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DEVELOPMENT OF A TOPOLOGY OPTIMIZATION METHOD FOR THE DESIGN OF COMPOSITE LATTICE RING STRUCTURES

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Composite lattice ring structures are known for their lightweight and high efficiency, which have a strong attraction in the aeronautical and aerospace industries. The general manufacturing process for such structures is to use wet filament winding technology. Due to the anisotropic properties of continuous fibers, the filament winding trajectory determines the mechanical properties of the composite lattice ring structures. In this work, a topology optimization method is proposed to generate the efficient filament winding trajectory, which follows the load transfer path of the composite part and can offer higher mechanical strengths. To satisfy the periodicity requirement of the structure, the design space is divided into a prescribed number of identical substructures during the topology optimization process. In order to verify the effectiveness and capability of the proposed approach, the topological design of ring structures with the different number of substructures, the ratio of outer to inner radius and the loading case is investigated. The results reflect that the optimal topology shape strongly depends on the substructure numbers, radius ratio and loading case. Moreover, the compliance of the optimized structures increases with the total number of substructures, while the structural efficiency of the optimized structures decreases with the radius ratio. Finally, taking the specified topological structure as the object, the conceptual design of a robotic filament winding system for manufacturing the composite lattice ring structure is presented. In particular, the forming tooling, integrated deposition system, winding trajectory and manufacturing process are carefully defined, which can provide valuable references for practical production in the future

Keywords: composite lattice ring structures, topology optimization, winding trajectory, robotic filament winding

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1. Introduction

Fiber-reinforced composite materials are widely used in weapon equipment, automobiles, construction and other fields due to their high specific strength, high specific modulus, fatigue resistance, corrosion resistance and other excellent properties. For example, more than 50 % of the structural weight of Airbus A350 XWB is composed of composite materials [1]. The fiber-reinforced composite materials can be utilized to produce lattice structures to obtain extraordinary strong and light structural parts, such as space launchers [2], aircraft fuselage sections [3] and so on. The composite lattice structures were first developed and produced by the Russian Central Research Institute for Special Machinery (CRISM) in the 1980s to reduce the weight of rockets [4]. In 2011, the EU FP7 WASIS project [5, 6] was started to solve some problems related to the application of composite lattice structures in commercial aircrafts. It can be seen that the composite lattice structures offer a great potential to replace traditional metal structures.

The flat lattice ring structure is one of the composite lattice structures, and a typical composite lattice ring structure was reported in [7]. The lattice ring structure is composed of several substructures with the same configuration and is widely used in engineering, such as load-bearing fuselage rings. It has the characteristics of cyclic symmetry and good designability. The performance of lattice structures depends not only on the lattice pattern but also on the number of substructures. In the conventional composite lattice ring structures design, the unidirectional spiral, circumferential, and axial ribs are the main elements of this kind of structure, and the width and thickness of ribs, and helical angle are often used as the design parameters. The pattern of lattice structures is often defined as regular, such as rectangle, diamond, triangle, etc. However, due to the simple use of traditional lattice patterns as design principles, the potential of composite lattice ring structures has not been fully exploited. With the development of aeronautical and aerospace fields, researchers are constantly pursuing aerospace structures with lighter weight and better performance. Exploring innovative and efficient structural forms has become a key step in promoting the development of aeronautical and aerospace technology.

In order to make better use of the anisotropic properties of composite materials, the fibers should be placed along the direction of load transfer in the parts to obtain higher mechanical properties [8]. As one of the most potential structural design methods, the topology optimization method is often used in the conceptual design stage of engineering structures. In recent years, with the rapid development of topology optimization in theoretical research and practical application, the topology optimization method has become an effective technique for weight reduction and performance design, especially in the aircraft and aerospace industry [9–11]. Under the given boundary conditions and design constraints, the optimal material layout corresponding to the most effective load transfer path in the design space can be obtained by the topology optimization method. Hence, through the topology optimization method to determine the rib arrangements of the composite lattice ring structures, an innovative and efficient structure form can be obtained.

