Mechanical Design of the Six-cable Driven Parallel Mechanism in FAST Telescope

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Abstract. A six-cable driven parallel mechanism is adopted for realizing the position and orientation control of the Five-hundred-meter Aperture Spherical radio Telescope (FAST). The span of the cable driven parallel mechanism is 600m, which will be the largest cable robot in the world. The main purpose of this paper is to discuss mechanical design of the six-cable driven parallel mechanism. In this paper, dimension design based on its statics performance is adopted. More important, research development and results of the electrical and signal cable transmission method encourage the use of the large cable driven parallel mechanism. The expectation of this paper is to expand the application of the large cable driven parallel mechanism.

Introduction

China is now building the largest single dish radio telescope in the world in Guizhou province, which is called Five-hundred-meter Aperture Spherical radio Telescope (FAST) [1].

Fig. 1 shows the conceptual design of the FAST. The feed support system of FAST includes two parts: one is a six-cable driven parallel mechanism with a large span that drives the feed adjustable mechanism equipped with a coarse positioning; the other one is a feed adjustable mechanism, which is also called as focus cabin. The diameter of the focus cabin is about 13m.

Figure 1. Conceptual design of the FAST.

Cable driven parallel mechanism developed rapidly since the beginning of the 1980s, mainly used for lifting, undersea salvage, large radio telescopes and wind tunnel support systems. Cable driven parallel mechanism has advantages of simple configuration, high load ability, large workspace, low price and high speed [2-4].

This paper focus on the study of the cable driven parallel mechanism in FAST, including the modeling and mechanical design. Besides, the mechanical design of the electrical and signal cable transmission mechanism is also discussed in this paper.
Modeling of the Six-Cable Riven Parallel Mechanism with Large Span

Fig. 2 is the six-cable driven parallel mechanism in FAST, and two coordinates are set up: an inertial frame $\mathbb{R}: O - XYZ$ is located at the center of the reflector's bottom. Another moving frame $\mathbb{R}': O' - X'Y'Z'$ is located at the center of the moving platform. $B_i$ ($i = 1,2,...,6$) are the connected points of the cables and cable towers, and $A_i$ ($i = 1,2,...,6$) are the connected points of the cables and moving platform.

For analyses, the symbols used in this section are defined as:
- $O^\mathbb{R}$ is the $O'$ expressed in the inertial frame;
- $B_i^\mathbb{R}$ the vector $B_i$ expressed in the inertial frame;
- $A_i^\mathbb{R}$ the vector $A_i$ expressed in the inertial frame;
- $A_i^\mathbb{M}$ the vector $A_i$ expressed in the moving frame;
- $r_b$ the radius of the cable towers' distributed circle;
- $r_a$ the radius of the moving platform;
- $h$ the height of the cable tower;
- $\theta_a$ the distributed angle of the $A_i$, $\theta_b$ the equational distributed angle of $B_i$.

According to Fig. 2, the vector of the cables can be expressed as:

$B_i^\mathbb{R} = [r_b \cos(\theta_b \times i - 30'), r_b \sin(\theta_b \times i - 30'), h]^T \quad i = 1,2,...,6 \quad (1)$

$A_i^\mathbb{R} = \left\{ \begin{array}{c}
[r_a \cos((i - 1) \times \theta_b + \theta_a / 2), r_a \sin((i - 1) \times \theta_b + \theta_a / 2), 0]^T \\
[r_a \cos(\theta_b \times i - \theta_a / 2), r_a \sin(\theta_b \times i - \theta_a / 2), 0]^T
\end{array} \right. \quad i = 1,3,5 \quad (2)$

$A_i^\mathbb{M} = R \cdot A_i^\mathbb{R} - O^\mathbb{R} \quad (3)$

Where $R$ is the coordinate-axis rotation matrix.

Because the working velocity of the six-cable driven parallel mechanism is very low, typically 11.6mm/s, it has been seen as a static cable tension. Assuming $L_i = B_i^\mathbb{R} A_i^\mathbb{R}$, $u_i = L_i / \|L_i\|$, $\tau_i = O^\mathbb{R} A_i^\mathbb{R}$, static equilibrium equation of the six-cable driven parallel mechanism can be written as[5-7]:

$F = J^T \sigma \quad (4)$

Where $\sigma$ is the cable tension vector; $J^T$ the tension transmission matrix of the cable driven parallel mechanism; $F \in \mathbb{R}^n$ the wrench of the moving platform.

