REVIEW ARTICLE

Recent Patents on Cageless Rolling Bearings

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Abstract: ***Background*:** Rolling bearings are widely used as core components in mechanical equipment. Most bearings are equipped with a cage. However, when bearings work under conditions of large load and high speed, the cage will produce violent friction and collision between the rolling body and the rings of the bearing, which will reduce the stability of the bearing operation and even fracture the cage. Bearing cage significantly impacts the rotational accuracy and life of the bearing. Therefore, in recent years, many scholars have begun researching cageless rolling bearings. The cageless rolling bearing eliminates the various adverse effects brought about by the cage and reduces the weight of the bearing. However, the bearing structure must be reasonably designed to eliminate the reverse friction between adjacent rolling elements in cageless cases. Therefore, it is essential to design the structure of cageless rolling bearings and study their performance.

***Objective*:** By analyzing and summarizing the research on cageless rolling bearings in recent years, the current problems and the future development of cageless rolling bearings are analyzed to provide a reference for researchers in the related fields.

***Method*:** This paper reviews representative patents related to cageless rolling bearings, discusses the structure and performance of various cageless rolling bearings, and analyzes their advantages and disadvantages, mainly including full complement cageless bearings, isolation element bearings, and special cageless bearings. Each type of bearing is analyzed through ball bearings and roller bearings.

***Results*:** Through the analysis of the related patents on cageless rolling bearings, it is found that the main problems affecting the development of cageless rolling bearings are the irregular collision of rolling elements with each other, the friction between rolling elements and the adjacent elements, and the difficulty in machining the particular shape isolation and raceway. Future research focuses on how to improve the service performance of cageless rolling bearings comprehensively so that they can work under high speed and heavy load.

***Conclusion*:** Cageless rolling bearings simplify the bearing structure to increase the number of rolling elements. Therefore, the capacity of the rolling bearing is improved. The internal bearing friction can be reduced through structural innovation design. Cageless rolling bearings have broad development prospects

Keywords: Cageless rolling bearings, full complement cageless bearings, isolation element bearings, special cageless bearings, friction, load-carrying capacity.

1. INTRODUCTION

As a core mechanical equipment component, rolling bearings support rotating parts and reduce friction loss. In recent years, the development needs of aerospace, rail transportation, wind power generation, CNC machine tools, and other high-end technologies have driven the development of rolling bearing technology [1-4]. The internal heat source of the traditional bearing comes from the friction between the rolling element and the raceway, the friction between the cage and the guide surface of the ring, and the friction between the cage and the rolling element. However, the frictional loss ratio between the cage, the rolling element,

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and the surface of the ring is the largest [5-7]. To eliminate the adverse effects produced by the bearing cage, scholars at home and abroad conduct relevant research on cageless rolling bearings [8-13].

As a new type of non-standard rolling bearings, cageless rolling bearings discard the cage traditionally, avoiding the frictional resistance between the cage and rolling bodies, raceways, and guiding surfaces. The structure of cageless rolling bearings can be filled with a more significant number of rolling elements so that the load on a single rolling element is small and the bearing capacity is improved. Because of its good bearing performance, it has been widely used in the low-speed and heavy-duty industry [14, 15]. Full complement cylindrical roller bearings can be seen in wheel hubs and reducers [16] as well as on automobile transmissions [17, 18]. Cageless rolling bearings have the advantages of long service life and simple structure and are often used as backup bearings for active magnetic bearing systems [19, 20]. The research of cageless rolling bearings is an essential theme for global bearings to move towards lightweight, friction reduction, low energy consumption, and economy [21].

This paper is organized as follows: Firstly, it describes the classification of cageless rolling bearings and the current status of research. Secondly, it introduces various representative patents related to cageless rolling bearings. Thirdly, the main problems in the research and development of cageless rolling bearings are analyzed and summarized. Finally, the development of cageless rolling bearings is summarized, and the possible future direction is viewed.

2. CLASSIFICATION AND RESEARCH STATUS OF CAGELESS ROLLING BEARINGS

At present, the research of scholars at home and abroad on cageless rolling bearings is mainly categorized into the following three types: (1) Increasing the number of rolling elements while discarding the cage and spreading the rolling elements all over the bearing raceway, that is, full complement cageless bearings [22-27]. (2) Retaining the critical part of the cage structure for separating adjacent rolling bodies to realize cage discretization, that is, new isolation element bearings [28-31]. (3) Structural deformation of the inner and outer raceways of the bearing to limit the free movement of the rolling elements, that is special cageless bearings [32, 33].

2.1. Full Complement Cageless Bearings

Full complement bearings are filled with as many rolling elements as possible, which is more than the number of rolling elements in the same type and size of caged bearings [34-39], so they can withstand greater radial and axial loads, and improve the load distribution, which makes them more suitable for some high load conditions [40-42]. As shown in Fig. (**1**), the full complement cageless cylindrical bearing has the advantages of simple structure, high stiffness, and high rotational accuracy. As shown in Fig. (**2**), the full complement cageless deep groove ball bearings are filled with balls and can bear about 1.5 times the load of bearings with cages. High-temperature full complement deep groove ball bearings can work generally at about 300°C. It is widely used in metallurgy, kiln, glass, paint spraying equipment, and other high-temperature operation machinery. However, the clearance of this bearing is much larger than that of ordinary bearings, so it is not suitable for medium- and high- -speed running occasions; there are limitations to its use. On the other hand, an increase in the number of rolling elements in a cageless bearing often leads to an increase in the weight and price of the bearing, since rolling elements usually have a higher weight and higher manufacturing cost than a cage, especially those made of wear-resistant plastics. Therefore, cageless bearing is often especially important in the production of heavy-duty and metal-intensive equipment.

Fig. (1). Full complement cageless cylindrical bearings. *(A higher resolution / colour version of this figure is available in the electronic copy of the article)*.

Fig. (2). Full complement cageless deep groove ball bearings. *(A higher resolution / colour version of this figure is available in the electronic copy of the article)*.

In the starting and accelerating stages, the full complement cageless bearing is unstable because the rolling element loses the restraint of the original cage. When the traction friction between the rolling body and the raceway is not enough to overcome the rolling friction, slipping will occur. Moreover, increasing the number of rolling elements, resulting in a more complex movement of rolling elements in the raceway, friction, and irregular collision will occur more frequently between the rolling elements [43-47].

2.2. Isolation Element Bearings

Isolation element bearings are characterized by a change in the structure of the conventional cage compared to conventional bearings, where only the critical portion for separating the individual rolling elements is retained, characterized by a discrete isolator [48].

For rolling ball bearings, a smaller diameter spacer ball can be placed between the two load balls, as shown in Fig. (**3**). Load balls and spacer balls in the bearing operation only exist in rolling friction. Compared with the traditional bearing, this structure can significantly reduce the wear degree of the ball surface and is conducive to improving the service life of the bearing. The same principle can also be used for roller bearings, using smaller diameter spacer rollers in the load roller between the isolation. The advantages of the bearings with spacer balls or columns include their straightforward design, affordability, and environmental preservation. The diameter of the spacer ball (column) is slightly smaller than that of the load-bearing ball (column); the difference is almost indistinguishable by the naked eye. The disadvantage of this kind of isolation bearing is that the raceway can only be loaded with half of the load-bearing balls (columns), reducing the bearing load capacity to about half of the original.

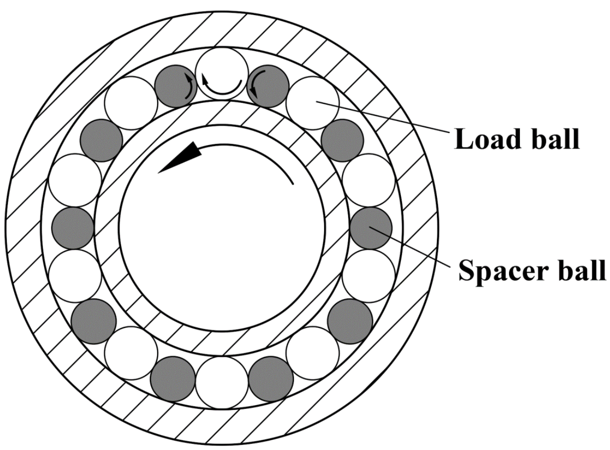

Fig. (3). Radial ball bearings with isolation balls. *(A higher resolution / colour version of this figure is available in the electronic copy of the article)*.

In slewing bearings with large loads, isolation rings are often used to isolate adjacent bearing balls. The isolation ring is designed to be circular with grooves on both sides, as shown in Fig. (**4**). This design can effectively reduce the space occupied by the isolation body in the raceway so that the bearing ball occupies more space in the raceway. Although the increase in the number of balls leads to a rise in the overall weight of the bearing, it also effectively improves the bearing carrying capacity, which is suitable for low-speed, heavy-duty machinery. However, the contact area between the rolling bodies and the isolation ring of such bearings is more significant than that of the isolation ball bearings, resulting in friction that is also slightly larger than that of the isolation ball bearings [49, 50].

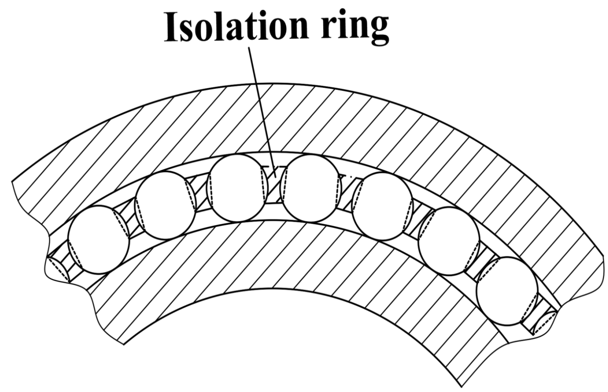

Fig. (4). Ball bearings with isolation ring.

As shown in Fig. (**5**), a helical spring is placed between the steel balls and used as an isolation [51]. When the bearing works, the neighboring balls are close to each other and the helical spring undergoes compression deformation. Under the action of the spring force, the collision between the neighboring balls is avoided, thus replacing the original cage function. In the work, the spring easily causes bearing vibration and scratching of the ball phenomenon. However, under large impact loads, this bearing has better shock absorption.

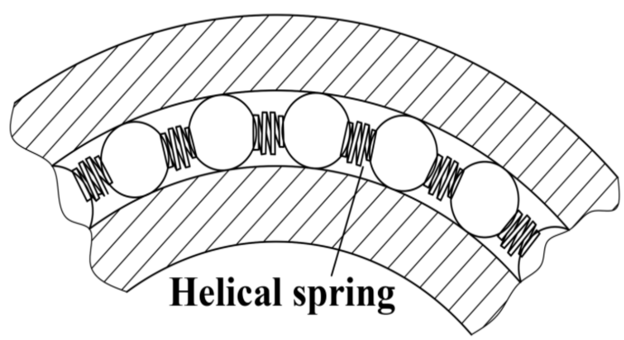

Fig. (5). Helical spring isolated body ball bearings.

German INA Bearing Company invented a ZSL-type bearing, as shown in Fig. (**6**). The isolation body is a small shelf with a slot in the center. This bearing makes the contact area between the roller and the isolation body smaller, thus reducing the friction caused by the isolation body and improving the limiting speed of the bearing. At the same time, due to the thinner isolation body, the spacing between the two adjacent rollers is smaller, the number of rollers in the bearing is more, which improves the bearing carrying capacity.

Fig. (6). ZSL-Type Isolation Cylindrical Roller Bearings. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

NTN Japan developed a high-load cylindrical roller bearing for wind turbines [52], as shown in Fig. (**7**). The rollers are uniformly placed in the raceway formed by the inner and outer rings. T-shaped isolation is used to isolate the rollers between two rollers. The shape of the T-shaped isolation is smaller than that of the conventional cage; the extra space allows the number of rollers to be increased to enhance the load-carrying capacity of the bearing. The friction area between the T-shaped isolation and the roller is reduced, thus reducing the heat caused by friction. This type of bearing has the advantages of strong bearing capacity, long life, and high speed. However, due to the large number of rollers, the overall weight of the bearing is large. Compared with ZSL--type bearing, it is cheaper because of its simple isolation structure and wear-resistant resin material.

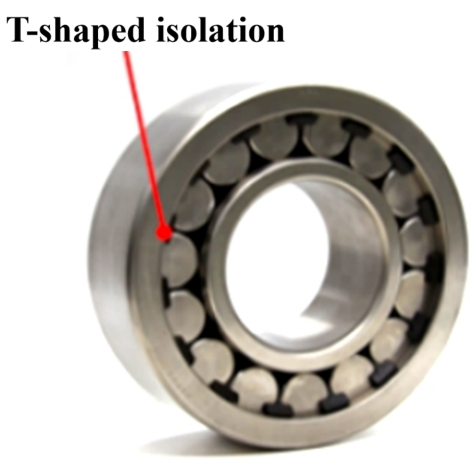

Fig. (7). T-Shaped isolation cylindrical roller bearing. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

2.3. Special Cageless Bearings

Special cageless bearings have an innovative design for the shape of the raceway to keep the individual rolling bodies from contacting each other and automatically dispersing in the movement process. The change in the bearing raceway will affect the movement characteristics between the rolling element and the raceway [53-56], which will make the movement of the rolling element in the rolling more complicated. So the contact angle, contact force, and contact radius between the rolling bodies and the raceway can be controlled by changing the raceway structure, to control the rolling speed of the rolling bodies and change the dynamic characteristics of the bearing [57-59].