2. Literature review and problem statement

For a complex axisymmetric shape composite part, the work [12] proposed an approach to obtain filament winding trajectory by using the principal stress field of the structure. In this approach, assuming that the part was isotropic, the principal stress field was obtained by initial finite element analysis. However, for the optimization engineering structure with the specific goal of lightweight or stiffness maximization, the application of topology optimization is more conducive to the optimization design. In order to overcome this shortcoming, the authors of [13, 14] developed a method combining topology design and fiber placement path based on load transfer path for 3D printing of carbon fiber-reinforced composite parts. The results showed that the optimized structure could effectively reduce the weight of the structure while meeting the requirements of mechanical properties. But the anisotropic behavior of continuous fiber-reinforced composites during topology optimization was not considered. In fact, it is complicated and challenging to consider both fiber angle and structural topology. The main reason for this is that the design variable of fiber orientation easily falls into local optima. In [15], a new load-dependent path planning approach was proposed to generate the 3D-printing path of continuous fiber-reinforced plastics. A topological optimization method called Solid Orthotropic Material with Penalization (SOMP) [16] was used to optimize the fiber angle and structure topology simultaneously. This method can accurately follow the load transfer path of parts and provide higher mechanical properties. But now the 3D printing still faces some manufacturing limitations, such as: resin materials are limited to thermoplastic resins; compared to filament winding technology, the production cost of using 3D printing technology to manufacture composite structures is extremely high; the 3D printing technology of continuous fiber-reinforced composites is not yet mature, some typical shortcomings, such as the poor adhesion between fibers and matrix, void formation, nozzle blockage, etc., need to be resolved [17].

As a common automated production technology of composite parts, filament winding has experienced considerable evolution over time. The traditional filament winding technology is mainly used to manufacture axisymmetric geometry parts, such as tubes, vessels, pressure tanks, grid-stiffened shell structures, etc. However, the traditional filament winding machine has obvious limitations in the production of composite products with asymmetric structure or novel complex shape. This need, the development of robot filament winding technology is promoted. Because the robot has the advantages of flexibility and controllability, so robotic filament winding is the most efficient and suitable way for manufacturing complex shape products. Moreover, the robotic filament winding has obvious advantages in process control, product quality, repeatability and production time. To date, some researchers used robotic filament winding technology to manufacture composite structures. For instance, the paper [18] introduced new robotic filament winding equipment for the manufacturing of anisogrid cylinder structures made of composites, and a novel deposition head for the sake of fibers stratification was also designed. Through the geometric and structural tests of composite structures, the parts made by robotic filament winding have better quality compared with the hand-made parts. Afterward, the work [19] proposed a design method for fabricating a fork part by robotic filament winding technology, and the feed deposition head invented by [20] was adopted. The results verified the potential of innovative robotic filament winding equipment for manufacturing complex shape composite parts. Unfortunately, to the authors' best knowledge, studies on composite lattice ring structures of robot filament winding are still lacking. Therefore, all this suggests that it is advisable to conduct a study on how to use the topology optimization method to obtain the optimal filament winding path and design the corresponding robot filament winding equipment.

3. The aim and objectives of the study

The aim of the study is to provide an innovative fiber trajectory design approach to obtain a continuous winding trajectory for composite lattice ring structures with maximum stiffness.

To achieve this aim, the following tasks are accomplished:

– the optimal filament winding trajectory corresponding to the most effective load transfer path in the design space is obtained by the topology optimization method. To verify the robustness of the proposed design method and illustrate the influence mechanism, some different substructure numbers, loading cases, and radius ratios are compared and analyzed;

– in order to verify the manufacturability of the optimized topologies, the conceptual design of a new robotic filament winding system for composite lattice ring structures is presented.

4. Materials and method

4. 1. Topology optimization method

Topology optimization is a mathematical method to optimize the distribution of materials in a given design space to achieve the most effective design or minimum weight structure. Therefore, in order to eliminate the sections with low stresses or hardly affected by load transfer, the topology optimization method is applied to obtain the load transfer path of the composite structure. For simplicity, the objective of the present topology optimization problem is limited to compliance minimization (stiffness maximization). The volume retention fraction of the material is defined as the volume-controlled constraint, and the element pseudo density value varying from 0 (void) to 1 (solid) for determining the optimal material layout is regarded as the design variable. A typical 2D ring structure shown in Fig. 1 is studied. The inner and outer radiuses of the ring structure are denoted by R_1 and R_2, respectively. The thickness of the inner skin is denoted by t. The design space is marked in gray color. Here, the inner hole is completely fixed and the tangential force F is applied on the outer contour.

