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Numeric Simulation on Spiral Flexure Spring Stiffness Influence Factors of Stirling Cryocooler

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Abstract: Stirling cryocooler becomes a research focus all over the world, because of its high efficiency, compact structure and low cost. Spiral flexure spring is a key component of stirling cryocooler, whose structure design, material selection and mechanical performance of is an important problem now. By means of in-depth study of spiral flexure spring of stirling cryocooler, the force model is established by finite element method, which is necessary to study its stiffness characteristics and analyze the influence factors. Then, spring stiffness theory model is established, which can prove simulation is correct. The method in the study is feasible and effective, which can be used to other type spring stiffness research. It also provides theoretical and engineering basis for design and analysis of s Stirling cryocooler spiral flexure spring.

Key words: Stirling cryocooler, spiral flexure spring, stiffness, finite element, influence factor

INTRODUCTION

Stirling cryocooler uses unique the way of closed cycle, which makes the research of stirling cryocooler become the current hot topic in the study of low temperature refrigeration system (Ding *et al*., 2007). Spiral flexure spring ensures that stirling cryocooler steadily and properly works. When it is working, spiral flexure spring is connected to reciprocating pistons, which ensures that there is clearance between piston and cylinder and provides necessary restoring force for reciprocating movement of the piston (Kaushik and Kumar, 2001). The performance of spiral flexure spring is directly related to running stability and output efficiency of stirling cryocooler. The research of inherent stiffness of spiral flexure spring has an important theoretical and engineering value for the performance and life of Stirling cryocooler (Gao *et al*., 2009). In this study, the mechanical numeric model of spiral flexure spring stiffness is established by finite element method. Then the relationship between structure and stiffness is analyzed. Meanwhile, theoretical research is contrasted with experimental results in the mechanical environment, which verifies that the correctness of the mechanical model in the end. The conclusions in the study provide theoretical and engineering basis for design and analysis on spiral flexure spring of stirling cryocooler.

FINITE ELEMENT MODEL OF SPIRAL FLEXURE SPRING STIFFNESS

In working station, spiral flexure spring is connected to reciprocating pistons, which ensures that there is clearance between piston and cylinder and provides necessary restoring force for reciprocating movement of the piston (Yuan *et al*., 2011a). Spiral flexure spring is fixed around and free in the middle. Its force situation can be simplified as what is shown in Fig. 1.

Finite element analysis of spiral flexure spring mainly refers to the analysis of stiffness performance. The axial stiffness of spiral flexure spring provides restoring force

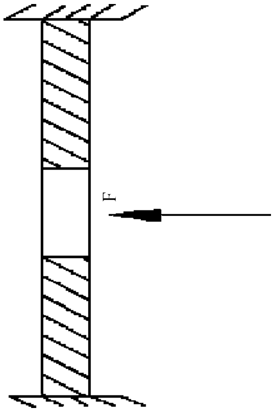

Fig. 1: Spiral flexure spring mechanics model

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for reciprocating movement of the piston. Through finite element software, finite element model is established to analyze load and displacement of spiral flexure spring. Finally, the relationship between them and stiffness will be got (Chen *et al*., 2011).

In the finite element analysis, the solid model of spiral flexure spring will be swept and meshed (Song and Allen, 2003). The meshing of spiral flexure spring model is shown in Fig. 2. Spring material is spring steel, which elasticity modulus is 210 GPa and which Poisson's ratio is 0.3. Outer diameter and inner diameter of spiral flexure spring are 125 mm and 15 mm. Movement and rotation degrees of freedom is restricted in outer edge of spiral flexure spring (Yuan *et al*., 2011b). Axial concentration is loaded in the edge of spiral flexure spring. Loading way of spiral flexure spring is shown in Fig. 3.