As shown in Fig. (**8**). Li proposed a logarithmic spiral raceway cageless ball bearing [60]. The radial clearance of the raceway and busbar parameters was designed based on the rolling friction balance and the introduction of the concept of axial friction angle so that the rolling body and the raceway form a friction self-locking effect. The spatial arrangement restricts the spatial position of the rolling body. It prevents the adjacent rolling body from touching the friction to achieve all the rolling body in the raceway of pure rolling or tends to pure rolling. However, the specific parameters of the bearing raceway are difficult to determine.

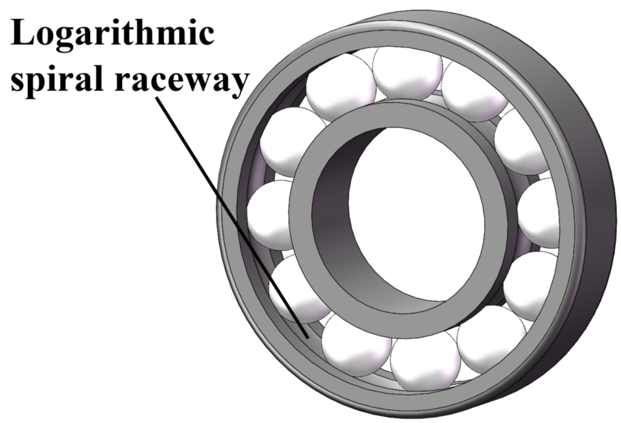

Fig. (8). Logarithmic helix raceway cageless ball bearings. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

3. RECENT PATENTS ON CAGELESS ROLLING BEARINGS

To better understand the current situation of the development of cageless rolling bearings, the following is an analysis of the relevant patents of cageless rolling bearings in recent years.

3.1. Full Complement Cageless Bearings

3.1.1. Full Complement Cageless Ball Bearings

Cai *et al.* [61] provided a full complement ball bearing, as shown in Fig. (**9**). It consists of an inner ring, an outer ring, and a rolling body. The middle part of the inner surface of the bearing outer ring and the outer surface of the inner ring are provided with a groove for the rolling element. The inner surface of the outer ring is provided with a retainer for restricting the axial movement of the rolling body. This bearing has a greater load-carrying capacity than bearings of the same size. However, the difficulty of disassembly and installation of this bearing has also been increased.

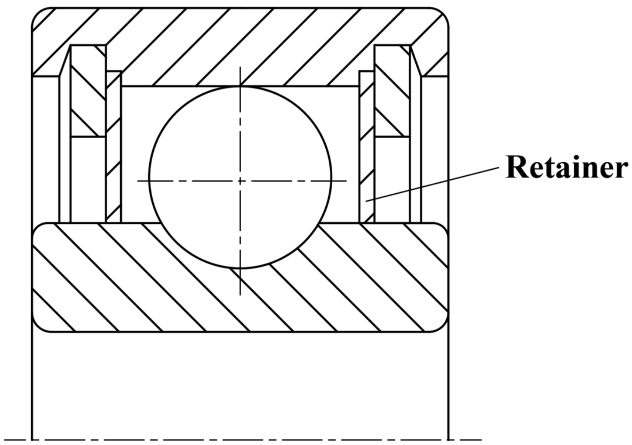

Fig. (9). Full ball bearing CN202360597U.

Kevin C [62] created a cage-less ball bearing that is both resistant to seizure caused by foreign particles and self-cleaning, as shown in Fig. (**10**). It removes at least one ball from the full ball bearing. A large circumferential clearance will appear when the remaining balls are placed next to each other. The bearings have a maximum circumferential clearance of 15° to about 90° and preferably a clearance of 40° to 60°, which allows the bearings to be used in harsh environments such as high winds and deserts. The bearing circumferential clearance is relatively large, which makes it easy to produce an uneven distribution of rolling balls and collision with each other. But in the case of large axial force, each ball can be better dispersed to avoid the above problems.

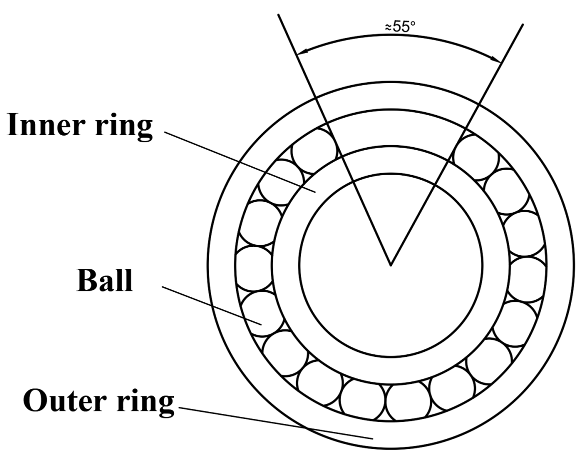

Fig. (10). Seize resistant ball bearing US6367978B1.

Zeng [63] proposed a spherical full ball bearing, as shown in Fig. (**11**). It includes an inner ring, an outer ring, and steel balls. The dust cover is provided on both sides of the steel balls. The side of the dust cover close to the outer wall of the inner ring is provided with a vertical bending part, and the side close to the inner wall of the outer ring is provided with a crimp part. A ball-filling hole is provided between the outer wall of the inner ring and the inner wall of the outer ring. The caliber of the ball-filling hole is gradually reduced horizontally from the edge of the outer ring to the middle of the outer ring. The bending part of this bearing dust cover is fitted with the first locating slot. The crimp part is fitted with the second locating slot to have a better dustproof effect and is easy to disassemble and install. But this bearing requires more pieces to be processed, which raises the processing costs.

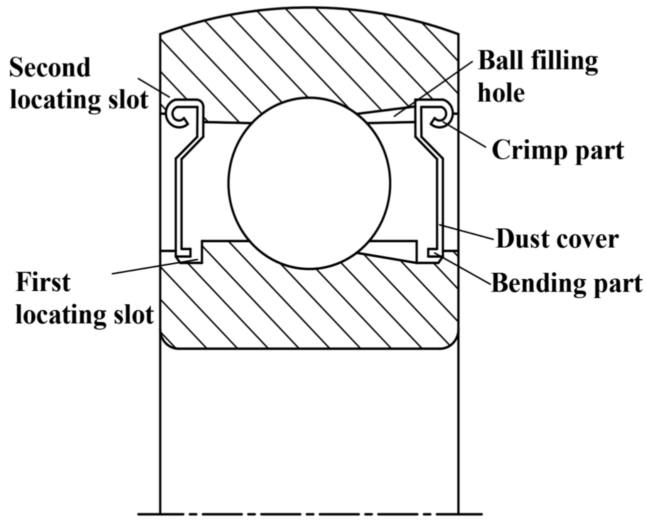

Fig. (11). Full ball bearing of sphere CN208457033U.

Hua *et al.* [64] provide a retainer-less automotive bearing, as shown in Fig. (**12**). It includes an inner ring, an outer ring, spherical balls, and a curved fixing plate. The inner surface of the outer ring is provided with a recessed arc-shaped upper groove, and the outer surface of the bearing inner ring is provided with a recessed arc-shaped lower groove. A permanent magnetic layer is embedded in the surface of the arc-shaped upper groove and the arc-shaped lower groove. The balls are also made of magnetic metal material. During operation, the balls are subjected to magnetic force up and down, which restricts the space for free movement of the balls. The rotary axis is connected to the fixing plate in the arc-shaped upper groove and the lower groove next to the installation of a rotary axis. The fixing plate can rotate around the rotating axis, allowing for both the insertion of the support ball into the interior and vertical fixation, ensuring the position of the support ball. The bearing ball and bearing inner and outer rings are not in direct contact with each other, which reduces the friction between the ball and bearing inner and outer rings and reduces the heat generated by the bearings in the work. However, the increase in magnetic materials will increase the overall cost of bearings.

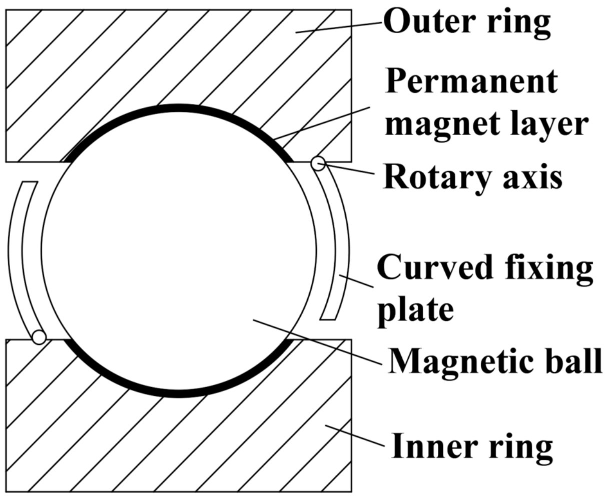

Fig. (12). Retainer-less automobile bearing CN108518417A.

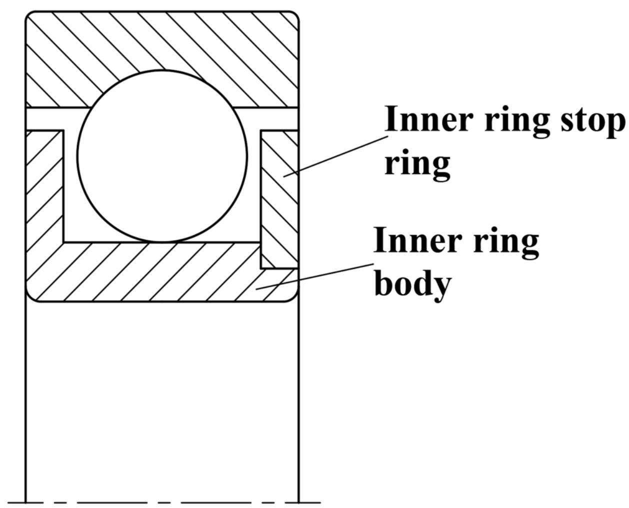

Fig. (13). Bearing inner ring and full-ball bearing CN105134765.

Zhu *et al.* [65] invented a cage-less full ball bearing, as shown in Fig. (**13**). This bearing includes balls, an inner ring, and an outer ring whose axes extend along the left and right sides. The inner ring of the bearing has a flat peripheral surface of constant diameter in the axial direction for rolling fit with the balls. The inner surface of the outer ring of the bearing has curved raceways for mating with the balls. Because the bearing inner ring is horizontal, the friction between the inner ring and the ball will be more intense, but its groove curvature is much larger than that of the bearing outer ring raceway. This eliminates the friction caused by differential sliding and reduces the friction torque. During the working process of the bearing, the ball moves radially outward under the action of centrifugal force and is closely fitted with the curved raceway of the bearing outer ring; the curved raceway limits the ball axial. This bearing is easy to process because the inner ring of the bearing is flat, the balls rotate smoothly with high stability. To prevent the deformation of the bearing inner ring due to wear and tear, resulting in increased clearance, it is necessary to timely replenish the bearing with grease.

Lu [66] created a thrust angular contact ceramic ball bearing, as shown in Fig. (**14**). The thrust angular contact ceramic ball bearing includes an outer ring, an inner ring, and ceramic balls. The inner and outer rings of the bearing are equipped with R-shaped raceways with locking ports. The surface of the raceways is carburized with GCr15 material. Ceramic balls are made of SiN4 material and are fully installed in the raceways. Compared with steel balls, ceramic ball bearings have a small friction coefficient and can work under high-speed working conditions. The inner and outer rings are heat-treated on the surface. The hardness, wear resistance and fatigue strength of the raceway surface have been greatly improved. But at the same time, bearing manufacturing costs will also increase.

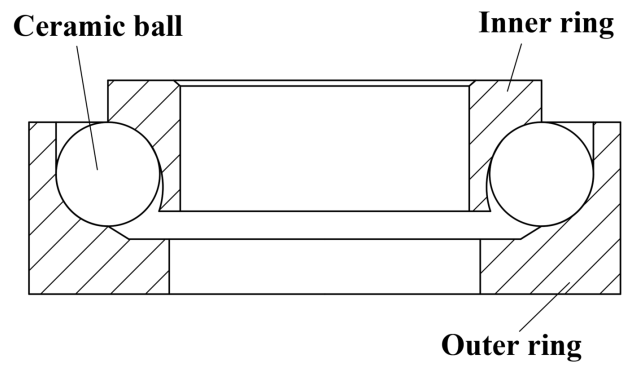

Fig. (14). Thrust angle contact ceramic ball bearing CN204344671U.