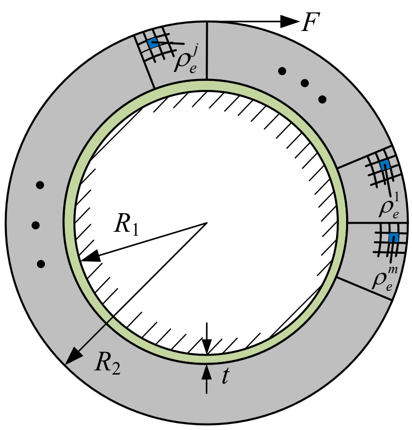

Fig. 1. A 2D ring structure with m substructures

The composite lattice ring structure is basically composed of several repeated substructures, which are assembled into a continuous structure by rotating replication. Hence, the composite lattice ring structure can be regarded as a kind of periodic structures. To fulfill the periodic constraint, the whole design space is circumferentially partitioned into m identical substructures, and all substructures should be meshed consistently. Hence, the density variables of each substructure at the same position remain the same, i. e., $\rho_e^1=\cdots\rho_e^j=\cdots\rho_e^m=\rho_e$, where j represents the substructure number and e denotes the element number within one substructure. Assuming the material is isotropic, the mathematical model of topology optimization can be written as:

$$\begin{aligned}&\text{find}: \rho=[\rho_1,\ldots,\rho_e,\ldots,\rho_{n_e}]^T\\&\min:\ C(\rho)=\mathbf{U}^T\mathbf{K}\mathbf{U}\\&\text{s.t.}\ :\ \begin{cases}\sum_{j=1}^{m}\sum_{e=1}^{n_e}\rho_e^j v_e^j-gV_0\le 0\\ \rho_e=\rho_e^1=\cdots\rho_e^j=\cdots\rho_e^m\\ \rho_e\in[\rho_{\min},1],\ \ (j=1\cdots m; e=1\cdots n_e),\end{cases}\end{aligned}\tag{1}$$

where C represents the structure compliance, $\mathbf{K}$ is the global stiffness matrix, $\mathbf{U}$ is the displacement field; ρ is the density variable vector of one substructure. Here, $\rho_{\min}=0.001$ is to avoid stiffness matrix singularity; g is the volume fraction of the whole design domain; V_0 denotes the volume of the whole design domain; v_e^j is the volume of the e^{th} element in the j^{th} substructure; m represents substructure numbers; n_e represents element numbers in one substructure; ρ_e^j is the density variable of the e^{th} element in the j^{th} substructure.

Here, the SIMP (Solid Isotropic Material with Penalization) interpolation model [5] is introduced to describe the corresponding relationship between material properties and density variables. So we have:

$$\mathbf{k}_e=\rho_e^p\mathbf{k}_e^0,\tag{2}$$

where $\mathbf{k}_e$ denotes the stiffness matrix of element e, $\mathbf{k}_e^0$ represents the stiffness matrix of solid element, p is the penalty factor. Then the sensitivity of the objective function with respect to the variable ρ_e can be easily obtained:

$$\frac{\partial C}{\partial\rho_e}=-\mathbf{U}^T\frac{\partial\mathbf{K}}{\partial\rho_e}\mathbf{U}=-\frac{p}{\rho_e}\sum_{j=1}^{m}c_e^j,\tag{3}$$

where c_e^j is the strain energy of element e in the j^{th} substructure.

4. 2. Robotic filament winding technology

In order to design the special robotic filament winding equipment, three fundamental steps need to be followed. First of all, based on the geometry of optimized composite lattice ring structures, the fiber placement tooling must be designed. The basic principles of the design are: the stability of the tape and the correct fiber compaction must be ensured in the process of winding and curing; ensure that the cured composite parts can be easily removed from the mold at the end of the molding process; due to the rotation range of robot joint is limited, a mold rotation mechanism is considered necessary to improve the production efficiency. Then, the integrated deposition system must be designed. Some design criteria should be met, such as process parameters of fiber tension, fiber deposition speed and winding trajectory can be controlled. Moreover, it should be easy to adapt to various robots, and easy to maintain and update. Finally, the winding trajectory must be determined to ensure that the fiber band is not loose and the continuous and harmonious movement of the deposition head, so as to obtain a high-quality process.

