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- (54) **APPARATUS FOR MEASURING IMBALANCE FORCES OF A TIRE/HUB ASSEMBLY OF A VEHICLE DURING MOTION OF THE VEHICLE**

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G01M 17/02 (2006.01)

- (58) **Field of Classification Search**
None
See application file for complete search history.

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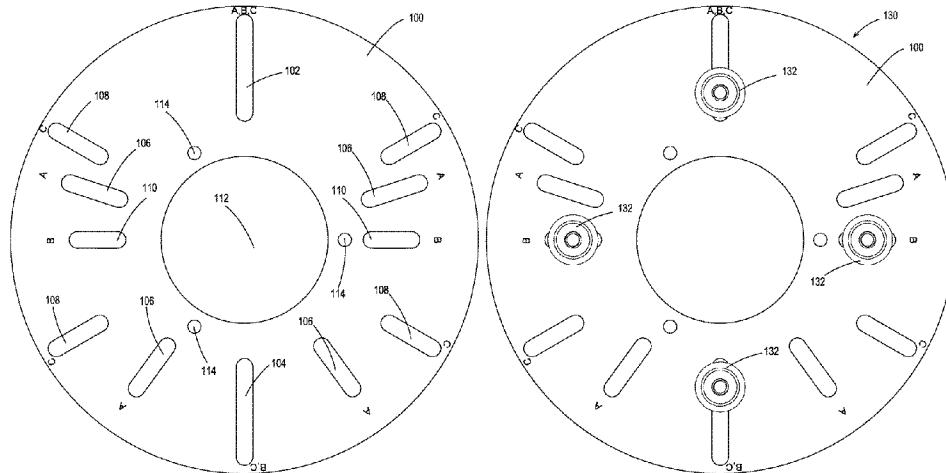
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- (57) **ABSTRACT**

An apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly is used to determine imbalance forces of the tire/hub assembly during motion of the vehicle. The apparatus includes a disk and a plurality of cup-shaped objects fixed at one end to the disk and extending perpendicularly outward from the disk. The plurality of cup-shaped objects are arranged a fixed radial distance from a radial center of the disk in a pattern that matches the lug nuts of the tire/hub assembly. The apparatus is mounted to the vehicle's tire/hub assembly by fitting the plurality of cup-shaped objects over the lug nuts of the tire/hub assembly. The apparatus further includes one or more inertial measurement units (IMU's) mounted to the disk to measure parameters that are used for calculating the imbalance forces during motion of the vehicle.

14 Claims, 31 Drawing Sheets



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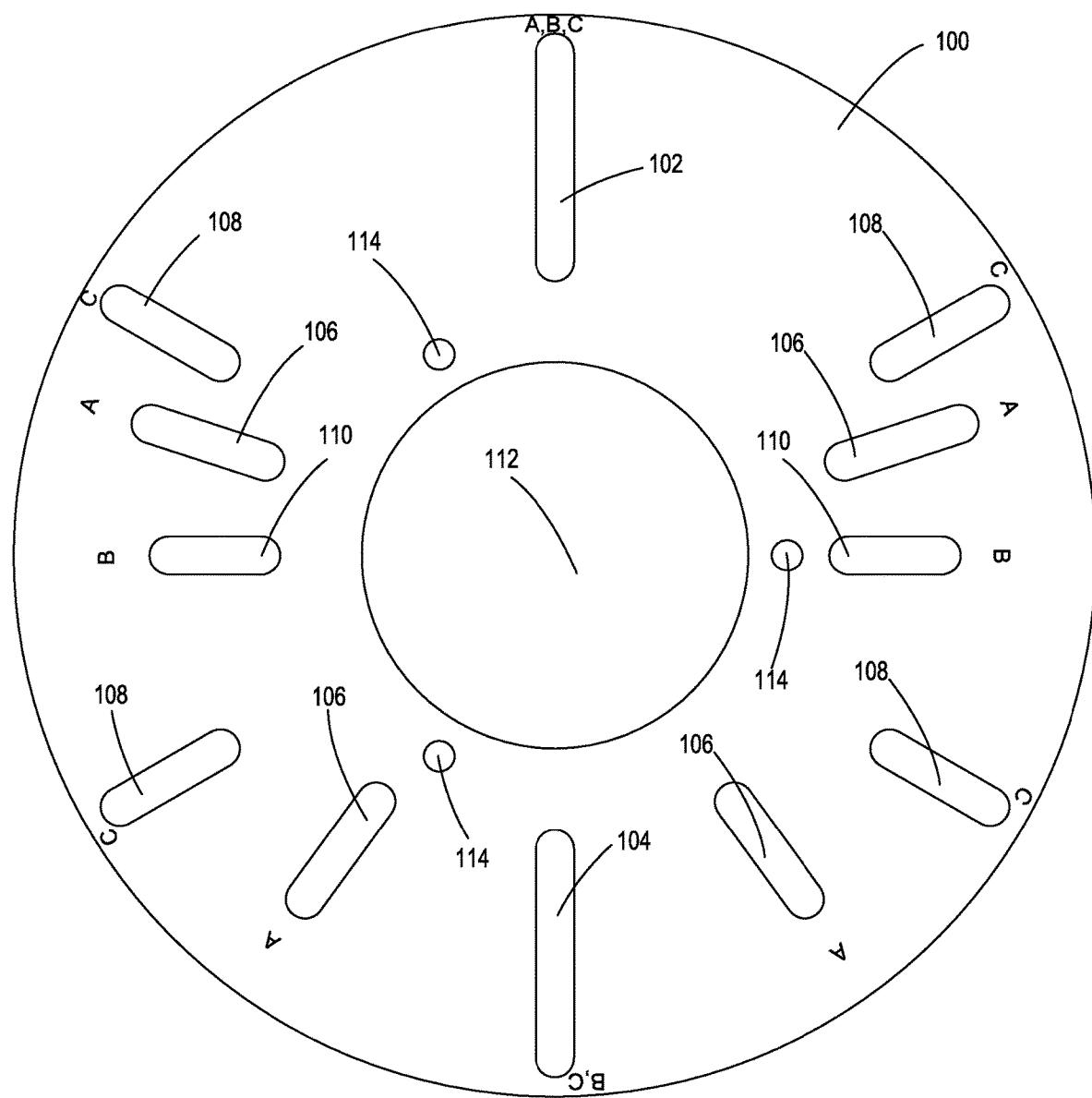


