Application and selection of circular bead wire rings for radial aircraft tires

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Abstract: Aircraft tires endure significant impact loads during takeoff and landing, increasing inflation pressure that is primarily borne by bead wires. Thus, enhancing aircraft tire bead fatigue resistance and optimizing structural stress distribution are crucial for radial aircraft tire design and development. Compared with polygonal bead wires, those with a circular cross-section have significant advantages in stress variation under load, and their production and application are increasingly mature. This paper explores the structural principles, application scenarios, and selection methods of circular bead wires, laying a solid theoretical foundation for product structure optimization and quality improvement.

Key words: aviation tire; circular bead wire; application; selection

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As the nation places increasing emphasis on the research and development of "bottleneck" technological projects for radial aircraft tires, the structural design of aircraft tires is becoming increasingly refined and is gradually entering a modern design phase. Currently, Computer-Aided Design (CAD) technology and ABAQUS finite element analysis technology are widely used. However, the structural design of domestic aircraft tires still primarily relies on repeated verification of test schemes to achieve the best application results in experiments.

In China, the gap between the technical strength, research and development, and design capabilities of domestic aviation tire R&D and manufacturing enterprises and those of leading foreign aviation tire enterprises is gradually narrowing. Establishing a set of theories and research methods for aviation tire structural design is the most urgent task in China's aviation tire technology field.

In the structural design of aircraft tires, the bead wire is the main component that bears the load, and its structural design stress analysis also falls under the category of geometric nonlinear analysis caused by deformation. Therefore, the preliminary theoretical research on design is even more crucial.

1 Application of circular steel wire bead in radial aircraft tire

Currently, the types of steel wire rings used in tires can be divided into regular hexagonal, oblique hexagonal, oblique heptagonal, rectangular, and circular steel wire rings based on their cross-sectional shapes after molding. The molding process of polygonal steel wire rings is relatively simple. During the winding process, a single steel wire is coated with rubber and wound from bottom to top in the designed groove of the winding disc, resulting in different polygonal cross-sectional shapes. Coating a single steel wire with rubber can enhance the overall mechanical properties, and the arrangement of wires between roots forms a linear structure. However, the wires in each layer are separated, and the stress changes in the steel wire ring are concentrated. This type of steel wire ring is commonly used in automobiles, construction machinery vehicles, and bias-ply aircraft tires.

1.1 Circular bead wire structure

The circular cross-section bead wire is divided into a bead

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wire core and an outer wrapped wire. The bead wire core is slightly thicker and forms a cylindrical ring after butt welding. Depending on different specifications, the outer wrapped wire is divided into multiple layers. The first layer of wire is closely arranged adjacent to the bead wire core until the layer is fully filled. The second layer is wound in the opposite direction to the first layer, closely adhering to the circumferential surface of the first layer of wire, and is fully filled in adjacent order to complete the second layer of winding. Similarly, the third, fourth, and subsequent layers are wound in this manner. As shown in figure 1:

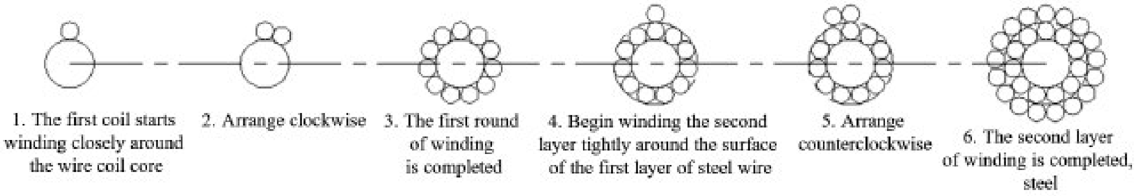

Figure 1 Schematic diagram of circular steel wire ring arrangement

1.2 Winding parameters for circular cross-section steel wire rings

The selection of bead wire winding parameters mainly includes: bead wire core diameter, outer winding wire diameter, winding lead number, winding layer number, number of wires per layer, winding angle, etc. The selection results can form different specifications and different wire arrangement patterns of circular bead wires.

The winding process of the circular steel wire ring can be described as follows: the core of the steel wire ring performs circular motion around its axis OZ within the XOY plane, while the outer steel wire performs reciprocal curved motion along the axial direction of the steel wire ring core (i.e., circular motion around the steel wire ring core within the XOZ plane). The two motions are coupled to form a helical motion, as illustrated in figures 2 and 3.