5. Results of topology optimization and robotic filament winding system design

5. 1. Topology result

In Fig. 1, let R_1=340 mm, R_2=500 mm, t=5, and F=500 N. The thickness of the ring structure is 10 mm. The material properties used in the topology optimization process are: E=70 GPa, υ=0.3, ρ=2,700 kg/m^3. The volume fraction g=0.3. The topology optimization process is operated in the commercial software, namely Altair-Inspire. The influence of various substructure numbers, the ratio of outer to inner radius, and loading case on the optimal topology shape and stiffness performance are considered, respectively.

5. 1. 1. Influence analysis of substructure numbers

In this subsection, eight cases for m=10, 16, 20, 24, 28, 32, 36, and 40 are studied and compared. The optimized topologies for the various partitions are shown in Fig. 2. The variation of structural compliance with the number of substructures is given in Fig. 3.

As shown in Fig. 2, the legible shapes of optimized structures can be obtained. Moreover, the intersection points along the radial direction of the optimized topology increase with substructure numbers. As the substructure number increases, the compliance of the structures increases accordingly, as indicated in Fig. 3.

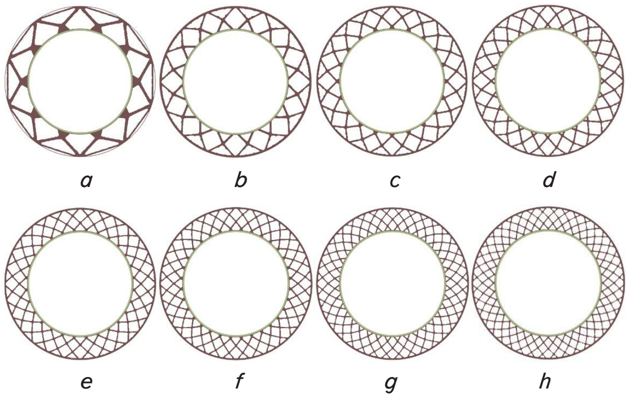

Fig. 2. Optimized topologies for the various partitions *m*: *a* – 10; *b* – 16; *c* – 20; *d* – 24; *e* – 28; *f* – 32; *g* – 36; *h* – 40

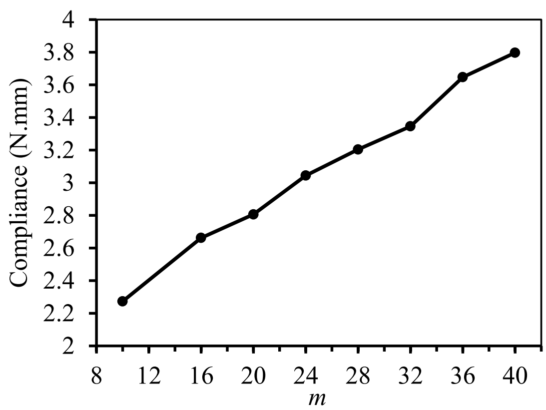

Fig. 3. Variation of structural compliance with the number of substructures, *m*

5. 1. 2. Influence analysis of radius ratio

In this subsection, $m=20$ and $R_3=500$ mm are fixed, the ratio of outer to inner radius $\mu=R_2/R_1=1.5$, 2, 2.5, 3, 4, and 5 is studied and compared. In order to compare the structural stiffness performance with different material contents, the unit mass stiffness defined by $\delta=1/CM$ is used as the evaluation index of structural efficiency, where C and M represent the structure compliance and mass, respectively. The optimized topologies for the different radius ratios μ are shown in Fig. 4. The unit mass stiffness δ of the optimized topology with various radius ratios μ is given in Fig. 5.

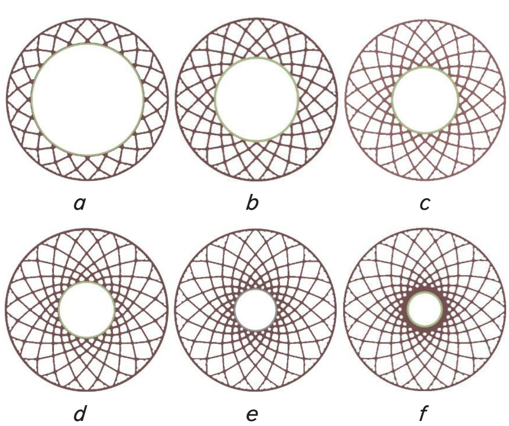

Fig. 4. Optimized topologies for the various radius ratio μ: *a* – 1.5; *b* – 2; *c* – 2.5; *d* – 3; *e* – 4; *f* – 5