Fig. 1A

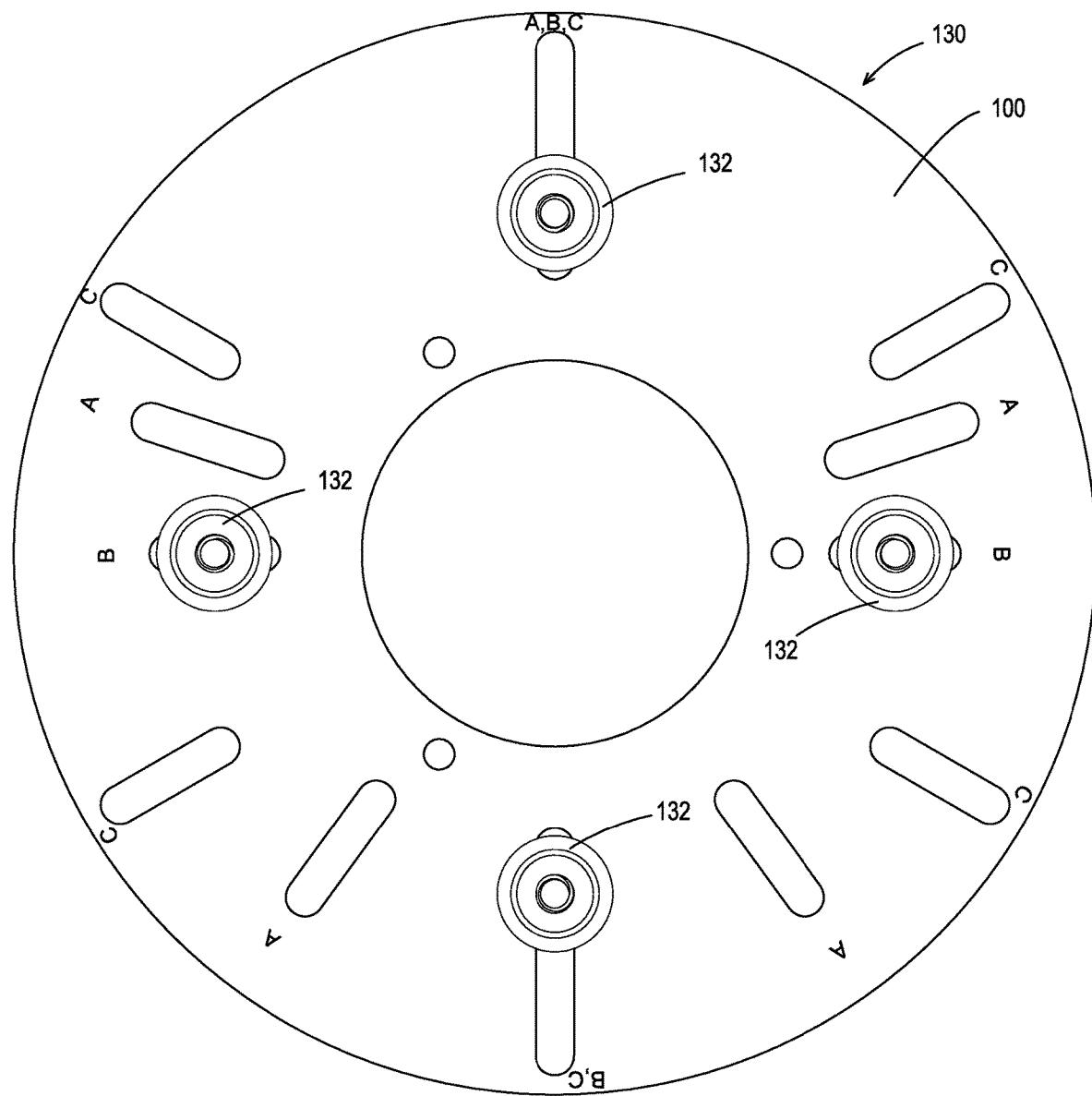


Fig. 1B

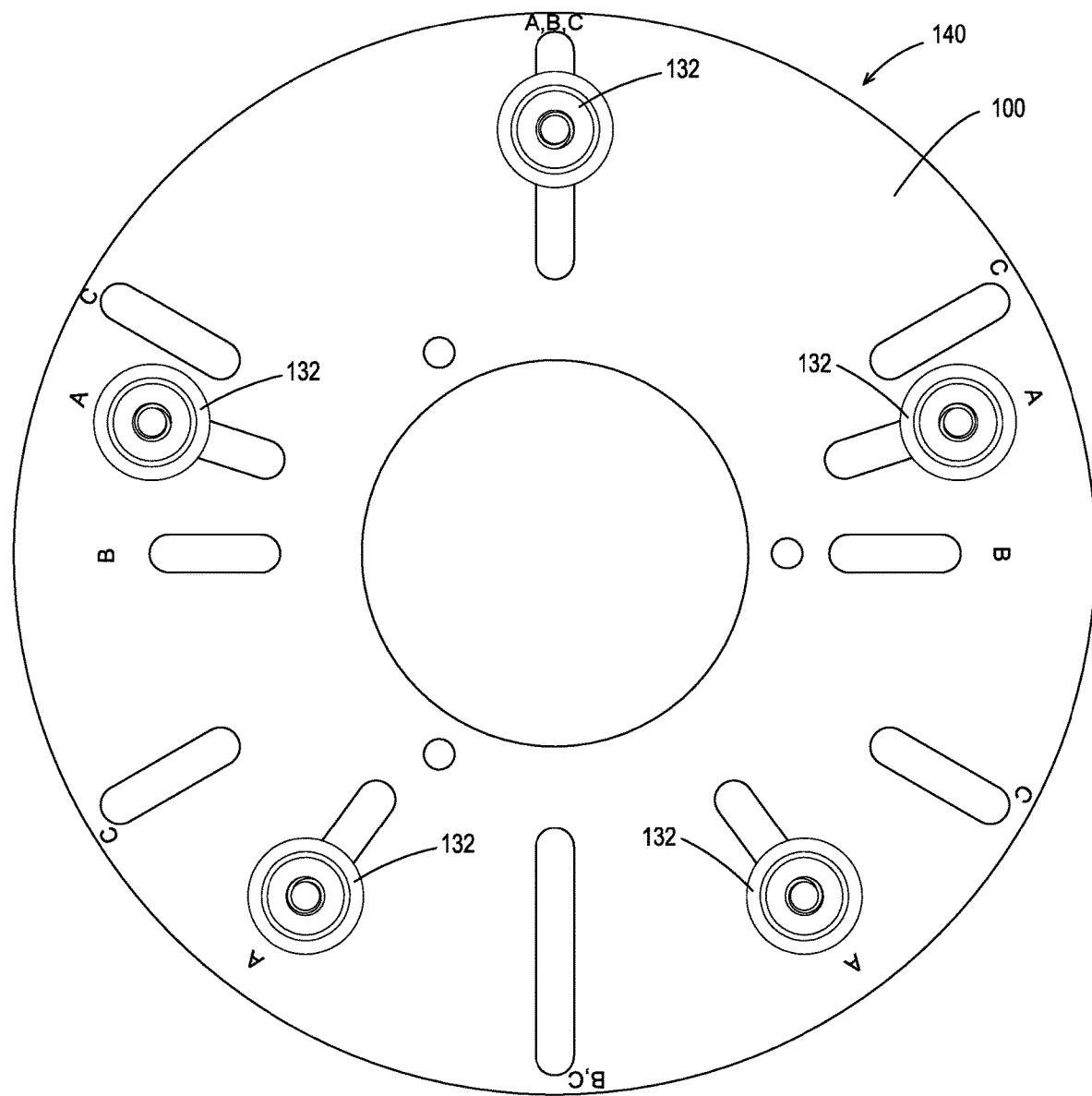


Fig. 1C

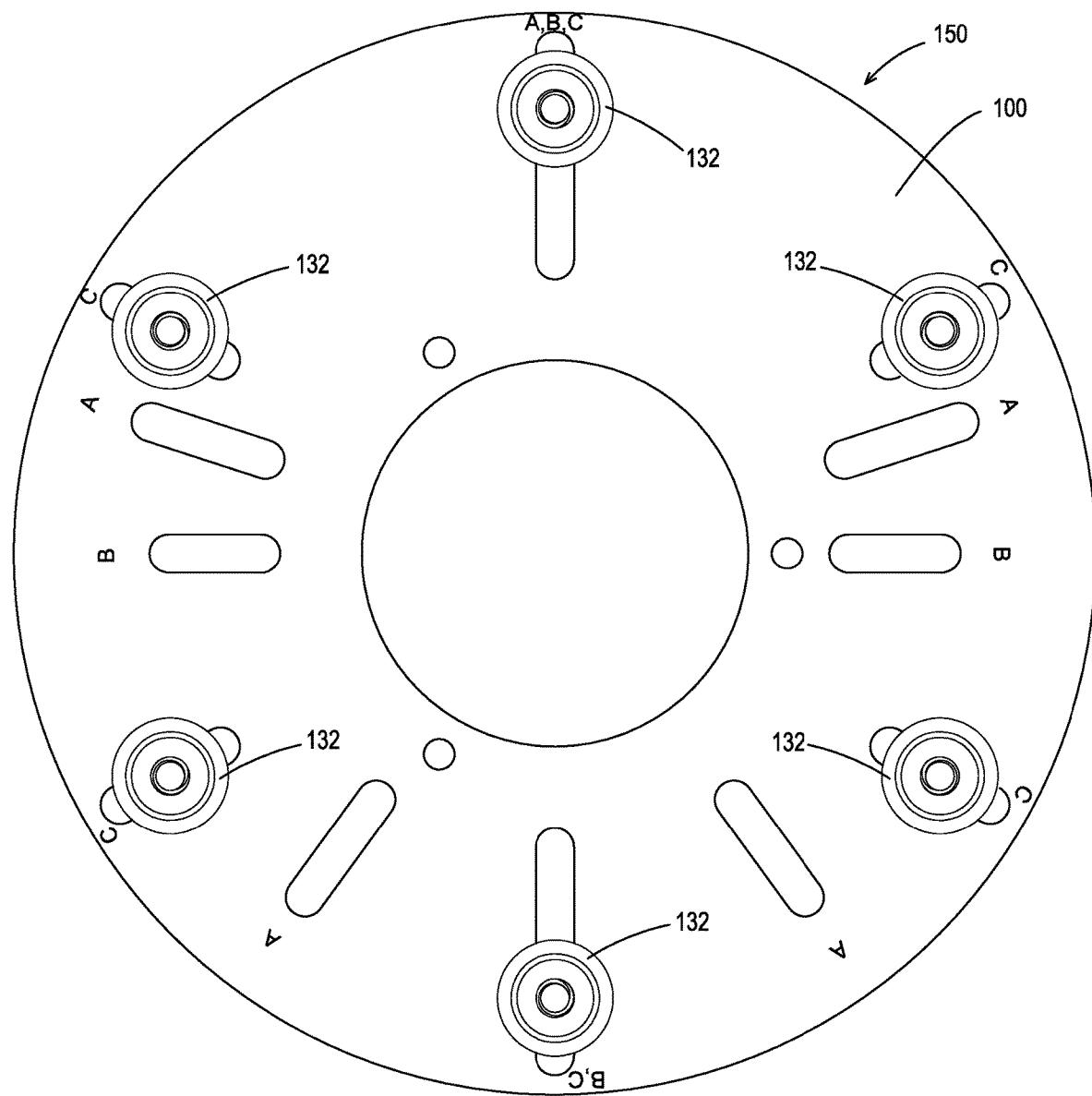


Fig. 1D

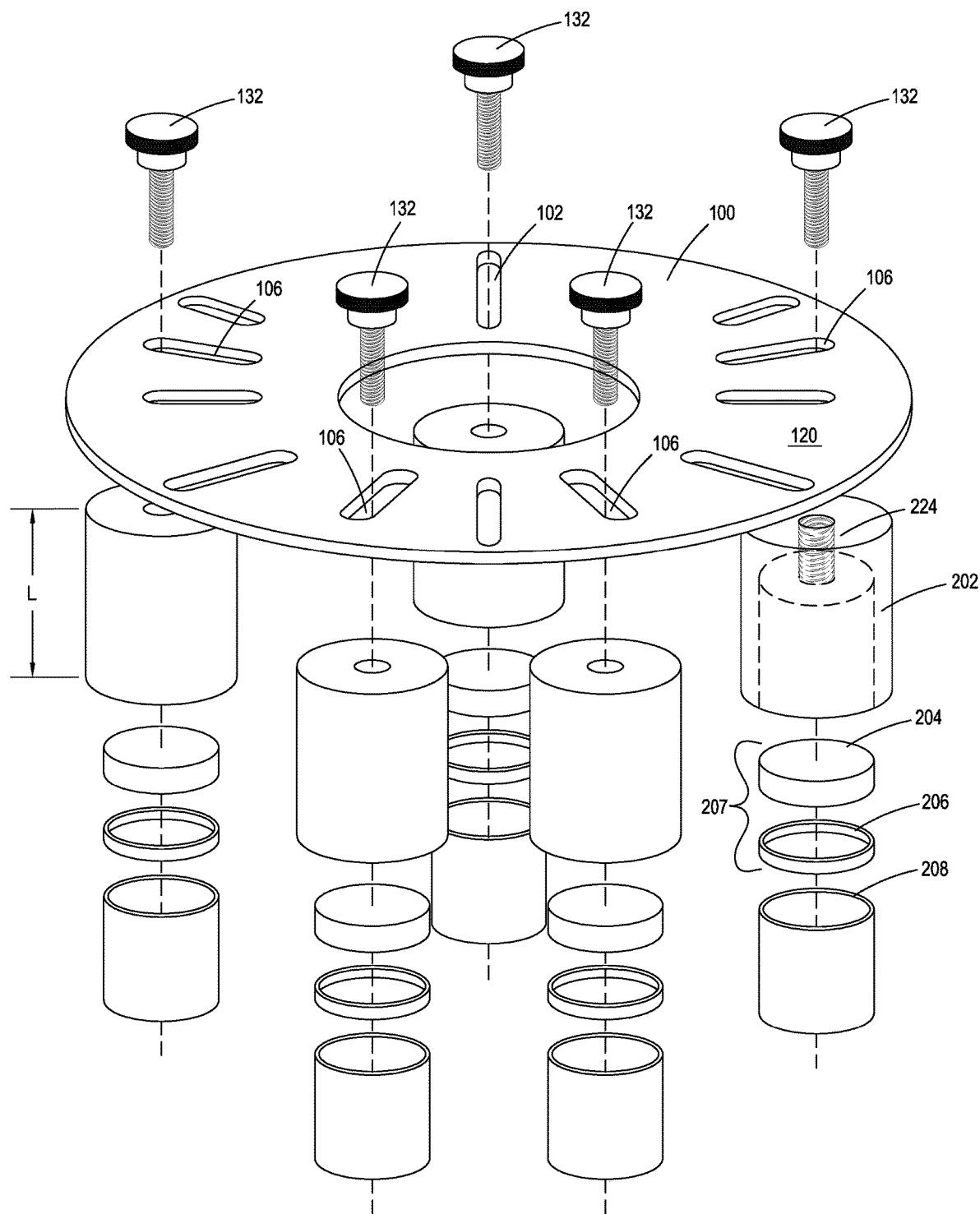


Fig. 2A

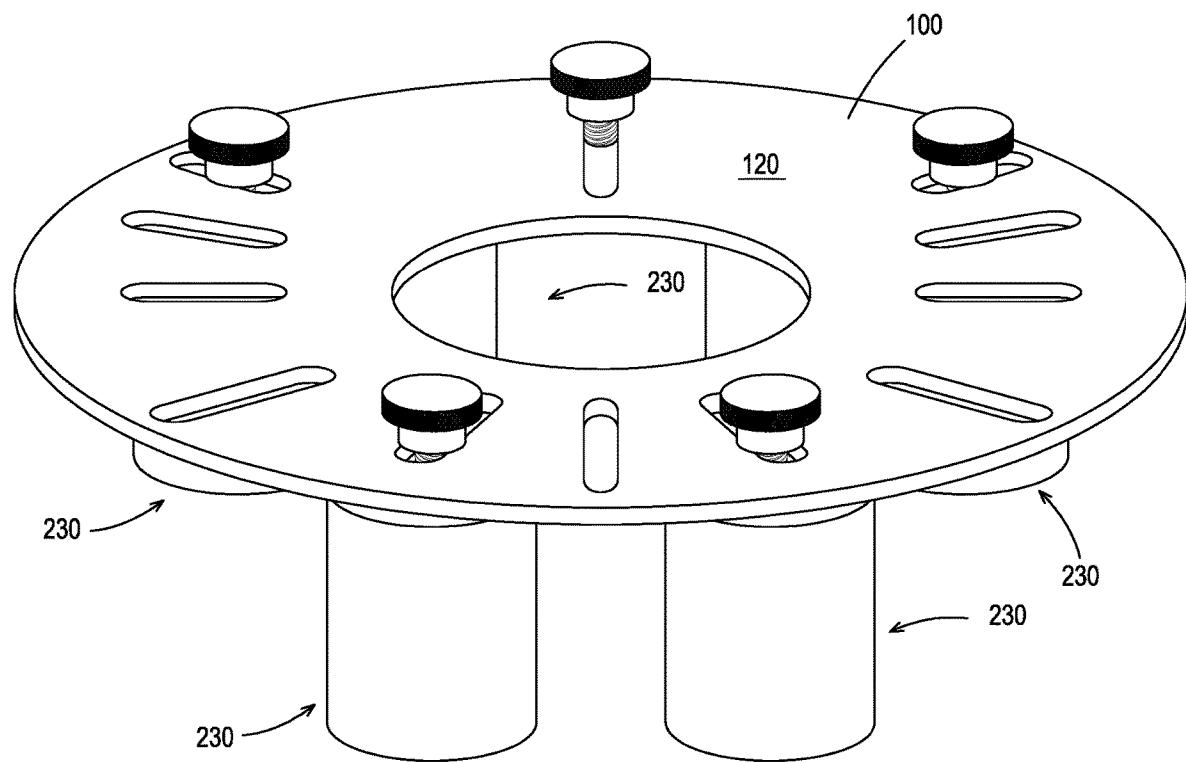


Fig. 2B

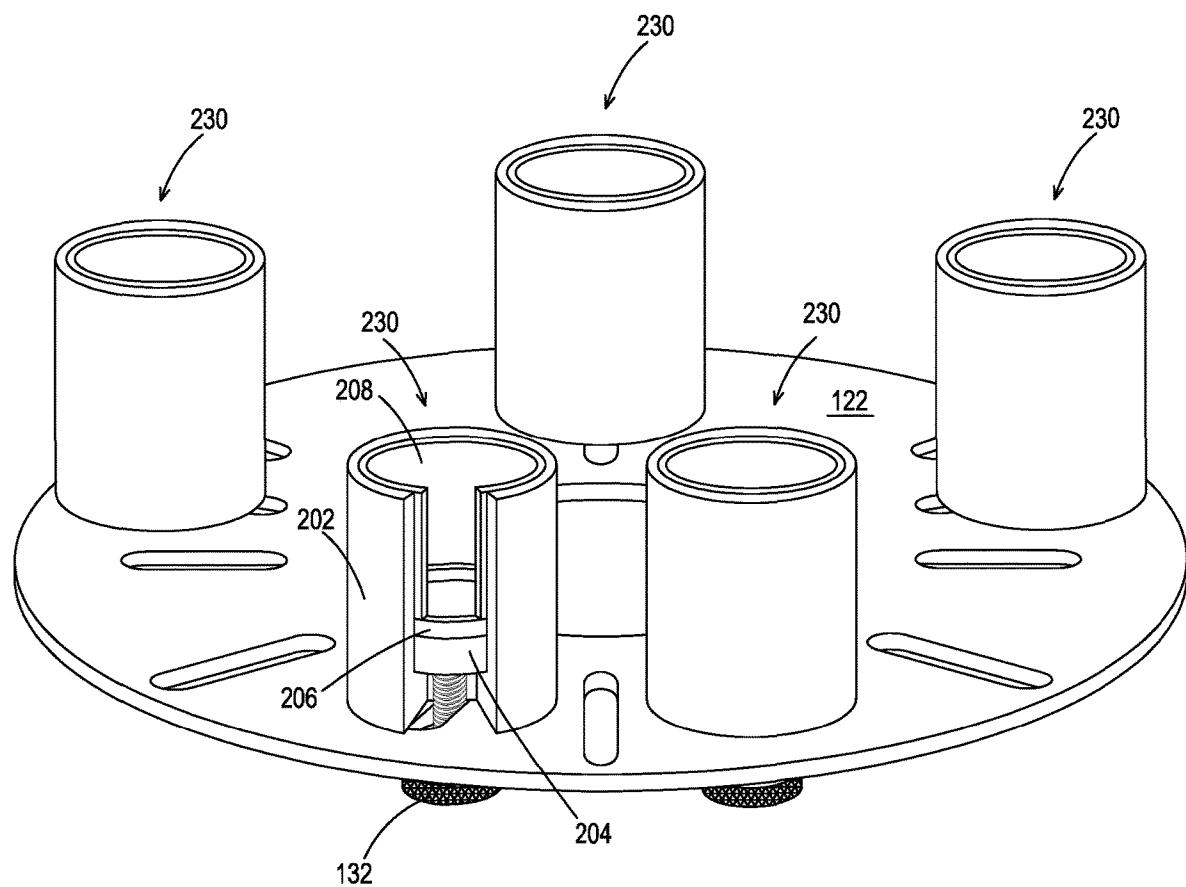


Fig. 2C

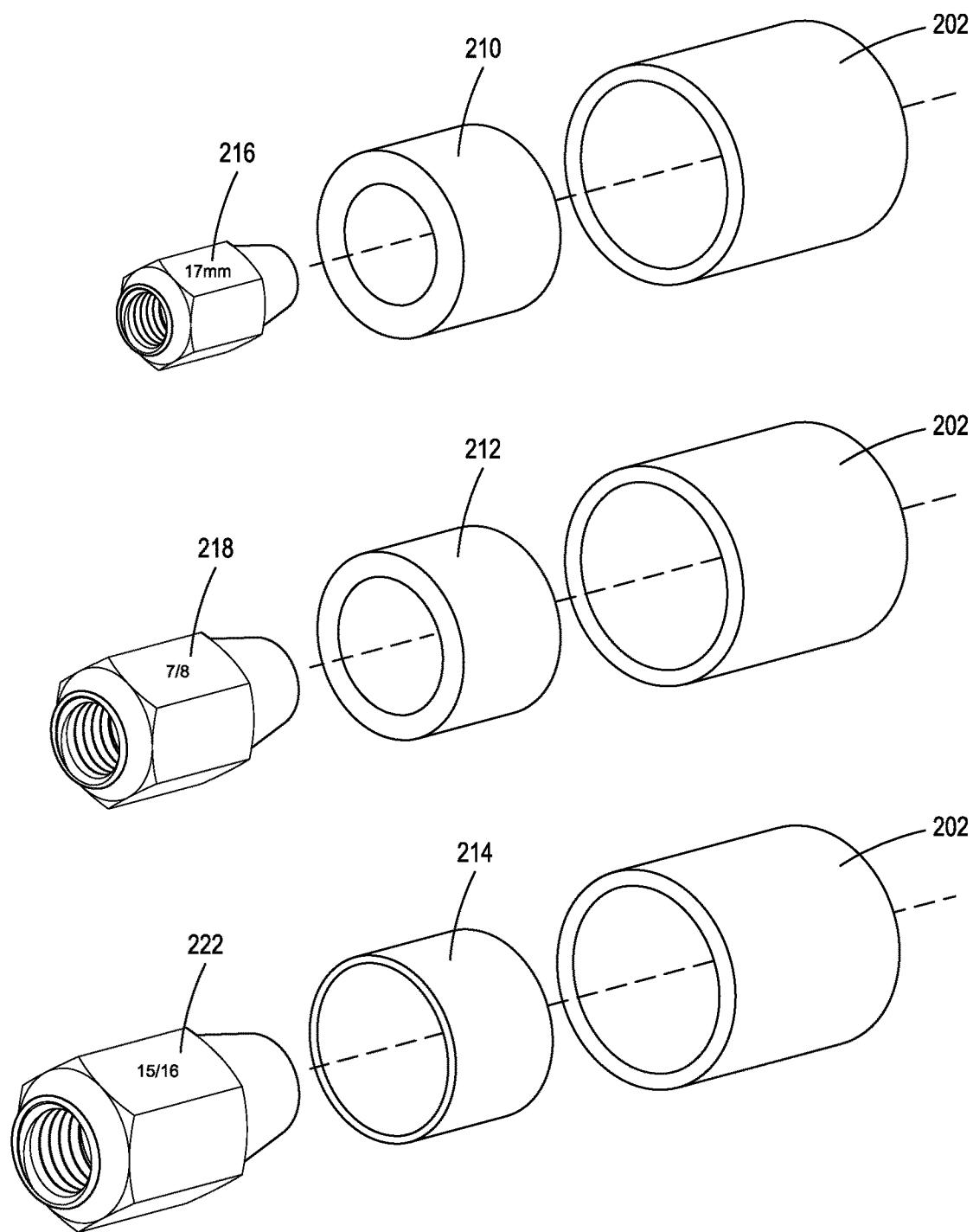


Fig. 2D

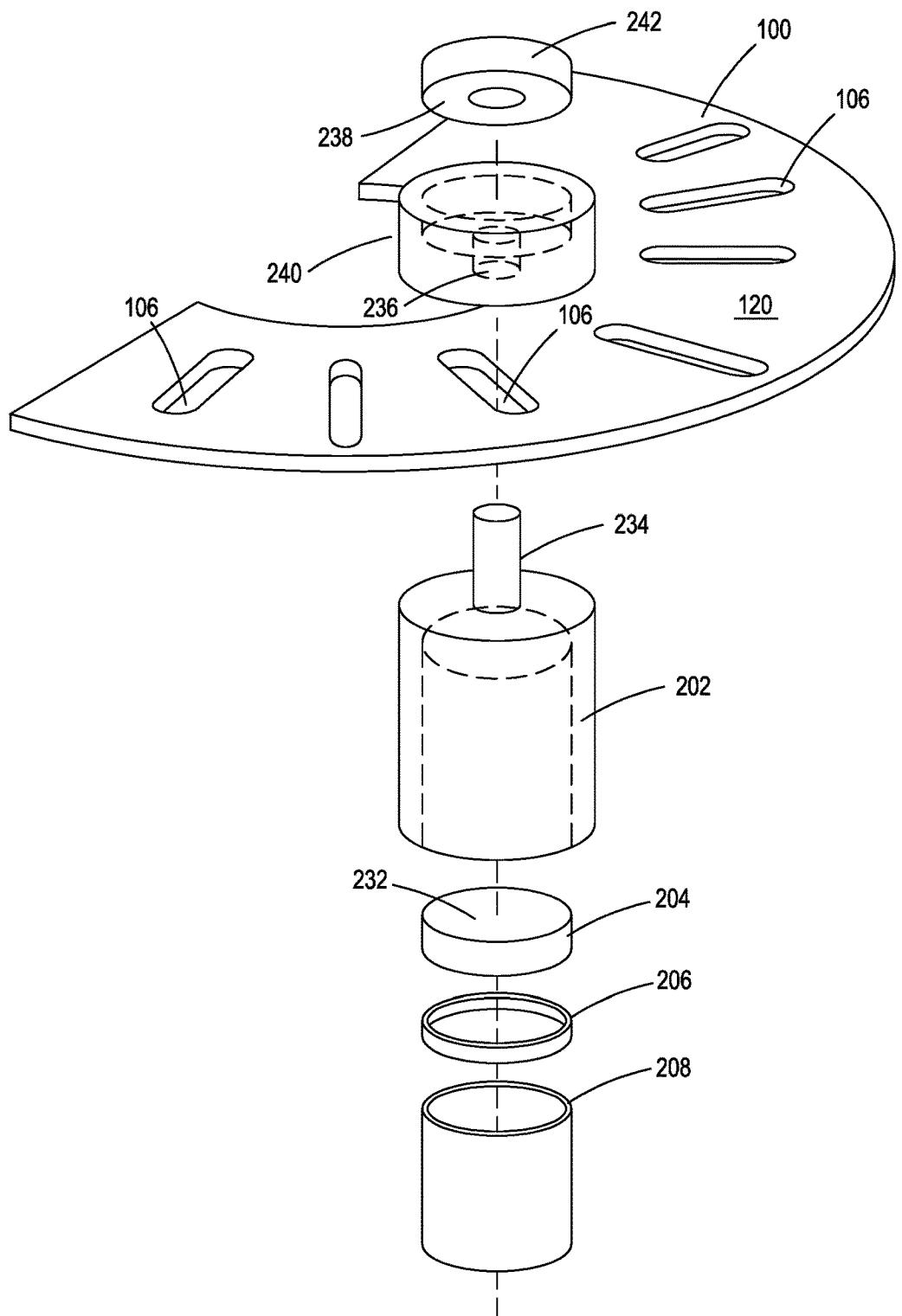


Fig. 2E

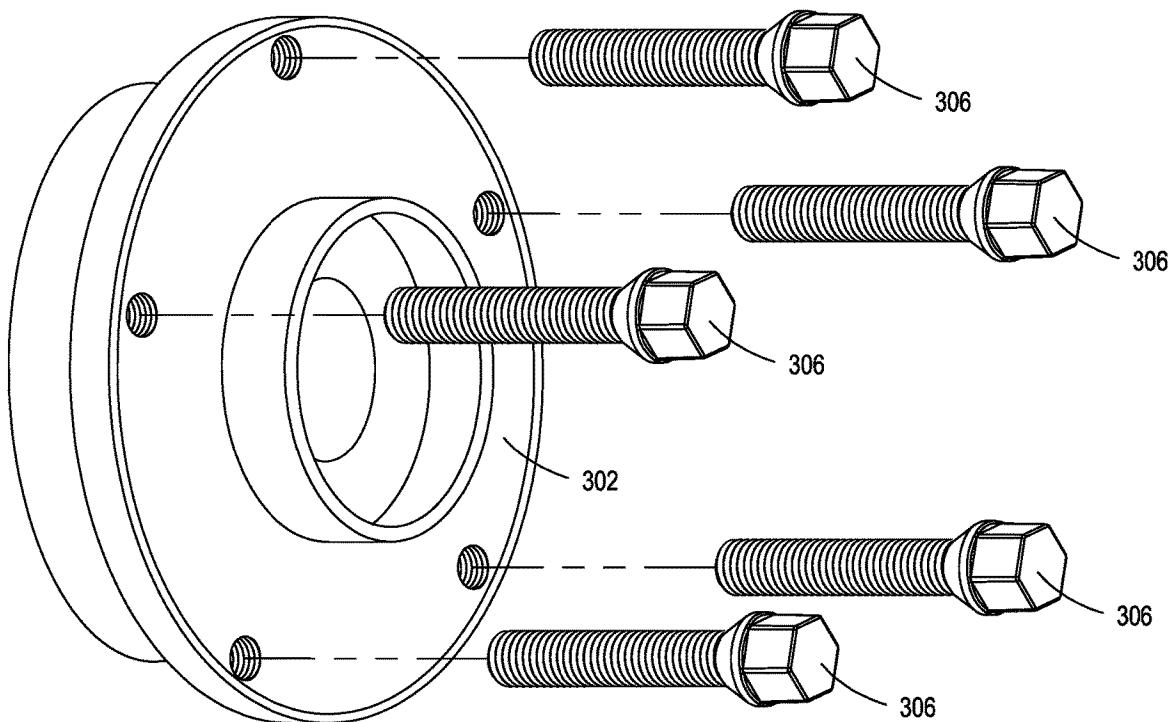
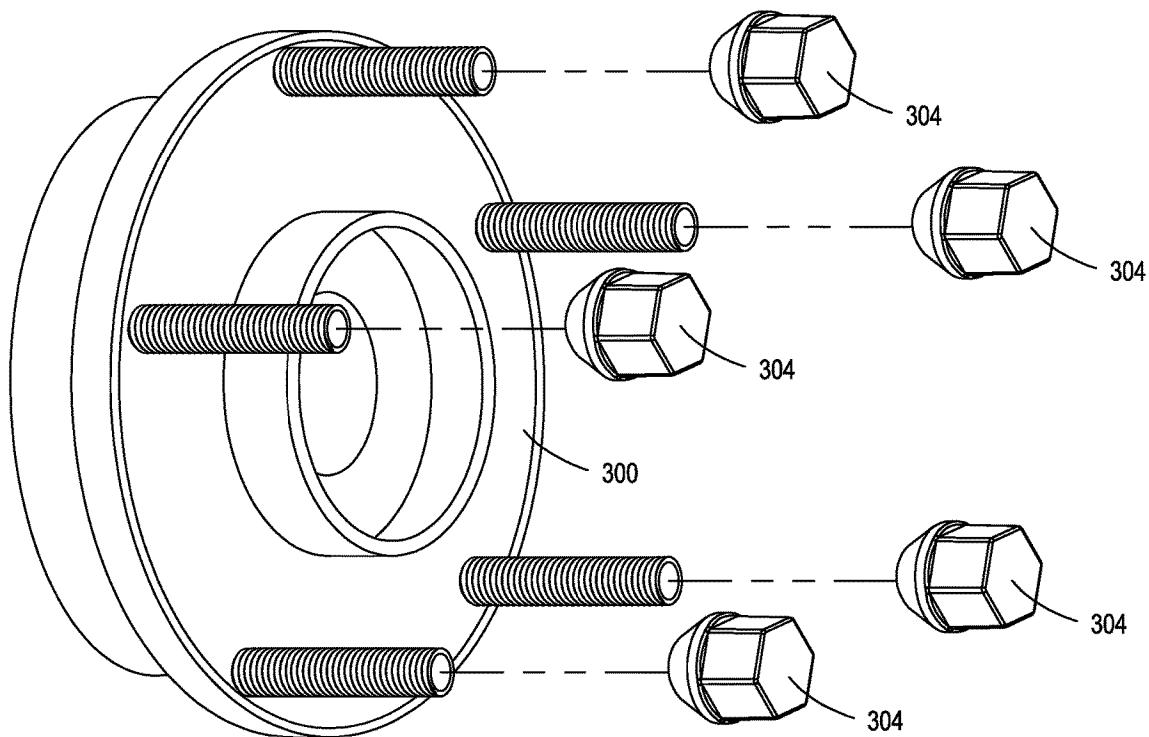


