14**B is a section as shown on FIG. **14**A. FIGS. **14**A and **14**B show knuckle wings **2606** engaged with balls **320** and TTEs **310** in shaft cavity receptacles **2507**. FIG. **14**B shows TTE recesses **301** formed in TTEs **310** for receiving balls **320**. FIG. **14**A illustrates counterclockwise rotation of lower shaft cavity **2502**L according to arrow R, enabling torque transfer in a corresponding counterclockwise direction in the following sequence (A) through (C): (A) from lower shaft cavity **2502**L via shaft cavity bearing surfaces **2504** and into TTEs **310**; (B) through TTEs **310** and into balls **320**; and then (C) through balls **320** and into knuckle wings **2606**. Such counterclockwise torque transfer as illustrated on FIG. **14**A is consistent with the general “clockwise looking downhole” rotation direction R as shown on FIG. **13**A, in that FIG. **14**A is a section shown on FIG. **13**A looking back along shaft assembly **2500** in an uphole direction. FIGS. **14**A and **14**B further show that during such counterclockwise torque transfer as illustrated, TTE bearing surfaces **302** bear upon shaft cavity bearing surfaces **2504**. FIG. **14**B also shows that during such counterclockwise torque transfer as illustrated, TTE recesses **310** bear upon balls **320**, and balls **320** bear upon knuckle recesses **2603** formed in knuckle wings **2606**.

[0127] With reference now to FIG. **15**, it will be understood that an opposite transfer sequence occurs at upper knuckle assembly **2600**U to that illustrated on FIG. **14**A, in which torque is transferred in the following sequence (A) to (C): (A) from knuckle wings **2606** on upper knuckle head **2602**U and into balls **320**; (B) through balls **320** and into TTEs **310**; and then (C) through

TTEs **310** and into upper shaft cavity **2502**U. This opposite sequence is like imagining torque transfer on FIG. **14**A in the opposite direction (clockwise) to rotation direction R as illustrated on FIG. **14**A.

[0128] It will be further appreciated by persons of skill in this art that Unitary Torque Transfer Elements ("UTTEs") **315** as shown on FIG. **4**C, for example, may substitute for selected assemblies of TTEs **310** and balls **320** on FIG. **14**A. The discussion of FIGS. **4**C and **4**D above applies equally to embodiments of knuckle-style transmission designs such as shown on FIGS. **13**A and **15**.

[0129] Momentary reference should now be made to embodiments illustrated on FIGS. **3**A and **6** as described above. It will be recalled that FIGS. **7**A and **7**B are "faux section" views of shaft assembly **100** substantially assembled at lower housing assembly **200**L per FIGS. **3**A, **4**A and **4**B, in which FIGS. **7**A and **7**B combine to schematically depict articulation during misaligned rotation. The reader should refer to the description of FIGS. **7**A and **7**B above for further understanding of those Figures. It will be further understood that the principles of FIGS. **7**A and **7**B nonetheless apply to knuckle-style embodiments such as illustrated on FIGS. **13**A and **15** even though not specifically illustrated. It will be seen by imagining knuckle embodiments such as illustrated on FIGS. **13**A and **15** superposed on FIGS. **7**A and **7**B that TTE balls **320** retain their relative position with respect to knuckle wings **2606** during articulation, even as knuckle wings **2606** displace with respect to lower shaft cavity **2502**L.

[0130] Now referring to FIGS. **14**A and **14**B, it will be further seen that TTEs **310** are given space within shaft cavity receptacles **2507** to permit sliding displacement of TTEs during articulation. (Refer to FIGS. **13**B and **13**C for additional detail on shaft cavity receptacles **2507**). Responsive to rotation and tilt of TTEs **310** around balls **320**, such sliding displacement of TTEs **310** further enables TTE bearing surfaces **302** and shaft cavity bearing surfaces **2504** to remain in contact throughout articulation.

[0131] As a result, torque transfer occurs through all knuckle wings **2606** and corresponding TTE assemblies **300** around the periphery of knuckle head **2602** during articulation, regardless of the change of angular deflection experienced by a particular shaft wing/TTE assembly during one articulated revolution. This arrangement in turn enables smooth torque transfer, keeping torque transfer force directions normal to the direction of rotation and keeping TTE assemblies **300** stable and contact-engaged against knuckle wings **2606** within shaft cavity receptacles **2507** throughout a complete articulated revolution. Point loads are avoided. This arrangement further limits stress and wear on the knuckle wing/TTE assembly units by ensuring that all units remain contact-engaged and participate in torque transfer throughout a complete articulated revolution. Situations are avoided in which torque might be transferred through perhaps only one or two knuckle wing/TTE assembly units at any moment in time because articulation has caused the other units to become contact-disengaged.

[0132] The following paragraphs further describe embodiments of an articulated transmission disposed to transmit torque via misaligned rotation according to a knuckle-style transmission design. A knuckle head **2602**L on FIG. **15**, for example, has a knuckle centerline about which knuckle head **2602**L is disposed to rotate. Knuckle head **2602**L on FIG. **15** has a plurality of knuckle recesses **2603**. Each knuckle recess **2603** is formed in a corresponding knuckle wing **2606** extending radially from the knuckle centerline. FIG. **15** also illustrates a shaft **2501** having a shaft centerline about which shaft **2501** is disposed to rotate. A shaft cavity **2502**L is disposed on shaft **2501**. Shaft cavity **2502**L has a plurality of shaft cavity receptacles **2507** formed therein, such that each shaft cavity receptacle **2507** is for receiving a corresponding knuckle wing **2606**.

[0133] FIG. **15** further illustrates a plurality of torque transfer elements (TTEs) **310**. Per FIG. **14**B, each TTE **310** provides a TTE recess **301** and a TTE bearing surface **302**. FIG. **15** further illustrates a plurality of balls **320**. FIG. **13**C, for example, illustrates that each shaft cavity receptacle **2507** provides a shaft cavity bearing surface **2504**.

[0134] FIGS. **13**A, **14**B and **15** illustrate that a knuckle wing **2606**, a TTE **319**, and a ball **320** are received into each shaft cavity receptacle **2507** such that within each shaft cavity receptacle **2507**, the ball **320** is received into the knuckle recess **2603** and the TTE recess **301**, and the TTE bearing surface **302** opposes the shaft cavity bearing surface **2504**. As a result, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle **2507** during an articulated revolution of shaft **2501**: (1) the TTE bearing surfaces **302** are free to slidably displace against corresponding shaft cavity bearing surfaces **2504**; (2) the knuckle recesses **2603** restrain the balls **320** from movement in at least a radial direction with respect to the knuckle centerline; and (3) the TTEs **310** are free to tilt about the balls **320**. As a result, torque transfer contact is maintained between the knuckle recess **2603**, the ball **320**, the TTE recess **301**, the TTE bearing surface **302** and the housing bearing surface **2504** within each shaft cavity receptacle **2507** through all positions of misaligned rotation in one articulated revolution of shaft **2501**.

[0135] FIGS. **13**A, **14**B and **15** further illustrate that the TTEs **310** float at least generally radially with respect to the shaft centerline when the TTE bearing surfaces **302** slidably displace against corresponding shaft cavity bearing surfaces **2504**.

[0136] Although the foregoing torque transfer description has been made with reference to lower knuckle assembly **2600**L as received in lower shaft cavity **2502**L on FIGS. **13**A, **14**A, **14**B and **15**, it will be understood that such description applies equally at upper knuckle assembly **2600**U/upper shaft cavity **2502**U shown on FIGS. **13**A and **15**.