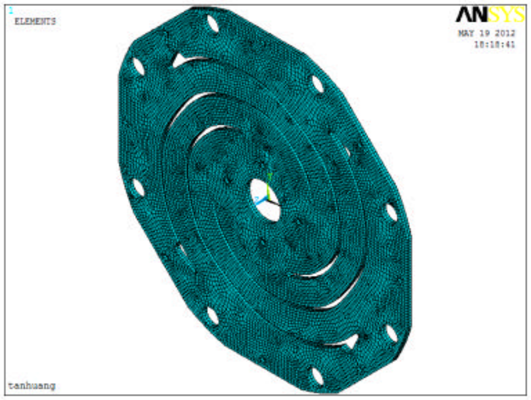

Fig. 2: Meshing of spiral flexure spring

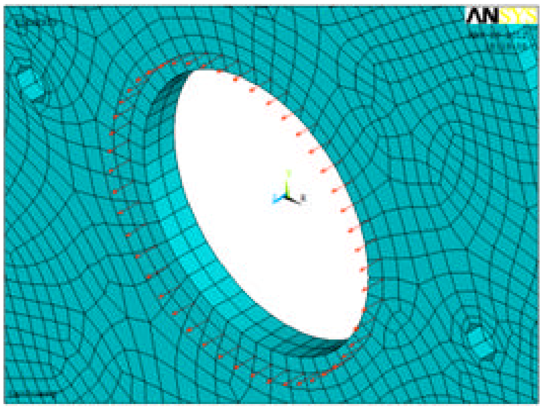

Fig. 3: Loading way of spiral flexure spring

NUMERIC ANALYSIS OF SPIRAL FLEXURE SPRING STIFFNESS INFLUENCE FACTORS

Spiral flexure spring plays a very important role in the stirling cryocooler. Axial stiffness of spiral flexure spring provides restoring force for Spring vibration system. When structure parameters of spiral flexure spring are changed, Its performance will be changed too (Liu *et al*., 2010). The different structural parameters is analyzed by the means of control variable method, which include spring thickness, inner diameter and line layout (Li *et al*., 2012).

Simulation of spring thickness influence: As finite element analysis, the thickness increases from 0.2-2 mm and each variation is 0.2 mm. Meanwhile, inner diameter and number of spiral arms will be kept 15 and 4 mm. By means of analyzing the change of displacement and stress, curves can be drawn, which are shown in Fig. 4 and 5.

By the Fig. 4, it can be obtained that the maximum displacement of spiral flexure spring will decrease with the

