Difference analysis of non-contact planar scroll spring with the same stiffness

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Abstract. In this paper, a set of mathematical models of non-contact planar scroll springs with the same stiffness are established. Based on ABAQUS simulation analysis software, the finite element modeling was carried out, and the modal, torsional stiffness, maximum stress and stress distribution of each plane scroll spring were analyzed. At the same time, the results of finite element analysis (torsional stiffness and maximum stress) are compared with the results of empirical formula, and some experimental data are introduced. The results show that the results of the two methods are basically the same, but there are still some differences. Although the empirical formula is more simple and general, the finite element simulation analysis still has a certain reference significance in the selection and design of spring, especially for the plane scroll spring with high precision mechanical properties.

1. Introduction

The non-contact planar scroll spring is generally a spiral spring made of slender and equal cross-section metal material wound on the plane, which generally provides reaction torque or driving torque for the mechanism[1], and is widely used in spacecraft hinge, switch and other mechanisms. According to the empirical formula, the stiffness and stress of the non-contact planar scroll spring are only related to its effective length under the same section. Based on ABAQUS finite element simulation analysis software, this paper analyzes the differences of modal, stiffness and stress of non-contact planar scroll spring with different number of turns and pitch under the condition of the same theoretical stiffness (i.e. the same section). At the same time, the simulation results of torsional stiffness and maximum stress of each plane spring are compared with the empirical formula.

2. Establishment of mathematical model

According to the relevant spring manuals and standards, the non-contact planar scroll spring has the following formula [2]:

\[ T' = \frac{Ebh^3}{12K_i} \]  
\[ l = n\pi\left(R_{\text{out}} + R_{\text{in}}\right) \]
out in \( R_t = n \)  

\[
\sigma = \frac{Eh\varphi}{2t} 
\]

Where \( T' \) is the torsional stiffness, \( l \) is the effective length, \( t \) is the pitch, \( E \) is the elastic modulus of the material, \( b \) is the section thickness, \( h \) is the section width, \( n \) is the effective number of turns, \( R_{out} \) is the outer ring radius, \( R_{in} \) is the inner ring radius, \( \delta \) is the maximum stress, \( \varphi \) is the deformation angle, \( K_1 \) is the empirical coefficient (1.25 when the outer ring rotates and 1 when the outer ring is fixed).

According to the above formula, in the case of the same section, the stiffness of the non-contact planar scroll spring is only related to the effective length \( l \), and the maximum stress is only related to the effective length \( l \) and the rotation angle \( \varphi \). The parameters of non-contact planar scroll spring are set as shown in Table 1. The width, thickness, inner diameter and effective length of the spring remain unchanged, only the number of turns and outer diameter are changed, and the pitch is adjusted accordingly.

| \( n \) | \( b \)/mm | \( h \)/mm | \( R_{in} \)/mm | \( R_{out} \)/mm | \( t \)/mm | \( l \)/mm |
|---|---|---|---|---|---|---|
| 4 | 10 | 0.6 | 7.5 | 49.5 | 10.5 | 715.9 |
| 5 | 10 | 0.6 | 7.5 | 38 | 6.1 | 714.3 |
| 6 | 10 | 0.6 | 7.5 | 30.5 | 3.8 | 715.9 |
| 7 | 10 | 0.6 | 7.5 | 25 | 2.5 | 714.3 |

3. Establishment of finite element model
The non-contact scroll spring model adopts Archimedes spiral equation, as shown in formula (5), and establishes a three-dimensional model of planar scroll spring in Creo\(^3\). Because this paper focuses on the performance research of planar scroll spring with different pitch and the same stiffness, and does not pay attention to the connection form of inner and outer coils\(^4\), the model is simplified appropriately, and the final model is established as shown in Figure 1.

\[
\begin{align*}
  r &= R_{in} + (R_{out} - R_{in})t_i \\
  \theta &= a + 360nt_i \\
  z &= 0
\end{align*} 
\]

Where \( a \) is the initial rotation angle of the scroll spring, take 0, \( t_i \in [0, 1] \), \( R_{in}, R_{out}, n \) refer to table 1.