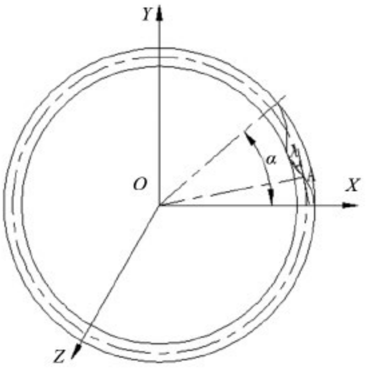

Figure 2 After completing one lead winding, the rotation angle of the wire coil core is α

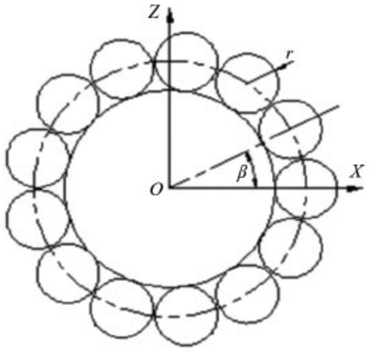

Figure 3 Schematic diagram of wire arrangement after completing the first layer of winding, where β represents the angle between adjacent wire sections

During the winding process, the core of the steel wire ring rotates once within the XOY plane, and the outer winding steel wire completes N lead spirals within the XOZ plane. For every lead of winding, the steel wire rotates by a little more than one revolution, ensuring that the end of the outer winding steel wire connects with the head of the steel wire in that layer after completing N leads. After winding one layer, a connecting point appears where the ends of the outer winding steel wire meet, and a copper sleeve is installed for connection.

After calculation, the relationship formula for the winding parameters during the winding process is:

$$\alpha=\frac{360°}{N} \tag{1}$$

$$\theta=360°+\frac{360°}{M \cdot N} \tag{2}$$

α—The angle of rotation of the wire coil core when wrapped with steel wire for 1 lead;

N—The number of wire winding leads in this layer;

θ—The angle of axial rotation of the steel wire wrapped around the steel wire coil core, with one lead of external steel wire winding;

M—The number of steel wires wound in the cross-section after winding this layer.

Equations (1) and (2) are the parametric equations for the circular bead wire winding machine. To form the first layer of outer bead wire as shown in figure 3, the lead setting is set to N=6 (the larger the lead setting value, the greater and uneven the stress on the bead wire; the smaller the lead number, the better the mechanical properties, but too small a lead can cause separation between the bead wires. The value for circular bead wires in aviation tires is generally between 5 and 8). In the figure, M=13, which allows us to obtain the values of α and θ. Based on these parameters, the winding direction is set, and the circular bead wire winding machine can wind the first layer of outer bead wire as shown in figure 3, and it can also automatically cut and splice. The second and third layers can be similarly wound.

1.3 Mechanical properties of circular steel wire rings

The force exerted on the circular steel bead ring primarily manifests as tensile stress, with over 70% of the load stemming from inflation pressure. Particularly during the landing process of aircraft tires, impact loads induce 30% to 50% deformation in the tires, leading to an increase in tire internal pressure and a corresponding doubling of the tensile stress borne by the steel bead ring.

The use of finite element analysis method can fully verify that the stress distribution within the cross-section of the circular steel wire bead is in the form of concentric rings. The stress distribution gradually increases from the inner core of the steel wire bead to the outermost steel wire, and the maximum stress is located at the contact area between the tire bead and the rim. However, compared with the stress performance of the hexagonal steel wire bead, the stress variation rate of the circular steel wire bead and its bottom rubber is smaller than that of the hexagonal steel wire bead, with no obvious stress concentration points, indicating a more optimized structural stress distribution.

2 Selection of circular wire rings

Currently, there is no national standard for round steel wire rings. GB/T 14450-2016 "Steel Wire for Bead" stipulates the classification code, dimensions, shape, weight, ordering content, test methods, inspection rules, etc. of tempered steel wire for automobile tire beads. This article cites some commonly used specifications of round cross-section steel wire rings produced by Otto Kuhlmann Automotive Systems Components GmbH in Germany, as shown in Table 1:

Table 1 Some commonly used specifications of round wire rings

Serial number	Specifications	Minimum theoretical breaking force (KN)	Diameter (mm)
1	1×5+(13+19+25)×1.5	196.95	14.00
2	1×3+(7+13+20)×2	239.34	15.00
3	1×5+(10+16+22)×2	290.36	17.00
4	1×6+(11+17+23)×2	311.50	18.00
5	1×6+(11+17+23)×2.2	375.00	19.20
6	1×5+(11+17+23+29)×1.8	393.26	19.40
7	1×5+(10+16+22+28)×2	459.20	21.00
8	1×6+(11+17+23+30)×2	492.40	22.00
9	1×5+(10+16+22+28)×2.2	554.45	22.60
10	1×5+(11+17+23+29+35)×1.8	564.41	23.00
11	1×5+(13+19+25+31+37+41)×1.5	570.17	23.00
12	1×6+(11+17+23+29+35)×2	697.42	26.00