Xu *et al.* [67] proposed a double outer ring full ball bearing, as shown in Fig. (**15**). It consists of an inner ring, a first outer ring, a second outer ring, a ball, and a rubber ring. The first outer ring consists of two half-outer rings, which are clamped through the second outer ring. A raceway is arranged between the inner ring and the first outer ring. A sealing groove is arranged in the position corresponding to the first outer ring and the inner ring, and a sealing rubber ring is arranged in the sealing groove. A retainer is arranged between the outer side of the rubber ring and the first outer ring and the second outer ring. The bearing avoids the friction between the rolling elements, and makes the rolling elements evenly distributed along the circumference, extending the service life. Because the bearing outer ring adopts a separate type, it has high machining accuracy, prevents interference during installation and aggravates wear.

Sun [68] provides a cageless bearing, as shown in Fig. (**16**). The inner ring of the bearing is provided with a steel ball inner raceway. The outer ring is composed of a left dial ring and a right dial ring. A ring groove is arranged inside the left turning ring and the right turning ring, and the ring groove is interfacing with each other to form an outer raceway. Inside the raceway, the steel ball is fully loaded and filled with grease on the raceway. When installing, firstly,

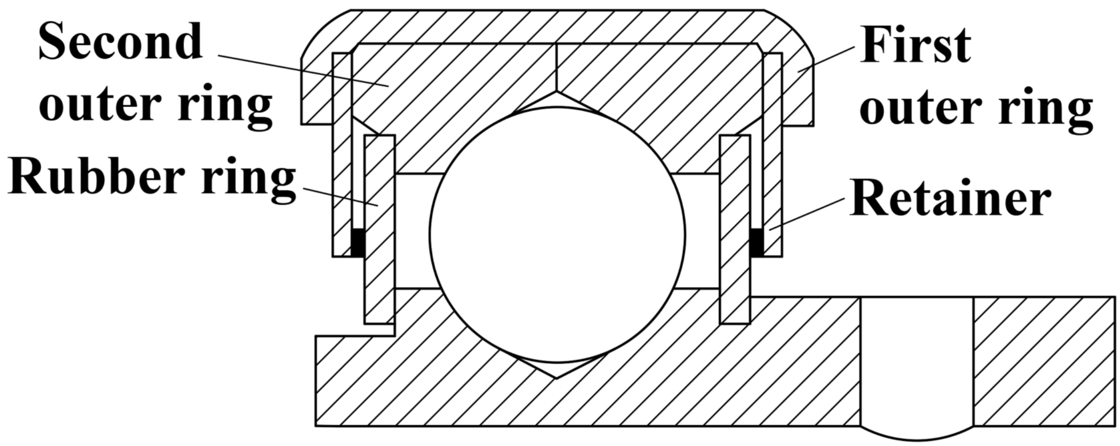

Fig. (15). Double-outer-ring full ball bearing CN105736580A.

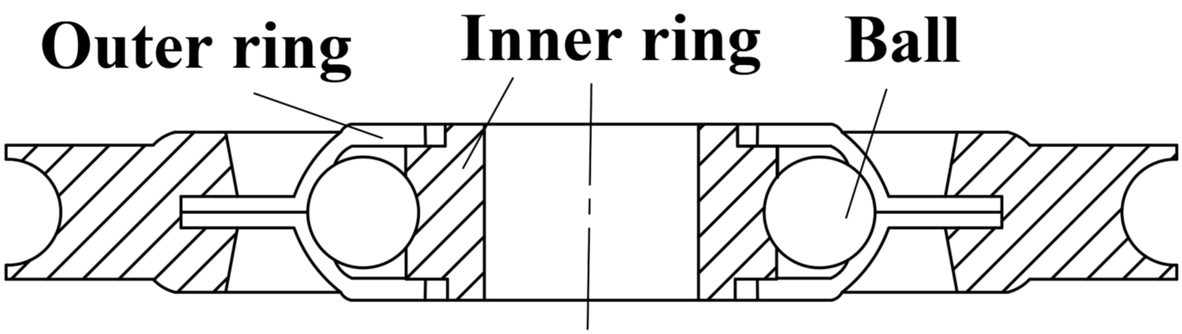

Fig. (16). Bearing without holding fram CN105240409A.

the inner ring of the bearing is placed on any toggle ring, then filled with steel balls, then filled with grease, and then another toggle ring can be installed. The bearing abandons the original cage and simplifies the bearing structure, the outer ring is a sealing device, and the sealing effect is better. The disadvantage is that the outer ring of the bearing is formed by the picking ring each other, and the processing accuracy of the two contact surfaces needs to be guaranteed, thus increasing the cost.

Liu *et al.* [69] proposed a full-complement ceramic ball bearing for aviation turbine engines, as shown in Fig. (**17**). The outer surface of the inner ring and the inner surface of the outer ring are respectively provided with ball channels. The density of the silicon nitride ball is 40% of the steel ball. The centrifugal force is small at high speed, the bearing has strong fatigue resistance and long life. The modulus of elasticity of the rolling body is higher than that of steel, the elastic deformation is small, and the dynamic stiffness of the bearing is high. The coefficient of thermal expansion is 1/3~1/4 of steel; the size change with temperature is small, so it is suitable for occasions with significant temperature changes. It has good wear resistance, high running accuracy, a long working life, and work reliability. However, the impact resistance of the ceramic ball is poor compared with that of the steel ball.

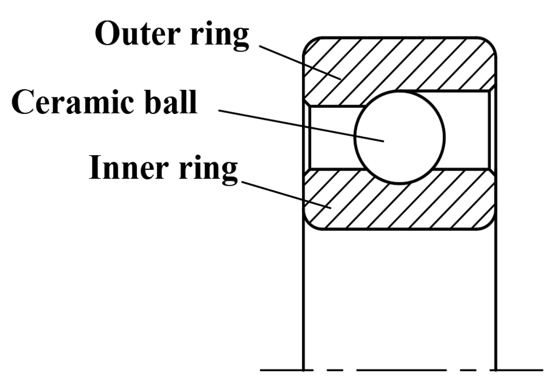

Fig. (17). Full-complement ceramic ball bearing for aviation turbine engine CN103671508A.

3.1.2. Full Complement Cageless Roller Bearing

He [70] invented a cageless full complement rolling linear contact spherical bearing, as shown in Fig. (**18**). It consists of an outer ring, an inner ring, and one or more rows of circular table body rollers. With one or more annular tracks between the inner surface of the outer ring and the outer surface of the inner ring, lubricating oil grooves are provided in the annular tracks. The width of the outer ring of the bearing is greater than the width of the inner ring of the bearing so that the lubricating oil overflowing outward due to the centrifugal principle in the bearing work can be collected by the outer ring to prevent the lubricating oil from being lost. The rollers are tightly fitted inside the ring raceway, and the rollers can roll inside the ring raceway. The rollers are cylindrical in the center, and the two ends are shaped like a round table body. When the bearing works, the two sides of the round table body and the outer ring of the bearing arc shape are consistent to restrict the rollers from falling off. The bearing has the advantages of convenient disassembly and reduced production cost. The roller is in linear contact with the outer ring and the inner ring, which can bear greater force and extend the service life of the bearing. However, due to the larger friction area of the bearing line contact, the higher the friction and temperature rise, the speed of the bearing is limited. Consequently, it is unable to operate under high-speed conditions.

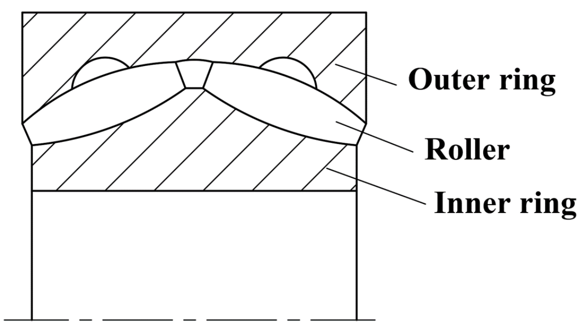

Fig. (18). Full roller linear-contact self-aligning bearing without holder CN109737138A.

Wang [71] proposed a cageless full roller bearing, as shown in Fig. (**19**). It mainly consists of the outer ring, the inner ring, rollers, and fixed ring. An object raceway is located between the outer wall of the inner ring and the inner wall of the outer ring of the bearing. The rollers are closely fit and evenly distributed in the raceway. The fixed ring is symmetrically set on both sides of the rollers. The inner side of the fixed ring is provided with a groove corresponding to the shape of the roller. It can prevent the roller from axial movement and skew during the working process. A few U-shaped grooves are uniformly arranged around the fixed ring. The locating blocks placed in the U-shaped groove are connected with the bearing outer ring by screws. This method abandons the traditional bearing cage and controls the roller movement with a fixed ring and the shape of the raceway. The advantage is that the disassembly of bearings is more convenient and the bearing capacity is better. The disadvantage is that this bearing needs to open a threaded hole in the outer ring, which increases the processing cost.

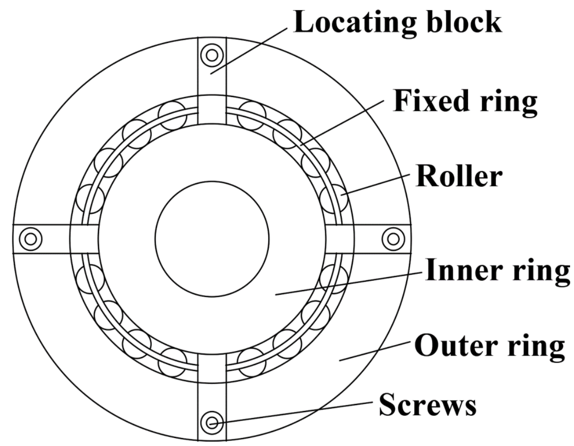

Fig. (19). Retainer-free full-roller bearing CN209212800U.

Wang *et al.* [72] invented a non-contact sealed double--column full-complement cylindrical roller bearing, as shown in Fig. (**20**). It consists of the inner ring, the outer ring, and the rollers. The dust cover is set on the outside of the rollers and placed between the outer ring and the inner ring of the bearing. A groove is set between the top of the dust cover and the raceway of the outer ring of the bearing. A spring ring is placed in the groove. This kind of full-complement cylindrical roller bearings has a low cross-section height and a very high radial load-carrying capacity. It is widely used in automobile gearboxes, reduction gearboxes of construction machinery, and the lifting industry. Instead of an ageing rubber seal, the bearing employs a dust cover and a spring ring. Grease must be applied in advance to prevent roller skew caused by dust cover wear if continuous operation over an extended period of time is required.

Xiang *et al.* [73] invented a cylindrical permanent magnet roller cageless bearing, as shown in Fig. (**21**). It consists of an inner ring of the bearing, an outer ring, and a cylindrical permanent magnetic roller. Cylindrical permanent magnetic rollers are distributed according to the principle that their magnetic inductance lines are balanced on the axis face of the roller. Adjacent rollers repel each other. The rollers are not in contact with each other under the constraints of the magnetic field force and the raceway, which reduces friction losses. The advantage is that the structure of the cylindrical roller bearing is simplified and the service life of the cylindrical roller bearing is extended. The disadvantage is that if friction loss occurs, the repulsive force of the inner and outer rings will change, resulting in an unstable running state of the rolling element and a skew phenomenon may occur.

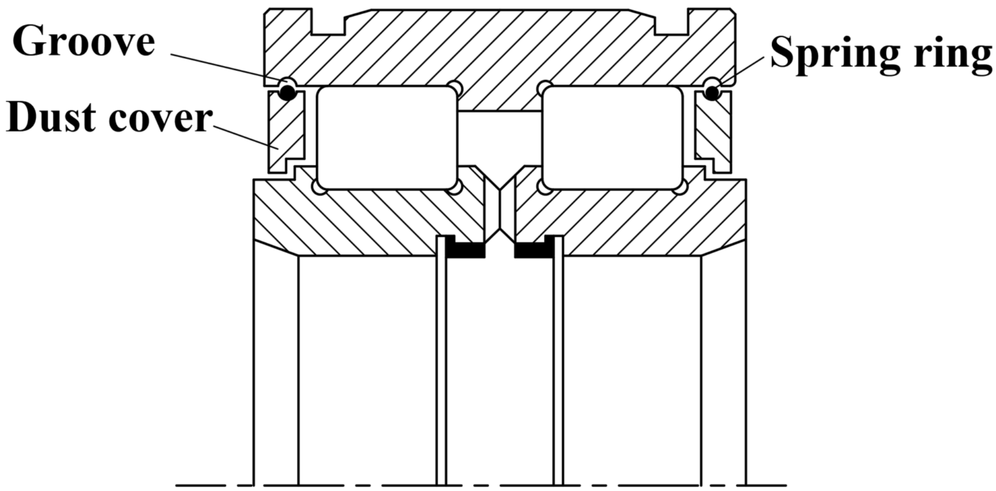

Fig. (20). Non-contact sealed double-column full-complement cylindrical roller bearing CN203926392U.