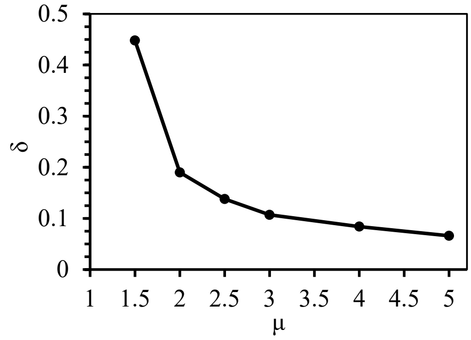

Fig. 5. Variation of unit mass stiffness against the radius ratio μ

It can be seen from Fig. 4 that all optimized topologies have legible shapes and the value of μ affects the configurations of the ribs. As μ increases, the structural efficiency of the optimized topology decreases accordingly, as shown in Fig. 5.

5. 1. 3. Multiple-load-case design

In this subsection, the topology optimization design of the ring structure under multiple-load-case is studied. Two normal forces $F_1=500$ N and $F_3=500$ N, and two tangential forces $F_2=500$ N and $F_4=500$ N are applied on the outer contour, as shown in Fig. 6, *a*. The fixed constraint acts on the inner hole. Other parameters are defined as: $R_1=340$ mm, $R_2=500$ mm, $t=5$, $m=20$. The optimal topology is shown in Fig. 6, *b*.

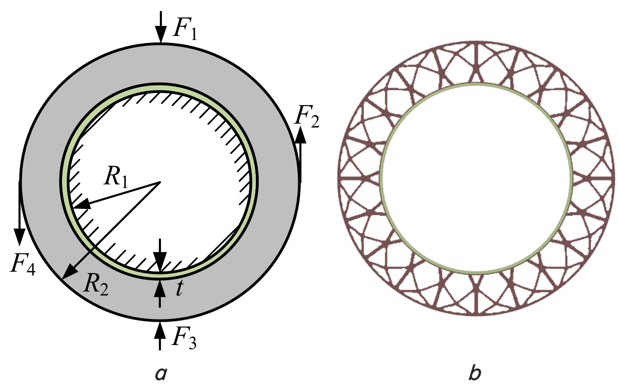

Fig. 6. Multiple-load-case design: *a* – geometry and loading conditions; *b* – optimal topology

It can be observed that the obtained optimal topology has a clear pattern including an outer skin and ribs, and the topological shape highly depends on the loading case.

5. 2. Conceptual design of robotic filament winding system and planning of manufacturing process

For simplicity, the topology configuration of the substructure number $m=24$ (Fig. 2, *d*) is taken as an example; the conceptual design of the robotic filament winding system and planning of the manufacturing process is developed in this section. The impregnated carbon fiber material is selected to produce the composite lattice ring structure. The thickness of each layer of fiber band is assumed to be 0.135 mm. The thickness and width of the ribs are 10 mm and 5 mm, respectively. To manufacture the composite lattice ring structure, 74 layers of 5 mm wide fiber band are necessary.

5. 2. 1. Conceptual design of robotic filament winding system

In order to ensure the flexibility of the robot, reduce the collision probability between the fiber placement tooling and the integrated deposition system, and improve the control accuracy and repeatability of the process parameters, the design of the robotic filament winding system should consider these compactness, structural lightness, stiffness, and functionality principles. As shown in Fig. 7, the robotic filament winding equipment is mainly composed of five systems: integrated deposition system, fiber placement tooling, robot, servo motor and support bracket.

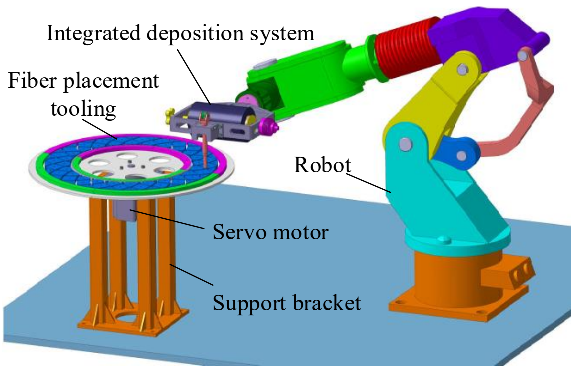

Fig. 7. Conceptual design of the robotic filament winding equipment

The integrated deposition system is equipped at the robot end-effector. In order to reduce programming effort and improve fiber throughput, the fiber placement tooling can be rotated around the center, and the servo motor is used to provide rotating power and control the amount of rotation accurately by programming. The support bracket is used to support the fiber placement tooling and servo motor.

