Kinematics Analysis of the 6-DOF Test-bed for the Sliding Bearing of Marine Gas Turbine

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Abstract. In order to solve the problem of simulating complex sea conditions on the sliding bearing test bed of marine gas turbines, a six-degree-of-freedom platform based on the Stewart platform is used to build the test bed. By reasonably arranging the positions of the hinge points on the upper and lower platforms, the inverse kinematics solution is used to calculate the length change of the six driving rods, finally, the simulation was verified by Matlab, which proved that the design is reasonable and feasible, and it can accurately simulate the complicated sea conditions encountered by marine gas turbines during sea navigation. Furthermore, it lays the foundation for further sliding bearing of marine gas turbines test and research.

Keywords: Marine gas turbines, sliding bearing test bed, matlab, stewart.

1. Introduction
Marine gas turbines have gradually become the core power equipment of large surface ships. With the navy’s strategic transformation towards sea, the navy must go out and put forward higher requirements for the reliability and life of the main power system of gas turbines [1]. At present, the bearing system of marine gas turbine is one of the bottlenecks that restrict the life and reliability of the whole machine. The main manifestation is that the rolling bearing is a life-limiting part of the gas turbine and the reliability is not high. During the service process, gas turbines of ships have been returned to the factory for maintenance several times due to the damage and replacement of rolling bearings, which affects the normal use of gas turbines and increases the cost of maintenance of gas turbines. [2]. Sliding bearings have higher reliability and service life, and lower maintenance costs, these advantages make it a development trend to replace rolling bearings in gas turbines.

However, unlike gas turbines used on the ground, the operating environment of marine gas turbines is quite special. In the course of navigating at sea, the ship encounters irregular side-to-side and front-to-back sway caused by complicated sea conditions. The hull changes back and forth in trim, heel, bow, stern, pitch, roll and other postures [3]. The load generated by the ship will be transmitted to the bearing through the hull and the gas turbine support. Therefore, the sliding bearing test bed of the ship gas turbine is required to be able to simulate the complex sea conditions. Therefore, this article intends to build a marine gas turbine sliding bearing test bed that can simulate real-time sea conditions based on the Stewart six-degree-of-freedom platform, and further analyze and verify its kinematics.
2. The structure design of the 6-DOF Test-bed for the sliding bearing of the marine gas turbine

The six-degree-of-freedom test bed for sliding bearing studied in this paper is mainly composed of the sliding bearing test bed body and the Stewart six-degree-of-freedom motion platform as shown in Fig.1, the platform includes an upper moving platform, a lower static platform and six freely telescopic drive rods. The upper moving platform, the lower static platform and the six drive rods that can be freely and independently extended are connected by ball hinges [4-6]. By controlling the telescopic lengths of the six driving rods, the upper platform can realize a total of six degrees of freedom movement along the three coordinate axes of space and rotation around the three coordinate axes of space. In this paper, the upper platform radius $r$ is 1500mm, the lower platform radius $R$ is 2000mm, and the initial position of the upper and lower platforms $h$ is 2100mm.

![6-DOF test bed for sliding bearing of marine gas turbine](image)

**Figure 1.** 6-DOF test bed for sliding bearing of marine gas turbine

3. Platform kinematics analysis of the platform

The Stewart platform is mainly composed of an upper platform, a lower platform, six branches and hinges between the branches [7,8]. In this article, the six branches are telescopic links driven by hydraulic cylinders, and the hinges are universal ball hinges. The mechanism has 18 kinematic pairs, among which there are 6 with 1 degree of freedom, 6 universal hinges on the upper and lower platforms have 3 degrees of freedom, and the number of independent closed loops is 5, so the degree of freedom is:

$$ F = 6 \times (1 + 3 + 3) - 6 \times 5 - 6 = 6 $$

3.1. Establishment of coordinate system

Establish a static coordinate system $\{A\}$, which is located on the lower platform; a dynamic coordinate system $\{B\}$ [9,10], which is located on the upper platform, the lower platform is fixed and the upper platform moves relative to the lower platform, as shown in Fig.2. The hinges of the lower platform are distributed on the circle of radius $R$, and the center coordinates of hinges are $A_i (i = 1, 2 \ldots 6)$. The hinges of the upper platform are distributed on the circle of radius $r$, and the center coordinates of hinges are $B_i (i = 1, 2 \ldots 6)$, the length vector of the six branches is $L_i (i = 1, 2 \ldots 6)$. 
The rotation transformation matrix of the coordinate \{B\} relative to the coordinate \{A\} is \(A_{B}^{A}\), and the position of the origin of the \{B\} coordinate system in the \{A\} coordinate system is \(B_{0}\):

\[
B_{0} = [x, y, z]^T
\]

\[
A_{B}^{A} = \begin{bmatrix}
\cos \beta \cos \gamma & \cos \beta \sin \gamma - \sin \beta \cos \alpha & \sin \beta \sin \gamma + \cos \beta \sin \alpha \\
\sin \beta \cos \gamma & \sin \beta \sin \gamma + \cos \beta \cos \alpha & -\cos \beta \sin \gamma + \sin \beta \sin \alpha \\
-s\theta & s\theta \cos \gamma & c\theta \sin \gamma & c\beta \sin \gamma
\end{bmatrix}
\]

In the above formula, \(s\theta = \sin \theta, c\theta = \cos \theta (\theta = \alpha, \beta, \gamma)\), \(\alpha, \beta, \gamma\) are the angles of the upper platform rotating around the three coordinate axes [11].

