Static and Dynamic Analysis of a 2T3R Five-degree-of-freedom Parallel Mechanism

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Abstract. Taking a 2T3R five-degree-of-freedom 4-SPRR-SPR parallel mechanism as the research object, a three-dimensional model and a finite element model of the parallel mechanism are established. Through the static analysis of the mechanism, the weak link of the whole mechanism is analyzed. It is then modally analyzed to analyze the natural frequency and mode shape of the mechanism. On the basis of the harmonic response analysis, the vibration resistance performance and the maximum influence frequency of the mechanism under external force are obtained.

1. Introduction
The five-degree-of-freedom parallel robot is a more important type of parallel mechanism with less degrees of freedom. It is more flexible than the three- or four-degree-of-freedom parallel robot. It is characterized by simple structure and easy control compared with the six-degree-of-freedom parallel robot. There are good application prospects in polishing, etc. [1-4], but there are relatively few studies on 4-SPRR-SPR five-degree-of-freedom parallel mechanism at home and abroad[5-6].

In this paper, a 2T3R five-degree-of-freedom 4-SPRR-SPR parallel mechanism is used for static analysis and modal analysis for harmonic response analysis. Analyze the weak points of the mechanism's force and anti-vibration, and provide theoretical support for building the prototype. The 3D model of the 4SPRR-SPR parallel mechanism is shown in Figure 1. The mechanism consists of a rotating shaft platform, a fixed platform frame and five branches connected to the fixed platform frame. The first branch is a -SPR branch, which consists of a rotating pair (R) and a moving pair (P). A ball pair (s). The 2, 3, 4, and 5 branches are -SPRR branches, which are composed of two rotating pairs (R), one moving pair (P), and one ball pair (s)[7].

Figure 1. 4-SPRR-SPR Three-dimensional model of parallel mechanism
2. Static Analysis of 4-SPRR-SPR Parallel Mechanism

2.1. Building a finite element model

By considering the application environment of the 4-SPRR-SPR parallel mechanism, since the 4-SPRR-SPR parallel mechanism is a complex space geometry mechanism[8], the 3D model is first modeled in SolidWorks, and then the built complex 3D model is saved in xt format. And imported into the ansys, set the material to 45 steel, the density is 7890, the modulus of elasticity is 209 Gpa, and the Poisson's ratio is 0.269. The meshing is automatically divided by the system, and the finite element model of the 4-SPRR-SPR parallel mechanism is shown in Figure 2.

![Figure 2. 4-SPRR-SPR Parallel mechanism finite element model](image)

2.2. Static analysis

In ansys, simulate the loading of the organization in the actual working environment. Apply a force of 500 N to the moving platform of the mechanism and then fix it at the four low angles of the frame. Then the stress strain diagram of the 4-SPRR-SPR parallel mechanism can be obtained as shown in Figure 3.

![a) Parallel mechanism stress map](image)

![b) Parallel mechanism strain diagram](image)

**Figure 3. 4-SPRR-SPR Parallel mechanism stress strain diagram**
It can be seen from the stress diagram of the parallel mechanism that the overall force of the mechanism is relatively small, and the stress from the frame to each branch is relatively small. Only the stress on the moving platform is larger, and the maximum stress appears at the branch 3. But they are all within reasonable limits of the design. It can be seen from the strain diagram of the parallel mechanism in Figure 3(b) that the overall strain of the mechanism is very small. It mainly occurs on each branch and moving platform, and the maximum strain occurs at the end of the branch 3 and the moving platform. The maximum strain is 0.0009mm. Fully in line with the actual application, the 4-SPRR-SPR parallel mechanism meets the static stiffness design requirements.

3. Modal analysis of 4-SPRR-SPR parallel mechanism

3.1. Modal analysis results and conclusions

Using the Modal module in ANSYS, the static platform is fixed according to the actual working condition of the 4-SPRR-SPR parallel mechanism, and then the undamped linear structure is freely vibrated. Only the payload on the zero constraint is considered in the module. Other loads will be can be ignored[9].

The nonlinear modal analysis solver analyzes and solves the 4-SPRR-SPR parallel mechanism, and obtains the first 6 natural frequencies of the mechanism (as shown in Table 1 and its corresponding mode (as shown in Figure 4).

| Order | Frequency /Hz |
|-------|---------------|
| 1     | 17.367        |
| 2     | 17.917        |
| 3     | 27.418        |
| 4     | 65.439        |
| 5     | 79.048        |
| 6     | 87.078        |

Figure 4. 4-SPRR-SPR Parallel mechanism natural frequency

(a) 1st order (b) 2nd order (c) 3rd order (d) 4th order (e) 5th order (f) 6th order

The 6 modes of the parallel mechanism
The first-order modal pattern is shown in Figure 4a. The vibration mode is mainly reflected in the parallel mechanism swinging left and right along the ZX plane. The displacement mainly occurs on the thrust ball bearing at the tail of the moving platform and the 4th and 5th branches, wherein the ball joint of the 4th branch is connected with the frame. The displacement is the largest.