5. 2. 2. Conceptual design of fiber placement tooling

The design of fiber placement tooling is one of the critical problems for manufacturing composite lattice ring structures. In particular, the mold structure needs to be carefully defined to ensure that the cured composite parts can be easily extracted from the mold at the end of the forming process. As shown in Fig. 8, the fiber placement tooling for the composite lattice ring structures can be subdivided into three main elements:

1) Mold, which determines the geometry shape of the final product. Fig. 9 shows the schematic of fiber placement inside the rib groove. The thickness and width of the grooves are the same as the ribs. The mold is dismountable and composed of many mold parts. For the convenience of the operator to take out the cured composite part, the outer ring and inner ring consist of two half rings mold parts, respectively, and all mold parts can be fixed with the baseplate by bolts. The silicone rubber is selected as the material of the mold due to its low cost and simplicity of manufacture. Moreover, due to the high coefficient of thermal expansion of silicone rubber, it provides the rib with good lateral compaction during the curing process of composite parts. In order to manufacture silicone mold by using the casting technique, a 3D printed master model will be developed.

2) Attachment frame, which is the transition connector between fuselage and composite lattice ring structure. Its function is to ensure the smoothness of the contact surface and the reliability of the connection, and aid the ring structure to support axial loads. The cross section of the attachment is L-shaped. Stainless steel is selected as the material of the attachment frame, and the roll bending process will be used to manufacture the attachment frame mainly because of the low cost.

3) Baseplate, which supports and drives the mold to rotate around the center. The baseplate will be made of stainless steel.

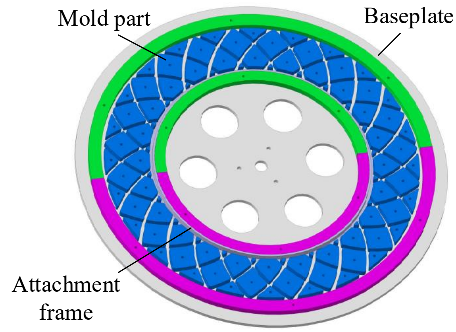

Fig. 8. Conceptual design of fiber displacement tooling

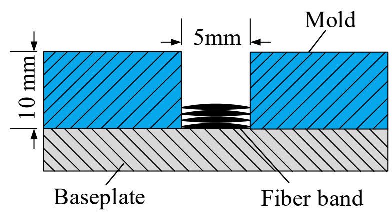

Fig. 9. Schematic of fiber placement inside the rib groove

5. 2. 3. Integrated deposition system

The function of the integrated deposition system is to perform the winding trajectory. In order to guarantee the high flexibility of the robot and controllability of winding tension, an innovative integrated deposition system is adopted in this paper [17], as shown in Fig. 10.

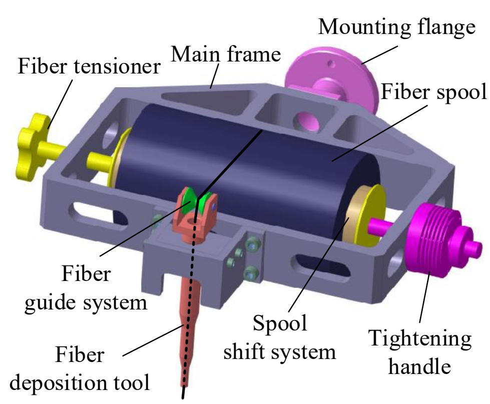

Fig. 10. The structure of the integrated deposition system

The system is a modular structure, which consists of some critical subsystems: main frame, spool shift system, fiber tensioner system, fiber guide system, fiber spool, mounting flange and fiber deposition tool. The main frame is a structure to assemble other subsystems together. The fiber tensioner and tightening handle can set the wanted value of the force squeezing the fiber on the winding mold during winding. The fiber guide system is a component that controls the direction of the fiber from the spool to the deposition system. The mounting flange is used to realize the connection with the robot end-effector. The fiber deposition tool is used to fill the impregnated fibers into the rib grooves. The fiber spool can be extracted and replaced by unscrewing the tightening handle. Due to the requirements of lightweight design, the anticorodal aluminum alloy is chosen to build the structure.