2.1 Selection of circular bead wire core and steel wire material

The core of the bead wire and the outer wrapped steel wire are both made of high-strength, high-quality carbon structural steel, which undergoes high-temperature tempering treatment. The surface of the steel wire is plated with low-tin bronze or high-tin bronze, with the plating thickness controlled at 0.12±0.07 mm. The factory specifies that the adhesive force between a 1 mm diameter steel wire and the adhesive is not less than 685 N. The core of the bead wire is required to have good welding performance and corrosion resistance, and is specially made of C9D high-quality carbon structural steel, with a carbon content of about 0.09%, a tensile strength of 590~610 MPa, and an elongation rate of 11.8%~13.6%. The outer wrapped steel wire is specially made of C82D, with a carbon content of about 0.82%, a tensile strength of 2,050~2,500 MPa, and an elongation rate of 6.0%~6.7%.

The use of specially selected material for the bead wire core and externally wrapped steel wire enhances the strength and fatigue resistance of the bead wire, and it also boasts a high yield ratio, which is of great significance for optimizing tire structure design.

2.2 Design and selection of circular bead wire

Referring to the chapter on aircraft tires in Volume 4 (Tires) of the "Rubber Industry Manual", for radial aircraft tires, the design method of static safety multiples is currently adopted, with the selection of a strength safety multiple not less than 5 times. In the formula for calculating the force on the bead wire in the manual, the inner contour area of the tire cross-section is not clearly defined as the cross-sectional area after inflation, nor is it clearly defined that the distance between the two tire toes is the distance between the tire toes after assembly on a dedicated rim. The existing calculation process can only be based on the relevant data in the uninflated tire cross-sectional contour diagram, resulting in data errors and deviations in bead wire selection.

In figure 4, the radial aircraft tire with a circular bead wire 1, after being mounted on the dedicated rim 2 specified by TRA and inflated to the rated pressure, changes its tire profile from K to K′. The height and width of the tire cross-sectional profile increase, changing from D to D′ and B to B′ respectively. The carcass layer and carcass belt reinforcement layer of the radial aircraft tire typically include any suitable cord, such as nylon 66 cord or a composite structure cord of aromatic polyamide and nylon cord. After tire inflation, depending on the different skeleton materials used, the expansion rate of the cross-sectional width ranges from 1% to 10%, and the expansion rate of the outer contour diameter ranges from 0% to 7.5%. The area shown in region A′ in figure 4 is the axial cross-sectional area of the tire after inflation, and the illustration shows a quarter of the area. The growth rate of the tire cross-sectional area is 8% to 15%, which is larger than that of radial tires for automobiles.

For the strength calculation of the circular bead wire of radial aircraft tires, a new algorithm for static load safety is adopted below, which is closer to the actual situation of static loading. Based on the membrane-network theory of tires, considering the deformation of the cross-section during actual inflation, the increase in cross-sectional contour area is calculated based on an average expansion rate of 12%. As shown in figure 4, in the axial cross-section of the entire radial aircraft tire and its assembled rim, the tensile force on bead wire 1 (one of the four) is analyzed, and the following relationship is obtained:

$$T_g=P_0\times(S_A'+S_C) = P_0\times(K_{section}S_A+S_C) \qquad (3)$$

$K_{section}$—the coefficient of increase in the axial sectional area of pneumatic tires, with a value ranging from 8% to 15%;

T_g— the tension of the steel wire ring, N;

$S_{A'}$—half of the cross-sectional area of the tire after inflation, m²;

S_A—Half of the uninflated cross-sectional area of the tire, m²;

S_C —1/4 m² of the axial cross-sectional area of the rim diameter and bead toe width.

In the above formula, P_0 is known. The values of SA and SC are obtained by using relevant drawing design software tools to calculate the standard section dimensions and standard rim dimensions in figure 4, respectively. This method is fast, simple, and easy to operate.