3.2. Isolation Element Bearings

3.2.1. Isolation Element Ball Bearings

Evgenij *et al.* [74] provide a radial thrust single-row ball bearing, as shown in Fig. (**22**). The bearing consists of an inner ring having a groove with a circumferential radius surface, an outer bearing ring, a separate isolation ring, and a series of balls. The inner surface of the outer ring is cylindrical. An isolation ring is positioned on the outer ring and in contact with the balls, while a comparable isolation ring is inserted on the other side for closing. The maximum number of balls mounted therein is disposed partly in the raceway of the inner ring and partly in the circumferential radius groove space of the inner and outer carrier rings. Because the isolation ring is non-split, it will lead to increased processing costs, but the contact stress between the roller and the isolation ring will be smaller, and the installation will be more convenient.

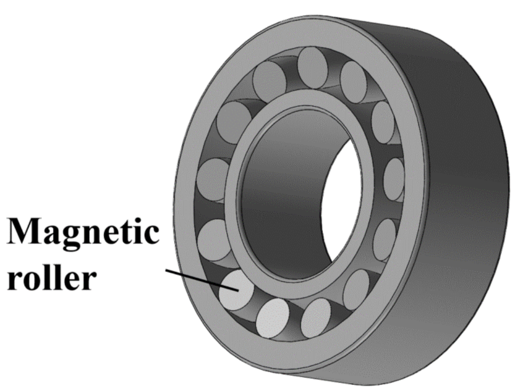

Fig. (21). Cylindrical permanent magnet roller cageless bearing CN209818522U. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

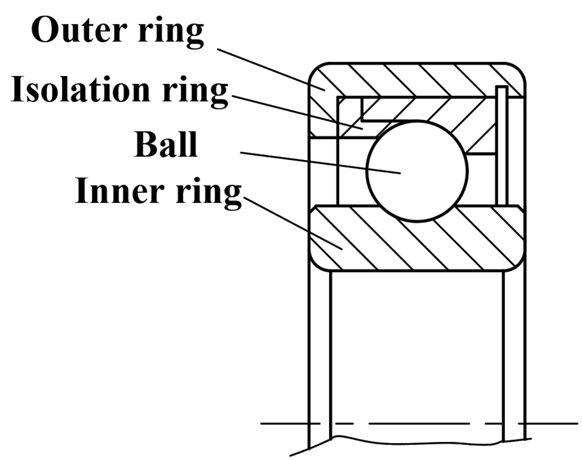

Fig. (22). Radial-thrust single-row cageless ball bearing RU 2538903C1.

Pan *et al.* [75] disclosed a cageless high-speed ball bearing with a shaped isolator, as shown in Fig. (**23**). It consists of an outer ring of the bearing, an inner ring of the bearing, a spherical rolling body, and an isolator. The isolator is a cylinder at both ends, and the middle is a rotating body formed by a concave special curve around the axis of the isolator connected with the cylinder at both ends of the isolator. Isolators are placed in the raceway with the same number of balls. The isolator is tangent to the adjacent ball and raceway. The isolator eliminates the collision between the cage and the ball and separates the isolator. The advantage is that the isolator and ball for rolling friction and heat are much lower than traditional bearings. The disadvantage is that the isolator busbar shape processing accuracy is difficult to ensure.

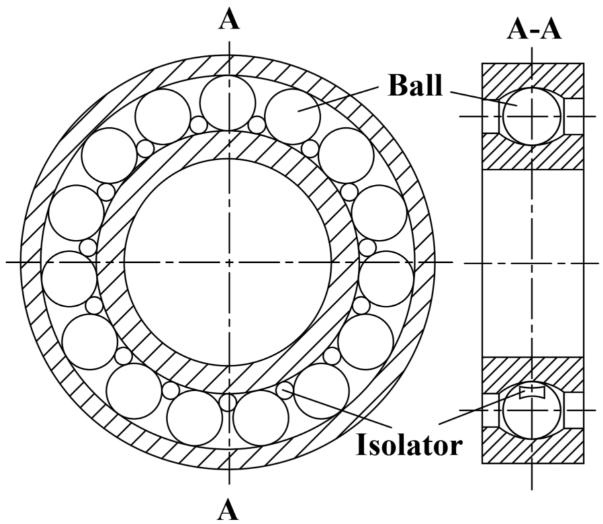

Fig. (23). No-cage high-speed ball bearing adopting special-shaped isolators CN110219887A.

Mark *et al.* [76] designed a cageless ball bearing, as shown in Fig. (**24**). The bearing has an outer ring extending circumferentially around a center axis. The inner ring is provided inside the outer ring and extends circumferentially around the center axis to be coaxial with the outer ring. Between the inner and outer rings of the bearing, a plurality of load balls is provided without contacting each other. A plurality of spacer balls are arranged between adjacent load balls so that the spacer balls and the corresponding pair of load balls roll contact. This bearing can make the sliding friction between the ball and the cage become rolling friction, effectively reducing the friction loss. The disadvantage is that the bearing disassembly and installation is difficult.

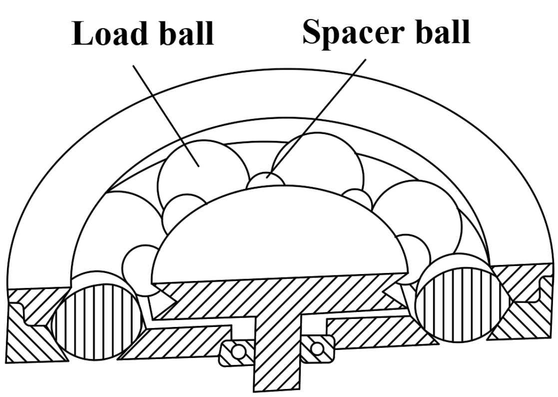

Fig. (24). Cageless bearing and transmission US20200166075A1.

3.2.2. Isolation Element Roller Bearings

Schmidt [77] investigated a cageless roller bearing with a sealed cover, as shown in Fig. (**25**). It consists of an outer ring, an inner ring, load rollers, and spacer rollers. The diameter of the spacer rollers is smaller than that of the load rollers; they are placed in the raceway alternately with the load rollers. When the inner and outer rings rotate, the spacer roller is driven by the load roller to rotate. A retaining ring is set on both sides of the ball body to prevent the axial movement of the rolling body. In the working process, this roller bearing has smooth running and low noise. There is rolling friction between the rollers, and the service life of the bearing is long. Additionally, the original equipment for machining the bearing can remain unchanged. The economic benefits are considerable. The disadvantage is that the increase in the number of rolling elements will lead to an increase in the overall weight of the bearing. The roller skew phenomenon, that appeared in the work, can only be applied to low-speed occasions.

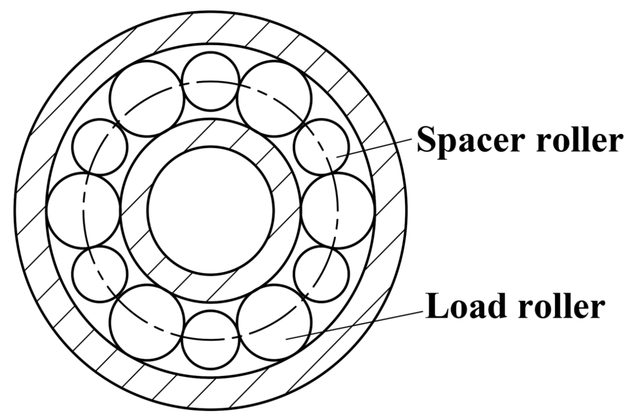

Fig. (25). Protectire frame less roller bearing having sealing cover CN1475679.

Li *et al.* [78] invented a cageless rolling bearing, as shown in Fig. (**26**). It consists of an outer ring, a large roller, a small roller, and an inner plastic ring. Several large rollers are uniformly placed on a raceway comprising the inner and outer rings. Small rollers are provided between the large rollers. The small rollers are placed between the large rollers on the upper or lower side. Small rollers on the upper side are tangent to the outer ring of the bearing and the adjacent large rollers. Small rollers on the lower side are tangent to the inner ring of the bearing and the adjacent large rollers. This bearing is compact and the individual spheres are tangent to prevent the roller from moving and tilting. Small rollers separate the large rollers and act as a traditional cage. The diameter size of the roller can be changed so that the bearing can work under different working conditions. The advantages of this bearing are an increased number of rolling elements, increased bearing load, removal of the original cage structure, and reduction of noise. The disadvantage is that if the roller is lost after the bearing works for a long time, the roller of different layers is removed from the tangential state, and the bearing as a whole will be unstable.

Pan *et al.* [79] invented a retainer-free surface micro texture self-lubricating cylindrical roller bearing with an

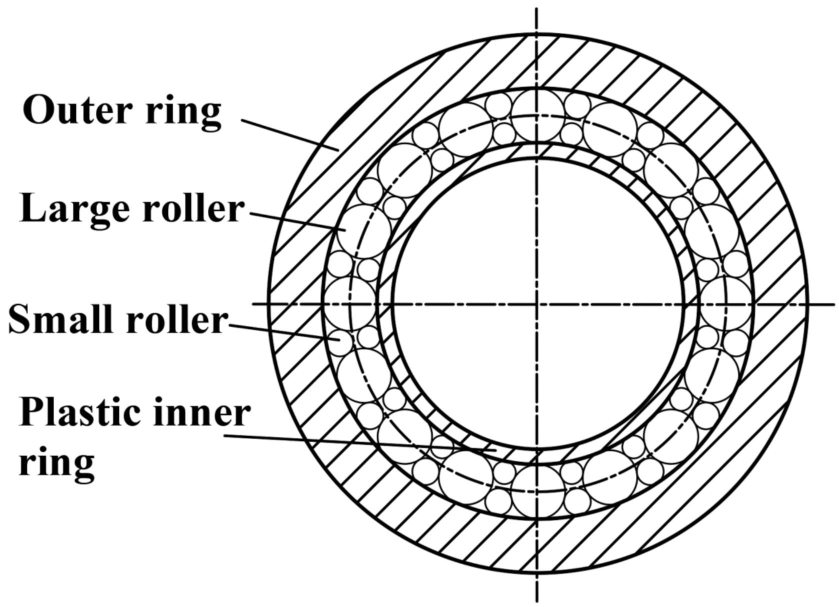

Fig. (26). Retainer-free rolling bearing CN104454975A.

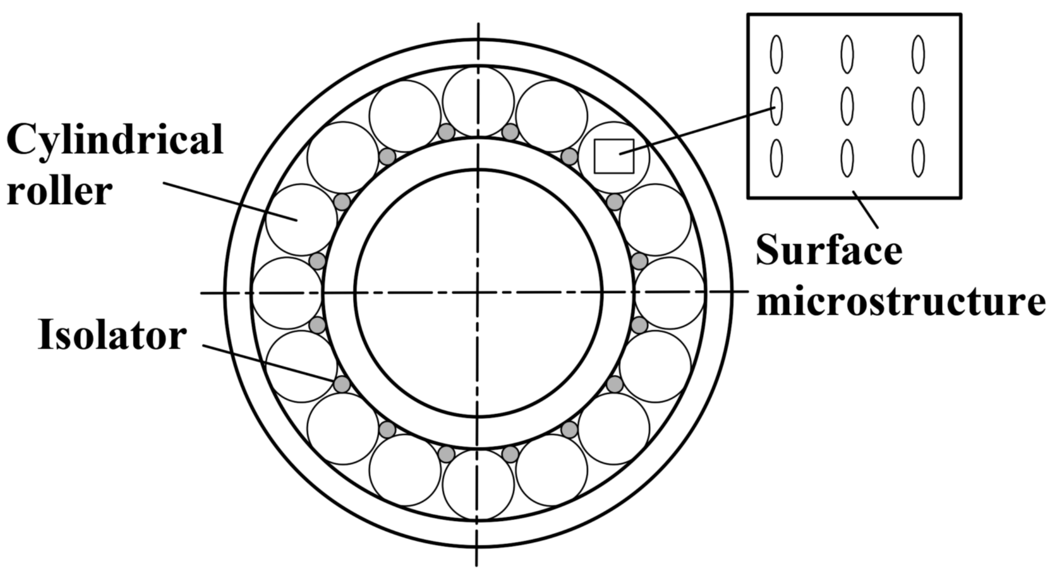

Fig. (27). Retainer-free surface micro-texture self-lubricating cylindrical roller bearing with isolator CN110219892.

isolator, as shown in Fig. (**27**). This bearing isolates the cylindrical rollers by discretizing the conventional cage and using small-diameter needles as isolators. At work, the isolator in the radial direction needs to travel outward in response to the centrifugal effect. The isolator diameter must be greater than the maximum gap between the two neighboring rollers so that it can not fly away from the neighboring rollers. Because the isolator is full of the gap between the inner ring and the roller, the radial gap is reduced to avoid the roller skew phenomenon. A surface microstructure or grid can accommodate lubricant to realize self-lubrication in roller surface processing. There is only rolling friction between the bearing isolator and the cylindrical roller. Surface microstructure can also reduce the contact area between rollers and isolators, raceways and reduce friction, which is of great significance in the application of heavy load and high-speed equipment. However, its disadvantage is the high cost of surface microstructure processing.