[0137] The foregoing description of torque transfer in knuckle-style embodiments has been made with reference to FIGS. **13**A through **15** in which ball **320** is interposed between and received in TTE recess **301** and knuckle recess **2603**. It will be nonetheless appreciated that, consistent with the broader scope of this disclosure, alternative knuckle-style embodiments may provide TTE **310** reversed within shaft cavity receptacle **2507**, such that ball **320** is interposed between and received in TTE recess **301** and a new recess provided in shaft cavity bearing surface **2504**. In such “reverse” knuckle-style embodiments, knuckle bearing surface **2604** may be plain (without knuckle recess **2603** formed therein) and disposed to contact TTE bearing surface **302** during torque transfer.

[0138] FIGS. **12**A through **12**D illustrate examples of such “reverse” knuckle-style embodiments. Note that FIGS. **12**A through **12**D are also described above as depicting a “reverse” embodiment from the embodiment shown on FIG. **4**A. However, persons of ordinary skill in this art will appreciate that the “reverse” embodiments depicted on FIGS. **12**A through **12**D also serve to illustrate “reverse” knuckle-style embodiments such as shown in FIGS. **13**A, **14**A and **14**B, for example. The components depicted on FIGS. **12**A through **12**D need only to be substituted for the corresponding components depicted on FIGS. **13**A, **14**A and **14**B. Regarding “reverse” knuckle-style embodiments with Unitary Torque Transfer Elements (UTTEs) **315** as illustrated on FIGS. **12**C and **12**D, it will be further appreciated that UTTEs **315** on FIGS. **12**C and **12**D substitute for balls **320** and TTEs **310** on FIGS. **13**A, **14**A and **14**B. UTTEs **315** are described in more detail below with reference to FIGS. **5**H and **5**I.

[0139] The foregoing description of torque transfer has been made with reference to illustrated embodiments in which two housing assemblies **200**U and **200**L (or knuckle assemblies **2600**U, **2600**L) are provided, one at each end of shaft **101** (or **2501**). The scope of this disclosure is not limited, however, to two housing assemblies on shaft **101** or **2501**. Other embodiments (not illustrated) may provide only one housing assembly on shaft **101** or **2501**, on a selected end thereof, with the other end of shaft **101** or **2501** not articulating. In such other embodiments, the scope of this disclosure is further not limited as to the selected end of shaft **101** or **2501** (upper or lower) on which the single housing assembly is to be provided.

Torque Backlash

[0140] Referring now to FIGS. **3**A and **6**, it will be understood that counterclockwise torque backlash will be created in upper and lower housing assemblies **200**U, **200**L whenever clockwise torque through shaft **101** is reduced, stopped or even reversed. Torque backlash may be momentary or sustained, responsive to corresponding changes in transmitted torque over time through shaft **101**.

[0141] FIG. **4**A illustrates that during torque backlash in lower housing assembly **200**L, clockwise torque is no longer transferred through balls **320** and TTEs **310**. Instead, counterclockwise torque backlash causes shaft backlash surface **105** to bear upon housing backlash surface **202**. Although not specifically illustrated, it will be understood that the corresponding effect occurs in upper housing assembly **200**U.

[0142] FIGS. **9**A through **9**F illustrate currently preferred embodiments of alternative backlash energizer assemblies, which, when provided, seek to remediate negative effects of torque backlash. FIG. **9**A is a section similar to FIG. **4**A, except depicting an alternative embodiment including backlash energizer assembly **400**. FIG. **9**B is an exploded view of backlash energizer assembly **400** from FIG. **9**A in isolation. FIGS. **9**C and **9**D, FIGS. **9**E and **9**F, and FIGS. **9**G and **9**H are each matched pairs of cutaway section views and corresponding exploded isolation views of alternative backlash energizer embodiments **404**, **404**A and **420**.

[0143] Referring first to FIGS. **9**A and **9**B, backlash energizer assemblies **400** each include set screw **101**, puck **402**, and Belleville washer **403**. Pucks **402** are preferably of unitary hard material construction, such as metal or ceramic. Referring now to FIGS. **4**A and **9**A together, each backlash energizer assembly **400** is shown on FIG. **9**A interposed between a shaft backlash surface **105** and a corresponding housing backlash surface **202** per FIG. **4**A. Each Belleville washer **403** is configured to contact and provide compression bias against shaft backlash surface **105** such that torque backlash will act against Belleville washer **403**'s bias during backlash events. Each Belleville washer **403** is further positioned to react against puck **402** as received into a corresponding recess in housing backlash surface **202**. Set screws **401** may be inserted from the outside of lower housing **205**L through openings **208** provided for such purpose. Set screws **401** engage threads provided in openings **208** to set a user-desired compression bias for Belleville washers **403** against shaft backlash surfaces **105**.

[0144] It will thus be appreciated from FIGS. **9**A and **9**B that backlash energizer assemblies **400** dampen and absorb torque backlash during backlash events. Belleville washers **403** (and their associated compression bias) receive torque backlash, and may further temporarily store some of the torque backlash energy during backlash events. Several technical advantages are thus provided. Wear between shaft backlash surface **105** and housing backlash surface **202** is reduced, Concussive energy loss between shaft backlash surface **105** and housing backlash surface **202** is also reduced by removal of a gap between the two. Further, torque energy during backlash events is not completely lost. Referring to FIG. **9**A, any torque backlash energy stored in Belleville washers **403** during a backlash event will be released when clockwise torque is reestablished (per rotation direction R). Further, compression bias of Belleville washers **403** tends to keep shaft wings **106**, balls **320**, TTEs **310** and housing bearing surfaces **203** fully engaged by continuous contact during both normal torque transfer periods and torque backlash events. This in turn: (1) reduces wear on contact surfaces on shaft wings **106**, balls **320**, TTEs **310** and housing bearing surfaces **203**; (2) reduces concussive energy loss during a transition back to normal torque after a torque backlash event; and (3) reduces the chance of TTE assemblies **300** becoming dislocated between shaft wings **106** and housing bearing surfaces **203** during torque backlash events.

[0145] FIGS. **9**C and **9**D illustrate an alternative embodiment to the backlash energizer assembly **400** of FIGS. **9**A and **9**B. On FIGS. **9**C and **9**D, torque backlash remediation is provided by a single puck **404**. Similar to puck **402** in backlash energizer assembly **400**, puck **404** is preferably of unitary hard material construction, such as metal or ceramic. Puck **404** on FIGS. **9**C and **9**D provides advantages of simplicity of construction and assembly over backlash energizer **400** on

FIGS. **9**A and **9**B, at the expense of advantages that may be provided by the compression bias of Belleville washer **403** in backlash energizer **400**, described above.

[0146] FIGS. **9**E and **9**F illustrate an alternative embodiment to the backlash energizer embodiment illustrated on FIGS. **9**C and **9**D. On FIGS. **9**E and **9**F, a laminated puck **404**A substituted for the plain single puck **404** of FIGS. **9**C and **9**D. Laminated puck **404**A provides a resilient laminate construct for opposing contact with shaft backlash surface **105**, in which the laminate preferably includes alternating elastomer layers **405** and metal layers **406**. The laminate, however, may be of any suitable materials. The scope of this disclosure is not limited in this regard. The scope of this disclosure is further not limited to the design of laminate, including as to number of layers and their thicknesses. Puck **404**A on FIGS. **9**E and **9**F provides similar advantages of simplicity of construction and assembly as puck **404** on FIGS. **9**C and **9**D, and the laminar construction of puck **404**A may also provide some (or all) of the advantages that may be provided by the compression bias of Belleville washer **403** in backlash energizer **400**, described above.