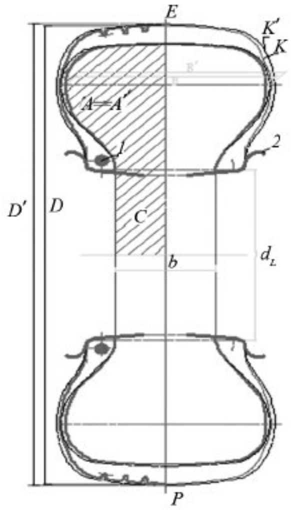

Figure 4 Cross-sectional view of radial aircraft tire

$$P_D=S_x\cdot\sigma_x+\Sigma F_d\cdot\sigma_b \quad (4)$$

P_D— Nominal breaking force of the bead wire, N;

S_x— cross-sectional area of the bead wire core, mm2;

σ_x— Nominal tensile strength of the bead wire core, with a value of 600 MPa here;

F_d—sum of the cross-sectional wire areas of the externally wrapped steel wires, mm^2;

σ_b— the nominal tensile strength of the externally wrapped steel wire, with a value of 2100 MPa here.

$$5 \leqslant N_S=\frac{P_D}{T_Z} \leqslant 6.5 \quad (5)$$

N_S—static safety margin

The upper limit imposed on the static safety factor is due to the selection of a lighter-weight wire ring. The value of P_D in formula (4) is a theoretical value, and the actual fracture load of a circular wire ring is influenced by various factors. The fracture load calculated according to formula (4) is typically 0% to 12% higher than the minimum theoretical fracture load listed in Table 1, taking into account the following influencing factors:

(1)The outer wrapped steel wires of the circular steel wire ring form a spiral trajectory in space, with each layer of steel wires forming a spatial mesh structure between them. Radial force is transmitted in the form of compression between the same layers, while the force between steel wires in adjacent layers is transmitted in the form of a spatial grid. For steel wire rings made of the same material, the winding lead directly affects the mechanical properties of the steel wire ring. The greater the lead number, the more uneven and higher the stress distribution of the steel wire ring, while the smaller the lead (the larger the lay length), the better the mechanical properties of the steel wire ring. in figure 2, the angle λ between the projection of the winding direction of the steel wire at point A onto the center plane of the steel wire ring core and the tangent to the central axis of the steel wire ring core at this point is determined by the lead number. The greater the lead number, the larger the angle λ, and the uneven stress distribution of the steel wire affects the breaking force of the entire steel wire ring.

(2)In formula (4), the nominal tensile strength of the bead core σx and the nominal tensile strength of the externally wound wire σb, with the manufacturer's average supply values reaching over 610 MPa and 2,200 MPa respectively, are set at lower values here, which has a certain impact on the calculation results.

(3)The total breaking force borne by the bead wire core generally does not exceed 5%. Its joint adopts the current butt welding process, and the tensile strength performance of the joint decreases by about 10%. Each layer of bead wire has a copper-sheathed joint, which has little impact on the overall performance of the bead wire, but the manufacturing process determines its objective performance impact.

(4)The circular steel bead wire, with its outer surface wrapped in steel wire and plated with tin bronze, enhances its adhesion to the rubber material during the tire vulcanization process. From the vulcanized product, it can be observed that the rubber material has penetrated into the outer layer and even deeper, which optimizes the overall mechanical properties of the steel bead wire to a certain extent.

The static safety multiple design only calculates the strength of the circular bead wire using internal pressure tension. In use, aircraft tires are not only subjected to internal pressure, but also to tension generated by torque and centrifugal force under high-speed conditions, which falls within the scope of dynamic load-bearing safety multiple. Using ND to represent the dynamic load-bearing safety multiple of radial aircraft tires, for heavy-duty and demanding (high torque) automobile tires, the design dynamic load-bearing safety multiple of the bead wire is greater than 2.3. There is no literature discussing this aspect for aircraft tires, and it requires our continuous exploration.

$$N_D=\frac{P_D}{T_Z} \quad (5)$$

N_D— Dynamic load safety factor;

P_D— the combined force generated by the actual load inflation pressure, torsional moment, and centrifugal force in aviation tires.

Due to the complex structural characteristics of circular steel wire rings, accurately determining their breaking force requires testing on a specially designed steel wire ring breaking test machine, which is only a single test using the tension extension method. In China, most circular steel wire ring manufacturers perform theoretical calculations of breaking force based on a single steel wire, while some manufacturers modify their tooling and conduct tests on bidirectional tensile testing machines with a load capacity of over 60T, resulting in significant data errors. There are currently no relevant reports on specially designed breaking equipment for circular steel wire rings in China. Currently, the calculation of steel wire ring breaking force still uses static safety load multiples.

To ensure that the supply of steel wire rings meets performance requirements, when providing procurement standards for steel wire rings, it can be stipulated that the strength variation range of products within the same procurement batch should not exceed 200 MPa. Additionally, the minimum tensile strength should be specified as follows: the tensile strength of the core of the steel wire ring should not be less than 600 MPa, and the tensile strength of the outer wire should not be less than 2100 MPa. The total elongation at break for both steel wire materials should not be less than 5%, and the yield ratio should be greater than 85%.