Pan *et al.* [80] proposed a hollow spiral isolator cageless cylindrical roller bearing, as shown in Fig. (**28**). It includes an inner ring, an outer ring, and several cylindrical rollers

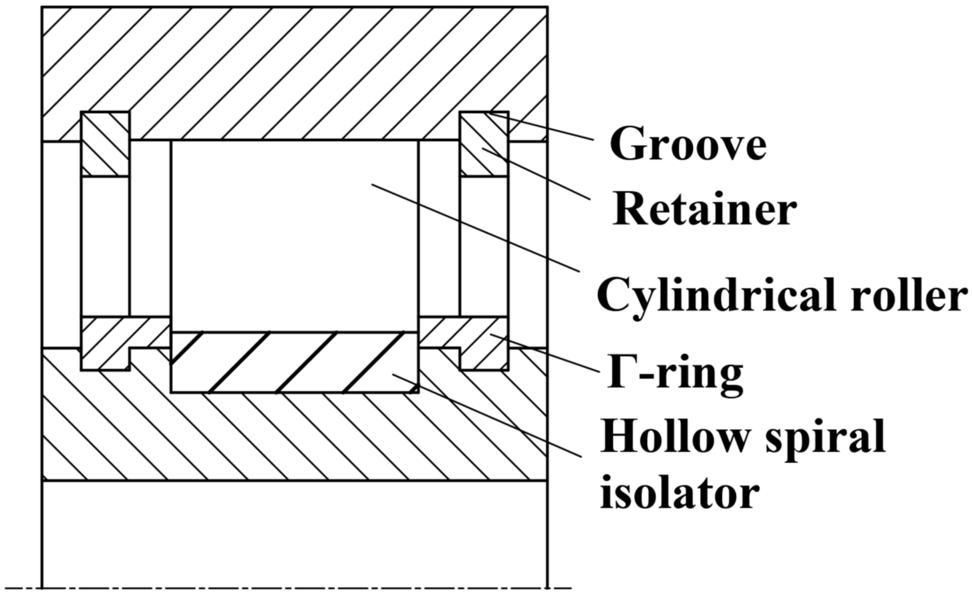

Fig. (28). Hollow spiral isolator holder-free cylindrical roller bearing CN214661506U.

between the inner and outer rings. There is an isolator between the two neighboring cylindrical rollers and the inner ring; the isolator separates the cylindrical rollers uniformly. At the same time, the isolator is full of the gap between the inner ring and the roller so that the radial gap is reduced to avoid the roller skew phenomenon. The isolator is a hollow isolator made of a steel strip with a special section. The inner and outer rings of the bearing are provided with ring grooves to insert different types of retainer, the inner ring is inserted into the Γ-ring, the outer ring is inserted into the outer ring stop ring. The bearing has a simple structure, and pure rolling friction is formed during the movement of the bearing. The advantage is to reduce friction, reduce weight, and reduce the driving torque of the bearing. The spiral gap on the surface of the isolator can also be embedded with abrasive particles to keep the working surface of the cylindrical roller clean. The Γ-ring limits the axial movement of the hollow spiral isolator, prevents it from slipping out, and improves safety. However, the shape of the retainer is special, which increases the processing cost.

Pan *et al.* [81] investigated a flange-free isolator cylindrical roller bearing with self-holding function, as shown in Fig. (**29**). It includes an inner ring, an outer ring, and an annular sealing ring between the inner ring and the outer ring and several rollers. An isolator is provided between every two adjacent rollers and the inner ring. The inner and outer rings of the bearings have no edge and open annular groove and annular raceway. The annular sealing ring is provided with annular bumps and a micro-convex body. Rollers have annular bumps on both sides and an annular raceway in the middle. The isolator is with annular bumps in the middle. This bearing is easy to assemble. The roller on both sides of the ring-shaped convex circle is embedded in the inner and outer ring of the ring-shaped raceway, limiting the axial movement of the roller. The isolator, the roller, and the inner ring on the annular raceway are close to each other. The isolator is located in the roller annular convex circle on the inside, so the isolator of the axial runout is also limited. This will make the roller movement more stable and will not cause skew. The sealing ring is installed in the ring groove of the inner and outer rings. This significantly improves the sealing and dustproof ability; the micro-convex body on the ring seal reduces friction. The disadvantage is the high processing cost.

Bungert [82] invented a cageless roller bearing, as shown in Fig. (**30**). The roller bearing has a first and second running surface. Each running surface is covered with rollers, the rollers on different running surfaces are placed tangentially. Both running surfaces can rotate around the bearing shaft. The force applied to the first running surface can drive the body of the second rolling surface through the upper roller. The bearing cancels the original cage, the rollers on different running surfaces support each other, and the structure is compact, avoiding the roller skew phenomenon, effectively reducing the friction and heat generation. However, the size of the isolator is small, and the processing accuracy is higher.

3.3. Special Cageless Bearings

3.3.1. Special Cageless Ball Bearings

Kawashima [83] proposed a deceleration slope raceway cageless ball bearing, as shown in Fig. (**31**). In this bearing, a reducing grade is locally provided in the outer raceway to reduce the contact and friction between the balls of the cageless bearing or rolling friction guideway. The characteristic of this bearing is that it keeps the ball automatically dis-

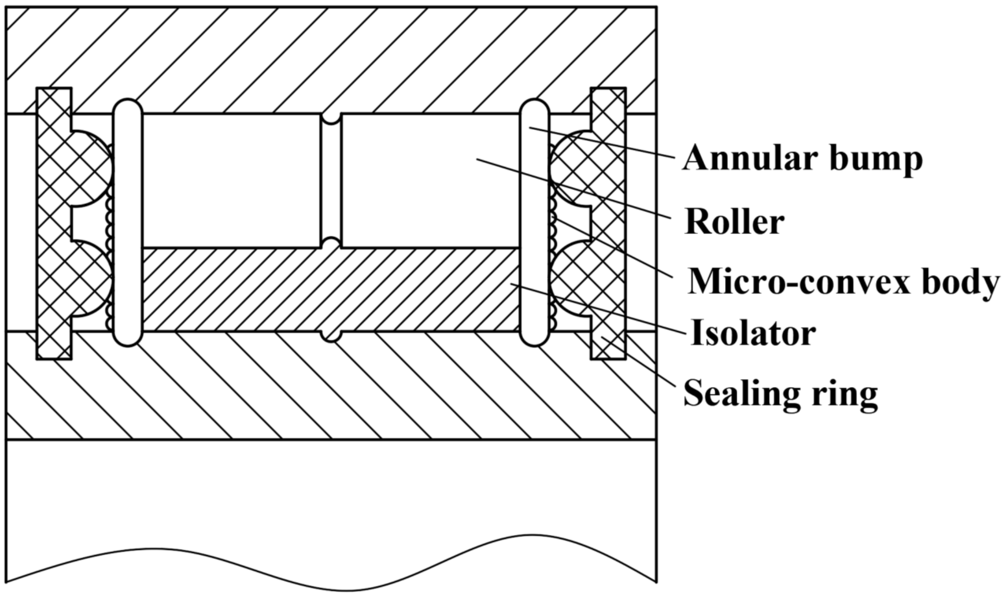

Fig. (29). Flange-free isolator cylindrical roller bearing with self-holding function CN216430272U.

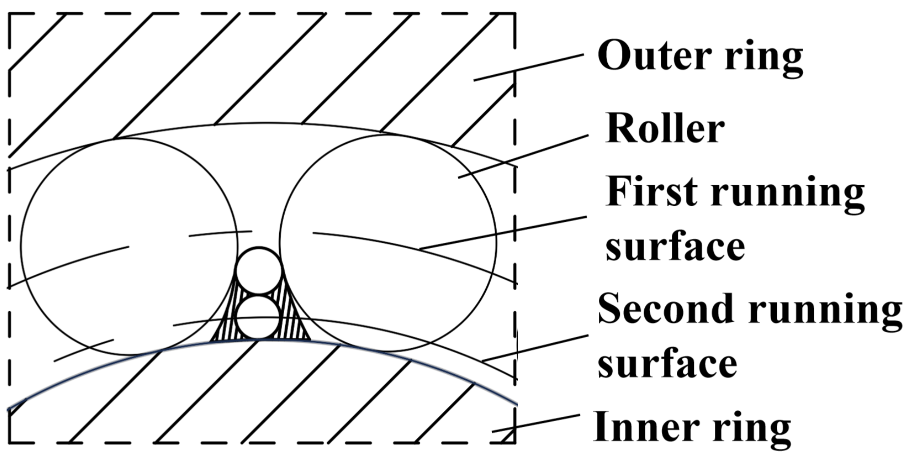

Fig. (30). Bearings with reverse rotating bearings DE102015221210A1.

persed without contact with each other under the stable running state. However, the technology still needs to be more mature and has yet to form a product in the market.

Guo *et al.* [84] investigated a cageless curved-groove ball bearing, as shown in Fig. (**32**). It consists of an outer ring, steel balls, and an inner ring. The inner ring and outer ring of this bearing are set up as curved tracks with an equal number of "peaks" and "valleys" that fit each other. The steel balls are distributed all over the raceway to make a full complement bearing. The outer and inner rings have curved grooves with thick walls on one side and thin walls on the other. When the steel balls move to the "peaks" and "valleys" of the raceway during operation, the steel balls oscillate up and down according to the changes in the shape of the raceway. This bearing can increase the amplitude of the curved groove ball bearing according to the demand, reduce the oscillation frequency, and, at the same time, improve the bearing capacity and change the rotary motion into reciprocating linear motion. The disadvantage is that the raceway structure is complex and the processing accuracy is difficult to guarantee.

Zhao *et al.* [85] provided a particular raceway cageless ball bearing with the automatic discretization of rolling bodies, as shown in Fig. (**33**). It consists of an outer ring

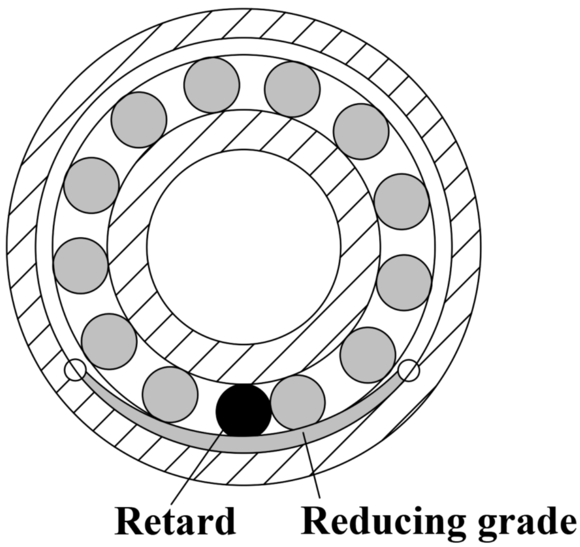

Fig.(31). Rolling Device and Using Method Thereof US20100226603A1. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

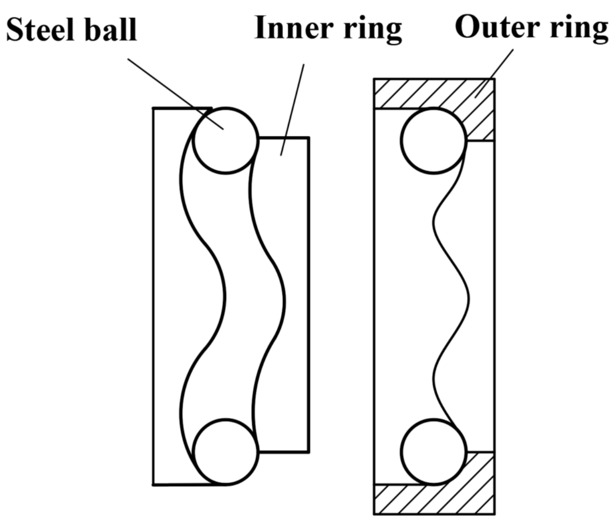

Fig. (32). Cageless curved-groove ball bearing US2020224715A1.

with a decelerating groove, inner ring, and balls. The inner and outer rings of the bearing are provided with spherical raceways. The spherical balls are arranged on the raceways and leave a space size of one ball. When mounted, the decelerating groove of the outer ring of the bearing is placed directly under the bearing. When the bearing is not working under gravity, there is a gap between the first and last balls, the remaining balls are in close contact. When the bearing starts to rotate, each ball passes through the decelerating groove and then decelerates, thus changing from close contact with the latter rolling element to a separate state. After all the balls pass through the decelerating groove, they are automatically discrete. This bearing reduces the collision problem between the balls and improves the life of the bearing, which can be used in high-speed and heavy-duty operating environments. However, the motion of the ball is complicated and its stability is poor during the start and stop stage.