Fig. 3A (PRIOR ART)

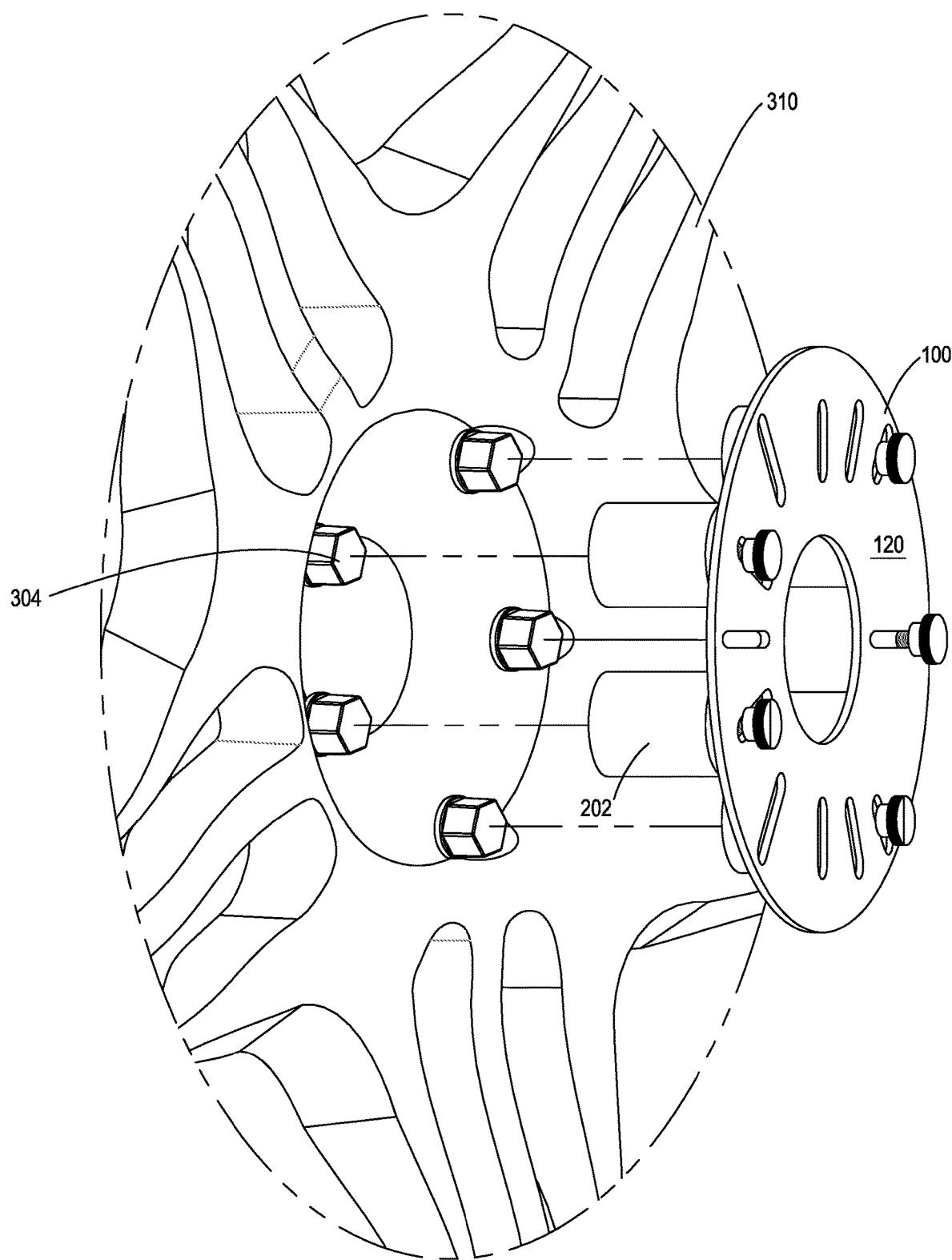


Fig. 3B

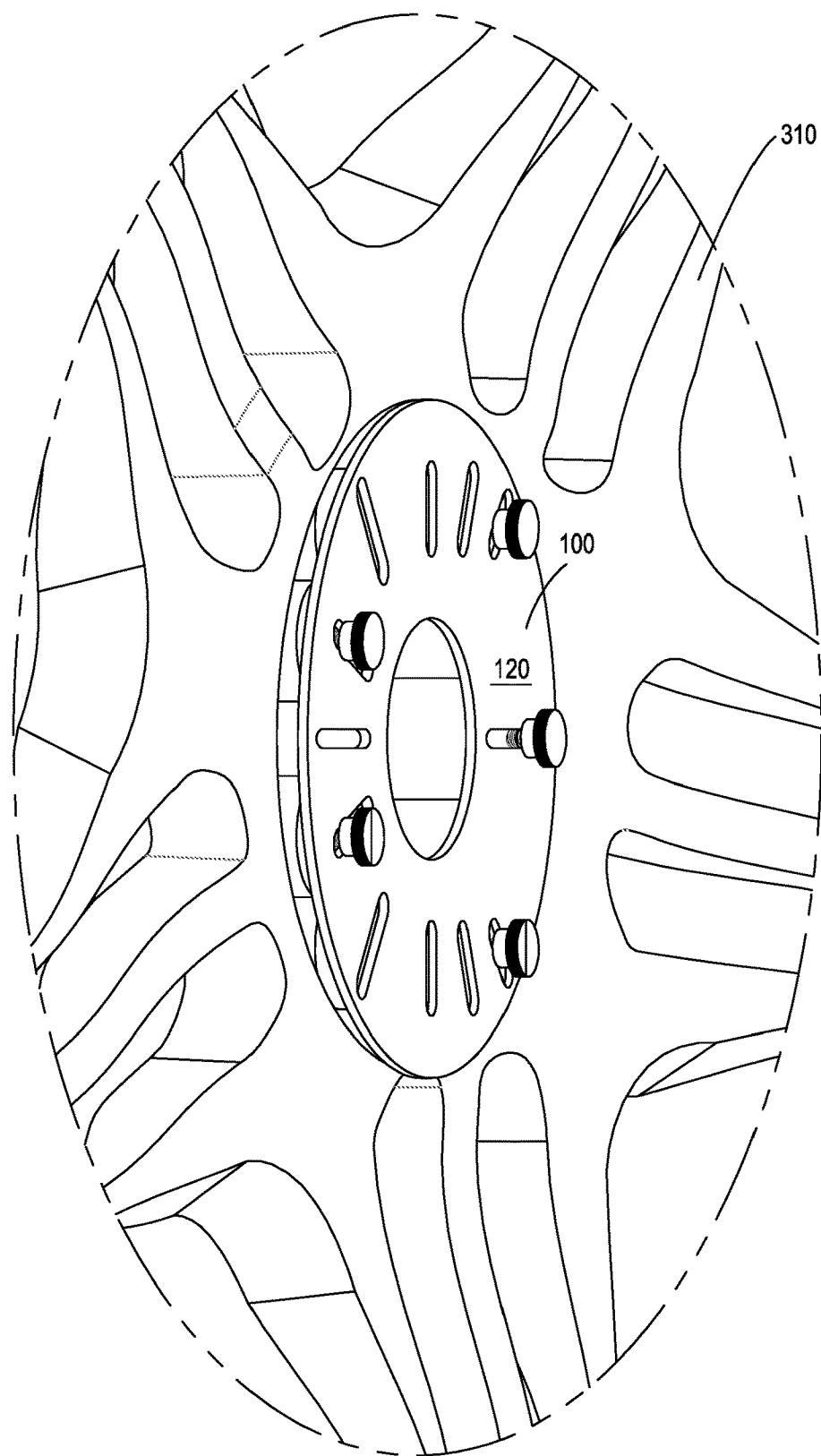


Fig. 3C

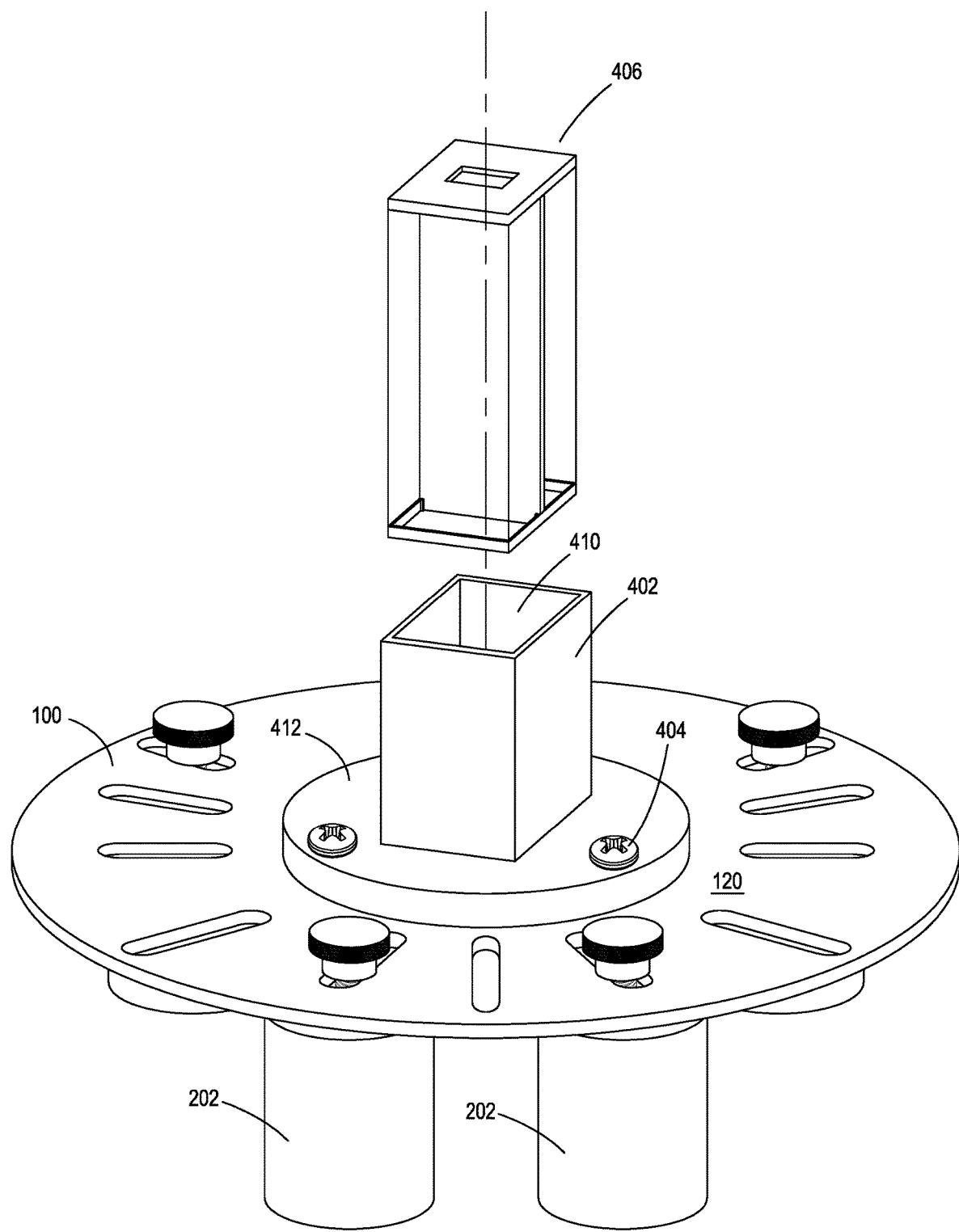


Fig. 4A

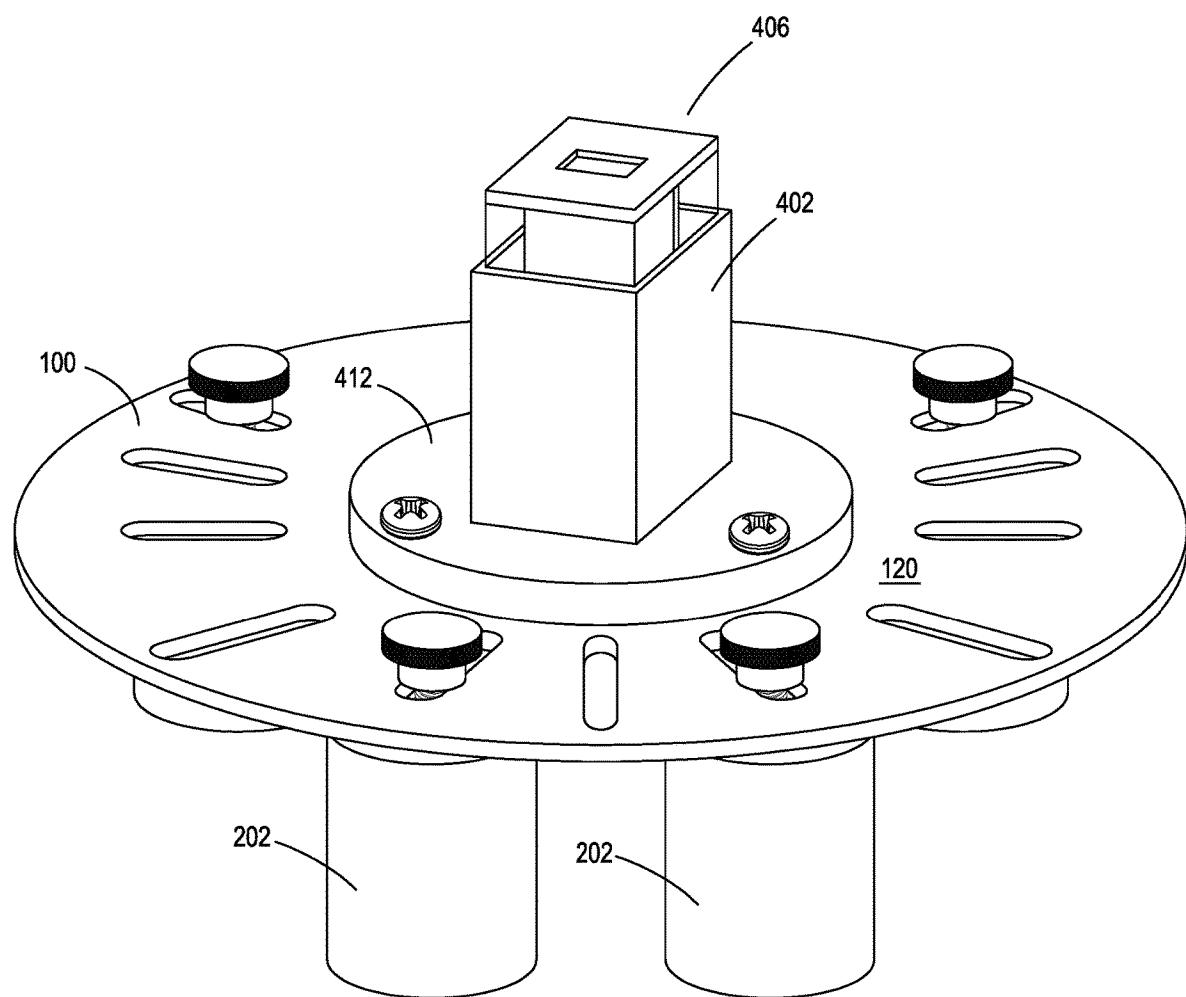


Fig. 4B

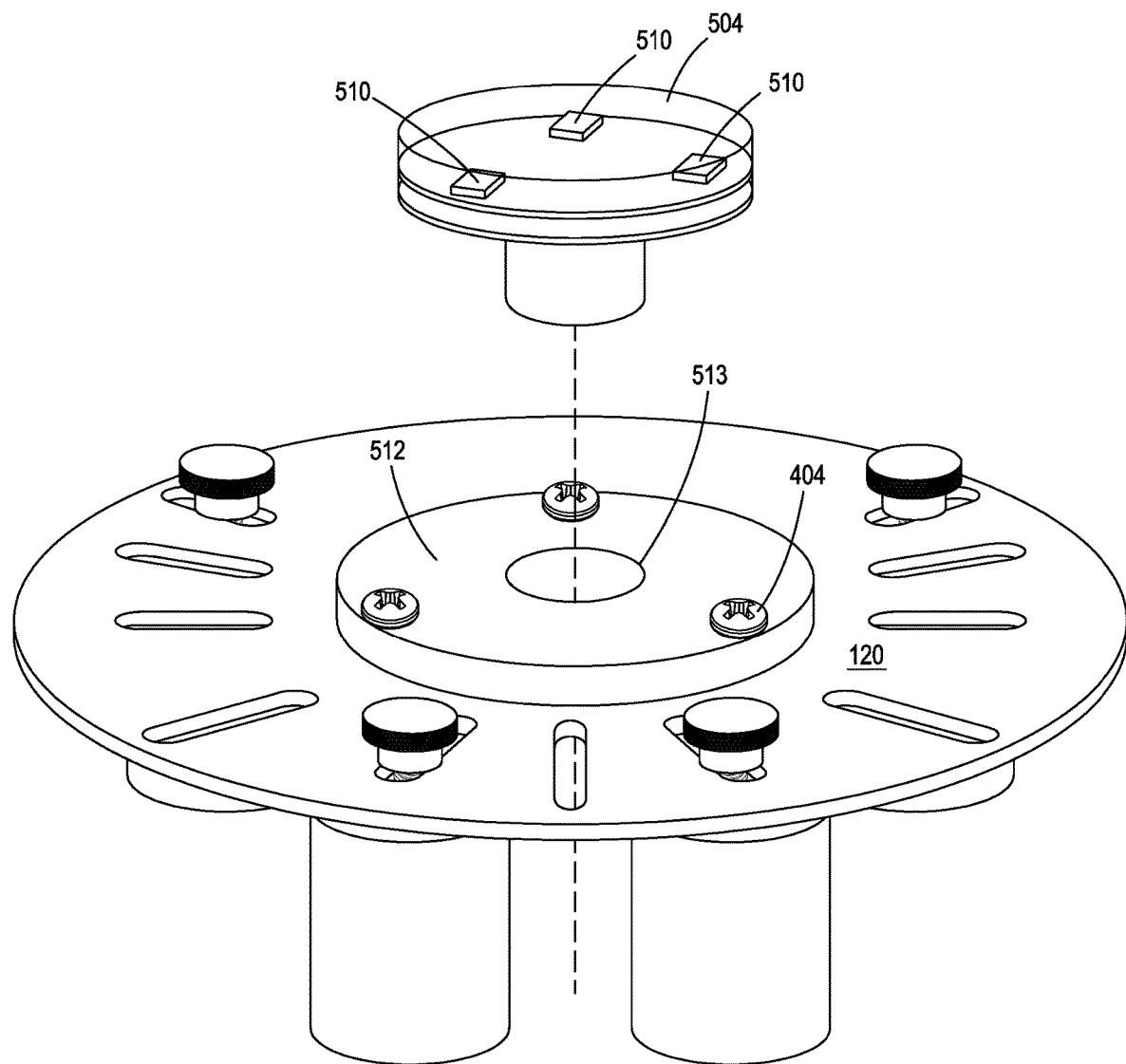


Fig. 5A

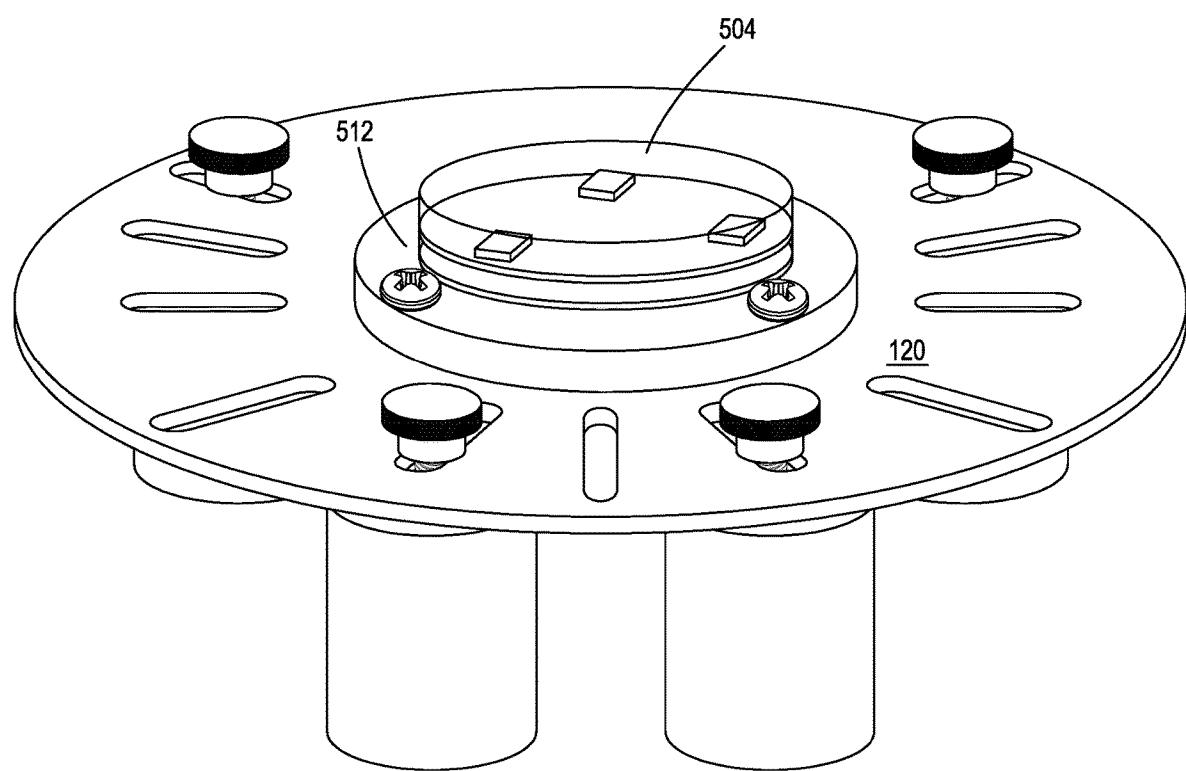


Fig. 5B

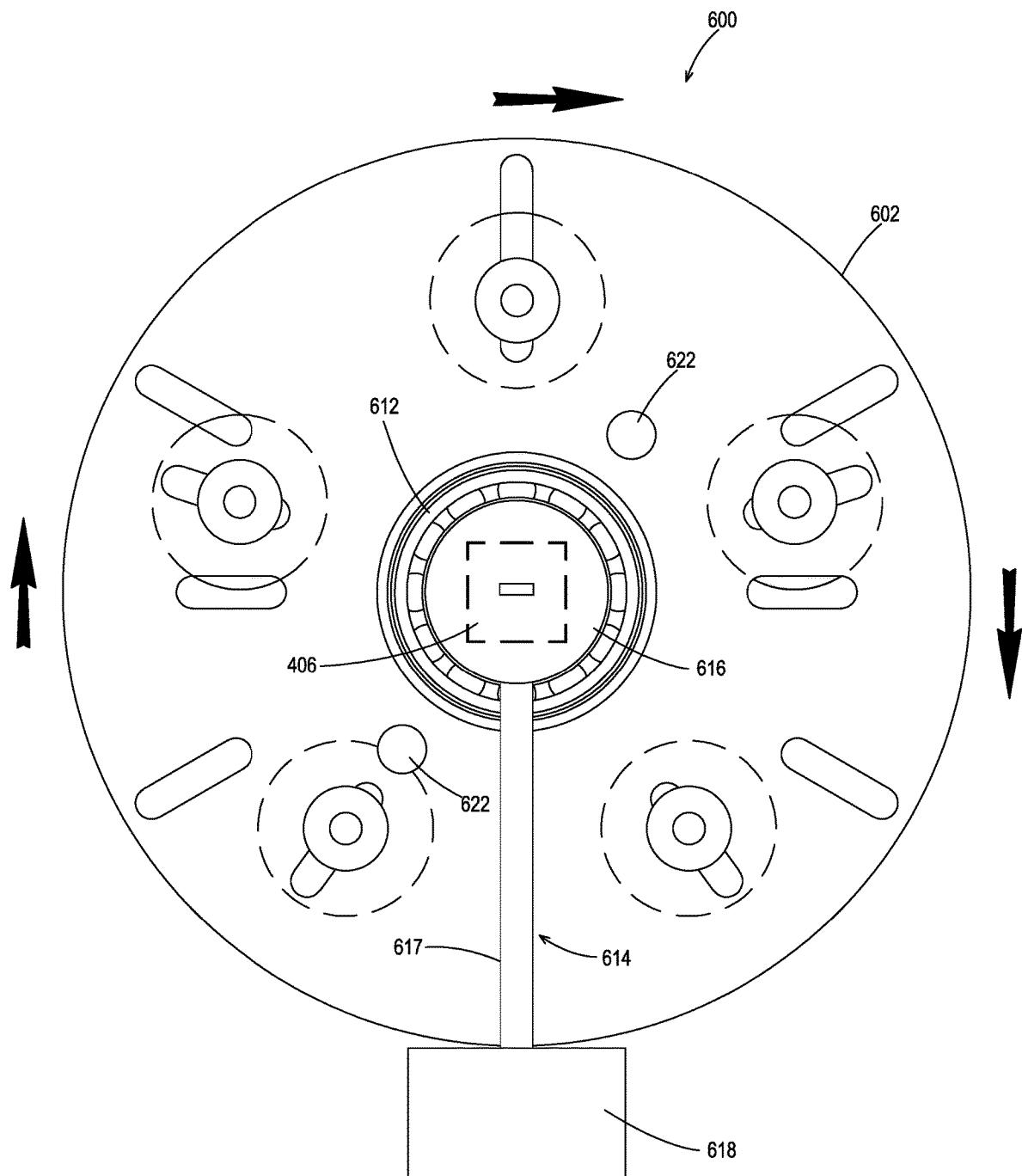


Fig. 6A

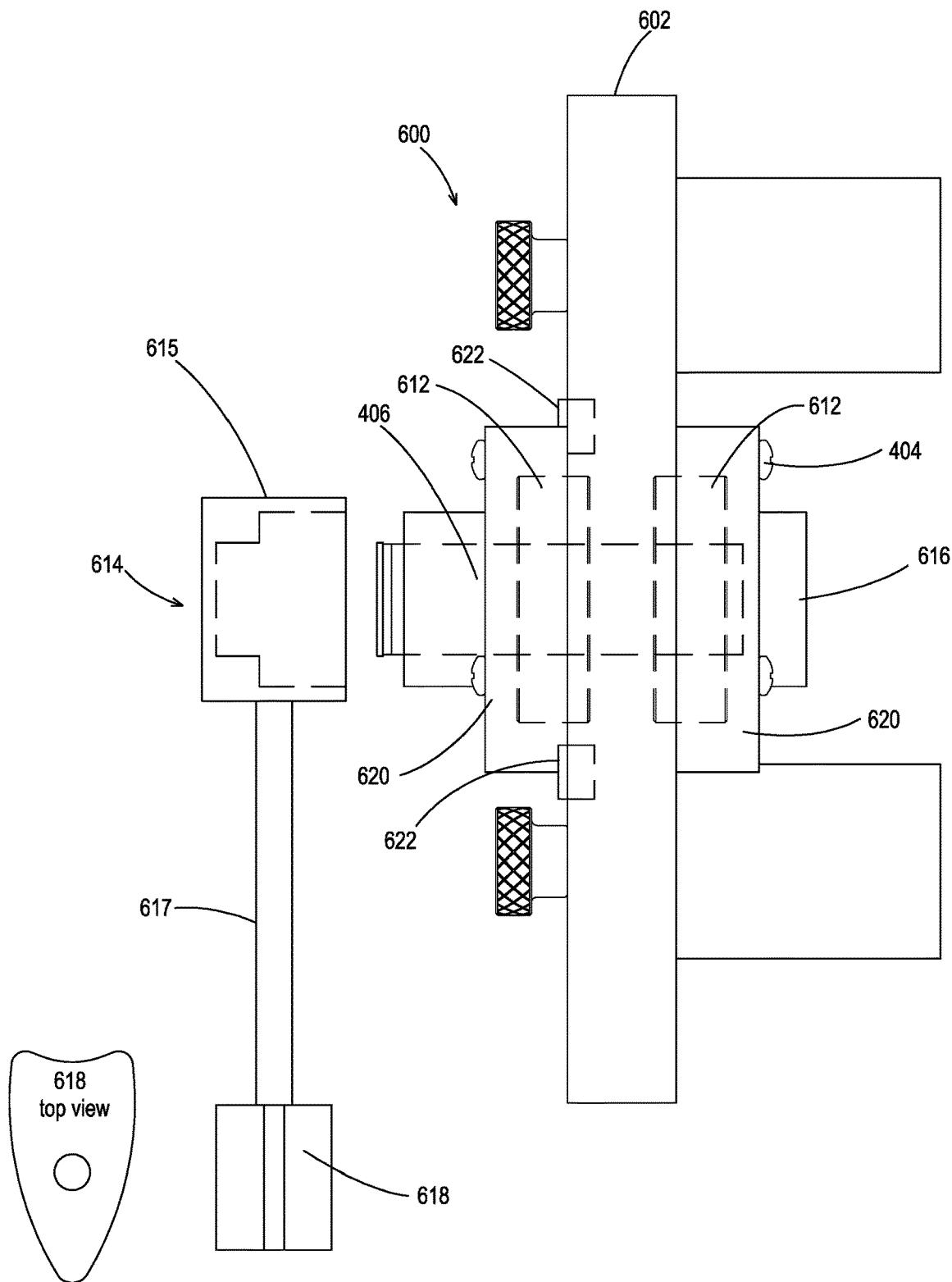


Fig. 6B

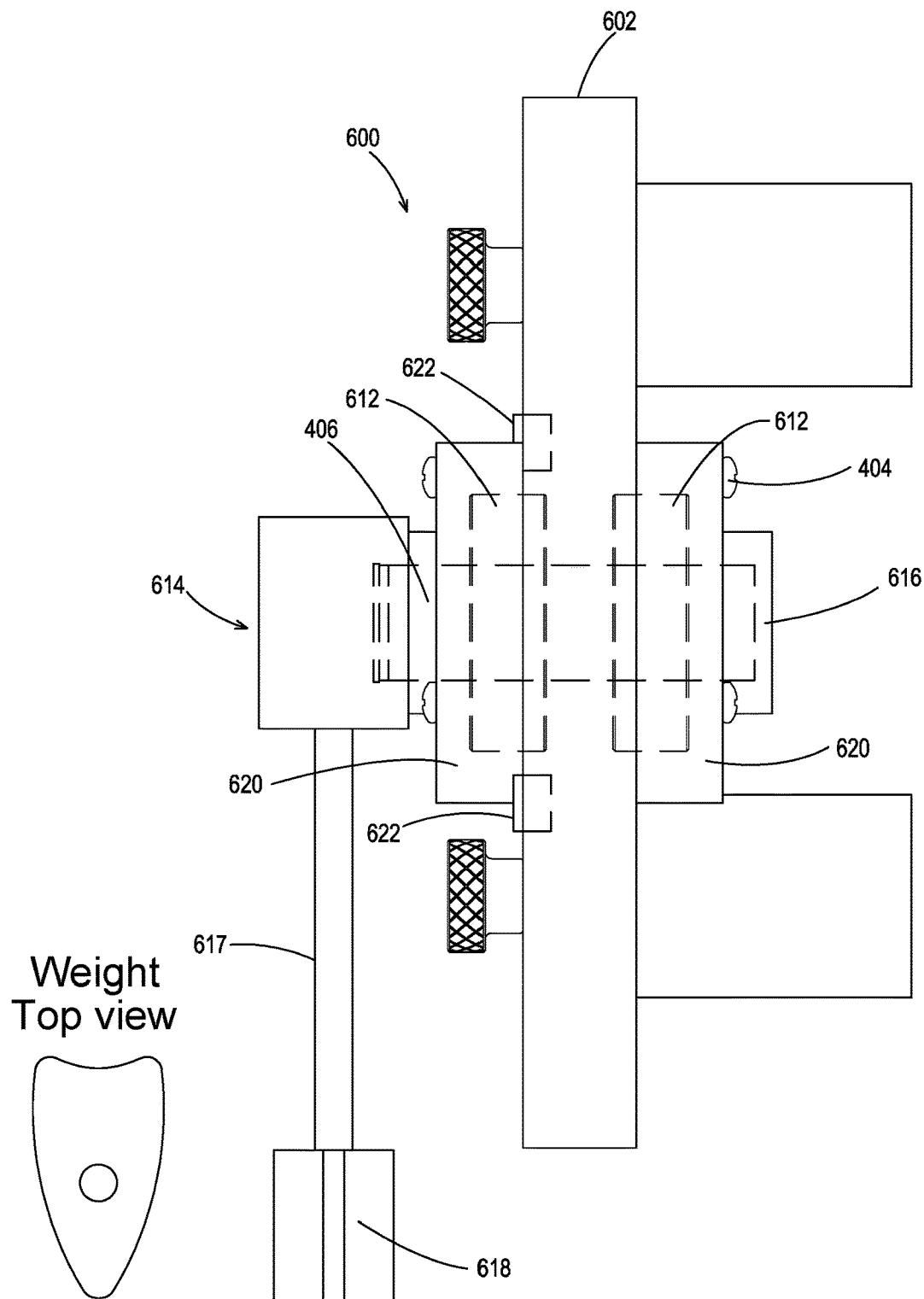


Fig. 6C

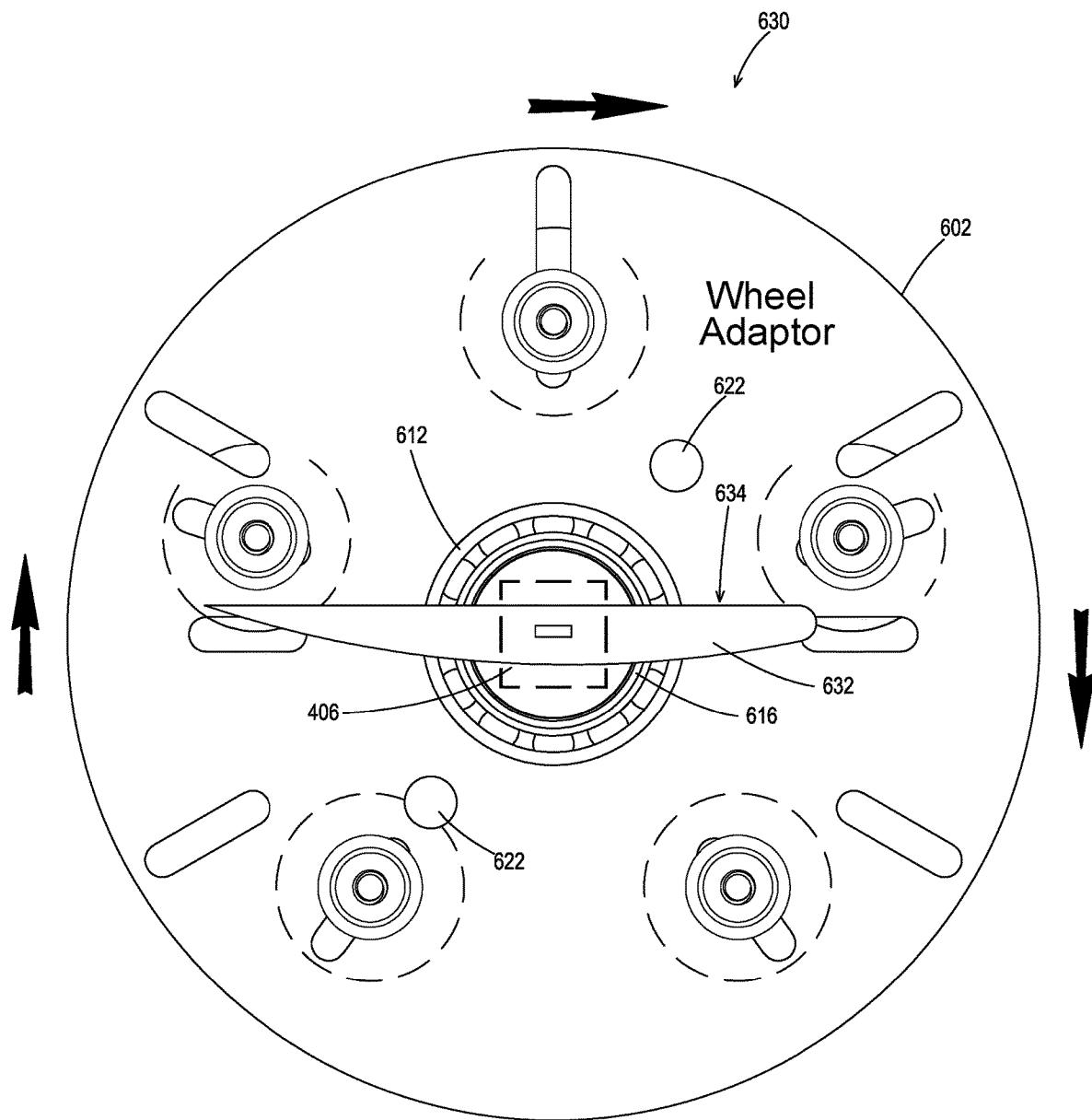


Fig. 6D

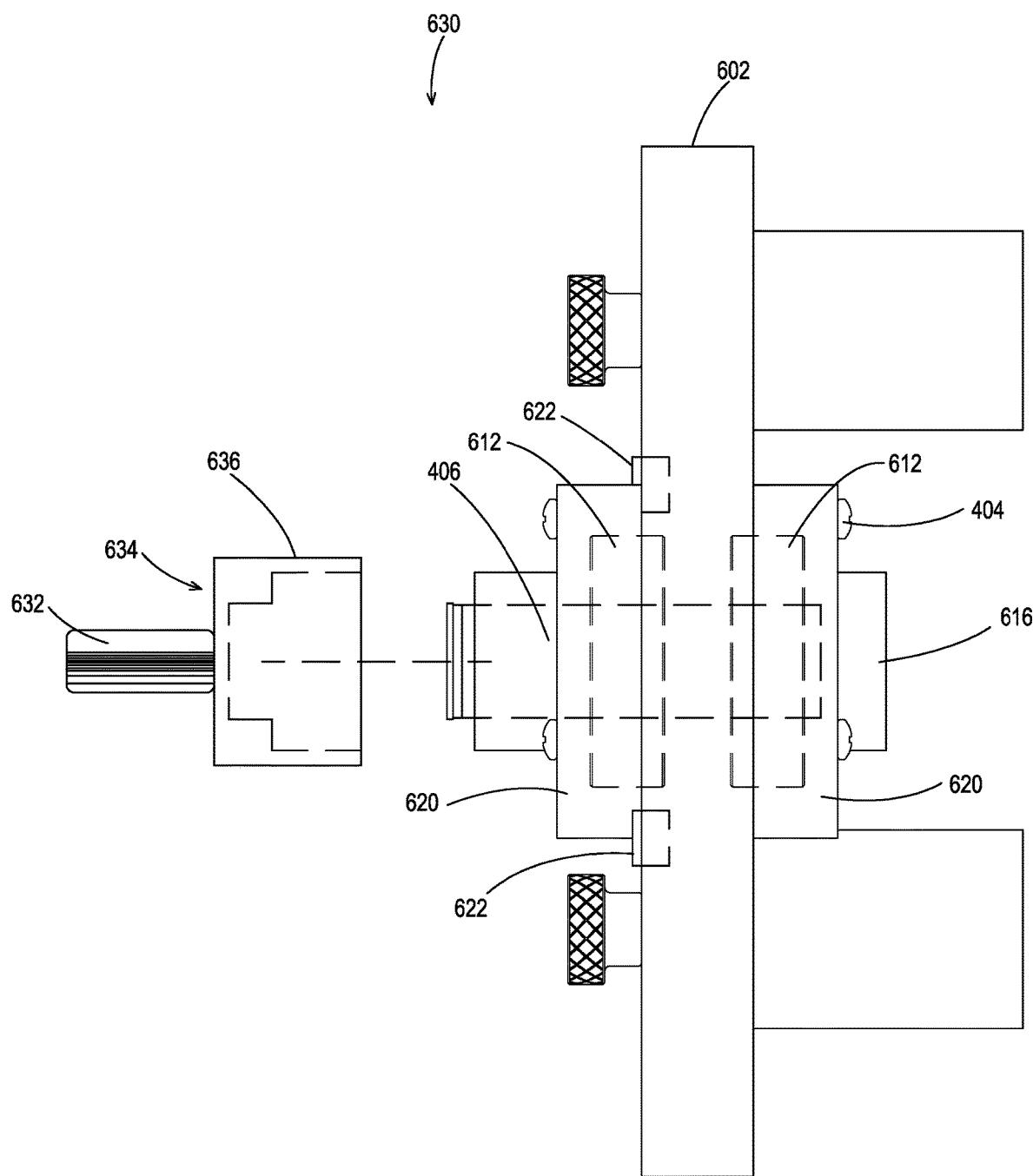


Fig. 6E

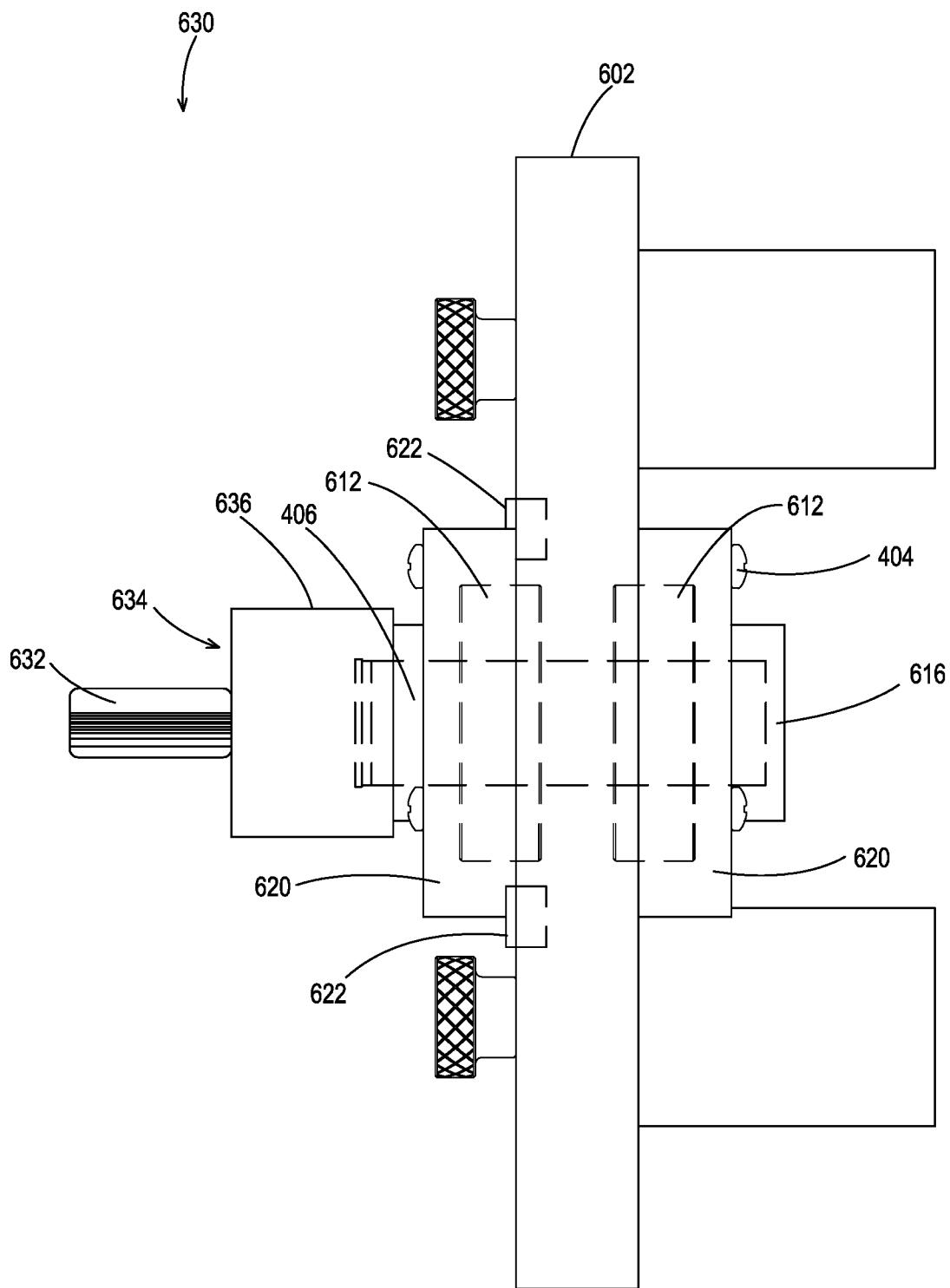


Fig. 6F

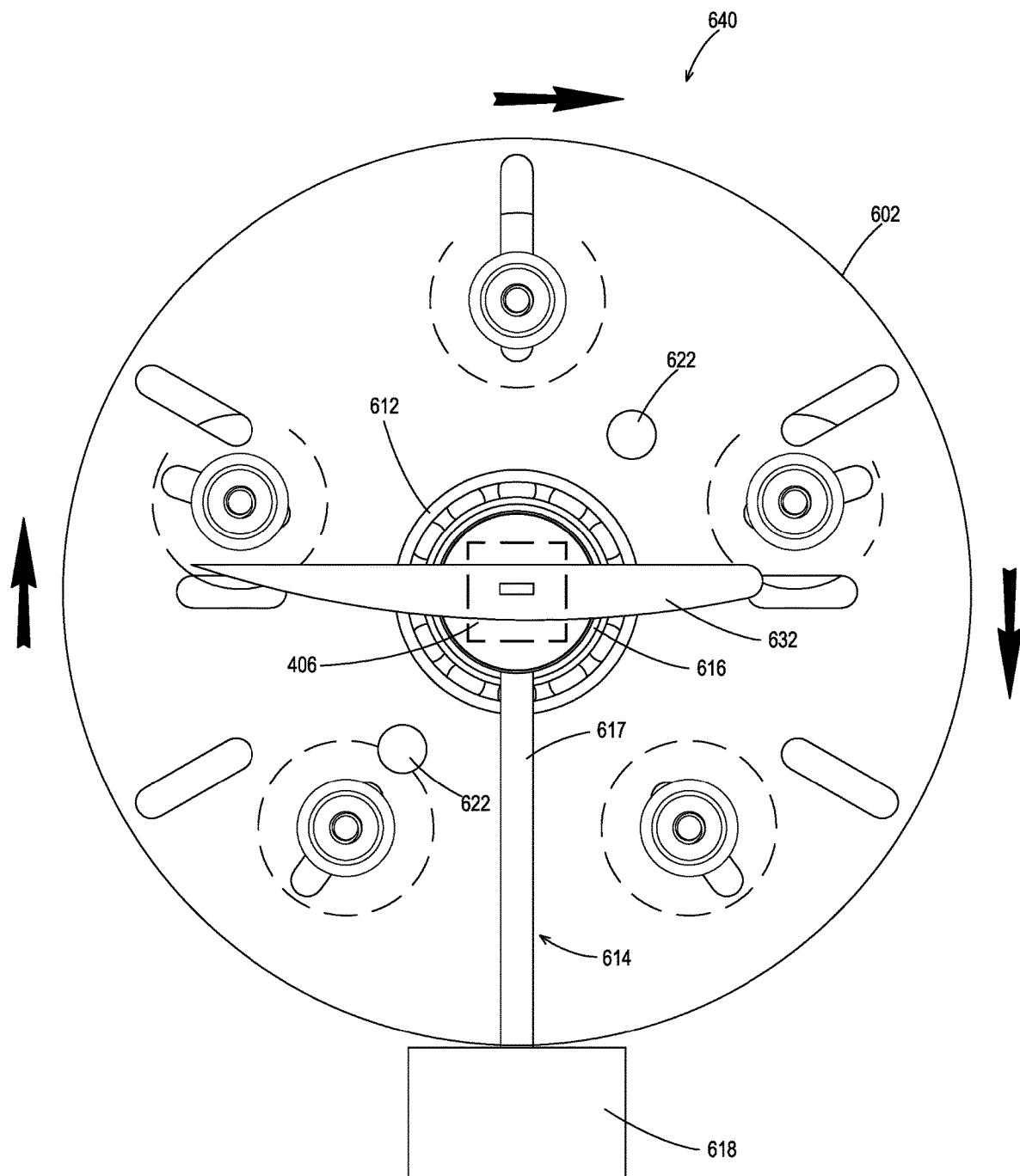


Fig. 6G

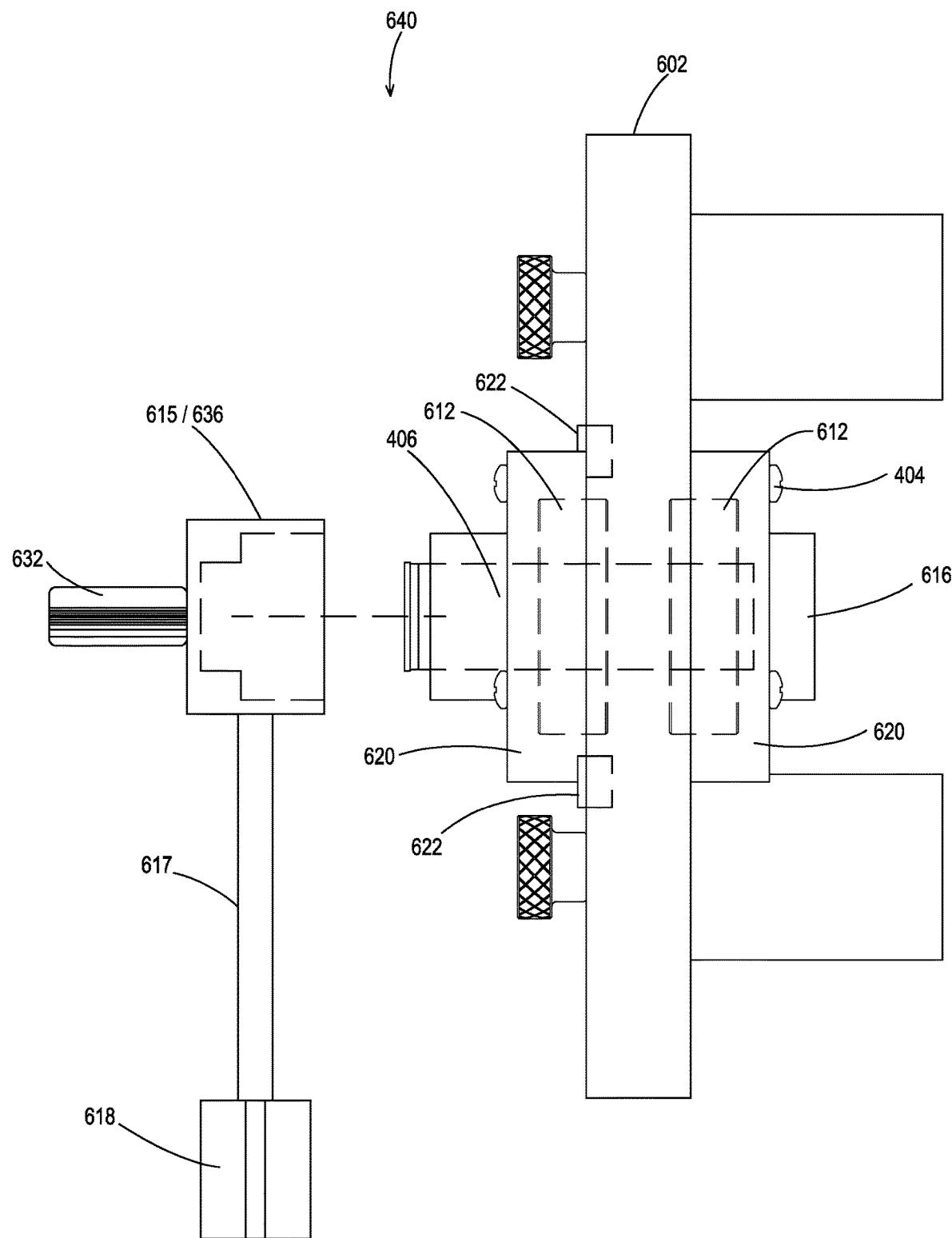


Fig. 6H

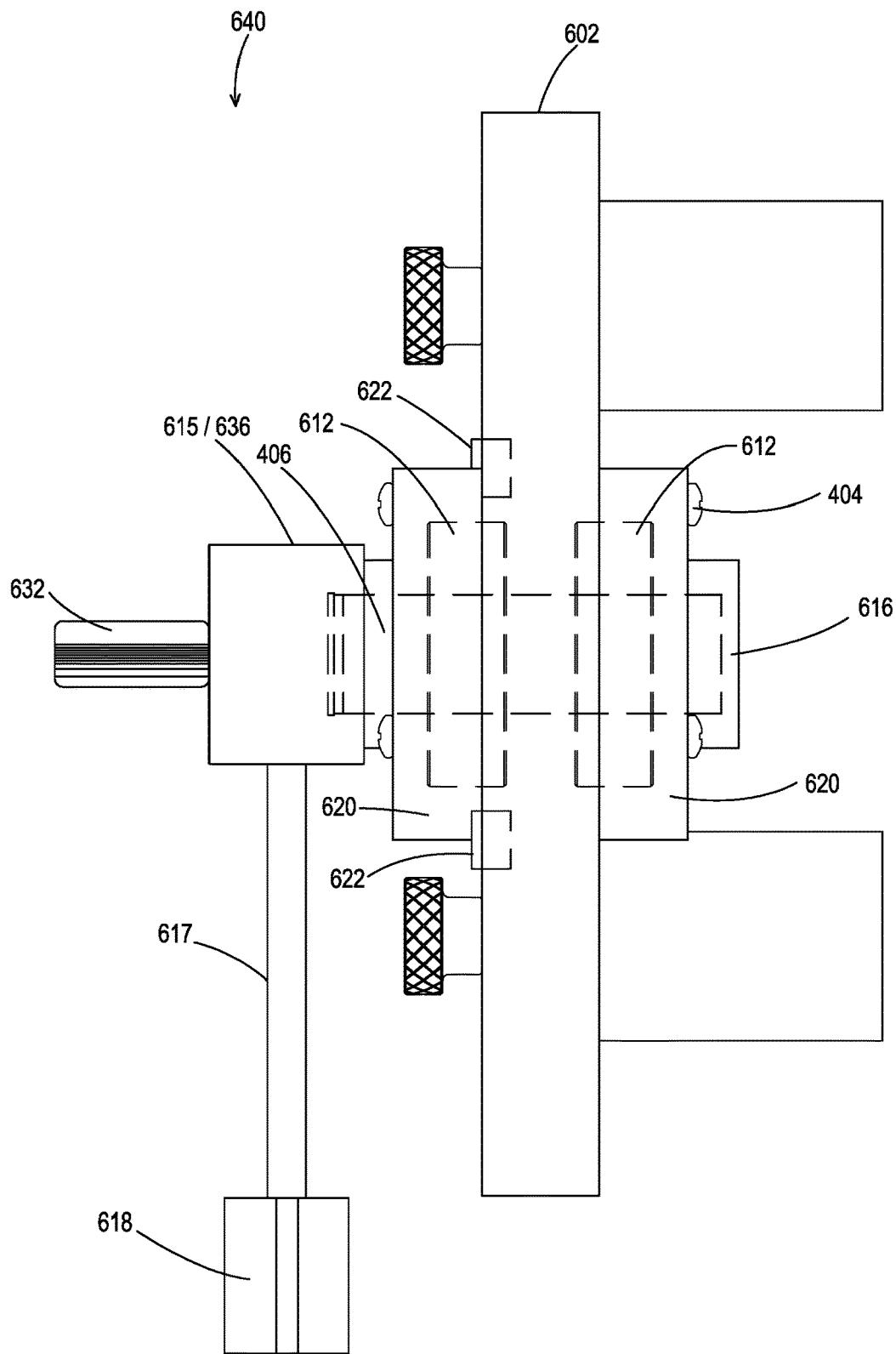


Fig. 6I

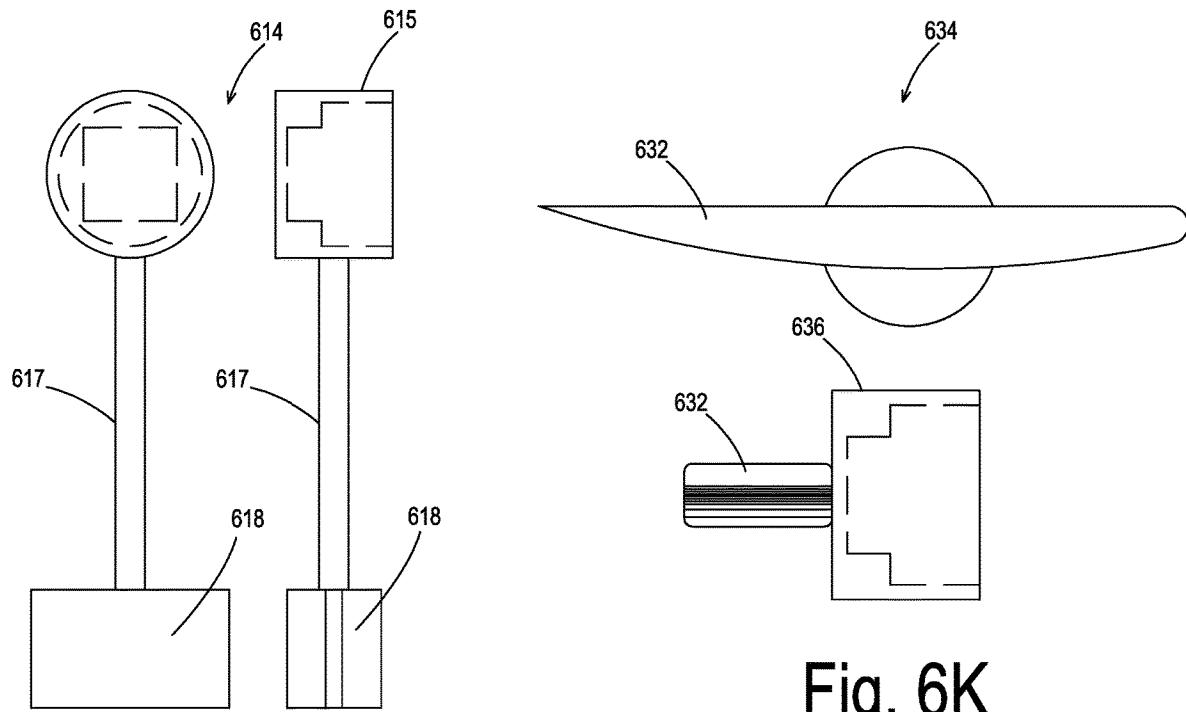


Fig. 6K

Fig. 6J

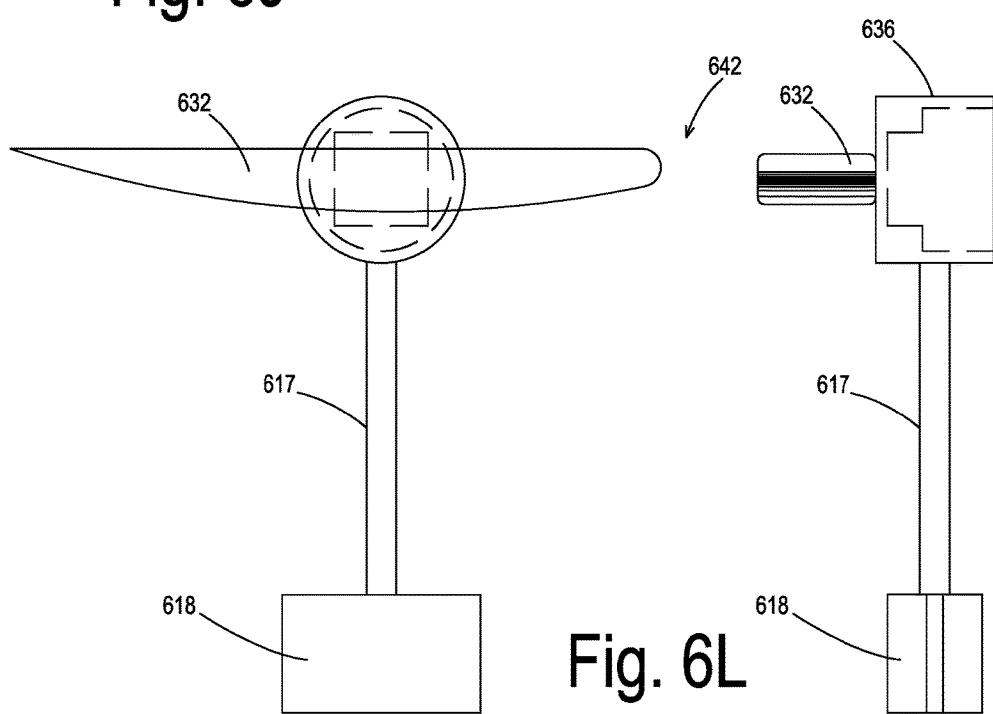


Fig. 6L

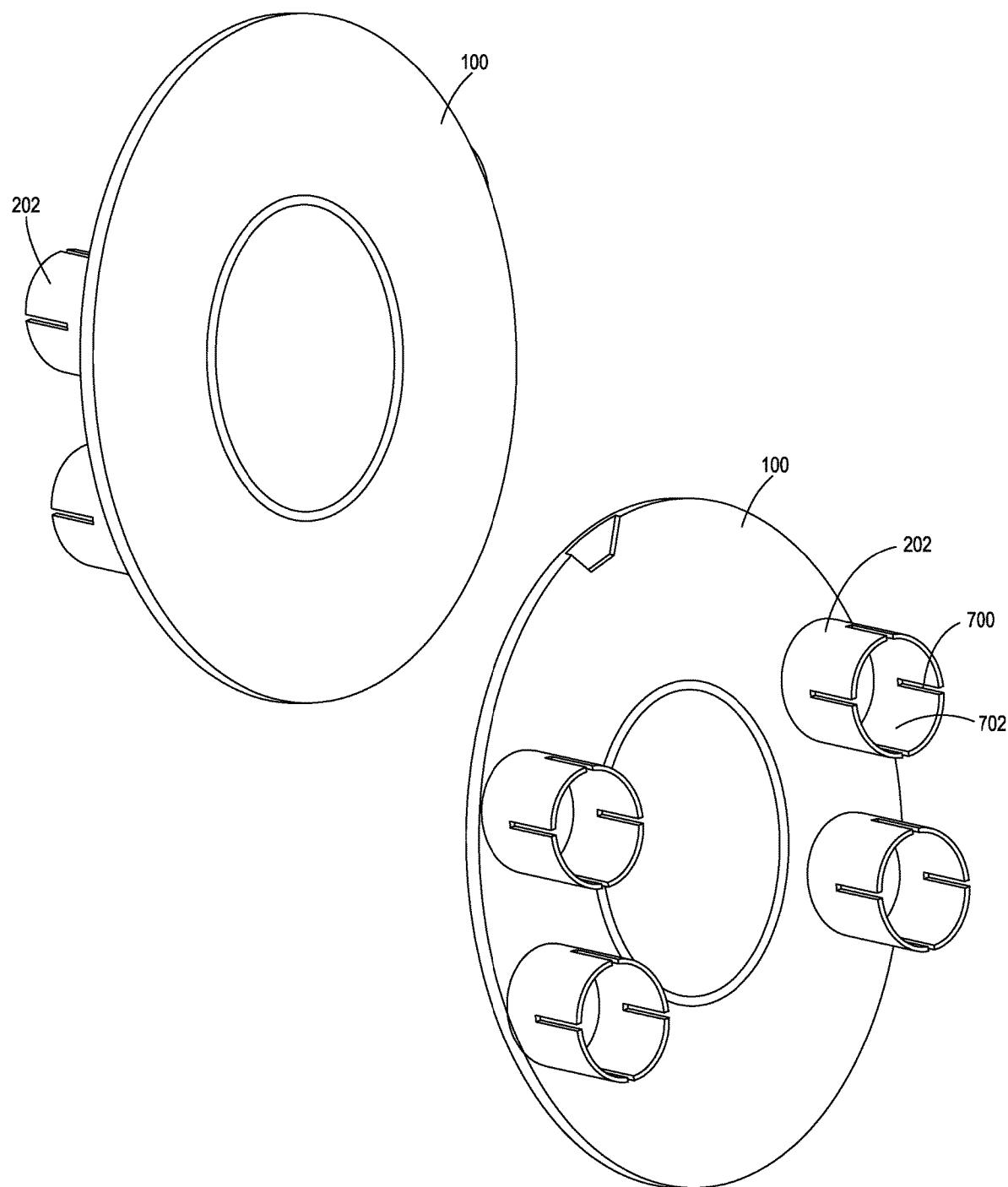


Fig. 7A

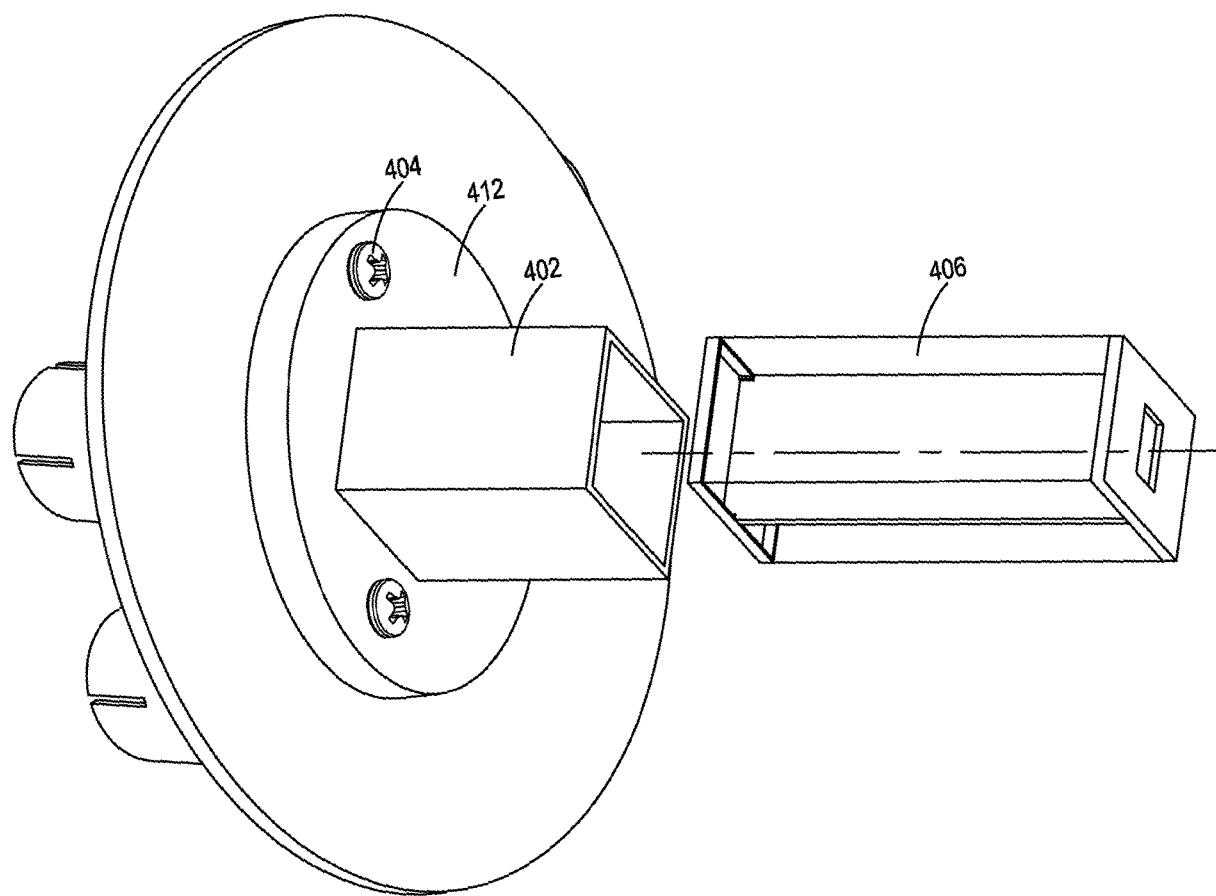


Fig. 7B

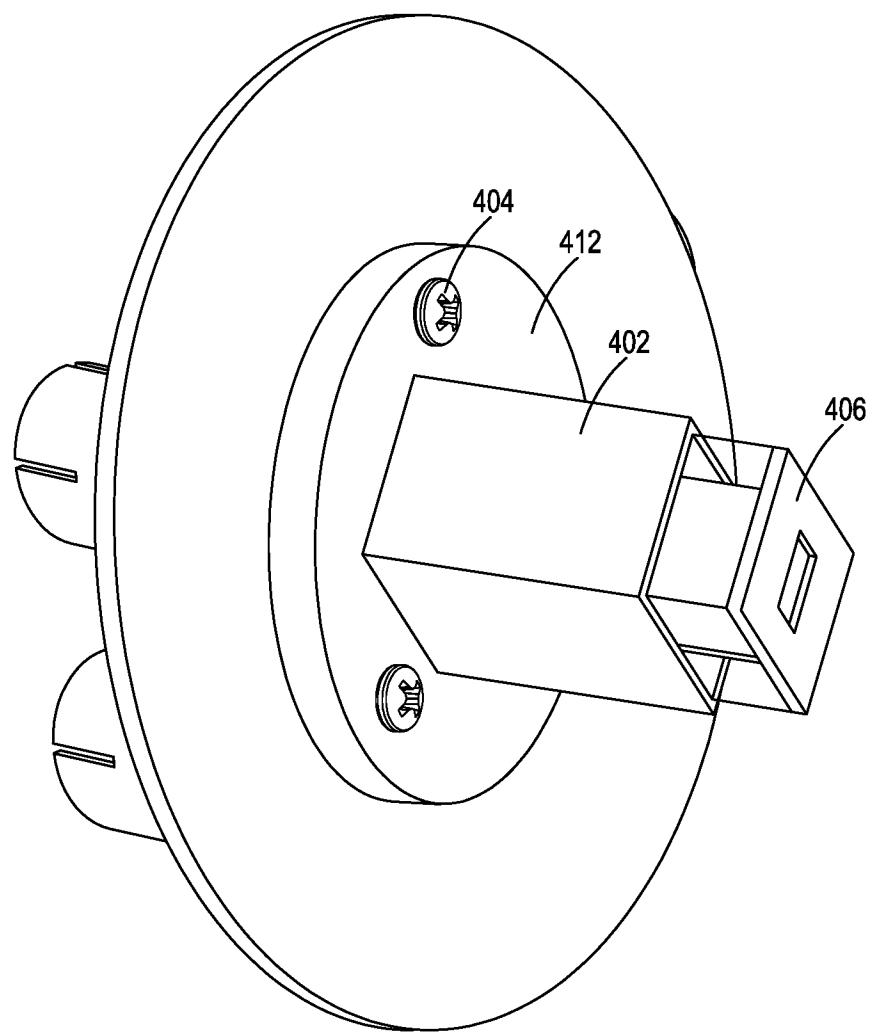


Fig. 7C

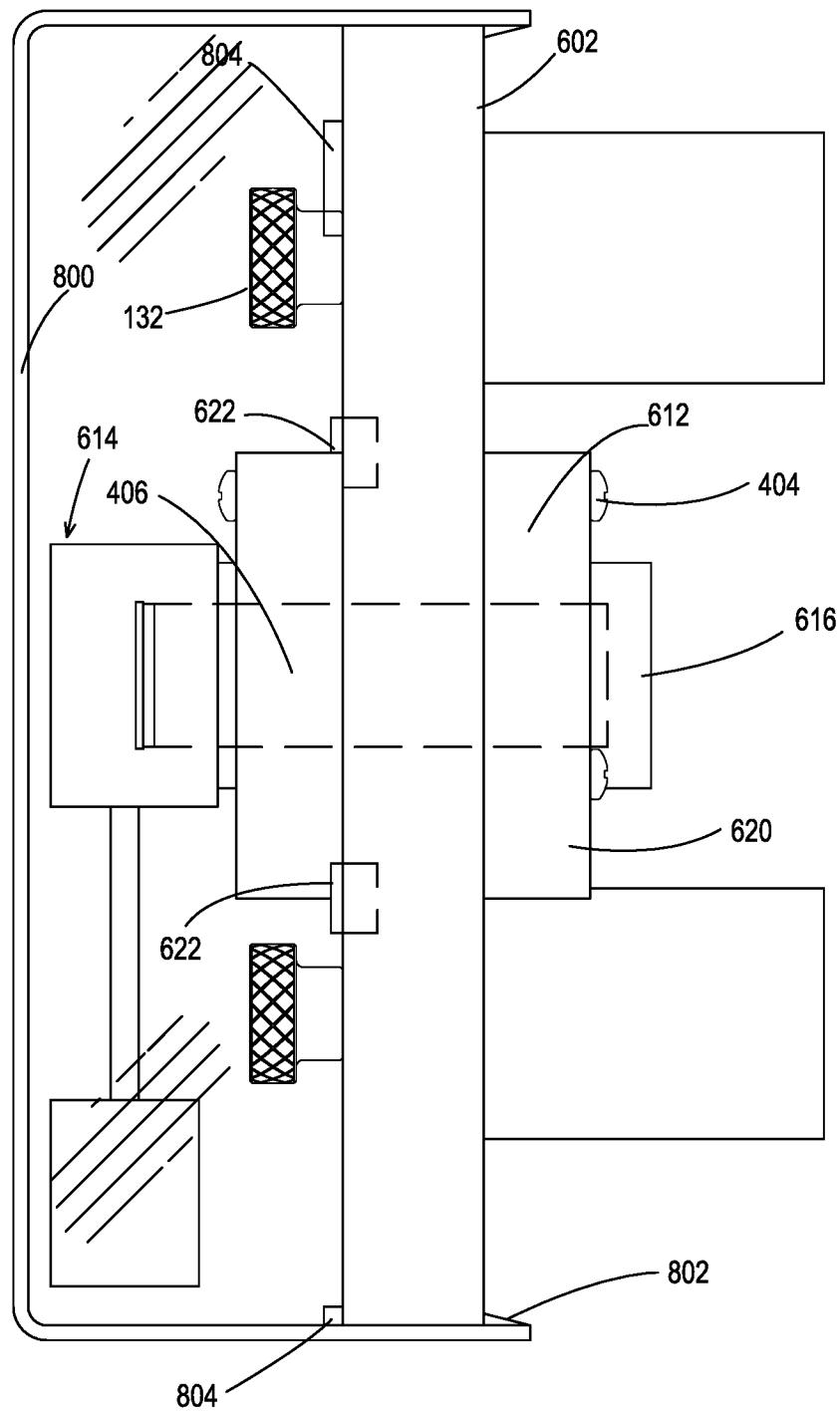


Fig. 8A

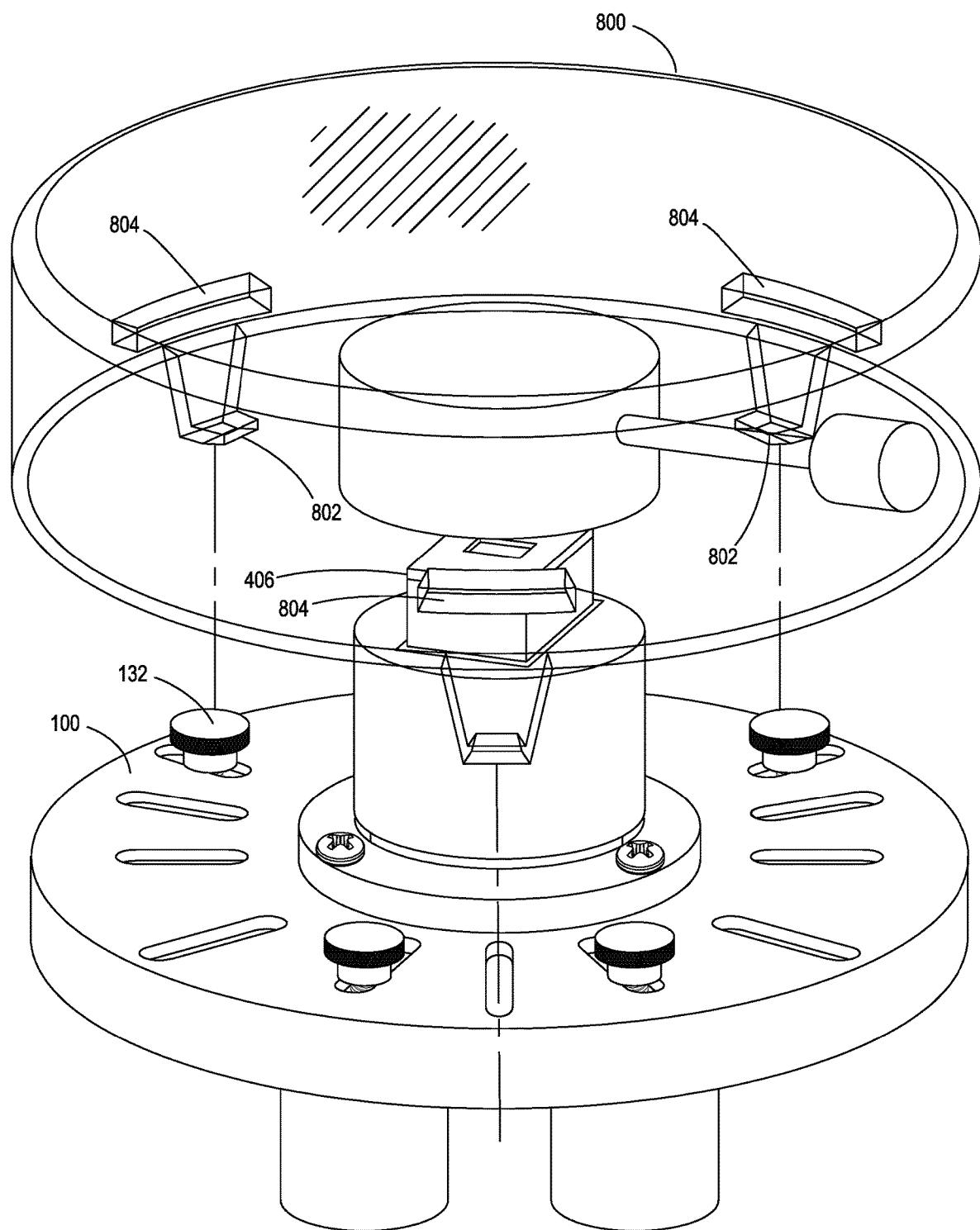


Fig. 8B

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**APPARATUS FOR MEASURING
IMBALANCE FORCES OF A TIRE/HUB
ASSEMBLY OF A VEHICLE DURING
MOTION OF THE VEHICLE**

BACKGROUND OF THE INVENTION

“Tire balance” refers to distribution of mass within a vehicle tire or the entire wheel, including the rim, on which the vehicle tire is mounted. Tire balance may also be referred to as “tire unbalance” or “tire imbalance.” As described in U.S. Pat. No. 6,595,053 (Parker), which is incorporated by reference herein, the balancing of vehicle wheel assemblies is most often accomplished by removing the tire/wheel assemblies from the vehicle and mounting each of the tire/wheel assemblies on an off-car-balancer. The off-car balancer rotates the tire/wheel assembly, measures the imbalance forces and displays the amount and location of weight to add to the wheel to bring the tire/wheel assembly into a balanced condition. One example of an off-car balancer is The Road Force® Elite wheel balancer, which is commercially available from Hunter Engineering Company, Bridgeton, Mo.

As also described in U.S. Pat. No. 6,595,053, a tire/wheel assembly may be balanced so that it produces negligible forces when rotated on the off-car balancer, but the same assembly may cause significant imbalance forces when mounted on the vehicle and rotated using the vehicle’s bearings and axle. The imbalance forces of a tire/wheel assembly will remain constant between the off-car balancer and the vehicle only if the relationship between the tire/wheel assembly and the axis of rotation is the same for the two mountings. Achieving the desired on-car wheel balance with only an off-car balancer involves both accurately mounting the wheel on the balancer and then accurately mounting the tire/wheel assembly on the vehicle’s hub. Possible causes of wheel-to-vehicle mounting inaccuracy include clearance between the balancer hub and the rim pilot hole, runout of the hub pilot diameter or mounting face, rust or grime between rim and vehicle hub, runout in studs and runout in lug nuts.