![Creo 3D model (n = 7)](image1)

![ABAQUS finite element model (n = 7)](image2)

The model generated by Creo is transferred to neutral format and imported into ABAQUS. The middle surface is extracted to establish a model suitable for shell element. A small segment of inner ring (about 25 mm in length) is split to simulate the inner ring spindle. The plane scroll spring is made of steel, the elastic modulus is set as 2.06e5, the Poisson's ratio is set as 0.3, and the model shell element attribute is given. Two analysis steps are established: frequency extraction analysis step and static general analysis step, and output variables are set, including Mises (Mises stress), RM (reaction moment), RF (reaction force), etc. The general contact is established, the contact attribute is
hard contact, no friction, and the reference point is established, and the MPC constraint is established between the reference point and the outer ring. The boundary conditions are established, the fixed constraint is imposed on the split part of the inner ring, and the rotation displacement of the reference point is 6.28 rad (UR3). The grid density is set reasonably and S4R element is used to divide the grid. Establish and analyze the operation for analysis. [5][6]

According to the above steps, the model is analyzed and the analysis structure is processed accordingly.

4. Results of finite element analysis

4.1. Modal analysis results

In the frequency extraction step, only the first 30 order frequencies are extracted. As shown in Table 2, only the first 8 order frequencies are listed. Through the analysis, it can be concluded that with the increase of the number of turns, the pitch becomes smaller, and the frequency of the plane scroll spring obviously increases, and the difference between the minimum pitch and the maximum pitch fundamental frequency in the table is nearly one time.

| n(t/mm) | 1-order | 2-order | 3-order | 4-order | 5-order | 6-order | 7-order | 8-order |
|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| 4 (10.5)| 16.2    | 22.4    | 23.9    | 28.2    | 33.9    | 37.0    | 40.3    | 50.0    |
| 5 (6.1) | 21.6    | 29.6    | 32.2    | 35.6    | 44.3    | 46.1    | 51.3    | 57.0    |
| 6 (3.8) | 27.1    | 36.6    | 40.9    | 43.8    | 54.1    | 59.4    | 64.0    | 68.7    |
| 7 (2.5) | 33.2    | 44.1    | 50.2    | 52.8    | 66.1    | 74.1    | 78.2    | 85.5    |

4.2. Other mechanical properties

In the static general analysis step, the maximum stress (Mises), maximum contact stress (cpress), reference point reaction torque (RM) and reaction force (RF) of plane scroll spring are shown in Table 3, and the cloud diagram of stress (Mises) is shown in Figure 3. Through the data analysis, it can be concluded that the maximum stress (Mises) decreases with the increase of the number of turns, and the pitch decreases slightly, and the maximum reaction torque (i.e. torsional stiffness) is basically the same as the maximum reaction force.

| n(t/mm) | the maximum stress Mises/MPa | reaction torque RM/N.mm | reaction force RF/N | maximum contact stress CPRESS/MPa |
|---------|------------------------------|-------------------------|---------------------|----------------------------------|
| 4 (10.5)| 671.8                        | 331.5                   | 44                  | 1.3                              |
| 5 (6.1) | 645.8                        | 329.5                   | 43                  | 1.0                              |
| 6 (3.8) | 627.1                        | 327.5                   | 42                  | 1.0                              |
| 7 (2.5) | 618.3                        | 328                     | 41.5                | 1.0                              |
4.3. Stress distribution along the spring

The distribution of stress along the length direction of the plane scroll spring is shown in Figure 4. The abscissa is the length of participating in deformation, and the normalization processing is adopted (the initial position of the inner ring participating in deformation is 0, and the end of the outer ring is 1). Through data analysis, it can be concluded that with the increase of the number of turns, the pitch becomes smaller, the maximum stress becomes smaller, and the stress fluctuation amplitude along the length direction becomes smaller. And the number of peaks is basically consistent with the number of effective circles. By processing the curve data, it is found that the mean value of stress distribution along the length is basically the same.
5. Comparison between finite element analysis and empirical formula