$\sigma = [\sigma_1, \sigma_2, \cdots, \sigma_6]^T \quad (5)$
By introducing catenary equation of a single cable, which has been deeply researched and widely applied in architecture, the real cable length and tension can be calculated by using iterative algorithm. The specific solving process has been clearly explained in some references [8,9]. The cable tensions of the six-cable driven parallel mechanism should satisfy:

\[
\begin{align*}
\sum_{i=1}^{6} \sigma_{ix} &= 0 \\
\sum_{i=1}^{6} \sigma_{iy} &= 0 \\
\sum_{i=1}^{6} \sigma_{iz} &= 0 \\
\sum_{i=1}^{6} M_{ix} &= 0 \\
\sum_{i=1}^{6} M_{iy} &= 0 \\
\sum_{i=1}^{6} M_{iz} &= 0
\end{align*}
\]

(7)

Where \( \sum_{i=1}^{6} \sigma_{ix} = 0 \) is the tension in X-direction of the six-cable driven parallel mechanism, and \( \sum_{i=1}^{6} M_{ix} = 0 \) is the torque in X-direction of the six-cable driven parallel mechanism.

According to equation (1) ~(6), the cable tension of the six-cable driven parallel mechanism can be calculated.

Mechanical Design of the Six-cable Driven Parallel Mechanism

During the mechanical design of cable driven parallel mechanism, two issues are concerned: dimensional design of the cable driven parallel mechanism and mechanical design of the electrical cable transmission mechanism.

Dimensional Design of the Cable Driven Parallel Mechanism

On the basis of the configuration and performance requirement, dimensional parameters of cable driven parallel mechanism can be optimized. As shown in Fig. 1, the configuration of the cable driven parallel mechanism is already known. Cable tension and workspace are considered for dimensional design of the six-cable driven parallel mechanism of FAST.

In Fig. 3, the maximum tracking angle of the feeds is 40°, and the tracking angle is realized by the pose angle of the six-cable driven parallel manipulator and the A-B rotator. The focus surface is a spherical crown from about 140m to 176m above the active reflector. Six-cable driven parallel mechanism drives the focus cabin to make sure the nine feeds move on the focus surface.

![Figure 3. Work surface and dimensional parameters of the FAST.](Image)

After analyzing, the cable tension of the six-cable driven parallel mechanism is within 100kN to 300kN (Fig. 4). Considering the safety factor, the diameter of cable is chosen as 46mm.
Figure 4. Cable tension of the six-cable driven parallel mechanism.

Mechanical Design of the Electrical and Signal Cable Transmission Mechanism

In FAST, six cables drive the feed receivers, which are equipped in focus cabin, to receive radio wave. Electrical and signal cables should transmit from the cable tower to the focus cabin. However, the connection between the focus cabin and ground is flexible, and the cable length of the cable driven parallel mechanism is variable. So, based on the cable driven mechanism, the transmission of electrical and signal cable mechanism should be discussed.

There are three kinds of the electrical and signal cable transmission mechanism, including curtain-style mechanism, hanging off mechanism and special cable type mechanism.

Fig. 5 shows the curtain-style mechanism, which is similar as a sliding curtain. The mechanism design of the curtain type scheme is simple and easy to realize with high reliability. However, the suspension along the cable is not uniform, so it may affect the tilt angle of the focus cable.

Figure 5. Curtain-style mechanism.

In Fig. 6, The design of the hanging off mechanism references to the loop type mechanism used on high mountain cable. But the mechanism design is very complicated and the reliability is difficult to guarantee.
Fig. 7 shows the cable package mechanism. The cable core is electrical and signal cable, and the structure is easy. However, it break the traditional cable structure, and the reliability is not easy to guarantee.

In the above three kinds of design mechanism, the cable package type is the most simple mechanism, but it also the most difficult mechanism to be realized with high requirement for cable. The realization of the hanging off mechanism depends on the complex mechanism design, which can not guarantee the reliability. The curtain-style mechanism is simple, even though the dynamic performance is complicated, which is chosen as the electrical and signal cable transmission mechanism finally.

Conclusions

This is the first time to adopt a cable driven parallel mechanism for a giant telescope. During the application, the six-cable driven parallel mechanism in FAST fully uses the cable characteristics, and realize precise control by reasonable layout and algorithm. Through the mechanical design, theoretical analysis, and study of the electrical and signal transmission method, it is found that the cable parallel robot meets the performance requirements of the 500 meter aperture spherical radio telescope (FAST) in Guizhou. It is expected to expand the application of the large cable driven parallel mechanism in future.

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References