5. 2. 4. Design of winding trajectory

In order to guarantee the forming accuracy of composite parts, three basic rules need to be considered in the designing of winding trajectory: the winding trajectory is continuous; each rib groove must not be crossed more than once for each layer; ensure that the fiber is evenly covered with the rib grooves of the winding mold. The scheme of the winding trajectories for the composite lattice ring structure is shown in Fig. 11, and the complete fiber winding steps for one layer are given in Table 1.

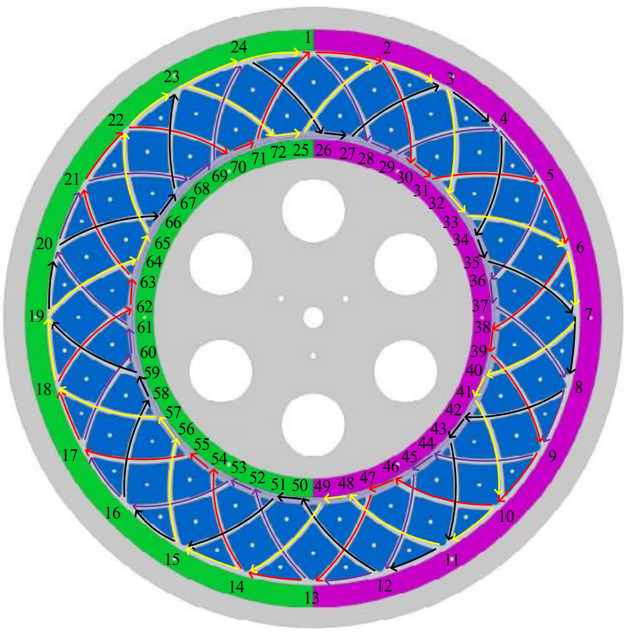

Fig. 11. The scheme of the winding trajectories

Table 1

The complete fiber winding steps for one layer

Step	Trajectory	Step	Trajectory	Step	Trajectory	Step	Trajectory	Step	Trajectory
1	1–2	21	21–22	41	17–60	61	50–51	81	41–10
2	2–30	22	22–70	42	60–61	62	51–15	82	10–11
3	30–31	23	70–71	43	61–20	63	15–16	83	11–48
4	31–5	24	71–1	44	20–21	64	16–58	84	48–49
5	5–6	25	1–28	45	21–68	65	58–59	85	49–14
6	6–38	26	28–29	46	68–69	66	59–19	86	14–15
7	38–39	27	29–4	47	69–24	67	19–20	87	15–56
8	39–9	28	4–5	48	24–26	68	20–66	88	56–57
9	9–10	29	5–36	49	26–27	69	66–67	89	57–18
10	10–46	30	36–37	50	27–3	70	67–23	90	18–19
11	46–47	31	37–8	51	3–4	71	23–72	91	19–64
12	47–13	32	8–9	52	4–34	72	72–25	92	64–65
13	13–14	33	9–44	53	34–35	73	25–2	93	65–22
14	14–54	34	44–45	54	35–7	74	2–3	94	22–23
15	54–55	35	45–12	55	7–8	75	3–32	95	23–24
16	55–17	36	12–13	56	8–42	76	32–33	96	24–1
17	17–18	37	13–52	57	42–43	77	33–6	–	–
18	18–62	38	52–53	58	43–11	78	6–7	–	–
19	62–63	39	53–16	59	11–12	79	7–40	–	–
20	63–21	40	16–17	60	12–50	80	40–41	–	–

The point «1» is the starting point of filament winding, and the winding direction is always oriented toward clockwise. The whole operation is cyclical, and it will be repeated as many times as the number of layers to be implemented.

5. 2. 5. Planning of manufacturing process

The manufacturing process consists of the following main phases:

1. Installation and debugging of the robotic filament winding equipment.

2. Programming of the robot movement according to the predefined winding trajectory.

3. The release agent is applied on the surface of the base-plate and rib grooves for easy removal of the composite parts. The adhesive is applied on the surface of the attachment frame to make the attachment frame and ribs have strong adhesion and reliable connection. Then the impregnated fibers are filled in the rib grooves by using the robotic filament winding equipment. It is worth noting that in order to facilitate continuous winding, it becomes unavoidable that no fibers in some areas, so the epoxy resin is used to fill these areas.

4. After the filament winding process, the mold with the composite part is moved to a separate room where the composite part is cured in an autoclave or at room temperature.