[0147] FIGS. **9**G and **9**H illustrate backlash energizer assembly **420** as a yet further alternative embodiment to backlash energizers previously described with reference to FIGS. **9**A and **9**B, **9**C and **9**D, and **9**E and **9**F. Backlash energizer assembly **420** includes set screw **421**, plate **422** and ball **423**. Backlash energizer assembly **420** on FIGS. **9**G and **9**H is similar in overall design to backlash energizer assembly **400** on FIGS. **9**A and **9**B, except that plate **422** in assembly **420** substitutes for puck **402** in assembly **400**, and ball **423** in assembly **420** substitutes for Belleville washer **423** in assembly **400**. Also, comparing FIGS. **9**G and **9**A, the recess provided in lower housing **205**L for plate **422** and ball **423** on FIG. **9**G may have to be adapted dimensionally to suit plate **422** and ball **423** as compared to the corresponding recess for puck **402** and Belleville washer **403** on FIG. **9**A. Preferably the recess provided on FIG. **9**G leaves sufficient clearance from ball **423** to allow ball **423** to rotate within such recess. Backlash energizer assembly **420** on FIGS. **9**G and **9**H thus further facilitates keeping shaft wings **106**, balls **320**, TTEs **310** and housing bearing surfaces **203** fully contact-engaged during both normal torque periods and torque backlash events even when (especially when) there is relative articulating movement between shaft backlash surface **105** and housing backlash surface **202**. It will be appreciated that in previously described embodiments (FIGS. **9**A and **9**B, **9**D and **9**E, and **9**F and **9**G), keeping shaft wings **106**, balls **320**, TTEs **310** and housing bearing surfaces **203** fully contact-engaged during relative articulating movement between shaft backlash surface **105** and housing backlash surface **202** requires sliding contact between shaft backlash surface **105** and Belleville washer **403**, and pucks **404** and **404**A respectively. Such sliding contact may lead to wear and/or loss of contact between shaft backlash surface **105** and Belleville washer **403**, and pucks **404** and **404**A respectively. Rolling contact between shaft backlash surface **105** and ball **423** on FIGS. **9**G and **9**H remediates any such concerns brought on by corresponding sliding contact in other backlash energizer embodiments.

[0148] Regarding transmissions according to a knuckle-style design, and referring now to FIGS. **13**A and **15**, it will be understood that counterclockwise torque backlash (looking downhole) will be created in upper and lower knuckle assemblies **2600**U, **2600**L whenever clockwise torque through shaft **2501** is reduced, stopped or even reversed. Torque backlash may be momentary or sustained, responsive to corresponding changes in transmitted torque over time through shaft **2501**.

[0149] FIG. **14**A illustrates that during torque backlash in lower knuckle assembly **2600**L, clockwise torque (looking downhole) is no longer transferred through balls **320** and TTEs **310**. Instead, counterclockwise torque backlash causes knuckle backlash surface **2609** to bear upon shaft cavity backlash surface **2505**. Although not specifically illustrated, it will be understood that the corresponding effect occurs in upper knuckle assembly **2600**U.

[0150] As described above, FIGS. **9**A through **9**H illustrate currently preferred embodiments of alternative backlash energizer assemblies, which, when provided, seek to remediate negative effects of torque backlash. FIG. **9**A is a section similar to FIG. **14**A, except depicting an alternative embodiment including backlash energizer assembly **400**. FIG. **9**B is an exploded view of backlash energizer assembly **400** from FIG. **9**A in isolation.

[0151] FIGS. **9**C and **9**D, FIGS. **9**E and **9**F, and FIGS. **9**G and **9**H are each matched pairs of cutaway section views and corresponding exploded isolation views of alternative backlash energizer embodiments **404**, **404**A and **420**. FIGS. **9**A through **9**H are described in detail above with reference to FIG. **4**A. Those of ordinary skill will understand that the above description of FIGS. **9**A through **9**H with reference to FIG. **4**A applies analogously to deployments of backlash energizer assembly **400**, pucks **404** and **404**A, and backlash energizer assembly **420** on embodiments of a knuckle-style transmission design such as illustrated on FIGS. **13**A through **15**.

[0152] It will be understood that the scope of this disclosure with reference to a knuckle-style transmission design is not limited to the backlash energizer designs and embodiments described above with reference to FIGS. **9**A through **9**F. As noted above with reference to FIGS. **9**A through **9**F, the scope of this disclosure is not limited to any specific backlash energizer embodiment or configuration thereof. Some embodiments may provide no backlash energizer at all, or a hybrid including backlash energizers in some locations and not others. Some embodiments may further provide hybrids in which different backlash energizer designs are mixed on one housing assembly, or over two housing assemblies (upper and lower). Such embodiments providing mixed configurations may also include hybrid embodiments in which no backlash energizer is provided at selected locations.

[0153] It will be understood that the scope of this disclosure is not limited to the backlash energizer designs described above. The scope of this disclosure is not limited to any specific backlash energizer embodiment or configuration thereof. Some embodiments may provide no backlash energizer at all, or a hybrid including backlash energizers in some locations and not others. Some embodiments may further provide hybrids in which different backlash energizer designs are mixed on one housing assembly, or over two housing assemblies (upper and lower). Such embodiments providing mixed configurations may also include hybrid embodiments in which no backlash energizer is provided at selected locations.

Alternative TTE Embodiments

[0154] FIGS. **5**A through **5**K illustrate various alternative Torque Transfer Element ("TTE") embodiments. Earlier disclosure identified TTE assemblies **300** included in the illustrated embodiments of upper and lower housing assemblies **200**U, **200**L on FIGS. **3**A, **4**A, **4**B and **6**. FIG. **5**A illustrates TTE assembly **300**A, which for reference is the same TTE embodiment as TTE assembly **300** depicted on FIGS. **3**A, **4**A, **4**B and **6**. FIGS. **5**B through **5**G illustrate TTE assemblies **300**B through **300**G respectively. TTE assemblies **300**B through **300**G are alternative embodiments to TTE assembly **300**A on FIG. **5**A. FIG. **5**H illustrates unitary TTE **315** as an alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**I is a section as shown on FIG. **5**H. FIG. **5**J illustrates spheroidal TTE **316** as a further alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**K is a section as shown on FIG. **5**J. Regarding knuckle-style transmission designs, it will be understood that the TTE descriptions of FIGS. **5**A through **5**K in this disclosure with reference to transmission embodiments seen on FIGS. **3**A and **6** will apply analogously to corresponding TTE deployments on knuckle-style transmission embodiments such as illustrated on FIGS. **13**A through **15**.

[0155] Referring now to FIG. **5**A, TTE assembly **300**A includes TTE **310**A and ball **320**A, which correspond to TTE **310** and ball **320** on TTE assembly **300** on FIGS. **3**A, **4**A, **4**B and **6**. TTE **310**A on FIG. **5**A includes TTE recess **301**A and TTE bearing surface **302**A, which correspond to TTE recess **301** and TTE bearing surface **302** on TTE assembly **300** on FIGS. **3**A, **4**A, **4**B and **6**.