5.1. Stiffness comparison
Referring to formula (1), the empirical formula stiffness of non-contact planar scroll spring is obtained, and the maximum reaction torque of ABAQUS analysis structure is processed to obtain the simulation analysis stiffness. As shown in Table 4, there is a certain difference between the simulation analysis stiffness and the empirical formula stiffness.

| n(t/mm) | maximum reaction torque (Nmm) | simulation analysis stiffness (Nmm/rad) | empirical formula stiffness (Nmm/rad) |
|---------|-------------------------------|----------------------------------------|--------------------------------------|
| 4 (10.5)| 331.5                         | 52.8                                   |                                      |
| 5 (6.1 )| 329.5                         | 52.5                                   |                                      |
| 6 (3.8 )| 327.5                         | 52.1                                   | 42.9                                 |
| 7 (2.5 )| 328                           | 52.2                                   |                                      |
| Simulation analysis of mean stiffness | | 52.4 | |

In order to further analyze the difference between simulation analysis and empirical formula calculation results, based on the model parameters of 7 turns (t = 2.5), 10 plane scroll springs made of stainless steel (3Cr19Ni9Mo2N) were machined, and the stiffness was measured. The measurement results are shown in Table 5. The results show that there are some differences in the stiffness between the tested spring individuals, but on the whole (mean value) the test stiffness is closer to the simulation stiffness.
Table 5 stiffness test of plane scroll spring (n = 7, t = 2.5)

| Test piece No | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 |
|---------------|----|----|----|----|----|----|----|----|----|----|
| test stiffness (Nmm/rad) | 44.6 | 44.8 | 51.2 | 46.6 | 52.1 | 46.4 | 51.7 | 49.1 | 54.2 | 53.7 |

| Test mean (Nmm/rad) | 49.4 |
|--------------------|------|
| mean error | 9.7% | 9.3% | 3.6% | 5.7% | 5.5% | 6.1% | 4.7% | 0.6% | 9.7% | 8.7% |

5.2. Maximum stress comparison

According to formula (3), calculate the deformation of spring in $2\pi$. Combined with the simulation results of ABAQUS, it is shown in Table 6. There are still some errors in the calculation of the maximum stress in the simulation analysis and the empirical formula, mainly because the empirical formula is conservative (K2 is introduced in the stress check, and 2 is taken in the outer ring rotation). At the same time, it can be found that the average stress calculated by simulation analysis is basically consistent with the maximum stress calculated by empirical formula.

Table 6 Comparison of simulation analysis and empirical formula maximum stress

| n(t/mm) | maximum stress calculated by simulation analysis (MPa) | average stress calculated by simulation analysis (MPa) | maximum stress calculated by empirical formula (MPa) |
|---------|-------------------------------------------------------|------------------------------------------------------|------------------------------------------------------|
| 4 (10.5)| 671.8                                                 | 541.2                                                | 562.2                                                |
| 5 (6.1) | 645.8                                                 | 542.9                                                |                                                      |
| 6 (3.8) | 627.1                                                 | 542.0                                                |                                                      |
| 7 (2.5) | 618.3                                                 | 543.4                                                |                                                      |

6. Conclusion

1) From the perspective of modal analysis, with the increase of the number of turns, the pitch becomes smaller and the fundamental frequency becomes larger;

2) From the stress point of view, with the increase of the number of turns, the pitch becomes smaller, the maximum stress decreases slightly, the fluctuation of stress along the length direction becomes smaller, and the distribution is more uniform;

3) The comparison between the simulation analysis and the empirical formula shows that there are some differences in stiffness calculation and stress calculation. The empirical formula is conservative, but it is more simple and general. The process and results of finite element simulation have a certain reference significance in the selection and design of plane scroll spring, especially for the plane scroll spring with high precision torque requirements;

4) Due to the convergence of ABAQUS, there is no friction in the analysis process, and the applied displacement of the outer ring is only one circle in the analysis process, so the large angle condition with friction should be further considered.

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