3.2. Kinematics inverse solution

Knowing the position and posture of the moving platform, solving the displacement changes of the six branches is called the inverse kinematics process. During the design process, the hinge points of the upper and lower platforms are arranged according to Fig.3:

Figure 2. Stewart platform coordinate position.

Figure 3. Top view of the Stewart platform.
In this figure, the angle between the upper platform and is , and the angle between the lower platform and is . Therefore, the coordinate positions of \( A_i \) and \( B_i (i = 1, 2 \ldots 6) \) can be calculated easily. At this time, the coordinates of each hinge point center of the upper platform in the coordinate system \( O_A - X_A Y_A Z_A \) are:

\[
B_i' = \frac{\Delta T}{A_i} + B_0, i = 1, 2 \ldots 6
\]  

(4)

And the length vector of the six branches \( L_i \) can be expressed in the coordinate system as:

\[
L_i = B_i' - A_i, i = 1, 2 \ldots 6
\]  

(5)

So that the inverse kinematics equation can be obtained:

\[
\Delta L_i = \sqrt{L_{ix}^2 + L_{iy}^2 + L_{iz}^2} - L_{i0}, i = 1, 2 \ldots 6
\]  

(6)

\( L_{i0} \) is the initial length of the \( i \)-th branch, \( \Delta L_i \) is the movement change of the \( i \)-th branch. Obviously, in the above formula, when the coordinate positions of \( A_i \) and \( B_i (i = 1, 2 \ldots 6) \) are known, the result is only related to six unknown quantities \((x, y, z, \alpha, \beta, \gamma)\). Therefore, on the premise of knowing the position and posture of the platform, it is relatively easy to obtain the movement change of the branch chains [12-14]. Considering that the ship has longitudinal shift, vertical movement, roll, pitch and other actions in actual operation, the standard working position parameters of the ship in six degrees of freedom are given here, as shown in Tab.1.

**Table 1. Ship standard working position index.**

| Degree of freedom   | Displacement |
|---------------------|--------------|
| Longitudinal shift  | ±100mm       |
| Traverse            | ±100mm       |
| Vertical            | ±100mm       |
| Pitching            | ±10°         |
| Roll                | ±10°         |
| Yaw                 | ±10°         |

For further theoretical analysis and verification, we roughly regard the motion of a ship under irregular waves as the superposition of a series of sine and cosine motions [15], then the function of the platform pose parameter \((x, y, z, \alpha, \beta, \gamma)\) is:

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} = \begin{bmatrix}
  0.1 \sin(0.04\pi t) \\
  0.1 \sin(0.03\pi t) \\
  0.1 \sin(0.03\pi t) + h
\end{bmatrix}
\]  

(7)

\[
\begin{bmatrix}
  \alpha \\
  \beta \\
  \gamma
\end{bmatrix} = \begin{bmatrix}
  10^5 \sin(0.03\pi t) \\
  10^5 \sin(0.04\pi t) \\
  10^5 \sin(0.06\pi t)
\end{bmatrix}
\]  

(8)
3.3. Matlab simulation verification

According to the previous introduction, using Matlab for further simulation verification. Firstly, consider that there is only a single axial displacement (taking longitudinal shift as an example), as shown in Fig. 4; then, considering a single angle change (taking the roll angle change as an example), as shown in Fig.5; and finally, considering the changes in rod length caused by the six unknown quantities parameters \((x, y, z, \alpha, \beta, \gamma)\), as shown in Fig.6:

![Figure 4](image)

**Figure 4.** Changes in rods length when only the longitudinal shift factor is considered

![Figure 5](image)

**Figure 5.** Changes in rods length when only the roll angle factor is considered

![Figure 6](image)

**Figure 6.** Changes in rods length when the six factors are considered
It can be seen from the figures that when only the longitudinal shift or roll angle changes are considered, the rods length changes show regular sine and cosine motion, and the motion of the corresponding rods is symmetrically distributed, it means when a branch chain rod reaches the highest limit position, the corresponding rod will reach the lowest limit position. When the six parameters are comprehensively considered to act on the platform, the changes of the rods length shows a sin-cosine motion as a whole, and there is no mutual interference and singularity between the rods. The rod can be extended to 2.63m, and the shortest rod can be compressed to 2.35m, which proves that the design is reasonable and feasible.

4. Conclusion
This paper is to simulate the complicated sea conditions encountered by marine gas turbines when sailing on the sea surface. Based on the Stewart platform, a six-degree-of-freedom test bed for the sliding bearings of marine gas turbines is built, and then the kinematics analysis and simulation of the Stewart support platform are carried out. Through the inverse kinematics solution, the movement changes of the six branch chains connecting the upper and lower platforms of Stewart are obtained, and further simulation verification is carried out by Matlab. The obtained movement displacement diagram of the six branch chains proves the rationality and accuracy of the design.

At the same time, the successful design and construction of the test bench laid the foundation for the next step of simulating various tests of ship gas turbine sliding bearings under sailing conditions, and created a better future for the application and development of my country's marine gas turbine sliding bearings.

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