5. After the curing process, disassemble the mold and take out the final components. Then the dimensional inspection and mechanical processing (where required) are performed. Moreover, the defects such as delamination, unsticking, inclusion and porosity are checked by nondestructive testing.

The 3D model of the final component of the composite lattice ring structure is shown in Fig. 12.

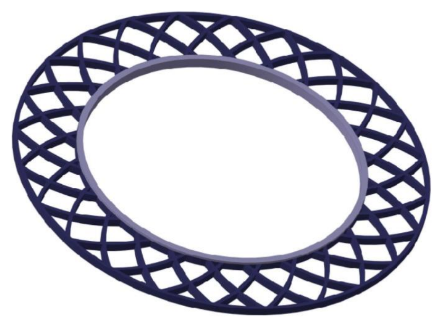

Fig. 12. The 3D model of the final component of the composite lattice ring structure

It can be seen that the final component of the composite lattice ring structure consists of two parts: fiber structures and attachment frame. They are marked in black and gray color, respectively.

6. Discussion of the results of the study of topology optimization and robotic filament winding system design

In this paper, the topological optimization methodology is applied for the innovative design of composite lattice ring structures. The influence analysis of substructure numbers, loading cases, and radius ratios on topologic shapes and mechanical performance has revealed the following:

– all obtained topologies have clear patterns including an outer skin and stiffeners, and the topological shapes highly depend on the substructure numbers, radius ratio of the ring and loading cases, as shown in Fig. 2, 4, 6. It can be seen from Fig. 3 that the compliance of the topological structures increases with the substructure numbers. The reason is that with the increase of the number of substructures, the design space of substructures decreases, and the influence of periodic constraints on searching for the optimal solution increases;

– it can be seen from Fig. 5 that the structural efficiency of the topological structures decreases with the increase of the radius ratio value. The reason is that the stress at the fixed position of the inner ring increases with the decreasing inner diameter. Furthermore, a large number of materials are piled up in the fixed position, resulting in the low efficiency of material use.

According to the principles of structural lightness, compactness, efficiency and functionality, the conceptual design of robotic filament winding equipment for manufacturing the optimized composite lattice ring structure is developed. In particular, the forming tooling, integrated deposition system, winding trajectory and manufacturing process are carefully defined to verify the manufacturability of the optimized topologies.

Compared with the traditional composite structure design method, such as sizing and shape optimizations, the advantage of the proposed method is that the structural form with maximum stiffness can be designed according to the predetermined geometric constraints and load conditions.

As an innovative methodology, the topological method is proposed to design the composite lattice ring structures. The first limitation of this work is that the anisotropic behavior of composites during topology optimization is not considered, for potential further structure weight reduction, which can be considered in further research. Moreover, the proposed design method and robotic filament winding system are only applicable for two-dimensional composite structures, and further research is needed for complex three-dimensional composite structures.

The disadvantage of the study is that we cannot carry out the production and testing of composite lattice ring structure specimens due to the lack of sufficient experimental conditions at this stage. Hence, experimental investigations and manufacturing applications should be carried out in the future.

7. Conclusions

1. Based on the density method and SIMP interpolation scheme, the topology optimization model of periodical ring structures was established to aim at maximum stiffness. Then the optimal filament winding trajectory corresponding to the most effective load transfer path in the design space was obtained based on the topological results. Numerical examples with different substructure numbers, radius ratios and loading cases were designed to verify the effectiveness of the proposed method. The topological results revealed the optimized structures were mainly composed of inner and outer skin, and ribs connecting the inner and outer skin. The substructure numbers, radius ratio, and loading case greatly influence the topological shape and mechanical property. The structural stiffness becomes weaker when the total number of substructures increases, and the structural efficiency decreases with the increase of radius ratio. Using topology optimization as a design tool, the optimized lattice layout is different from that of conventional composite lattice design. This work provides valuable insights for the more efficient use of composite materials in the novel composite structure design.

2. In order to manufacture the optimized composite lattice ring structures, the concept design of a new robotic filament winding system was proposed. The forming tooling, integrated deposition system, winding trajectory and manufacturing process were carefully designed, so as to provide valuable references for practical production in the future. Because the system is a modular structure, it can realize the manufacturing of different composite parts with complex shapes only by replacing the fiber placement tooling. Moreover, the system combines the fiber winding technology with the industrial robotic equipment, which improves the development prospect and automation degree of the traditional winding technology.

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