2.3 Model selection verification

Taking the design of the steel bead used in a certain specification of military radial aircraft tire as an example, after being installed on a dedicated rim specified by TRA and inflated to a rated pressure of 882 kPa, the tire's outer contour changes from K to K'. The tire's radial outer diameter increases from 1,200 mm to 1,235 mm, with a radial expansion rate of 2.91%, which falls within the range of contour diameter expansion rate of 0% to 7.5%. The axial expansion changes from 450 mm to 475 mm, with an axial expansion rate of 5.55%, which falls within the range of section width expansion rate of 1% to 10%. The section contour area increases by 13.87%. The area shown in region A' in figure 4 represents the axial cross-sectional area of the inflated tire. The figure shows a quarter of the area, which falls within the range of section tire area growth rate of 8% to 15%.

The circular steel bead used in radial aircraft tires of this specification after molding and vulcanization, and the tensile force exerted on the steel bead, are calculated using formula (3):

$$T_g=P_0\times(S_A'+S_C)$$

Using CAD drawing software, the area of $S_A'+S_C$ is calculated to be 0.0824 m^2, and P_0= 882 kPa. Substituting these values into the formula, we obtain T_g=72.68 kN. Using formula (5), it is concluded that the breaking force of the steel wire ring is not less than 363.4 kN. Based on Table 1, the initially selected steel wire ring model is No. 5, which is 1×6×(11+17+23)×2.2, with a minimum theoretical breaking force of 375 kN. Substituting the relevant parameters of the steel wire ring into formula (4) for verification, we obtain a theoretical breaking force of 404.49 kN, which meets the design requirements.

After the design and selection of the bead wire, the radial aircraft tire was trial-produced. According to the "Aircraft Tire Test Method" (GBT9747-2008) and the "Military Aircraft Tire Test Method" (GBJ108B-98), the following tests were conducted for verification:

(1) Hydraulic burst test

Five aviation tires were selected and subjected to a hydraulic burst test using a burst testing machine to verify whether they meet the performance requirement of having a burst pressure greater than 4 times the standard internal pressure. The measured burst pressures ranged from 4,230 to 4,650 kPa, which is 4.8 to 5.3 times the standard internal pressure of 882 kPa, thus meeting the design requirements. The burst locations were all on the tire shoulders, and the bead wire remained intact, indicating that the bead wire strength meets the design requirements.

(2) Durability test

Using a durability testing machine, we simulated the sliding and durability tests of aviation tires. All experimental data met the standards, with no deformation or damage to the steel wire rings. The performance of the steel wire rings met the design requirements.

(3) Dynamic simulation test

The dynamic simulation test method includes: 95 normal taxi-takeoff tests, 5 overloaded taxi-takeoff tests, 95 normal landing-taxi tests, 5 overloaded landing-taxi tests; 5 field airport taxi-takeoff tests, 5 field airport landing-taxi tests; 1 2.0 times overloaded high-speed takeoff test, etc.

The trial production of aviation tires utilizes the dynamic simulation test machine from TestingService GmbH (Aachen Testing Service GmbH, Germany) to simulate various operational conditions of tires on the runway. After testing, the results meet the technical standards issued by C A A C (Civil Aviation Administration of China), and also pass the performance testing requirements of the aviation tire national military standard G J B. Further verification shows that the selection of circular steel wire rings fully meets the design requirements.

3 Conclusion

Currently, high-performance radial aircraft tires have widely adopted circular cross-section steel belts. In China, only a handful of companies, such as Shandong Shengtong Steel Cord Co., Ltd. and Shandong Daye Co., Ltd., are capable of producing circular steel belts. Harbin Institute of Technology Hongtu Rubber and Plastic Technology Co., Ltd. has jointly developed circular steel belt production equipment with Harbin Institute of Technology, which can produce circular steel belts of various specifications and sizes, supplying domestic aircraft tire production and research enterprises.

The circular cross-section bead wire possesses high tensile strength and exhibits no stress concentration characteristics, playing a pivotal role in optimizing the structural stress of radial aircraft tires and reducing tire weight. However, the structural stress analysis of circular bead wire still requires continuous research and exploration, particularly under dynamic loading conditions, where there remains significant room for further study and exploration.

In China, with the gradual breakthroughs in key projects related to aviation tires, the mass production of aviation tires urgently requires a large supply of supporting circular steel wire rings, which brings about the application demand for specialized equipment for producing circular steel wire rings. At the same time, it provides a platform for equipment suppliers involved in technological breakthroughs in this field to engage in research and development, manufacturing, and supply.

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