As further described in U.S. Pat. No. 6,595,053, on-car balancers can eliminate some of the mounting accuracy problems by performing the balance measurements after the tire/wheel assembly is in its final mounted position on the vehicle. Although on-car balancers are available, they are not very popular because of setup difficulties, operational limitations, and safety issues.

Despite the many efforts made by the industry, including those described in U.S. Pat. No. 6,595,053, there still remains an unmet need for an on-car balancer that is inexpensive, convenient to use, and which can capture parameters necessary for calculating imbalance forces when the vehicle is actually in motion. The present invention fulfills such a need.

SUMMARY OF THE PRESENT INVENTION

In one preferred embodiment, the present invention provides an apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly for use in determining imbalance forces of the tire/hub assembly during motion of the vehicle. The apparatus includes a disk, a plurality of cup-shaped objects, and one or more inertial measurement units (IMU’s). Each cup-shaped object is rigidly fixed at one end to the disk and extends perpendicularly outward from the disk. The plural-

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ity of cup-shaped objects are arranged a fixed radial distance from the radial center of the disk in a pattern that matches the lug nuts of the tire/hub assembly. Each cup-shaped object is hollow along at least a portion of its length that is distal from the disk. The hollow portion has a diameter that is larger than a diameter of the lug nuts of the tire/hub assembly so as to allow the apparatus to be mounted to the vehicle’s tire/hub assembly by fitting the plurality of cup-shaped objects over the lug nuts of the tire/hub assembly. 5 The one or more IMU’s are mounted to the disk and are configured to measure parameters that are used for calculating the imbalance forces during motion of the vehicle. One or more of the cup-shaped objects may include a magnet fixedly mounted at an end of the cup-shaped objects 10 that is proximate to the disk so as to magnetically engage with one of the lug nuts when the apparatus is attached to the tire/hub assembly of a vehicle, and thereby inhibit the apparatus from coming off of the vehicle when the vehicle 15 is in motion.

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BRIEF DESCRIPTION OF THE DRAWINGS

Preferred embodiments of the present invention will now be described by way of example with reference to the 25 accompanying drawings:

FIGS. 1A-1D show a disk for use with the apparatus of the present invention.

FIGS. 2A-2C show details of cup-shaped objects for use with the apparatus, and also show details of how the 30 cup-shaped objects are attached to the disk.

FIG. 2D show details of how the cup-shaped object is fit over a lug nut.

FIG. 2E shows a partial view of an alternative assembly for rapidly attaching the disk to a tire/hub assembly.

FIG. 3A shows prior art tire/hub assemblies.

FIGS. 3B and 3C show how the apparatus of the present invention engages a tire/hub assembly.

FIGS. 4A and 4B show a single, center-mounted IMU of the assembly.

40 FIGS. 5A and 5B show an alternative embodiment of the assembly having multiple IMU’s.