[0156] Referring now to FIG. **5**B, TTE assembly **300**B includes TTE **310**B and ball **320**B. TTE assembly **300**B on FIG. **5**B is an alternative embodiment to TTE assembly **300**A on FIG. **5**A. TTE **310**B on FIG. **5**B includes TTE recess **301**B and laminated TTE bearing surface **302**B. Bearing surface **302**B on FIG. **5**B includes a laminate for opposing contact with housing bearing surface **203** (refer FIG. **4**B, for example), in which the laminate preferably includes alternating TTE elastomer layers **303** and metal layers **304**. The laminate, however, may be of any suitable materials. The scope of this disclosure is not limited in this regard. The scope of this disclosure is further not limited to the design of laminate, including as to number of layers and their thicknesses. TTE assembly **300**B on FIG. **5**B, with its laminated bearing surface **203**, enables resilient contact with housing bearing surface **203** with some compression bias. With further reference to FIG. **4**B, such compression bias assists with keeping shaft wings **106**, balls **320**B, TTEs **310**B and housing bearing surfaces **203** fully engaged by continuous contact during both normal torque transfer periods and torque backlash events. In particular, and referring momentarily to FIG. **4**A, it will be understood that compression bias from TTE assemblies **300**B may retain shaft wings **106**, balls **320**B, TTEs **310**B and housing bearing surfaces **203** together during misaligned rotation.

[0157] Referring now to FIGS. **5**C, **5**F and **5**G together, TTE assemblies **300**C, **300**F, **300**G each include TTEs **310**C, **310**F, **310**G and balls **320**C, **320**F and **320**G respectively. TTE assemblies **300**C, **300**F and **300**G are further alternative embodiments to TTE assembly **300**A on FIG. **5**A. TTEs assemblies **310**C, **310**F and **310**G on FIGS. **5**C, **5**F and **5**G each include TTE bearing surfaces **302**C, **302**F and **302**G respectively. TTE bearing surfaces **302**C, **302**F and **302**G each differ from TTE bearing surface **302**A on FIG. **5**A in that they have curvature, whereas TTE bearing surface **302**A on FIG. **5**A is substantially planar. TTE bearing surface **302**C on FIG. **5**C is curved in a longitudinal transmission assembly direction as superposed on FIG. **3**A, for example, TTE bearing surface **302**F on FIG. **5**F is curved in a transverse direction, and TTE bearing surface **302**G on FIG. **5**G is curved in both longitudinal and transverse directions. With momentary reference to FIGS. **4**A and **4**B, curvature on TTE bearing surfaces **302**C, **302**F and **302**G further assists with continuous contact between housing bearing surfaces **203** and TTE bearing surfaces **302**C, **302**F and **302**G during misaligned rotation.

[0158] Referring now to FIG. **5**D, TTE assembly **300**D includes TTE **310**D and ball **320**D. TTE assembly **300**D on FIG. **5**D is a further alternative embodiment to TTE assembly **300**A on FIG. **5**A. TTE **310**D on FIG. **5**D includes TTE bearing surface **302**D. TTE bearing surface **302**D on FIG. **5**D differs from TTE bearing surface **302**A on FIG. **5**A in that TTE bearing surface **302**D includes angled faces at the periphery, whereas TTE bearing surface **302**A on FIG. **5**A is substantially planar. Embodiments according to FIG. **5**D are useful to provide clearance at the edges of bearing surface **302**D in limited space deployments where the corners of TTE **310**D might interfere with corners in housing receptacle **207** (refer to FIG. **4**B, for example).

[0159] Referring now to FIG. **5**E, TTE assembly **300**E includes TTE **310**E and ball **320**E. TTE assembly **300**E on FIG. **5**E is a further alternative embodiment to TTE assembly **300**A on FIG. **5**A. TTE **310**E on FIG. **5**E includes TTE recess **301**E and TTE bearing surface **302**E. TTE recess **301**E on FIG. **5**E differs from TTE recess **301**A on FIG. **5**A in that TTE recess **301**E provides internal hard facing **305**. (It will be understood that internal hard facing **305** is actually integral with TTE recess **301**E although illustrated as a separate item for clarity). an angled face, whereas TTE bearing surface **302**A on FIG. **5**A is substantially planar. It will be recalled that ball/CV designs consistent with this disclosure call for rotation and tilt of TTEs around corresponding balls. It will be further appreciated that internal hard facing **305** on TTE recesses **301**E, per FIG. **5**E, reduces contact wear on TTE recesses **301**E during such rotation and tilt between balls **320**E and TTE recesses **301**E. Since TTEs **310**E are potentially more expensive and harder to manufacture/acquire than balls **320**E, hard facing **305** on TTE recesses **301**E allows balls **320**E to become sacrificial during service life.

[0160] Referring now to FIGS. **5**H and **5**I, FIG. **5**H illustrates unitary TTE (or "UTTE") **315** as an alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**I is a section as shown on FIG. **5**H. Unitary TTE **315** on FIGS. **5**H and **5**I include TTE bearing surface **302**H. Unitary TTE **315** on FIGS. **5**H and **5**I differs from TTE assembly **300**A on FIG. **5**A in that the one-piece construction of unitary TTE **315** eliminates the need for a separate TTE **310**A and ball **320**A as in the embodiment of FIG. **5**A. It will be noted from earlier description that by interposing a ball between TTEs and shaft wings, ball/CV designs consistent with this disclosure allow the TTE an additional degree of freedom to rotate and tilt relative to the shaft wings during articulation. In embodiments such as on FIG. **5**A, the additional freedom to rotate and tilt manifests itself primarily by sliding movement between the TTE and the ball. However, in the embodiment of FIG. **5**H, the additional freedom to rotate and tilt is forced into sliding movement between the ball and the shaft wing. Forcing the sliding movement to be between ball and shaft wing may be desirable in some applications. A first example of such an alternative unitary TTE (or "UTTE") transmission embodiment is illustrated on FIGS. **4**C and **4**D, and a second example is illustrated on FIGS. **12**C and **12**D.

[0161] FIGS. **4**C and **12**C each depict respective exemplary transmission embodiments including unitary TTEs **315** similar to those depicted on FIGS. **5**H and **5**I. FIG. **4**D is a section as shown on FIG. **4**C, and FIG. **12**D is a section as shown on FIG. **12**C. Comparing FIG. **4**C to FIG. **4**A, UTTEs **315** on FIG. **4**C substitute for balls **320** and TTEs **310** on FIG. **4**A. FIGS. **4**A and **4**B show shaft wings **106** engaged with balls **320** and TTEs **310** in housing receptacles **207**. In contrast, FIGS. **4**C and **4**D show shaft wings **106** engaged with UTTEs **315** in housing receptacles **207**. FIG. **4**C illustrates torque transfer in a clockwise direction in the following sequence (A) through (B): (A) from shaft wings **106** on shaft head **102** into UTTEs **315**; and then (B) through UTTEs **315** and into lower housing **205**L via housing bearing surfaces **203**. Such clockwise torque transfer on FIG. **4**C is consistent with clockwise rotation direction R as shown on FIG. **4**C. FIGS. **4**C and **4**D further illustrate that during such clockwise torque transfer, UTTE bearing surface **302**H bears upon housing bearing surface **203**. FIG. **4**D also shows that during such clockwise torque transfer, shaft recesses **103** formed in shaft bearing surfaces **104** bear upon UTTEs **315**. Now comparing FIG. **12**C to FIG. **12**A, UTTEs **315** on FIG. **12**C substitute for balls **320** and TTEs **310** on FIG. **12**A. FIGS. **12**A and **12**B show shaft wings **1106** engaged with balls **320** and TTEs **310** in housing receptacles **1207**. In contrast, FIGS. **12**C and **12**D show shaft wings **1106** engaged with UTTEs **315** in housing receptacles **1207**. FIG. **12**C illustrates torque transfer in a clockwise direction in the following sequence (A) through (B): (A) from shaft wings **1106** on shaft head **1102** into UTTEs **315**; and then (B) through UTTEs **315** and into lower housing **1205**L via housing recesses **1203** formed in housing bearing surfaces **1204**. Such clockwise torque transfer on FIG. **12**C is consistent with clockwise rotation direction R as shown on FIG. **12**C. FIGS. **12**C and **12**D further illustrate that during such clockwise torque transfer, shaft bearing surface **1104** bears upon UTTE bearing surface **302**H. FIG. **12**D also shows that during such clockwise torque transfer, UTTEs **315** bear upon housing recesses **1203** formed in housing bearing surfaces **1204**.