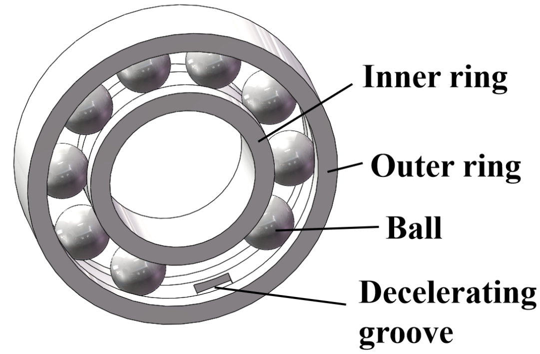

Fig. (33). Special retainer-free ball bearing with automatically dispersed rolling bodies CN216519170U.

Paul R [86] invented a low friction side load bearing assembly, as shown in Fig. (**34**). The assembly includes a telescopic member with a concave conical outer surface that can be slide-mounted on a spindle and a cageless rolling bearing surrounding the telescopic member. Cageless rolling bearings include a ring housing containing an inner ring of a ball bearing engaged with a sleeve member. A spring-loaded bias mechanism pushes the sleeve member along the rotating axis of the spindle so that its conical outer surface is wedged into the inner ring of the ball bearing. The advantage is that it eliminates the need for bearing retainers and allows the bearing assembly to self-adjust wear. The disadvantage is that the bearing structure is complex and the installation and disassembly are difficult.

Paul [87] invented an energy storage flywheel assembly based on cageless rolling bearings, as shown in Fig. (**35**). It consists of a vertically rotating flywheel, a shaft connected to the flywheel, and a cageless shaft thrust ball bearing that can be rotated to support the lower end of the shaft. The stator of this bearing contains a set of three free-floating bearing balls in a groove. The rotor is also a set of three free-floating bearing balls located in the groove of the cylindrical stator, and a single intermediate bearing ball located between and engaged with the three bearing balls of the stator and the three bearing balls of the rotor. This bearing can be operated to increase its limiting speed.

Wang [88] invented an angular contact bearing without a cage, as shown in Fig. (**36**). It includes an outer ring, and an inner ring is provided in the outer ring. A ball is provided between the inner ring and the outer ring. A limiting device is provided on the surface of the outer ring. A device for making adjustments, which includes a ring that restricts movement, is located within the inner ring. A limiting groove is formed in the inner wall of the limiting ring along a direction perpendicular to the inner wall of the inner ring. A

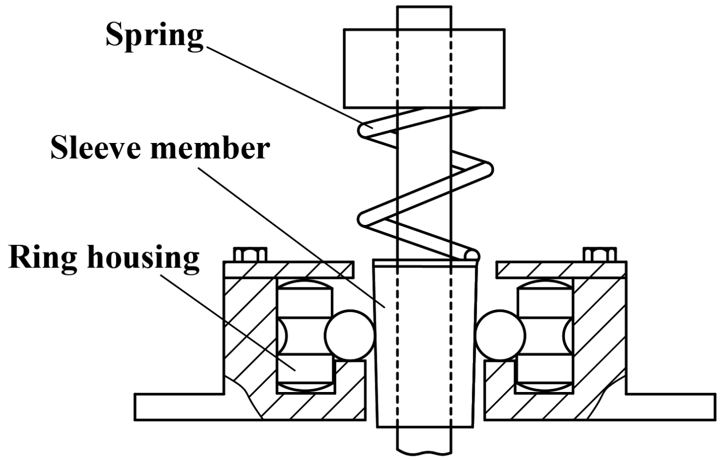

Fig. (34). Side load-bearing assembly US10047790B2.

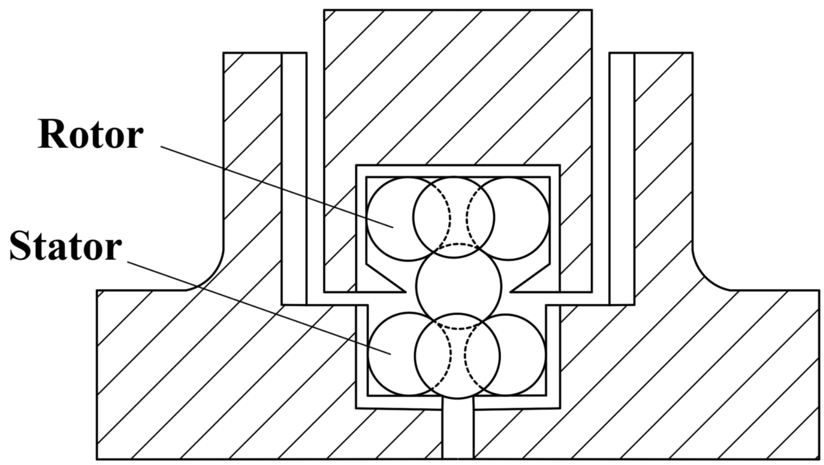

Fig. (35). Energy storing flywheel and bearing assembly US20140260779A1.

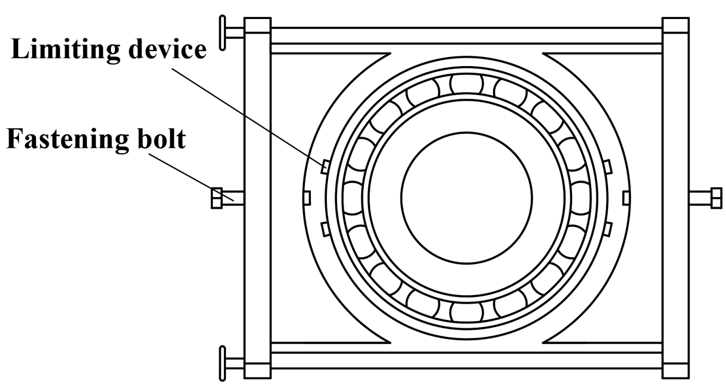

Fig. (36). Retainer-free angular contact bearing CN211371041U.

fastening bolt is threadedly connected to the inside of the limiting groove. The other end of the fastening bolt is in contact with the inner wall of the inner ring. The advantage of this bearing is that the structure is simple, and the effect of adjusting the inner diameter of the limit ring can be achieved by replacing the limit ring with different thicknesses. The inner diameter of the inner ring can also be adjusted by rotating the fastening bolt, thereby squeezing the inner ring in the limit groove. The disadvantage is that the number of balls increases and the overall weight of the bearing increases.

3.3.2. Special Cageless Roller Bearings

Mohamed [89] disclosed a serrated cage-less bearing, as shown in Fig. (**37**). This bearing maintains the space between successive rollers and the relative position between parts by inserting a jagged band between the rollers and the inner and outer rings, where the jagged band separates the rollers, the function of the original cage is realized. The bearing realizes the linear movement of the roller. The bearing space occupied by the original cage is eliminated. The number of rollers can be controlled by changing the jagged band shape and the roller diameter. However, the accuracy of the raceway is difficult to guarantee, and the processing cost is higher.

He [90] studied a rolling bearing with three rollers, a purely mechanical cageless rolling bearing, as shown in Fig. (**38**). There are three layers of rollers between the inner and outer rings of this bearing. The rollers in the same layer have the same diameter and clearance size, and the number of rollers in different layers is the same. The rollers of the inner and outer layers are tangent to the raceways and the rollers of the middle layer simultaneously. The diameter of the rollers decreases from the inner ring to the outer ring. When the bearing works, the middle layer rollers and the inner and outer layers rollers rotate in the opposite direction, there is only rolling friction between each other. This bearing has a higher limit speed, longer bearing life and longer maintenance-free time. However, the number of this bearing roller is too much, resulting in the overall weight increase.

Wang [91] proposed a unidirectional bearing without a cage, as shown in Fig. (**39**). It consists of a bearing outer ring, stop block, spring frame, roller, and bearing inner ring. The inner and outer rings of the bearing are mounted according to the exact center axis. A plurality of sprag devices are provided on the inner wall of the bearing outer ring and matched with the rolling bodies for unidirectional rotation of the rollers. A compressible spring frame is provided between the two rollers. When the bearing rotates clockwise, the spring frame is compressed by force. There is no direct collision between the rollers under the action of the spring force. The advantage of this bearing is that the elastic plate is in contact with the rolling body. The surface contact is transformed into linear contact, which prolongs the service life of the bearing. In the event of failure of the roller and the stop block, the rolling element is still locked by the spring frame, which significantly improves the safety of the bearing. However, the bearing structure is more complex and the processing is more difficult.

Rainer *et al.* [92] invented an axially suspended roller cageless bearing, as shown in Fig. (**40**). On the surface of the inner ring of this bearing, a large number of grooves can accommodate the rollers, and the grooves are arranged uniformly along the circumference. The groove allows the roller to rotate in a fixed space. The rolling body is set into a cylindrical shape. A large number of rollers are distributed in the groove along the circumference, and the ends of the rollers are aligned with each other and placed at an Angle of 45° relative to the bearing axis. The roller can be turned in the groove of the bearing inner ring. This bearing can carry more axial force and can be widely used in heavy machinery, such as crane support bearings, automobile turntable bearings, and so on. Canceling the original cage can also add more rolling elements to increase bearing life. However, the increase in the number of rollers of this bearing will lead to an increase in the overall weight of the bearing, which is not applicable in light equipment.

Tang *et al.* [93] designed a cageless bearing by changing the structure of the inner and outer rings of the bearing, as shown in Fig. (**41**). A uniform semi-cylindrical groove is formed in the outer circumference of the inner ring or the inner circumference of the outer ring of the bearing along the axial direction, which is equivalent to the integration of the cage and the inner and outer rings of the bearing. A roller is placed in the groove to ensure that the depth of the groove is less than the radius of the roller and the width of the opening of the groove is greater than the diameter of the roller so that the roller is confined between two adjacent teeth of the gear structure. It is also possible to set a certain angle between the groove and the axial direction of the bearing to form a tapered roller bearing. In practical application, several depressions can be arranged on the surface of the groove, thus reducing the contact area and surface friction between the roller and the groove. The increase in the contact area between the roller and the inner ring will lead to more serious wear, but also improve the bearing capacity. The bearing does not require a separate cage, which prevents the cage from being subjected to large centrifugal forces, shocks, and vibrations, thus preventing the bearing from failing due to damage to the cage and simplifying the bearing structure. However, this bearing does not solve the phenomenon of roller skew caused by working wear.

Zhao *et al.* [94] invented a cageless cylindrical roller bearing, as shown in Fig. (**42**). It consists of a bearing outer ring, a bearing inner ring, raceways, rivet holes, rivets, and rollers. A plurality of rows of raceways are provided on the surface of the inner ring of the bearing. The raceways consist of multiple rows that are joined together using rivet holes. These rivet holes have countersunk holes at both ends. Raceway and rivet jointly limit the position of the roller to avoid axial inclination of the roller. A roller with a built-in round hole is arranged on the surface of the raceway; each roller is connected through a rivet and arranged on the rivet hole. This bearing simplifies the structure of the

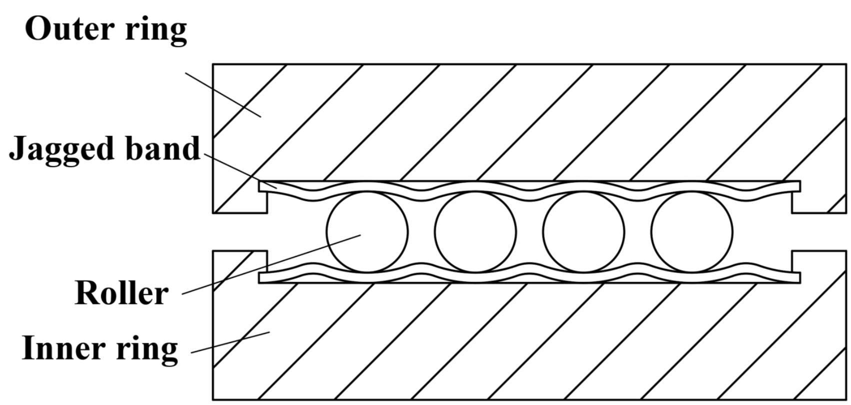

Fig. (37). Separation of rollers in cageless anti-friction bearings WO2019114914A1.

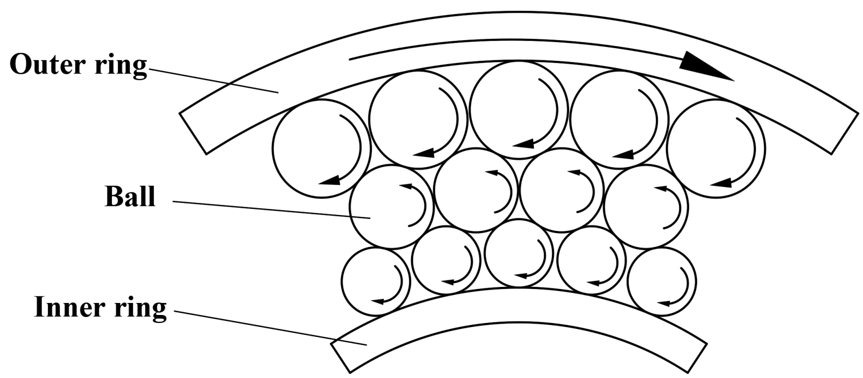

Fig. (38). Rolling bearing with triple rollers CN103062216A.