FIGS. 6A-6L show alternative embodiments of the present invention having a floating center shaft assembly and a single IMU mounted to a radial center of the floating center 45 shaft assembly.

FIGS. 7A-7C show an alternative embodiment of the apparatus having cup-shaped objects that are friction-fit to the lug nuts.

FIGS. 8A and 8B show a cover that may be placed over 50 the wheel-mounted assembly of FIGS. 6A-6F.

**DETAILED DESCRIPTION OF THE
INVENTION**

55 Certain terminology is used herein for convenience only and is not to be taken as a limitation on the present invention.

The words “a” and “an”, as used in the claims and in the corresponding portions of the specification, mean “at least one.”

60 A general overview of one preferred embodiment is described with respect to FIGS. 3A, 3B, 3C, 4A and 4B. FIG. 4B shows a fully assembled apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly for use in determining 65 imbalance forces of the tire/hub assembly during motion of the vehicle. The tire/hub assembly and its corresponding lug nuts 304 are best shown in FIG. 3B. In FIGS. 3B and 3C,

element 310 represents a center cutaway of a vehicle rim which is part of the tire/hub assembly. FIG. 3A shows two conventional hub assemblies that may form part of the tire/hub assembly. The upper diagram of FIG. 3A shows a hub with studs, collectively, labeled as 300. A lug nut 304 is attached to a distal end of each stud. The lower diagram of FIG. 3A shows a hub with threaded holes, collectively, labeled as 302. A lug bolt 306 is attached to each threaded hole. Not shown in FIGS. 3A and 3B is the tire which is located between the hub 300 and the lug nuts 304 in the upper diagram of FIG. 3A, and between the hub 302 and the ends of the lug bolts 306 in the lower diagram of FIG. 3B. As described herein, the lug nuts 304 perform the same function as the lugs at the end of the lug bolts 306, and thus they can be considered as equivalent elements.

Referring again to FIGS. 3B, 3C, 4A and 4B, one preferred embodiment of the apparatus in the present invention includes an assembly of the following elements:

- i. a disk 100 (generally cylindrical plate),
- ii. a plurality of cup-shaped objects 202 (also, interchangeably referred to herein as "cups 202," and
- iii. one or more IMU's 406 (an IMU may also be referred to as an "IMU sensor").

The disk 100 has an outer facing surface 120 and an inner facing surface 122 (labeled in FIG. 2C). The inner facing surface 122 faces the hub 300 when the apparatus is mounted to the vehicle's tire/hub assembly.

FIGS. 3B and 3C show a partially assembled apparatus that includes the disk 100 and the cup-shaped objects 202, whereas FIGS. 4A and 4B show all of the above-listed elements i.-iii. In each of these figures, the disk 100 and the cup-shaped objects 202 are part of an overall assembly 230 of thumbscrew 132, cup 202, magnet 204, magnet capture ring 206, and the appropriately sized adapter 210, 212, or 214, all of which are described in more detail below.