[0162] Referring now to FIGS. **5**J and **5**K, FIG. **5**J illustrates spheroidal TTE **316** as an alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**K is a section as shown on FIG. **5**J. Spheroidal TTE **316** on FIGS. **5**J and **5**K include TTE bearing surface **302**I. Spheroidal TTE **316** on FIGS. **5**J and **5**K differs from unitary TTE **315** on FIGS. **5**H and **5**I in that the shaped one-piece construction of spheroidal TTE **316** simplifies construction and manufacturing while still providing the advantages of a one-piece TTE. As noted above, a one-piece TTE eliminates the need for a separate TTE **310**A and ball **320**A as in the embodiment of FIG. **5**A. Per disclosure from immediately above with reference to FIG. **5**H, interposing a ball between TTEs and shaft wings enables ball/CV designs consistent with this disclosure to allow the TTE an additional degree of freedom to rotate and tilt relative to the shaft wings during articulation. In embodiments such as on FIG. **5**A, the additional freedom to rotate and tilt manifests itself primarily by sliding movement between the TTE and the ball. However, in the one-piece embodiments of FIGS. **5**H and **5**I, the additional freedom to rotate and tilt is forced into sliding movement between the ball and the shaft wing. Forcing the sliding movement to be between ball and shaft wing may be desirable in some applications.

[0163] FIGS. **8**A and **8**B illustrate yet further TTE embodiments. FIG. **8**A is a section similar to FIG. **4**A, except depicting Bellville TTE assembly **330** as a further alternative embodiment to TTE assembly **300**A as shown on FIG. **5**A, for example. FIG. **8**B is an exploded view of Belleville TTE assembly **330**. Belleville TTE assembly **330** on FIGS. **8**A and **8**B differs from TTE assembly **300**A on FIG. **5**A in that bearing cup **331** and Belleville washer **332** on Belleville TTE assembly **330** are substituted in for TTE **310**A on TTE assembly **300**A. The combination of bearing cup **331** and Belleville washer **332** give Belleville TTE assembly **330** on FIGS. **8**A and **8**B an added compression bias. Similar to TTE assembly **300**B on FIG. **5**B, such compression bias in Belleville TTE assembly **330** assists with keeping shaft wings **106**, balls **320**, bearing cups **331**, Belleville washers **332** and housing bearing surfaces **203** on FIG. **8**A fully engaged by continuous contact during both normal torque transfer periods and torque backlash events. In particular, it will be understood that compression bias from Belleville TTE assemblies **330** may retain shaft wings **106**, balls **320**, bearing cups **331**, Belleville washers **332** and housing bearing surfaces **203** together during misaligned rotation.

[0164] FIG. **11** is a section similar to FIG. **4**A, except depicting an alternative "angled" TTE embodiment **310**Z bearing upon corresponding "angled" housing bearing surface **203**X. Comparing FIG. **4**A with FIG. **11**, the illustrated details remain unchanged (including engagement of balls **320** with corresponding shaft wings **106**), except that angled TTEs **310**Z on FIG. **11** are substituted for TTEs **310** on FIG. **4**A. Angled TTEs **310**Z on FIG. **11** each include TTE bearing surfaces **302**X each sloping at a user-selected angle Alpha (a) as shown on FIG. **11**. Lower housing **205**L on FIG. **11** further provides housing bearing surfaces **203**X each sloping at the user-selected angle Alpha (a) to match TTE bearing surfaces **302**X.

[0165] The angled TTE embodiment of FIG. **11** addresses radial vibration issues known to arise during articulated rotation. Especially at higher rotation speeds and torques, radial force vectors FV (as shown on FIG. **11**) arise and tend to cause radial instability among the TTE assembly components. This radial instability often manifests itself as radial vibration in and around the TTE assemblies. Such radial vibration may increase wear among TTE assembly components and at the interface of contact surfaces. Further, referring momentarily to FIGS. **3**B and **3**C, such radial vibration may also increase wear on hard facing **209** (or a thrust bearing in non-illustrated embodiments).

[0166] FIG. **11** illustrates angled TTEs **310**Z, with corresponding angled TTE bearing surfaces **302**X and angled shaft bearing surfaces **203**X, creating "ramps" with a slope bias preload force vector PL as also shown on FIG. **11**. It will be seen on FIG. **11** that these bias preload force vectors PL tend to counteract radial force vectors FV. As a result, radial vibration is discouraged, particularly in an embodiment such as illustrated on FIG. **11** where multiple angled TTEs **310**Z may act cooperatively to counteract radial force vectors FV arising around the entire housing periphery during articulated rotation. The scope of this disclosure is not limited, however, to providing angled TTEs **310**Z around an entire housing periphery as depicted in FIG. **11**. Non-illustrated embodiments may provide fewer angled TTEs **310**Z in combination with other designs.

[0167] The following paragraphs now describe alternative TTE embodiments specifically in association with "knuckle-style" transmission embodiments such as illustrated on FIGS. **13**A and **15**. To recap, FIGS. **5**A through **5**K illustrate various alternative TTE embodiments. Earlier disclosure identified TTE assemblies **300** included in the illustrated embodiments of upper and lower knuckle assemblies **2600**U, **2600**L on FIGS. **13**A, **14**A, **14**B and **15**. FIG. **5**A illustrates TTE assembly **300**A, which for reference is the same TTE embodiment as TTE assembly **300** depicted on FIGS. **13**A, **14**A, **14**B and **15**. FIGS. **5**B through **5**G illustrate TTE assemblies **300**B through **300**G respectively. TTE assemblies **300**B through **300**G are alternative embodiments to TTE assembly **300**A on FIG. **5**A. FIG. **5**H illustrates unitary TTE **315** as an alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**I is a section as shown on FIG. **5**H. FIG. **5**J illustrates spheroidal TTE **316** as a further alternative embodiment to TTE assembly **300**A on FIG. **5**A, and FIG. **5**K is a section as shown on FIG. **5**J. Those of ordinary skill will understand that the above description of FIGS. **5**A through **5**K with reference to FIGS. **3**A, **4**A, **4**B and **6** applies analogously to deployments of TTE embodiments according to FIGS. **5**A through **5**K on knuckle-style transmission embodiments such as illustrated on FIGS. **13**A through **15**.

[0168] FIGS. **16**A and **16**B illustrate yet further TTE embodiments. FIGS. **16**A and **16**B are similar in content to FIGS. **8**A and **8**B. FIG. **16**A is a section similar to FIG. **14**A, except depicting Bellville TTE assembly **330** as a further alternative embodiment to TTE assembly **300**A as shown on FIG. **5**A, for example. FIG. **16**B is an exploded view of Belleville TTE assembly **330**. Belleville TTE assembly **330** on FIGS. **16**A and **16**B differs from TTE assembly **300**A on FIG. **5**A in that bearing cup **331** and Belleville washer **332** on Belleville TTE assembly **330** are substituted in for TTE **310**A on TTE assembly **300**A. The combination of bearing cup **331** and Belleville washer **332** give Belleville TTE assembly **330** on FIGS. **16**A and **16**B an added compression bias. Similar to TTE assembly **300**B on FIG. **5**B, such compression bias in Belleville TTE assembly **330** assists with keeping knuckle wings **2606**, balls **320**, bearing cups **331**, Belleville washers **332** and shaft cavity bearing surfaces **2504** on FIG. **16**A fully engaged by continuous contact during both normal torque transfer periods and torque backlash events. In particular, it will be understood that compression bias from Belleville TTE assemblies **330** may retain knuckle wings **2606**, balls **320**, bearing cups **331**, Belleville washers **332** and shaft cavity bearing surfaces **2504** together during misaligned rotation.