The second-order modal pattern is shown in Figure 4b. The vibration mode is mainly reflected in the parallel mechanism swinging back and forth along the ZX plane. The displacement mainly occurs on the thrust ball bearing at the tail of the moving platform and the 4th, 5th and 3rd branches, wherein the displacement is maximum at the 5th branch.

The third-order modal pattern is shown in Figure 4c. The vibration mode is mainly reflected in the fact that the parallel mechanism is twisted along the Y axis, and the displacement mainly occurs on the parallel mechanism frame and the moving platform, wherein the displacement at the ball sub-fixing plate of the frame is the largest.

The fourth-order modal pattern is shown in Figure 4d. The vibration mode is mainly reflected in the parallel mechanism swinging up and down along the x-axis. The displacement mainly occurs on the moving platform and each branch, and the displacement of the fifth branch is the largest.

The fifth-order modal pattern is shown in Figure 4e. The vibration mode is mainly reflected in the fact that the parallel mechanism is twisted along the YZ plane, and the displacement mainly occurs on the mechanism frame and each branch, wherein the displacement of the fifth branch is the largest.

The 6th-order modal pattern is shown in Figure 4f. The vibration mode is mainly reflected in the left and right swing of the parallel mechanism along the YZ plane. The displacement mainly occurs on the moving platform and the 4th and 5th branches, wherein the displacement of the 5th branch is the largest.

In summary, the 1st and 2nd order modes show that the moving platform swings left and right along the ZX plane. There is little difference between the natural frequencies of the two. It shows that the stiffness of the moving platform along the ZX plane is similar. However, the natural frequencies of the 3rd to 6th order are much larger than the 1st to 2nd order. It is indicated that the motion stiffness of 3 to 6 is much larger than the motion stiffness of 1 to 2 steps. It can be seen from the vibration patterns of the various stages that the stiffness of the five branches and the moving platform and the frame joint is relatively weak, especially at the fifth branch (as shown in Table 2. However, the parallel mechanism runs at a lower speed during the operation, which indicates that the mechanism meets the application standards in terms of rigidity and stability.

| Order | Maximum displacement       | Displacement/m |
|-------|---------------------------|----------------|
| 1     | Ball pair of the 4th branch | 0.047709       |
| 2     | 5th chain                  | 0.042294       |
| 3     | Ball sub-fixing plate      | 0.049533       |
| 4     | 5th chain                  | 0.19242        |
| 5     | 5th chain                  | 0.11305        |
| 6     | 5th chain                  | 0.12537        |

4. Harmonic response analysis of parallel mechanism

Calculate the response of the linear structure at different frequencies and obtain an image of the response as a function of frequency. Under the premise of modal analysis of the parallel mechanism, the harmonic response analysis of the mechanism will be carried out by the complete method[10]. For the dynamic characteristics of the parallel mechanism, the high-order modal frequency is attenuated by the damping effect, so the influence of the low-order modal frequency or the fundamental frequency is mainly considered. The harmonic response analysis only considers the response of the mechanism in
the range of 0 to 90 Hz. Figure 5 to Figure 7 show the displacement response curves of the 4-SPRR-SPR parallel mechanism moving platform along X, Y, and Z.

![Figure 5](image1.png)  
**Figure 5.** Displacement response curve of moving platform along X axis

![Figure 6](image2.png)  
**Figure 6.** Displacement response curve of moving platform along Y axis

![Figure 7](image3.png)  
**Figure 7.** Displacement response curve of moving platform along Z axis

From the displacement response curves of X, Y, Z, it can be seen that in the vicinity of the natural frequency of the 1st and 2nd orders, the moving platform is easy to influence along the X and Z directions, and near the natural frequencies of the 3rd and 4th order, the moving platform is along the X, Y, The Z-direction has the most obvious effect, indicating that the 17Hz and 65Hz frequencies are most susceptible to damage to the 4-SPRR-SPR parallel mechanism. Therefore, in order to make the organization work properly, the frequency should be avoided as much as possible. Other natural frequencies have less resonance for the mechanism and do not affect the normal operation of the mechanism.

5. Conclusion

The static analysis of a 5 degree-of-freedom parallel mechanism is carried out by the finite element method. The maximum deformation of the mechanism when the mechanism is under force can be obtained, and the theoretical basis for the structural design and improvement of the mechanism is provided. Through the modal analysis of the 4-SPRR-SPR parallel mechanism, the first 6 natural frequencies and mode shapes of the mechanism can be obtained, and the natural frequency of the parallel mechanism meets the normal operation requirements. On this basis, the harmonic response analysis of the whole mechanism is carried out, and the weak links in the design of the mechanism are obtained, and the two frequencies that the mechanism should avoid in the work are pointed out. It provides a theoretical basis for the control of the 4-SPRR-SPR parallel mechanism.

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