Each cup-shaped object 202 is rigidly fixed at one end to the disk 100 and extends perpendicularly outward from the disk 100. The plurality of cup-shaped objects 202 are arranged a fixed radial distance from the radial center of the disk 100 in a pattern that matches the lug nuts 304 of the tire/hub assembly. Each cup-shaped object 202 is hollow along at least a portion of its length that is distal from the disk 100. The hollow portion has a diameter that is slightly larger than a diameter of the lug nuts 304 of the tire/hub assembly so as to allow the apparatus to be mounted to the vehicle's tire/hub assembly by fitting the plurality of cup-shaped objects 202 over the lug nuts 304 of the tire/hub assembly, as best illustrated in FIGS. 3B and 3C. The one or more IMU's 406 are mounted to the disk 100, as best illustrated in FIGS. 4A and 4B, and are configured to measure parameters that are used for calculating the imbalance forces during motion of the vehicle. In the embodiment of FIGS. 4A and 4B, a single IMU 406 is mounted in a center of the disk 100. Other embodiments that use multiple IMU's are described below with respect to FIGS. 5A and 5B.

The one or more IMU's 406 may be mounted to the disk 100 in any suitable manner. In the embodiment of FIGS. 4A and 4B, the single IMU 406 is mounted to the outer facing surface 120 of the disk 100 via IMU housing 402. The IMU housing 402 has a rectangular-shaped slot 410 and mounting plate 412 formed as one piece. The mounting plate 412 is attached via screws 404 to a center portion of the outer facing surface 120 of disk 100. The slot 410 receives the IMU 406, as illustrated in FIG. 4A which shows the IMU 406 exploded from the slot 410, and FIG. 4B which shows the IMU 406 fully inserted into the slot 410. The IMU 406

is securely retained in the slot 410 by any suitable means, such as friction fit, clamps, holding screws, or hook and loop fastener material.

FIGS. 5A and 5B show another embodiment of the apparatus wherein there are three IMU's 510 arranged in an equilateral triangle configuration, wherein each IMU is equidistant from the center of the disk 100. In this manner, each IMU is placed at 120 degree angles from the center of the disk 100. FIG. 5A shows one mounting embodiment wherein the three IMU's 510 are fixed to mounting flange 504, which is then attached to mounting plate 512 via a center hole 513 in the mounting plate 512. FIG. 5B shows the fully assembled view.

Lug nut configurations differ among vehicles in at least the following ways:

- i. number of lug nuts
- ii. diameter of the lug nuts
- iii. radial distance of the lug nuts from the center of the hub
- iv. lug patterns, namely, the arrangement of lug nuts along the fixed radius from the center of the hub (typically equidistant, but not always)

These parameters result in a large number of permutations of potential lug nut configurations. However, there are a handful of well-known configurations that cover a large percentage of vehicles. The assembly has various features to allow for its use with many different common configurations, as described below.

FIG. 1A shows the disk 100 by itself. The disk 100 includes a center opening 112 and device mounting holes 114 for receiving the screws 404 shown in FIGS. 4A, 4B, 5A, and 5B. The disk also includes the following slots:

- i. slot 102 for use with a 4, 5, or 6 lug patterns
- ii. slot 104 for use with 4 and 6 lug patterns
- iii. slot 106 for use with 5 lug patterns
- iv. slot 108 for use with 6 lug patterns
- v. slot 110 for use with 4 lug patterns

The various lug patterns are also represented by letters A, B, and C.