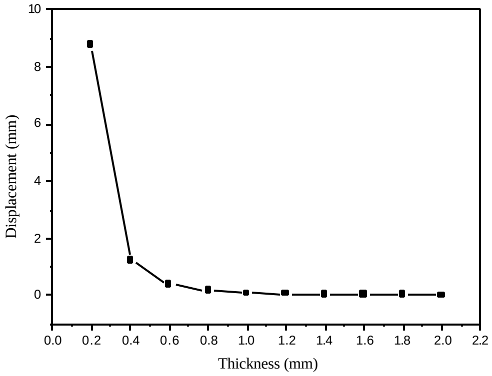

Fig. 4: Thickness and displacement diagram

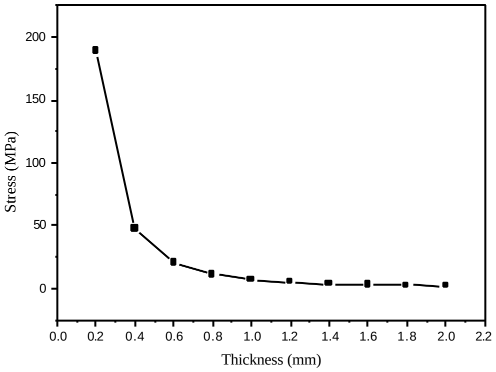

Fig. 5: Thickness and stress diagram

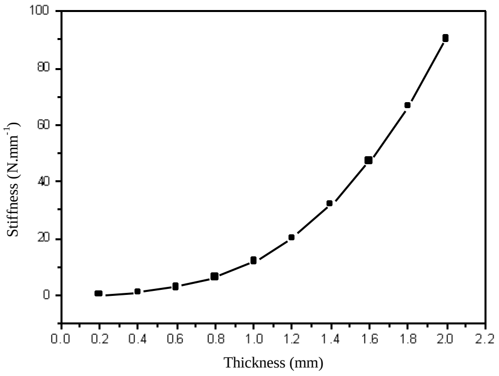

Fig. 6: Thickness and stiffness diagram

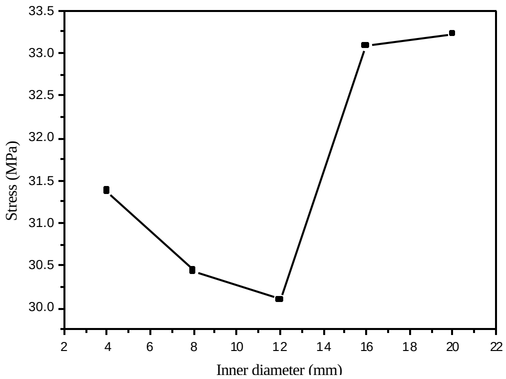

Fig. 8: Inner diameter and stress diagram

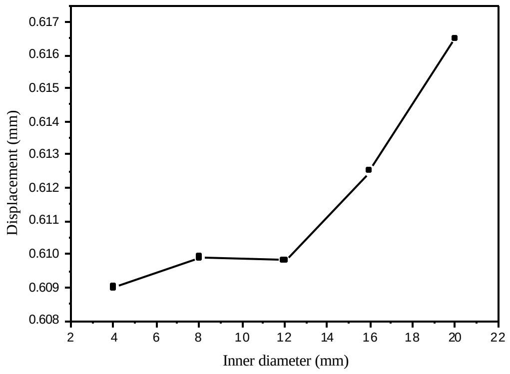

Fig. 7: Inner diameter and displacement

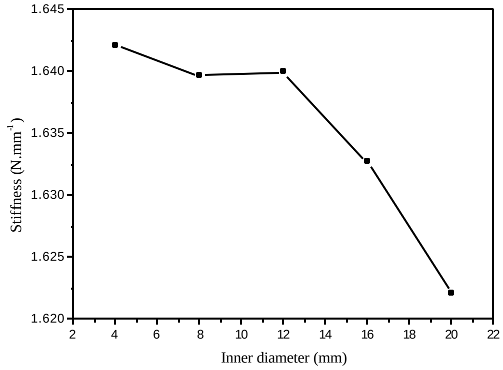

Fig. 9: Inner diameter and stiffness diagram

increase of the thickness of spiral flexure spring under the same load and inner diameter. When the thickness is 0.2 mm, the displacement is 8.78 mm and longest. When the thickness is 2 mm, the displacement is 0.011 mm and shortest. When the thickness is changed from 0.2 mm to 1 mm, the displacement is transformable significantly. On the contrary, when the thickness is changed from 1-2 mm, the transformation of the displacement is not significant.

By the Fig. 5, it can be obtained that the maximum stress of spiral flexure spring will decrease with the increase of the thickness of spiral flexure spring under the same load and inner diameter. When the thickness is 0.2 mm, the stress is 189.2 Mpa and biggest. When the thickness is 2 mm, the stress is 1.89 Mpa and smallest. When the thickness is changed from 0.2-1 mm, the stress is transformable significantly. On the contrary, when the thickness is changed from 1 mm to 2 mm, the transformation of the stress is not significant.

By the Fig. 6, it can be obtained that the stiffness of spiral flexure spring will increase with the increase of the thickness of spiral flexure spring under the same load and inner diameter. When the thickness is 2 mm, the stiffness is 90.25 N mm^{-1} and biggest. When the thickness is 0.2 mm, the stiffness is 0.11 N mm^{-1} and smallest. When the thickness is changed from 1 mm to 2 mm, the stiffness is transformable significantly. On the contrary, when the thickness is changed from 0.2-1 mm, the transformation of the stiffness is not significant.

Simulation of inner diameter influence: As finite element analysis, the inner diameter increases from 4+20 mm and each variation is 4 mm. Meanwhile, thickness and number of spiral arms will be kept 0.5 and 4 mm. By means of analyzing the change of displacement and stress, curves can be drawn, which are shown in Fig. 7 and 8.

By the Fig. 7, it can be obtained that the maximum displacement of spiral flexure spring will increase with the increase of the inner diameter of spiral flexure spring under the same load and thickness. When the inner diameter is 20 mm, the displacement is 0.6165 mm and longest. When the inner diameter is 4 mm, the displacement is 0.6090 mm and shortest.

By the Fig. 8, it can be obtained that the maximum stress of spiral flexure spring will decrease firstly and

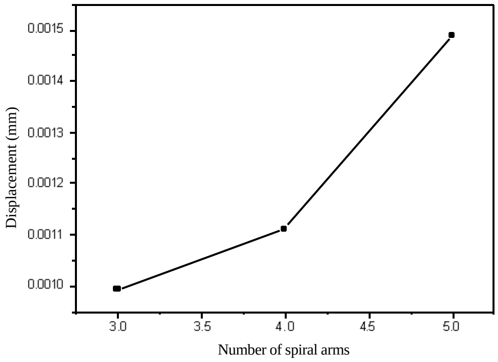

Fig. 10: Diagram of No. of spiral arms and displacement

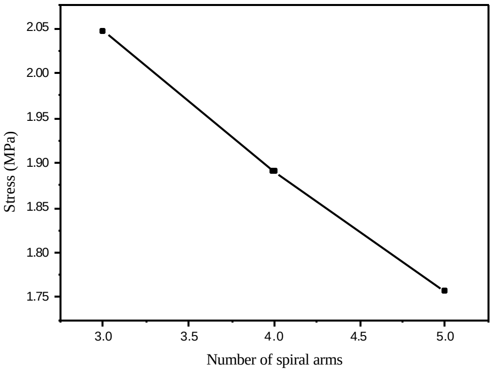

Fig. 11: Diagram of number of spiral arms and stress

increase then with the increase of the inner diameter of spiral flexure spring under the same load and thickness. When the inner diameter is 20 mm, the stress is 33.22 Mpa and biggest. When the thickness is 12 mm, the stress is 30.1 Mpa and smallest.

By the Fig. 9, it can be obtained that the stiffness of spiral flexure spring will decrease with the increase of the inner diameter of spiral flexure spring under the same load and thickness. When the inner diameter is 4 mm, the stiffness is 1.64 N mm^{-1} and biggest. When the inner diameter is 20 mm, the stiffness is 1.62 N mm^{-1} and smallest.