[0169] It will be understood that the scope of this disclosure with reference to knuckle-style transmission designs (such as seen on FIGS. **13**A and **15**) is not limited to the various TTE designs and embodiments described above with reference to FIGS. **5**A through **5**K and FIGS. **16**A, **16**B. The scope of this disclosure with reference to knuckle-style transmission designs is not limited to any specific TTE embodiment or configuration thereof. Some embodiments may provide hybrids in which different TTE designs are mixed on one of shaft cavities **2502**U/L, or over two knuckle assemblies **2600**U, **2600**L. Further, TTE designs as described above may be combined into single TTE embodiments (such as, for example, combining into one hybrid TTE embodiment the hard facing embodiment of FIG. **5**E with (1) a curved TTE bearing surface embodiment selected from FIG. **5**C, **5**F or **5**G, or (2) a one-piece TTE selected from FIGS. **5**H and **5**J).

[0170] It will therefore be appreciated that in some embodiments of knuckle-style transmission designs such as seen on FIGS. **13**A and **15**, and with further reference to FIGS. **16**A and **16**B, the transmission includes at least one TTE provided as a Belleville TTE assembly **330**, comprising a TTE bearing cup **331** contacting a TTE Belleville washer **332**, such that the TTE bearing cup **331** acts as a TTE recess and the TTE Belleville washer **332** acts as a TTE bearing surface

[0171] It will be further appreciated that in other embodiments of knuckle-style transmission designs such as seen on FIGS. **13**A and **15**, and with further reference to FIGS. **5**A through **5**K, the TTE **310** and corresponding ball **320** in at least one shaft cavity receptacle **2507** is, instead, a unitary workpiece such as unitary TTE **315** or spheroidal TTE **316** according FIG. **5**H or **5**J.

[0172] The following paragraphs further describe embodiments of knuckle-style articulated transmission designs (such as seen on FIG. **13**A through **15**) disposed to transmit torque via misaligned rotation via unitary TTEs (UTTEs) such as unitary TTE **315** or spheroidal TTE **316** according to FIG. **5**H or **5**J respectively. FIGS. **13**A through **15** must be imagined as if unitary TTEs **315** or spheroidal TTEs **316** substitute for TTE assemblies **300** as illustrated. Each UTTE thus has a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE.

[0173] According to such UTTE embodiments, therefore, lower knuckle head **2602**L on FIG. **15**, for example, has a knuckle centerline about which knuckle head **2602**L is disposed to rotate. In some embodiments, lower knuckle head **2602**L is generally cylindrical. Knuckle head **2602**L on FIG. **15** has a plurality of knuckle recesses **2603**. Each knuckle recess **2603** is formed in a corresponding knuckle wing **2606** extending radially from the shaft centerline. FIG. **15** also illustrates a lower shaft cavity **2502**L at a lower end of shaft **2501** having a shaft centerline about which shaft **2501** is disposed to rotate. In some embodiments, lower shaft cavity **2502**L is generally cylindrical. Shaft cavity **2502**L has a plurality of shaft cavity receptacles **2507** formed therein, such that each shaft cavity receptacle **2507** is for receiving a corresponding knuckle wing **2606**.

[0174] The transmission further provides a plurality of unitary torque transfer elements (UTTEs), such as such as unitary TTE **315** or spheroidal TTE **316** according to FIG. **5**H or **5**J. As noted, each UTTE provides a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE. FIG. **13**C or **14**B, for example illustrates that each shaft cavity receptacle **2507** provides a shaft cavity bearing surface **2504**. A knuckle wing **2606** and a UTTE are received into each shaft cavity receptacle **2507** such that within each shaft cavity receptacle **2507**, the UTTE spherical surface is received into the knuckle recess **2603**, and the UTTE bearing surface opposes the shaft bearing surface **2504**. As a result, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle **2507** during an articulated revolution of shaft **2501**: (1) the UTTE bearing surfaces are free to slidably displace against corresponding shaft cavity bearing surfaces **2504**; (2) the knuckle recesses **2603** restrain the UTTEs from movement in at least a radial direction with respect to the shaft centerline; and (3) the UTTEs are free to tilt within the knuckle recesses **2603**. As a result, torque transfer contact is maintained between (1) the knuckle recess **2603** and the UTTE spherical surface, and (2) the UTTE bearing surface and the shaft cavity bearing surface **2504** through all positions of misaligned rotation in one articulated revolution of shaft **2501**.

[0175] According to some UTTE embodiments of knuckle-style transmission designs such as seen on FIGS. **13**A and **15**, UTTEs float at least generally radially with respect to the shaft centerline when the UTTE bearing surfaces slidably displace against corresponding shaft cavity bearing surfaces **2504**. It will be further appreciated that the immediately foregoing UTTE disclosure was made with reference to lower knuckle head **2602**L and lower shaft cavity **2502**L at a lower end of shaft **2501**, all as shown on FIG. **15**. It will nonetheless be understood that the foregoing UTTE disclosure applies equally with reference to upper knuckle head **2602**U and upper shaft cavity **2502**U at an upper end of shaft **2501**, again all as shown on FIG. **15**.

[0176] It will be understood that the scope of this disclosure is not limited to the various TTE designs described above with reference to FIGS. **5**A through **5**K. The scope of this disclosure is not limited to any specific TTE embodiment or configuration thereof. Some embodiments may provide hybrids in which different TTE designs are mixed on one housing assembly, or over two housing assemblies (upper and lower). Further, TTE designs as described above may be combined into single TTE embodiments (such as, for example, combining the hard facing embodiment of FIG. **5** with a curved TTE bearing surface embodiment selected from FIG. **5**C, **5**F or **5**G into one hybrid TTE embodiment).

Release Channel Embodiments

[0177] FIGS. **10**A through **10**D illustrate additional embodiments in which “release channels” may be provided either in shaft wings or in torque transfer elements (“TTEs”). In some embodiments, a release channel may enable use of a larger ball with the TTEs. Advantages of providing a larger ball have been described above. Briefly, a larger ball allows a larger contact area between ball and TTE, which in turn discourages wear, particularly the potential for cracking, galling and fretting. However, a larger ball, with its larger circumference, requires additional space to allow the TTE to rotate and tilt relative to the shaft wing in order to maintain mutual contact during articulated/misaligned rotation. Thus, in exemplary embodiments described below with reference to FIGS. **10**A through **10**D provide such additional space in the form of release channels. It should be noted that when the ball is in a release channel, a potential for point loads may arise between TTE and ball, or between shaft wing and ball as the ball moves along the release channel during articulation. However, in such point load situations, the potential for friction between TTE and ball, or between shaft wing and ball, also decreases in response to the reduced surface contact between components. Thus, with reduced friction, the TTE is able to rotate and tilt relative to the shaft wing with more freedom. The resulting trade-off may be desirable in selected applications and embodiments.