To allow for interchangeability, the cup-shaped objects 202 are removably attachable to the disk 100 to allow a set of cup-shaped objects 202 to be reconfigured on the disk 100 to match the appropriate lug nut configuration for a particular vehicle. Likewise, different sets of cup-shaped objects 202 can be provided having different diameters to accommodate different diameter lug nuts 304. The slots 102-100 allow for changing the radial distance of the lug nuts from the center of the hub, as opposed to providing holes that would only accommodate one radial distance.

FIGS. 1B-1D show thumbscrews 132 which are used to fasten the cup-shaped objects 202 to the disk 100, as described below. FIG. 1B shows a 4 lug pattern that requires four thumbscrews 132 (one for each cup-shaped object 202), FIG. 1C shows a 5 lug pattern that requires five thumbscrews 132 (one for each cup-shaped object 202), and FIG. 1D shows a 6 lug pattern that requires six thumbscrews 132 (one for each cup-shaped object 202).

FIGS. 2A-2D show additional details of the cup-shaped objects 202, and they also show details of how the cup-shaped objects 202 are attached to the disk 100. The example in FIGS. 2A-2D uses the 5 lug pattern of FIG. 1B. FIG. 2A is an exploded top view of the apparatus, FIG. 2B is a fully assembled top view of the apparatus, FIG. 2C is a fully assembled bottom view of the apparatus, and FIG. 2D is an exploded view of different lug nut adapters (described below) for use with the cup-shaped object 202.

FIG. 2A shows five thumbscrews 132 which are used to fasten five cup-shaped objects 202 to the disk 100. Each thumbscrew 132 is inserted through an appropriate slot 102 or 106 associated with the 5 lug pattern of FIG. 1B, and is screwed into threaded holes 224 shown in phantom in a center of a distal portion of each cup-shaped object 202. When fully screwed in, a flange of each thumbscrew 132 is flush against the outer facing surface of the disk 100, and each thumbscrew 132 securely holds its respective cup-shaped object against the inner facing surface 122 of the disk 100, as shown in FIG. 2C.

FIG. 2A also shows magnet 204, magnet capture ring 206, and lug nut adapter 208 that are received inside each of the respective cup-shaped objects 202. The magnet 204 and magnet capture ring 206 form a magnet assembly 207 that is placed in a pocket area of the cup-shaped object 202 so as to be flush against a distal end surface of the cup-shaped object 202 (top portion of the cup-shaped object 202 when viewed in FIG. 2A, bottom portion of the cup-shaped object 202 when viewed in FIG. 2B). The magnet 204 is thus fixedly mounted at an end of the cup-shaped object 202 that is proximate to the disk 100. The magnet assembly 207 is held in place within the cup-shaped object 202 by friction fit. Adhesive may alternatively be used for this purpose. In use, the magnets 204 magnetically engage with the lug nuts 304 when the apparatus is attached to the tire/hub assembly of a vehicle, and thereby inhibit the apparatus from coming off of the vehicle when the vehicle is in motion. In one preferred embodiment, there is a magnet 204 in each cup-shaped object 202. However, depending upon the strength of the magnets 204, it may not be necessary to provide magnets 204 in each cup-shaped object.