Simulation of line layout influence: Next, line layout of spiral flexure spring is changed, which makes that the number of spiral arms is 3 or 5. By means of analyzing the change of displacement and stress, curves can be drawn, which are shown in Fig. 10 and 11.

By the Fig. 10 and the Fig. 11, it can be obtained that the maximum displacement of spiral flexure spring will increase with the increase of the number of spiral arms of spiral flexure spring under the same thickness and inner diameter. On the contrary, the maximum stress of spiral flexure spring will decrease.

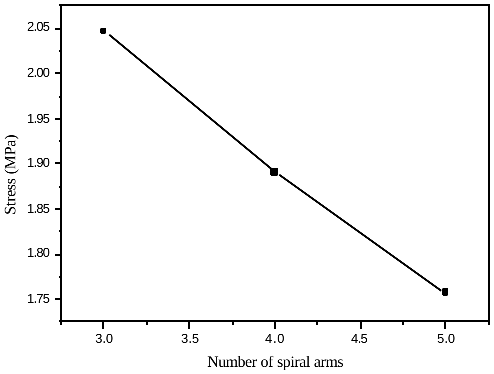

Fig. 12: Diagram of number of spiral arms and stiffness

By the Fig. 12, it can be obtained that the stiffness of spiral flexure spring will decrease with the increase of the number of spiral arms of spiral flexure spring.

STIFFNESS THEORY MODEL OF SPIRAL FLEXURE SPRING

The definition of axial stiffness is the force required to produce a unit deformation of spiral flexure spring in the direction of the axes. Spiral flexure spring is directly concerned with torsion, bending and strain energy. A micro section of spiral flexure spring is shown after the deformation in Fig. 13.

When a force F acts in the center of spiral flexure spring, the deformation will happen. As a result that, the deformation angle will form. The distance between the point of F and analysis points is involute radius R, so bending moment M and the torque T will happen.

$$M = FR\sin\alpha \tag{1}$$

$$T = FR\cos\alpha \tag{2}$$

To the micro section, the work done by the axial force F is equal to the stored energy of bending moment M and the torque T. Therefore:

$$Fds = Md\beta + Td\gamma \tag{3}$$

According to the material mechanics knowledge, the work done by the moment will be converted into energy which is stored in the spiral flexure spring. Therefore:

$$d\beta = \frac{M}{EI}dl \tag{4}$$

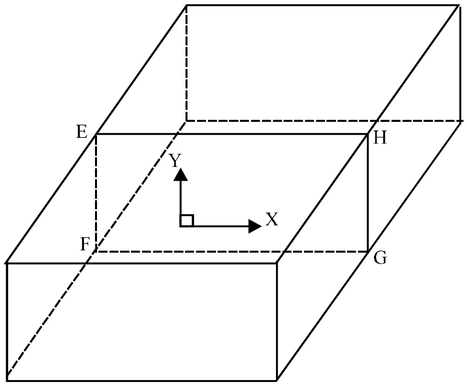

Fig. 13: Deformation of micro section

$$d\gamma = \frac{9T}{Gbh^3} dl \tag{5}$$

And the definition of stiffness formula is:

$$K = \frac{F}{s} \tag{6}$$

According the Eq. 1-6 theoretical formula of stiffness will be got. During solving the equations, the relevant literature is referred to simplify them[10]. Correction coefficient X is introduced to consider the boundary conditions:

$$K = \frac{16XGbh^3}{9R^3} \tag{7}$$

This is the final form of axial stiffness equation. In this equation, b is the width of the spiral arms, h is the thickness of spiral flexure spring and R is the radius of circle involute. Theoretical solution to calculate through the equation is consistent with the experimental result.

CONCLUSIONS

In this study, theoretical calculation and experimental research is studied for the spiral flexure spring stiffness, which is the core component of Stirling cryocooler. The performance of spiral flexure spring is analyzed and studied comprehensively by theoretical calculation of stiffness, finite element analysis and strain test.

The different structural parameters include spring thickness, inner diameter and line layout, is analyzed by the means of control variable method. The maximum displacement and stress of spiral flexure spring decreases with the increase of the thickness of spiral flexure spring but the stiffness gradually increases. The maximum displacement of spiral flexure spring increases with the increase of the inner diameter of spiral flexure spring but the stiffness gradually decreases. Finally, the maximum displacement of spiral flexure spring increases with the increase of the number of spiral arms of spiral flexure spring but the stiffness and stress gradually decreases.

The different load is applied in the process of stiffness calculation and it is combined with mechanics of materials and structural mechanics. The theoretical calculation formula of stiffness of spiral flexure spring will be deduced, which is consistent with experimental results.

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