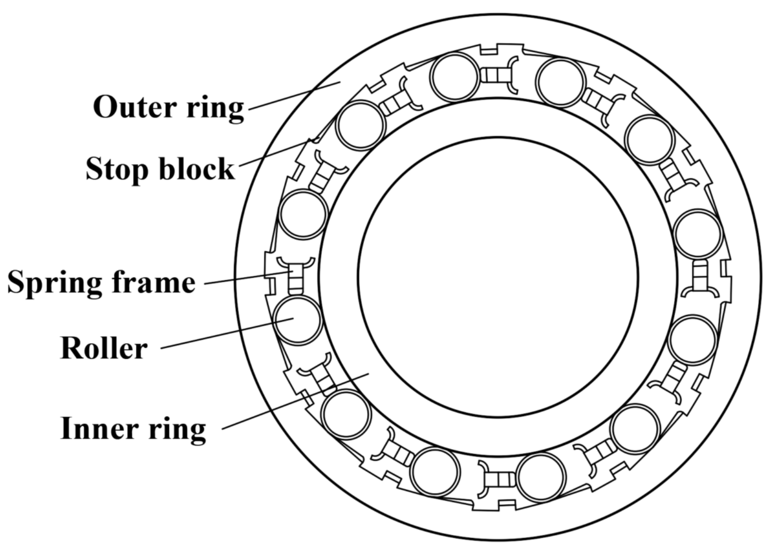

Fig. (39). Retainer-free one-way rolling bearing CN212717645U.

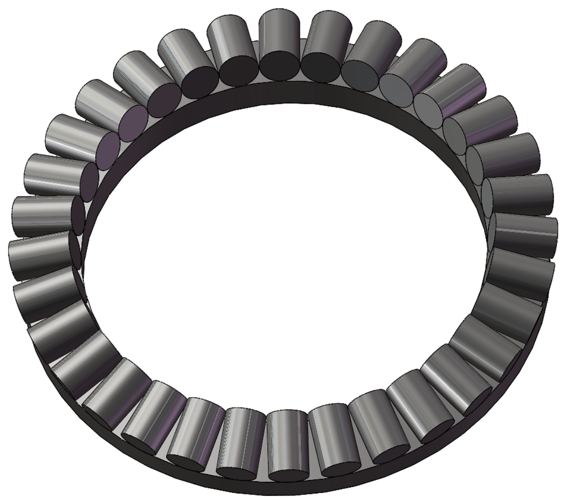

Fig. (40). Axial floating bearing EP2525112A1. *(A higher resolution / colour version of this figure is available in the electronic copy of the article).*

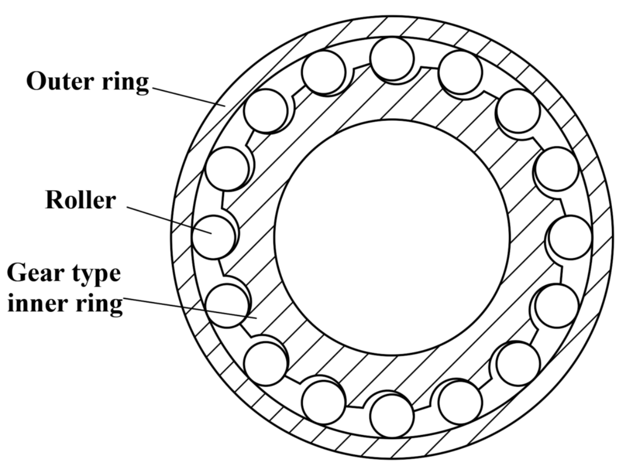

Fig. (41). Holder-free bearing CN114658759A.

traditional bearing, and the force of each roller is uniform, which improves the bearing capacity and has good economic benefits. However, the raceway structure is complicated and the processing cost is increased.

Li [95] proposed a cageless double row cylindrical roller bearing for heavy loads, as shown in Fig. (**43**). The bearing has two separate bearing outer rings and two rows of cylindrical roller sets. The two separated bearing outer rings are connected by flash welding. The separated bearing outer ring is provided with a convex ring retaining ring near the outer ring of the end face. The two convex ring retaining rings form a rectangular grooved raceway with a carburized layer. The retaining ring limits the movement space of the roller so that it cannot tilt. The raceway is coated with lubricating grease. This bearing adopts a double-row roller group in the bearing work, reducing friction, heat, and energy loss, creating more uniform force, and improving the service life. The disadvantage is that the separate outer ring requires flash welding, which increases the manufacturing cost.

Zhang *et al.* [96] provided a unidirectional rolling bearing without a cage, as shown in Fig. (**44**). This bearing is provided with a plurality of grooves evenly distributed circumferentially on the outer wall of the inner ring. A roller is provided in the grooves. The outer ring of the bearing is coaxial with the inner ring, the outer ring is set around the outer side of the inner ring. A special groove structure is designed on the inner wall of the outer ring of the bearing, which is used to restrict the roller from rotating only in one direction. However, this bearing does not solve the phenomenon of roller skew caused by working wear. Although the contact area between the roller and the inner ring of the bearing is larger, the friction will be more serious, but it can withstand greater centrifugal force and improve the bearing capacity.

Erich [97] designed a kind of ready-to-use cylindrical roller bearing, as shown in Fig. (**45**). It includes a thin-walled outer ring that can be formed without cutting. Radially outwardly oriented stop rings are provided on both sides of the outer ring. Similarly, the stop rings on both sides of the inner ring of the bearing are aligned with those on the outer ring. The rollers are placed in the resulting gap to roll cageless. This bearing achieves a lightweight design by creating a fixed, ready-to-fit needle roller bearing unit using positive clamping action. The disadvantage is that the contact area between the bearing and the inner and outer rings increase, and the friction heat generation is more serious.

Joseph [98] designed a cage-less cylindrical roller bearing, as shown in Fig. (**46**). This bearing consists of an inner ring, rollers, and an outer ring. The inner ring has grooves uniformly distributed along the circumference where cylindrical rollers can be placed. An independent roller is placed in each groove. The inner ring and outer ring of the bearing can cooperate and interlock. This bearing has a simple structure, high safety, and high-cost performance. Due to working wear, the contact surface between the roller and the inner ring may change, causing the roller to tilt. However, the increase in the contact area between the bearing and the inner and outer rings can improve the bearing capacity.

Ye *et al.* [99] proposed a cageless cylindrical roller bearing, as shown in Fig. (**47**). The bearing is provided with circumferentially uniformly distributed roller grooves along the outer surface of the inner ring of the bearing. The roller grooves are set open at one end along the axial direction of the inner ring of the bearing. Cylindrical rollers are placed in the roller grooves through the open end. In order to prevent the risk of the rollers falling off, a baffle plate is provided on the side wall of the inner ring of the bearing. The baffle limits the movement space of the cylindrical roller, so that it can not skew. The outer ring of the bearing sits on a support track formed by the cylindrical rollers. The bearing utilizes an open mounting and dismounting arrangement, eliminating the requirement for cage processing. This enhances the ease of maintenance and replacement of the cylindrical roller. The roller operation is more stable, and the production cost is lower.

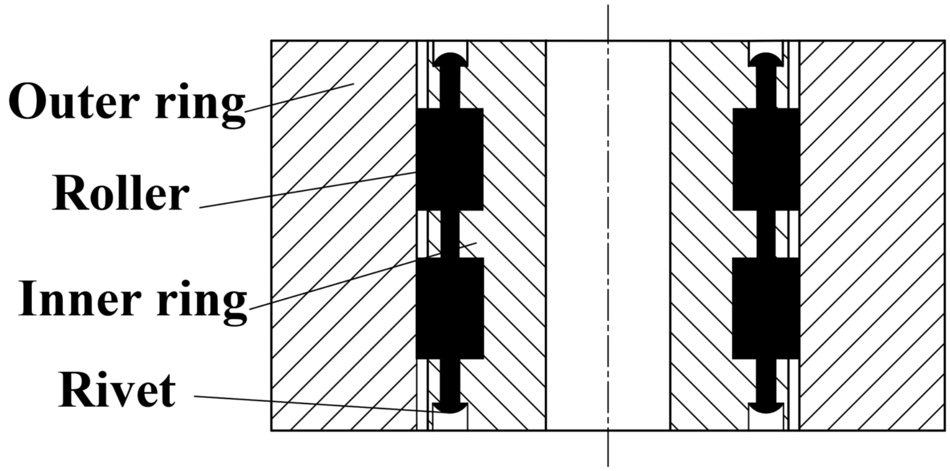

Fig. (42). No holder cylindrical roller bearing CN208089758U.

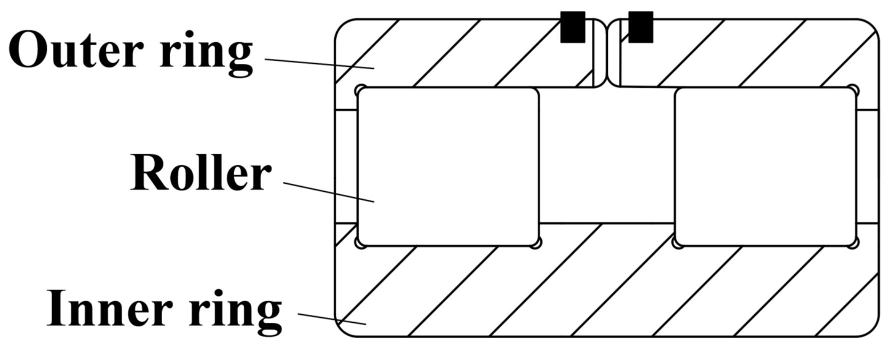

Fig. (43). Cageless double-row cylindrical roller bearing used for heavy load CN104653602A.

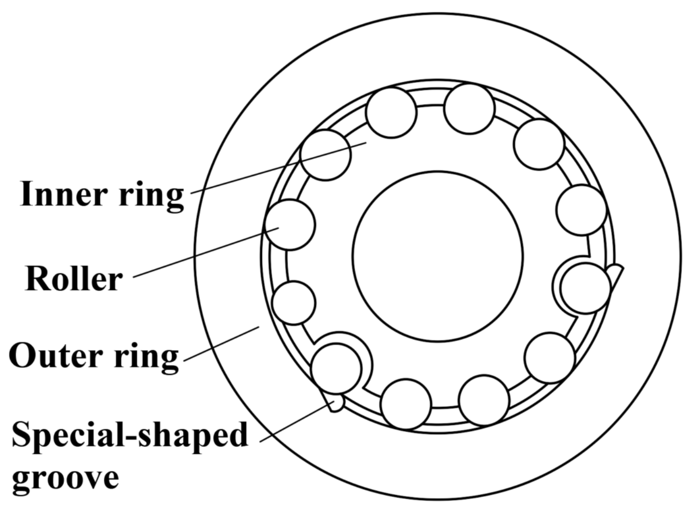

Fig. (44). Retainer-free one-way rolling bearing CN219692021U.

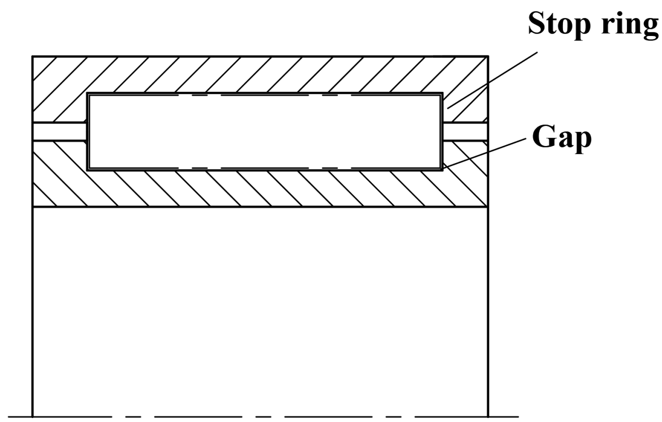

Fig. (45). Ready-to-install needle bearing comprising an inner and outer ring US2009074344A1.

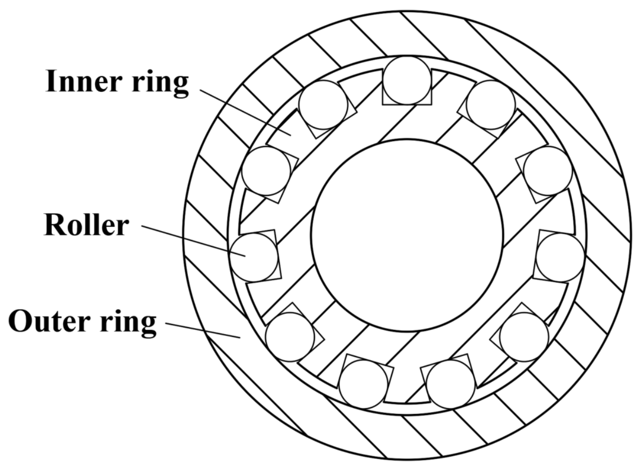

Fig. (46). Cageless bearing for use with mechanical device WO2014039797A1.