[0178] FIGS. **10**A and **10**B illustrate a release channel embodiment in which additional displacement space is afforded larger release channel balls **320**X in shaft head **102**. FIG. **10**B depicts shaft head **102** in which shaft release channels **107** are provided in shaft wings **106**A. FIG. **10**A is a section as shown on FIG. **10**B, and is analogous to FIG. **4**A except depicting shaft release channels **107** and associated features.

[0179] FIGS. **10**C and **10**D illustrate another release channel embodiment in which additional displacement space is afforded larger release channel balls **320**X in TTE **310**Y. FIG. **10**D depicts TTE release channel **311** provided in TTE **310**Y. FIG. **10**C is a section as shown on FIG. **10**D, and is again analogous to FIG. **4**A except depicting TTE release channel **311** and associated features.

[0180] Referring first to FIGS. **10**A and **10**B, shaft head **102** provides shaft wings **106**A in which each shaft wing **106**A includes a shaft release channel **107** in shaft recess **103** (refer to FIG. **4**B for shaft recess **103**, for example). Shaft release channels **107** are preferably curved in profile to match the circumference of larger release channel balls **320**X, and extend radially to the outer periphery of shaft wings **106**A in order to afford release channel balls **320**X as much additional displacement space as may be available to maintain mutual contact with shaft wings **106**A and TTEs **310**X during articulated/misaligned rotation. TTEs **310**X also provide larger TTE recesses therein to match the larger circumference of release channel balls **320**X.

[0181] Referring now to FIGS. **10**C and **10**D, TTEs **310**Y each include a TTE release channel **311**. TTE release channels **311** are preferably curved in profile to match the circumference of larger release channel balls **320**X, and extend radially inwardly towards shaft backlash surfaces **105** (refer to FIG. **4**A for shaft backlash surfaces **105**, for example). TTE release channels **311** thus afford release channel balls **320**X as much additional displacement space as may be available to maintain mutual contact with shaft wings **106**B and TTEs **310**Y during articulated/misaligned rotation. Shaft wings **106**B also provide larger shaft recesses therein to match the larger circumference of release channel balls **320**X.

[0182] The following paragraphs now describe alternative release channel embodiments specifically in association with “knuckle-style” transmission embodiments such as illustrated on FIGS. **13**A and **15**. FIGS. **17**A through **17**D illustrate additional embodiments in which “release channels” may be provided either in knuckle wings or in torque transfer elements (“TTEs”). In some embodiments, a release channel may enable use of a larger ball with the TTEs. Advantages of providing a larger ball have been described above. Briefly, a larger ball allows a larger contact area between ball and TTE, which in turn discourages wear, particularly the potential for cracking, galling and fretting. However, a larger ball, with its larger circumference, requires additional space to allow the TTE to rotate and tilt relative to the knuckle wing in order to maintain mutual contact during articulated/misaligned rotation. Thus, exemplary embodiments described below with reference to FIGS. **17**A through **17**D provide such additional space in the form of release channels. It should be noted that when the ball is in a release channel, a potential for point loads may arise between TTE and ball, or between knuckle wing and ball as the ball moves along the release channel during articulation. However, in such point load situations, the potential for friction between TTE and ball, or between knuckle wing and ball, also decreases in response to the reduced surface contact between components. Thus, with reduced friction, the TTE is able to rotate and tilt relative to the knuckle wing with more freedom. The resulting trade-off may be desirable in selected applications and embodiments.

[0183] FIGS. **17**A and **17**B illustrate a release channel embodiment in which additional displacement space is afforded larger release channel balls **320**X in knuckle head **2602**. FIG. **17**B depicts lower knuckle head **2602**L in which knuckle release channels **2607** are provided in knuckle wings **2606**A. FIG. **17**A is a section as shown on FIG. **17**B, and is analogous to FIG. **14**A except depicting knuckle release channels **2607** and associated features.

[0184] FIGS. **17**C and **17**D illustrate another release channel embodiment in which additional displacement space is afforded larger release channel balls **320**X in TTE **310**Y. FIG. **17**D depicts TTE release channel **311** provided in TTE **310**Y. FIG. **17**C is a section as shown on FIG. **17**D, and is again analogous to FIG. **14**A except depicting TTE release channel **311** and associated features.

[0185] Referring first to FIGS. **17**A and **17**B, lower knuckle head **2602**L provides knuckle wings **2606**A in which each knuckle wing **2606**A includes a knuckle release channel **2607** in knuckle recess **2603** (refer to FIG. **13**A for knuckle recess **2603**, for example). Knuckle release channels **2607** are preferably curved in profile to match the circumference of larger release channel balls **320**X, and extend radially to the outer periphery of knuckle wings **2606**A in order to afford release channel balls **320**X as much additional displacement space as may be available to maintain mutual contact with knuckle wings **2606**A and TTEs **310**X during articulated/misaligned rotation. TTEs **310**X also provide larger TTE recesses therein to match the larger circumference of release channel balls **320**X.

[0186] Referring now to FIGS. **17**C and **17**D, TTEs **310**Y each include a TTE release channel **311**. TTE release channels **311** are preferably curved in profile to match the circumference of larger release channel balls **320**X, and extend radially inwardly towards knuckle backlash surfaces **2609** (refer to FIG. **14**A for knuckle backlash surfaces **2609**, for example). TTE release channels **311** thus afford release channel balls **320**X as much additional displacement space as may be available to maintain mutual contact with knuckle wings **2606**B and TTEs **310**Y during articulated/misaligned rotation. Knuckle wings **2606**B also provide larger shaft recesses therein to match the larger circumference of release channel balls **320**X.

[0187] It will be further appreciated that the immediately foregoing release channel disclosure with reference to FIGS. **17**A through **17**D was made with reference to lower knuckle head **2602**L and lower shaft cavity **2502**L at a lower end of shaft **2501**, all as shown on FIG. **15**. It will nonetheless be understood that the foregoing release channel disclosure applies equally with reference to upper knuckle head **2602**U and upper shaft cavity **2502**U at an upper end of shaft **2501**, again all as shown on FIG. **15**.

[0188] It will be understood that the scope of this disclosure is not limited to the release channel designs described above. The scope of this disclosure is not limited to any specific release channel embodiment or configuration thereof. Some embodiments may provide no release channel deployments at all, or a hybrid including release channels in some locations and not others. Some release channel embodiments may further provide hybrids in which different release channel designs are mixed on one housing assembly, or over two housing assemblies (upper and lower). Such release channel embodiments providing mixed configurations may also include hybrid embodiments in which no release channel is provided at selected locations. Some release channel embodiments may incorporate one or more TTE designs selected from the embodiments depicted on FIGS. **5**A through **5**K, or **8**A and **8**B, or **11**, or **16**A and **16**B. Some release channel embodiments may provide "partial" release channels, in which, as the case may be: (A) shaft release channels **107** may not extend radially all the way to the outer periphery of shaft wings **106**A; or (B) TTE release channels **311** may not extend radially inwardly all the way within TTEs **310**Y to shaft backlash surfaces **105**. Alternatively, some release channel embodiments of knuckle-style transmission designs (such as seen on FIGS. **13** through **15**) may provide "partial" release channels, in which, as the case may be: (A) knuckle release channels **2607** may not extend radially all the way to the outer periphery of knuckle wings **2606**A; or (B) TTE release channels **311** may not extend radially inwardly all the way within TTEs **310**Y to knuckle backlash surfaces **2609**.

[0189] Although the inventive material in this disclosure has been described in detail along with some of its technical advantages, it will be understood that various changes, substitutions and alternations may be made to the detailed embodiments without departing from the broader spirit and scope of such inventive material, some embodiments of which are recited in the appended claims.