FIG. 2A also shows a lug nut adapter mounted inside each cup-shaped object 202. As discussed above, lug nuts come in a variety of different head diameters. To avoid excessive play when the apparatus is attached to the tire/hub assembly of a vehicle, an appropriately sized hollow lug nut adapter 208 is selected for the lug nuts of the vehicle so as to provide a snug fit, but not necessarily a friction fit. This also helps to ensure that IMU 406 or IMU's 510 are symmetrically arranged with respect to a center axis of the tire/hub assembly. The lug nut adapter 208 may be removable to allow for different sized adapters to be used with the same cup-shaped object 202 and may be held in place within the cup-shaped object 202 by friction fit. Alternatively, the lug nut adapter 208 may be permanently assembled within the cup-shaped object 202. If so, different cup-shaped objects 202 will be required for lug nuts of different head diameters.

The cup-shaped objects (cups) 202 have a depth of length, labeled as "L" in the leftmost cup 202 of FIG. 2A that is sufficient to accommodate a thread portion for receiving the thumbscrew 132, the magnet assembly 207, and the full depth of the lug nut 304.

FIG. 2B is a fully assembled top view of the apparatus of FIG. 2A, and FIG. 2C is a fully assembled bottom view of the apparatus of FIG. 2A. In FIGS. 2B and 2C, element 230 refers to the assembly of the thumbscrew 132, cup 202, magnet 204, magnet capture ring 206, and the appropriately sized adapter 210, 212, or 214.

FIG. 2D shows examples of three different lug nut adapters 210, 212 and 214 for use with the same cup-shaped object 202. The uppermost diagram shows lug nut adapter 210 for accommodating a 17 mm lug nut 216, the middle diagram shows a lug nut adapter 212 for accommodating a $\frac{7}{8}$ inch lug nut 218, and the bottommost diagram shows a lug nut adapter 214 for accommodating a $\frac{15}{16}$ inch lug nut

222. The lug nut adapters 210, 212 and 214 provide the same functionality as the lug nut adapter 208 described above and shown in FIG. 2A.

FIG. 2E shows a partial view of an alternative assembly 5 for rapidly attaching disk 100 to a tire/hub assembly when time-is-of-the-essence, particularly when interchangeability is due to different vehicles and varying hub/lug configurations are sequentially encountered and the threading and/or unthreading of thumbscrews, nuts, and cups, is impractical and labor intensive. Cup 202 still contains magnet 204, magnet capture ring 206, and may or may not require lug nut adapter 208 for attachment to vehicle lug nuts. Instead of a threaded type of attachment as shown in FIG. 2A, FIG. 2E shows cup 202 having an affixed cylindrical shaft 234 that 10 passes through slot 106 of disk 100. Magnetically locking cylinder 240 is pressed onto cylindrical shaft 234 through hole 236 and is firmly held in place because the disk facing surface 238 of the ring magnet 242 is the opposite polarity of the disk facing surface 232 of magnet 204, thereby 15 producing a strong magnetic clamp. All contact surfaces of cup 202, disk 100, and magnetic locking cylinder 240 may 20 produce abrasive or geometrically opposite mating surfaces to decrease lateral slippage when magnetically clamped.

The materials for constructing certain parts of the apparatus such as the disk 100, cup-shaped objects 202, and IMU housing 402 are preferably rigid and durable so as to withstand movement on a vehicle with minimal play. One suitable material is a thermoplastic polymer, such as acrylonitrile butadiene styrene (ABS). The selected material 25 must also not cause interference with the electronics of the IMU's. ABS has electrical insulation properties that are well-suited to the operating environment of the apparatus.

FIGS. 7A-7C show another embodiment of the apparatus of the present invention that includes an assembly of the 30 following elements:

- i. disk 100 (generally cylindrical plate),
- ii. a plurality of cup-shaped objects 202, and
- iii. one or more IMU's 406 (an IMU may also be referred to as an "IMU sensor").

The embodiment of FIGS. 7A-7C differs from the embodiment described above in that the disk 100 and the cup-shaped objects 202 are preferably formed as a single unit, such as by injection molding. Since the cup-shaped objects 202 are not removable, the single unit will be limited 40 in use to a particular lug nut pattern. However, fabrication costs may be lower due to the reduced number of parts, the elimination of any need for creating slots in the disk 100, and the relative inexpensiveness of injection molding. The remaining parts of the apparatus of FIGS. 7A-7C are the same as the embodiment described below, namely, the IMU housing 402 that is mounted to the single unit via screws 404, and that receives the IMU 406, as illustrated in FIGS. 7B and 7C. Alternatively, the single unit may have the 45 multiple IMU embodiment shown in FIGS. 5A and 5B attached thereto.

The embodiment of FIGS. 7A-7C also differs from the embodiment described above in that the cup-shaped objects 202 are designed to be friction fit over the lug nuts 304 of the vehicle, or over only a subset of the lug nuts of the 50 vehicle. For example, various models of the Ford® F150 truck have a six lug pattern. The embodiment of FIGS. 7A-7C provides four cup-shaped objects 202 that friction fit over four of the six lug nuts 304 in a manner similar to a conventional decorative center cap that is commercially 55 available for such a vehicle. Instead of using magnets inside the cup-shaped objects 202 for releasably attaching the apparatus to the lug nuts 304, the cup-shaped objects 202

include a plurality of slits or slots 700 which allow sidewall sections 702 of each cup-shaped object 202 to slightly flex outward to provide the friction fit. In the embodiment shown in FIGS. 7A-7C, each cup-shaped object 202 has four slits or slots 700 that define four sidewall sections 702.

The embodiment of FIGS. 7A-7C may also be able to accommodate different sized lug nut adaptors, such as illustrated in FIG. 2D. However, for such adaptors to work, the adaptors are preferably also constructed with matching slits or slots that align with the slits or slots 700 of the cup-shaped object 202, so that the sidewalls of the two parts (i.e., the adaptor and the cup-shaped object 202) slightly flex outward in unison to provide the friction fit.

In the embodiments described above, the IMU's are rigidly attached to the disk 100 so that they rotate with the disk 100 when the vehicle is in motion.

In alternative embodiments, the IMU's are mounted to the disk 100 in a manner that allows them to remain relatively stationary, in a manner similar to a hubometer (also, known as a hubodometer). These embodiments are referred to more generally as having a "non-rotating IMU" and as having a "floating center shaft assembly." These embodiments are all described with respect to a single IMU 406 mounted in a center of the disk 100. For ease of nomenclature, the combination of the disk 100 and the cup-shaped objects 202 is referred to as "wheel-mounted assembly 602."

FIGS. 6A-6C show one embodiment of an apparatus 600 that includes a non-rotating IMU/floating center shaft assembly. A floating center shaft 616 extends through a center of the wheel-mounted assembly 602. Two sets of bearings 612, shown in phantom in FIGS. 6B and 6C, are provided within the floating center shaft 616. The bearings 612 are inside of bearing cap 620. A weight stabilization assembly 614 includes a hub portion 615 that is attached to the distal end of the floating center shaft 616, a downward facing shaft 617 (meaning, downward facing when in operation) which can be rigid or flexible, and a contoured weight 618 fixed to a distal end of the downward facing shaft 617. A top view of the contoured weight 618 is also shown in a separate figure within FIGS. 6B and 6C. The non-rotating IMU 406 is attached to weight stabilization assembly 614 in the center of wheel-mounted assembly 602, as shown in phantom in FIG. 6A.

In one preferred embodiment, the disk portion of the wheel-mounted assembly 602 further includes a pair of magnets 622 mounted thereon in an opposed manner along a radial line extending through the radial center of the wheel-mounted assembly 602, that is, a fixed radial distance from the radial center of the disk portion. In this embodiment, the IMU 406 further includes a Hall effect sensor (not shown) that works in conjunction with the magnets to measure rotational speed of the wheel-mounted assembly 602 during motion of the vehicle.

FIG. 6A is a front elevation view of the apparatus 600. FIG. 6B is a side elevation view of the apparatus 600 and shows the weight stabilization assembly 614 exploded from the wheel-mounted assembly 602 and the floating center shaft 616. FIG. 6C is also a side elevation view of the apparatus 600 and shows the weight stabilization assembly 614 attached to the wheel-mounted assembly 602 and the floating center shaft 616.

FIGS. 6D-6F show another embodiment of an apparatus 630 that also includes a non-rotating IMU/floating center shaft assembly. This embodiment is similar to the embodiment of FIGS. 6A-6C, except that it relies upon an airfoil stabilizing structure 634, instead of the weight stabilization assembly 614, for stabilization of the IMU 406. The airfoil

stabilizing structure 634 comprises hub portion 636 and airfoil 632. The hub portion 636 and the airfoil 632 perform comparable functions as the hub portion 615 and the contoured weight 618 of the embodiment in FIGS. 6A-6C. The geometry of the airfoil stabilizing structure 634 is an example representation only.

FIG. 6D is a front elevation view of the apparatus 630. FIG. 6E is a side elevation view of the apparatus 630 and shows the airfoil stabilizing structure 634 exploded from the wheel-mounted assembly 602 and the floating center shaft 616. FIG. 6C is also a side elevation view of the apparatus 600 and shows the airfoil stabilizing structure 634 attached to the wheel-mounted assembly 602 and the floating center shaft 616.

FIGS. 6G-6I show another embodiment of an apparatus 640 that also includes a non-rotating IMU/floating center shaft assembly. This embodiment includes both of the stabilizing structures shown in FIGS. 6A-6C and 6D-6F. These figures are thus self-explanatory in view of the descriptions above of the two respective embodiments. The same hub portion is used for both stabilizing structures, and thus this element is labeled as hub portion 615/636. The three different views in FIGS. 6G-6I are similar to the three different views of FIGS. 6A-6C and 6D-6F, and thus are not described further. The embodiment of FIGS. 6G-6I is also shown with the magnets 622.

FIG. 6J shows a front and side elevation view of only the weight stabilization assembly 614 used in FIGS. 6A-6C. FIG. 6K shows a front and side elevation view of only the airfoil stabilizing structure 634 used in FIGS. 6D-6F. FIG. 6L shows a front and side elevation view of the combined weight stabilization assembly 614 and airfoil stabilizing structure 634 used in FIGS. 6G-6I.

FIGS. 8A and 8B show a clear cover 800 that may be placed over the wheel-mounted assembly 602 shown in FIGS. 6A-6C to reduce road turbulence that may cause the stationary IMU 406 to oscillate. The cover 800 may be secured to the wheel-mounted assembly 602 via cover tabs 802 that are molded into cover 800. A similar type of cover 800 may also be used with the embodiment FIGS. 6D-6F. The cover tabs 802 snap over the back of the wheel-mounted assembly 602 to secure it in place. Inside of the cover 800, approximately $\frac{3}{8}$ " from the opening, are three raised stops 804 that rest on the front side of the wheel-mounted assembly 602. The stops 804 keep the cover 800 in the required position over the wheel-mounted assembly 602, preventing the cover 800 from making contact with the weight stabilization assembly 614.

In one preferred embodiment, the cup-shaped objects 202 are cylindrically shaped, and define cylinders having solid circumferential sidewalls. However, the cup-shaped objects 202 can have other shapes, such as square or octagonal, since other shapes would still allow them to releasably engage lug nuts, particularly when using the magnetic attachment embodiment. Likewise, the lug nut adaptors may have a suitable internal diameter shape so as to snugly fit over the lug nuts, while having a different external diameter shape to conform to the shape of the cup-shaped objects 202.

In selected embodiments disclosed above, the cup-shaped objects 202 are rigidly fixed to the disk 100 via threaded bolts, such as thumbscrews. However, other ways to fasten the cup-shaped objects 202 to the disk 100 are within the scope of the invention, such as nuts and bolts, and adhesives. In an alternative embodiment, an integrally formed thread may extend from a distal end of the cup-shaped object 202, and the cup-shaped object 202 may be fastened to the disk

by inserting the thread through the hole in the disk 100 and fastening it using a nut on the opposite side of the disk 100.

In other embodiments, such as shown in FIGS. 7A-7C, the cup-shaped objects 202 and the disk 100 are formed as a unitary piece, and thus no fastening mechanism is needed.

The magnetic attachment embodiment is only one preferred structure for removably attaching the apparatus to the tire/hub assembly of the vehicle via the lug nuts of the tire/hub assembly. The scope of the present invention includes other attachment mechanisms that rely upon physical (as opposed to magnetic) attachment of the apparatus to the tire/hub assembly of the vehicle via the lug nuts of the tire/hub assembly, such as clamping mechanisms, and other types of physical fastening mechanisms.

Any IMU may be used that has a form factor and durability suitable for the environment described herein. One suitable IMU is the IMU described in U.S. Pat. No. 10,284,752 (Canfield et al.), which is incorporated herein by reference. Sample measured parameters that are used for calculating the imbalance forces during motion of the vehicle include, and which are captured by the IMU's include, but are not limited to, acceleration and angular rotation. The data captured by the IMU may then be used for at least the following purposes:

i. Determine where correction weights should be attached to the rim of the wheel to achieve improved balancing of the tire/hub assembly.

ii. Determine if the tire/hub assembly is so far out of balance that normal balancing (adding of correction weights) cannot correct the imbalance.

In use, the different embodiments of the apparatuses (referred to herein in the singular) are removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly. The vehicle is then driven on a road surface, and during motion of the vehicle, parameters measured by the one or more inertial measurement units (IMU's) mounted to the disk of the apparatus are collected, and then subsequently used for calculating the imbalance forces.

It will be appreciated by those skilled in the art that changes could be made to the embodiments described above without departing from the broad inventive concept thereof. It is understood, therefore, that this invention is not limited to the particular embodiments disclosed, but it is intended to cover modifications within the spirit and scope of the present invention.

What is claimed is:

1. An apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly for use in determining imbalance forces of the tire/hub assembly during motion of the vehicle, the apparatus comprising:

- (a) a disk;
- (b) a plurality of cup-shaped objects, each cup-shaped object being rigidly fixed at one end to the disk and extending perpendicularly outward from the disk, the plurality of cup-shaped objects being arranged a fixed radial distance from a radial center of the disk in a pattern that matches the lug nuts of the tire/hub assembly, each of the cup-shaped objects being hollow along at least a portion of its length that is distal from the disk, the hollow portion having a diameter that is larger than a diameter of the lug nuts of the tire/hub assembly so as to allow the apparatus to be mounted to the vehicle's tire/hub assembly by fitting the plurality of cup-shaped objects over the lug nuts of the tire/hub assembly; and
- (c) one or more inertial measurement units (IMU's) mounted to the disk and configured to measure param-

eters that are used for calculating the imbalance forces during motion of the vehicle,

wherein one or more of the cup-shaped objects includes a magnet fixedly mounted at an end of the cup-shaped objects proximate to the disk so as to magnetically engage with one of the lug nuts when the apparatus is attached to the tire/hub assembly of the vehicle, and thereby inhibit the apparatus from coming off of the vehicle when the vehicle is in motion.

2. An apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly for use in determining imbalance forces of the tire/hub assembly during motion of the vehicle, the apparatus comprising:

- (a) a disk;
- (b) a plurality of cup-shaped objects, each of the cup-shaped objects being rigidly fixed at one end to the disk and extending perpendicularly outward from the disk, the plurality of cup-shaped objects being arranged a fixed radial distance from a radial center of the disk in a pattern that matches the lug nuts of the tire/hub assembly, each of the cup-shaped objects being hollow along at least a portion of its length that is distal from the disk, the hollow portion having a diameter that is larger than a diameter of the lug nuts of the tire/hub assembly so as to allow the apparatus to be mounted to the vehicle's tire/hub assembly by fitting the plurality of cup-shaped objects over the lug nuts of the tire/hub assembly; and
- (c) a plurality of inertial measurement units (IMU's) mounted to the disk and configured to measure parameters that are used for calculating the imbalance forces during motion of the vehicle,

wherein the plurality of IMU's are mounted to the disk a fixed radial distance from the radial center of the disk in an evenly spaced pattern, and wherein the plurality of IMU's rotate with the disk during motion of the vehicle.

3. An apparatus configured to be removably attached to a tire/hub assembly of a vehicle via lug nuts of the tire/hub assembly for use in determining imbalance forces of the tire/hub assembly during motion of the vehicle, the apparatus comprising:

- (a) a disk;
- (b) a plurality of cup-shaped objects, each of the cup-shaped objects being rigidly fixed at one end to the disk and extending perpendicularly outward from the disk, the plurality of cup-shaped objects being arranged a first fixed radial distance from a radial center of the disk in a pattern that matches the lug nuts of the tire/hub assembly, each of the cup-shaped objects being hollow along at least a portion of its length that is distal from the disk, the hollow portion having a diameter that is larger than a diameter of the lug nuts of the tire/hub assembly so as to allow the apparatus to be mounted to the vehicle's tire/hub assembly by fitting the plurality of cup-shaped objects over the lug nuts of the tire/hub assembly;
- (c) a floating center shaft assembly attached to the disk; and
- (d) a single inertial measurement unit (IMU) mounted to a radial center of the floating center shaft assembly and configured to measure parameters that are used for calculating the imbalance forces during motion of the vehicle,

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wherein the floating center shaft assembly inhibits rotational movement of the single IMU during motion of the vehicle.

4. The apparatus of claim 3 wherein the disk includes a plurality of holes that define a lug nut pattern so as to allow the plurality of cup-shaped objects to be rigidly fixed to the disk in locations that correspond with the lug nut pattern.

5. The apparatus of claim 4 wherein each of the cup-shaped objects includes a hole at the one end, and each of the plurality of cup-shaped objects are removably attached to the disk via a fastener extending through one of the holes in the disk and also through the hole at the one end of the cup-shaped object.

6. The apparatus of claim 5 wherein the fastener is a threaded bolt, and the hole in the one end of the cup-shaped object includes threads for receiving the threaded bolt.

7. The apparatus of claim 3 wherein the cup-shaped objects are cylindrically shaped.

8. The apparatus of claim 7 wherein the cup-shaped objects are cylinders having solid circumferential sidewalls.

9. The apparatus of claim 3 wherein the disk includes a plurality of holes that define a plurality of different sets of lug nut patterns so as to allow the plurality of cup-shaped objects to be rigidly fixed to the disk in locations that correspond with the lug nut pattern of the tire/hub assembly of the vehicle that the apparatus is removably attached to.

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10. The apparatus of claim 9 wherein the plurality of holes are slot-shaped.

11. The apparatus of claim 3 wherein the floating center shaft assembly includes a weight stabilization assembly attached thereto for stabilization of the single IMU during motion of the vehicle.

12. The apparatus of claim 3 wherein the floating center shaft assembly includes an airfoil stabilizing structure attached thereto for stabilization of the single IMU during motion of the vehicle.

13. The apparatus of claim 3 wherein the single IMU includes a Hall effect sensor, and the disk includes a pair of magnets mounted thereon in an opposed manner a second fixed radial distance from the radial center of the disk, the Hall effect sensor and the magnets being used to measure rotational speed of the apparatus during motion of the vehicle.

14. The apparatus of claim 3 wherein one or more of the cup-shaped objects includes a magnet fixedly mounted at an end of the cup-shaped objects proximate to the disk so as to magnetically engage with one of the lug nuts when the apparatus is attached to the tire/hub assembly of a vehicle, and thereby inhibit the apparatus from coming off of the vehicle when the vehicle is in motion.

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