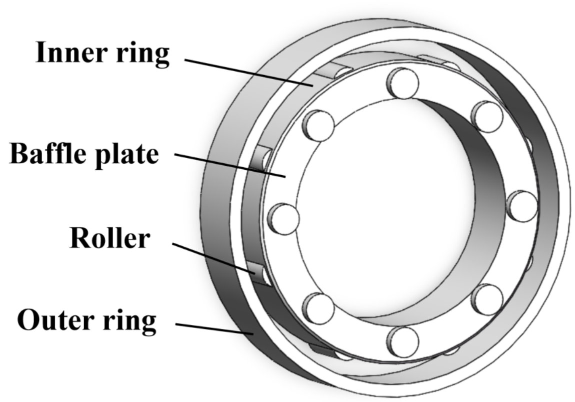

Fig. (47). Cylindrical roller bearing without retainer CN215805741U.

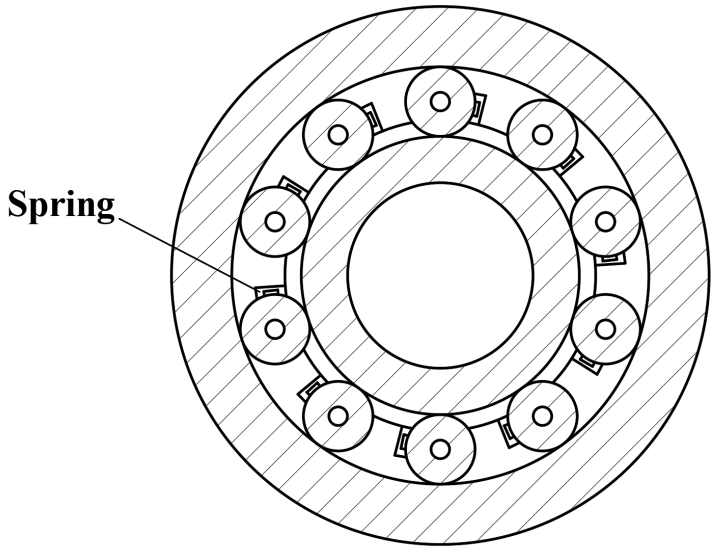

Fig. (48). Plate spring besides-star wheel retainer-free roller clutch CN214534151U.

Zang *et al*. [100] invented a spring-limited cageless roller bearing, as shown in Fig. (**48**). In this bearing, corresponding spring locating plates are installed at both ends of the bearing. These plates feature uniformly spaced limit notches along the circumferential center axis. Springs are embedded within these notches. Rollers are positioned against the sides of the notch openings, effectively restricting the movement of the rollers within the space. Prevent the rolling element from tilting. Moreover, the spring at both ends of the identical roller can be placed crosswise. The bearing uses a spring limit to replace the role of a traditional cage. It can accommodate more roller numbers, improve the bearing torque bearing capacity, simplify the bearing structure, and effectively reduce process costs. But this bearing processing is complex; if the parts are damaged, its will be difficult to repair.

A summary of the patents analyzed above is shown in Table **1**.

4. KEY PROBLEMS ON CAGELESS ROLLING BEARING

Through the continuous progress of science and technology and research scholars in recent years, cageless rolling bearings have been used in various fields due to their outstanding characteristics. However, there are still some problems limiting the development of cageless rolling bearings.

First, the full complement bearing structure increases bearing capacity and the reverse friction between neighboring rolling elements for the study of full complement bearings. Under high-speed rotating conditions, friction and irregular collisions between rolling elements will occur more frequently, significantly affecting the service life of full complement bearings. Moreover, full complement bearings require higher lubrication. If the lubrication is insufficient or of poor quality, the bearings may overheat or be damaged. As the rollers of full complement bearings move more frequently if the bearings are poorly closed, dust and impurities enter the bearings, which will cause early failure of the bearings.

Second, some problems in the research aspect of isolation bearing could be improved at this stage. Since there is no cage to keep the rolling elements in position, the distribution of lubricant may be different, and the friction of the bearing may increase during operation. A key issue is how to set the shape and position of the isolation body to substantially reduce the internal friction of the bearing and increase the limiting speed and load. In addition, due to the isolation element bearings being in their initial stage. There is no universal processing equipment on the market for the manufacturing of different isolators, which will lead to processing difficulties and increase processing costs. Moreover, fewer products and low market recognition, also need further research and development.

Third, for the new raceway cageless bearings, the local reducer raceway can realize the automatic dispersion of the roller. However, in the rotation process, the roller will come into contact with the reducer raceway at a high frequency, and the periodic contact will cause damage to the reducer raceway. Damage to the reducer raceway will make the bearing vibrate, affecting the dynamic performance of the bearing. If the damage is further expanded, it will lead to the failure of automatic dispersion of the rolling elements. The existing raceway optimization design only controls the radial and axial displacement of the rolling element by the radial clearance and the shape of the generating line, ignoring their internal relations. It is challenging to get the optimal bearing design parameters, so in high-speed conditions, the rolling body is easy to lose self-locking and severe slippage.

Table 1. Overview and classification of cageless rolling bearings.

Classify		Publication, Year	Characteristic	Patents Number
Full Complement Cageless Bearings	Full Complement Cageless Ball Bearings	Cai *et al.* 2012 [61]	By increasing the number of rolling elements, the bearing has a greater bearing capacity	CN202360597U
		Kevin C 2002 [62]	The large clearance makes the bearing suitable for complex environments	US6367978B1
		Zeng 2019 [63]	Have a better dustproof effect	CN208457033U
		Hua *et al.* 2018 [64]	The movement of the ball is restricted by magnetic force	CN108518417A
		Zhu *et al.* 2015 [65]	The plane inner ring structure reduces the friction torque	CN105134765
		Lu 2015 [66]	The ceramic ball material allows the bearing to operate at high speed	CN204344671U
		Xu *et al.* 2016 [67]	The separate outer ring makes the bearing disassembly more convenient	CN105736580A
		Sun 2016 [68]	The separate outer ring makes the bearing disassembly more convenient	CN105240409A
		Liu *et al.* 2014 [69]	The ceramic ball material allows the bearing to operate at high speed	CN103671508A
	Full Complement Cageless Roller Bearings	He 2019 [70]	The round table roller makes the bearing carrying capacity stronger	CN109737138A
		Wang 2019 [71]	Bearing capacity is better	CN209212800U
		Wang *et al.* 2014 [72]	Longer bearing life by discarding the original rubber seal	CN203926392U
		Xiang *et al.* 2019 [73]	The movement of the ball is restricted by magnetic force	CN209818522U
Isolation Element Bearings	Isolation Element Ball Bearings	Evgenij *et al.* 2015 [74]	The separate isolating ring reduces bearing friction	RU2538903C1
		Pan *et al.* 2019 [75]	The isolator eliminates the collision between the cage and the ball	CN110219887A
		Mark *et al.* 2020 [76]	Make the sliding friction between the ball and the cage become rolling friction	US20200166075A1
	Isolation Element Roller Bearings	Schmidt 2004 [77]	By increasing the number of rolling elements, the bearing has a greater bearing capacity	CN1475679
		Li *et al.* 2015 [78]	The separate rolling element reduces bearing friction	CN104454975A
		Pan *et al.* 2019 [79]	Surface microstructure can also reduce the contact area between rollers and isolators	CN110219892
		Pan *et al.* 2021 [80]	The isolator eliminates the collision between the cage and the ball	CN214661506U
		Pan *et al.* 2022 [81]	Separate isolators restrict roller movement	CN216430272U
		Bungert 2017 [82]	Make the sliding friction between the ball and the cage become rolling friction	DE102015221210A1
	Special Cageless Ball Bearings	Kawashima 2010 [83]	The reducing slope makes the roller automatically disperse	US20100226603A1
		Guo *et al.* 2020 [84]	Special raceway shape reduces bearing oscillation frequency	US2020224715A1
		Zhao *et al.* 2022 [85]	The reducing slope makes the roller automatically disperse	CN216519170U
		Paul R 2018 [86]	The bearing assembly to self-adjust wear	US10047790B2
		Paul 2014 [87]	The spheres limit each other to increase bearing speed	US20140260779A1
		Wang 2020 [88]	Limit ring adjust inner ring diameter	CN211371041U

Classify		Publication, Year	Characteristic	Patents Number
Special Cageless Bearings		Mohamed 2019 [89]	The number of rollers can be controlled by changing the jagged band shape and the roller diameter	WO2019114914A1
	Special Cageless Roller Bearings	He 2013 [90]	Make the sliding friction between the ball and the cage become rolling friction	CN103062216A
		Wang 2023 [91]	The surface contact becomes straight contact to improve bearing capacity	CN212717645U
		Rainer *et al.* 2012 [92]	By increasing the number of rolling elements, the bearing has a greater bearing capacity	EP2525112A1
		Tang *et al.* 2022 [93]	Cage and inner ring integration	CN114658759A
		Zhao *et al.* 2018 [94]	Raceway and rivet jointly limit the position of the roller	CN208089758U
		Li 2015 [95]	The separate outer ring makes the bearing disassembly more convenient	CN104653602A
		Zhang *et al.* 2023 [96]	Cage and inner ring integration	CN219692021U
		Erich 2009 [97]	Lightweight design	US2009074344A1
		Joseph 2014 [98]	Cage and inner ring integration	WO2014039797A1
		Ye *et al.* 2022 [99]	The baffle limits the movement space of the cylindrical roller	CN215805741U
		Zang *et al.* 2021 [100]	Cross-placement of springs restricts the movement of rolling elements	CN214534151U

CONCLUSION

By searching and analyzing the latest patents on the cageless bearing structure manufacturing method, it can be seen that there are many innovative designs of cageless rolling bearings. The cageless bearing structure can be categorized into full complement bearings, isolation element bearings, and special cageless bearings. The full complement bearings can be filled with rollers, allowing them to withstand higher radial and axial loads. However, the mutual friction between rollers is large and easy to heat. It has certain requirements for lubrication, heat dissipation and sealing, and is usually not suitable for working at high speed. Compared with the other two kinds of bearings, the number of rolling elements is more, resulting in an increase in the overall weight, and the manufacturing cost will also increase. The rolling isolation element bearings will initially keep the frame and roller sliding friction between the two forms into rolling friction form. The limit speed is increased, and the noise and vibration generated by the bearing during operation are small. Non-rolling isolator bearings use isolator frames or rings to isolate each rolling element, increase the number of rolling elements in the bearing, reduce the contact area between the rolling element and the cage, and improve the bearing capacity and limit speed, but sliding friction still exists. Compared with full complement bearings, the overall weight is light. The advantages of special cageless bearings over full complement bearings and isolation element bearings are that they can achieve more functional requirements and are suitable for complex working conditions. However, the structure of the bearing is usually more complex and difficult to process, so it is difficult to promote application.

Currently, cageless rolling bearings can achieve optimization in terms of a particular performance target demand, but they may adversely affect other aspects of the bearing. Due to the complexity of the working conditions of bearings, it is often difficult to meet the needs of practical applications. How to comprehensively improve the service performance of bearings through a variety of ways to combine to manufacture the required bearings with good comprehensive performance but also need further in-depth research.

CURRENT & FUTURE DEVELOPMENTS

As a particular bearing structure, cageless rolling bearings are different from traditional bearings in that cages fix the rolling elements. Cageless bearings improve the friction between the rollers, maximize the number of rollers, increase the bearing capacity and life, and simplify the bearing structure. However, the rolling elements lose the original cage restriction, and the rollers in the raceway between the movement of the more complex. However, to solve the collision and friction between neighboring rolling elements, is the main problem of future research on such bearings. In addition, the following research areas are likely the future direction of developing cageless rolling bearings.

[1] Due to the closed structure inside the high-speed motorized spindle, the system will generate a lot of heat during operation. The change of thermal preload of cage bearing combined with electric spindle under actual working conditions will be one of the main research directions in the future.

[2] Wind, sand, dust, and other debris are usually present in specific field environments. Part of the isolation body in the bearing is usually tiny. If the debris enters the bearing, it will lead to unstable operation,

noise increase, or even bearing failure. Improving the closure and maintenance of cageless rolling bearings is one of the future development directions.

[3] At present, the research direction of cageless rolling bearings usually focuses on optimizing a one-sided target. How to find the best balance between improving load-carrying capacity, reducing friction, reducing noise, and other objectives will be an essential issue for future research.

[4] Cageless rolling bearings can be combined with sensor technology and intelligent control technology. To realize intelligent monitoring and fault diagnosis of cageless rolling bearings and improve the stability and safety of equipment operation.

[5] Establishing a systematic and perfect evaluation standard for cageless rolling bearings. How to make non--standard bearings can be evaluated in a certain degree of wear behavior, load carrying capacity, and friction characteristics is also a vital issue.

AUTHOR'S CONTRIBUTIONS

It is hereby acknowledged that all authors have accepted responsibility for the manuscript's content and consented to its submission. They have meticulously reviewed all results and unanimously approved the final version of the manuscript

LIST OF ABBREVIATIONS

CNC = Computerized Numerical Control

CONSENT FOR PUBLICATION

Not applicable.

CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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