Claims

1. An articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate; a plurality of knuckle recesses, each knuckle recess formed in a corresponding knuckle wing extending radially from the knuckle centerline; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; a plurality of torque transfer elements (TTEs), each TTE providing a TTE recess and a TTE bearing surface; and a plurality of balls; wherein each shaft cavity receptacle provides a shaft cavity bearing surface; wherein a knuckle wing, a TTE, and a ball are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the ball is received into the knuckle recess and the TTE recess, and the TTE bearing surface opposes the shaft cavity bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the TTE bearing surfaces are free to slidably displace against corresponding shaft cavity bearing surfaces; (2) the knuckle recesses restrain the balls from movement in at least a radial direction with respect to the knuckle centerline; and (3) the TTEs are free to tilt about the balls.
2. The transmission of claim 1, in which the TTEs float at least generally radially with respect to the shaft centerline when the TTE bearing surfaces slidably displace against corresponding shaft cavity bearing surfaces.
3. The transmission of claim 1, in which: each knuckle wing further provides a knuckle bearing surface and a knuckle backlash surface such that each knuckle bearing surface opposes a knuckle backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle backlash surface and shaft cavity backlash surface.
4. The transmission of claim 3, in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.
5. The transmission of claim 3, in which the backlash energizer assembly includes a puck.
6. The transmission of claim 5, in which the puck includes a laminate of metal and elastomer layers.
7. The transmission of claim 1, in which at least one knuckle wing further includes a knuckle release channel, and in which knuckle release channels extend knuckle recesses such that balls may float within knuckle release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.
8. The transmission of claim 1, in which at least one TTE further includes a TTE release channel, and in which TTE release channels extend TTE recesses such that balls may float within TTE release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.
9. The transmission of claim 1, in which at least one TTE comprises a TTE bearing cup contacting a TTE Belleville washer, such that the TTE bearing cup acts as the TTE recess and the TTE Belleville washer acts as the TTE bearing surface.
10. An articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate; a plurality of knuckle recesses, each knuckle recess formed in a corresponding knuckle wing extending radially from the knuckle centerline; a shaft having a shaft centerline about

which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; and a plurality of unitary torque transfer elements (UTTEs), each UTTE providing a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE; wherein each shaft cavity receptacle provides a shaft cavity bearing surface; wherein a knuckle wing and a UTTE are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the UTTE spherical surface is received into the knuckle recess, and the UTTE bearing surface opposes the shaft cavity bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the UTTE bearing surfaces are free to slidably displace against corresponding shaft cavity bearing surfaces; (2) the knuckle recesses restrain the UTTEs from movement in at least a radial direction with respect to the knuckle centerline; and (3) the UTTEs are free to tilt within the knuckle recesses.

11. The transmission of claim 10, in which the UTTEs float at least generally radially with respect to the shaft centerline when the UTTE bearing surfaces slidably displace against corresponding shaft cavity bearing surfaces.

12. The transmission of claim 10, in which: each knuckle wing further provides a knuckle bearing surface and a knuckle backlash surface such that each knuckle bearing surface opposes a knuckle backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle backlash surface and shaft cavity backlash surface.

13. The transmission of claim 12, in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.

14. The transmission of claim 12, in which the backlash energizer assembly includes a puck.

15. The transmission of claim 14, in which the puck includes a laminate of metal and elastomer layers.

16. The transmission of claim 10, in which at least one knuckle wing further includes a knuckle release channel, and in which knuckle release channels extend knuckle recesses such that UTTE spherical surfaces may float within knuckle release channels responsive to said misaligned rotation of the shaft centerline with respect to the knuckle centerline.

17. An articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate, the knuckle head providing a plurality of knuckle wings, each knuckle wing extending radially from the knuckle centerline and providing a knuckle wing bearing surface thereon; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; a plurality of torque transfer elements (TTEs), each TTE providing a TTE recess and a TTE bearing surface; and a plurality of balls; wherein each shaft cavity receptacle provides a shaft cavity bearing surface with a shaft cavity recess formed therein; wherein a knuckle wing, a TTE, and a ball are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the ball is received into the shaft cavity recess and the TTE recess, and the TTE bearing surface opposes the knuckle wing bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the TTE bearing surfaces are free to slidably displace against corresponding knuckle wing bearing surfaces; (2) the shaft cavity recesses restrain the balls from movement in at least a radial direction with respect to the knuckle centerline; and (3) the TTEs are

free to tilt about the balls.
18. The transmission of claim 17, in which the TTEs float at least generally radially with respect to the shaft centerline when the TTE bearing surfaces slidably displace against corresponding knuckle wing bearing surfaces.
19. The transmission of claim 17, in which: each knuckle wing further provides a knuckle wing backlash surface such that each knuckle wing bearing surface opposes a knuckle wing backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle wing backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle wing backlash surface and shaft cavity backlash surface.
20. The transmission of claim 19, in which the backlash energizer assembly includes a puck separating a set screw and a backlash energizer Belleville washer.
21. The transmission of claim 19, in which the backlash energizer assembly includes a puck.
22. The transmission of claim 21, in which the puck includes a laminate of metal and elastomer layers.
23. The transmission of claim 17, in which at least one TTE comprises a TTE bearing cup contacting a TTE Belleville washer, such that the TTE bearing cup acts as the TTE recess and the TTE Belleville washer acts as the TTE bearing surface.
24. An articulated transmission disposed to transmit torque via misaligned rotation, the transmission comprising: a knuckle head having a knuckle centerline about which the knuckle head is disposed to rotate, the knuckle head providing a plurality of knuckle wings, each knuckle wing extending radially from the knuckle centerline and providing a knuckle wing bearing surface thereon; a shaft having a shaft centerline about which the shaft is disposed to rotate; a shaft cavity disposed on the shaft, the shaft cavity having a plurality of shaft cavity receptacles formed therein, each shaft cavity receptacle for receiving a corresponding knuckle wing; and a plurality of unitary torque transfer elements (UTTEs), each UTTE providing a UTTE spherical surface and a planar UTTE bearing surface on opposite sides of the UTTE; wherein each shaft cavity receptacle provides a shaft cavity bearing surface with a shaft cavity recess formed therein; wherein a knuckle wing and a UTTE are received into each shaft cavity receptacle such that within each shaft cavity receptacle, the UTTE spherical surface is received into the shaft cavity recess and the UTTE bearing surface opposes the knuckle wing bearing surface; wherein, responsive to misaligned rotation of the shaft centerline with respect to the knuckle centerline and regardless of angular deflection of the shaft centerline with respect to the knuckle centerline experienced within each shaft cavity receptacle during an articulated revolution of the shaft: (1) the UTTE bearing surfaces are free to slidably displace against corresponding knuckle wing bearing surfaces; (2) the shaft cavity recesses restrain the UTTEs from movement in at least a radial direction with respect to the knuckle centerline; and (3) the UTTEs are free to tilt within the shaft cavity recesses.
25. The transmission of claim 24, in which the UTTEs float at least generally radially with respect to the shaft centerline when the UTTE bearing surfaces slidably displace against corresponding knuckle wing bearing surfaces.
26. The transmission of claim 24, in which: each knuckle wing further provides a knuckle wing backlash surface such that each knuckle wing bearing surface opposes a knuckle wing backlash surface on a neighboring knuckle wing; each shaft cavity receptacle further provides a shaft cavity backlash surface to oppose a corresponding knuckle wing backlash surface; and wherein the transmission further includes a backlash energizer assembly interposed between at least one opposing knuckle wing backlash surface and shaft cavity backlash surface.