Dimensional Parameters Design for Flexible Cable Drive Parallel Mechanism

Liao Hongbo¹,a,*, Liu Kun¹,b, Zhang Xinyi¹,c, Chen Zhongkai¹,d, Yin Kun¹,e

¹Northwest Institute of Nuclear Technology, Xi’an, China
a, *Corresponding author: 13975890826@163.com
bhl20573577@qq.com
c2624738981@qq.com
dchzhkzt1989@163.com
eyinkun5991@foxmail.com

Abstract—In order to design the size parameters of flexible cable drive parallel mechanism quickly and accurately, a mathematical model of flexible cable drive parallel mechanism is established, and a design method of dimension parameters for flexible cable drive parallel mechanism is presented. By analyzing the kinematics and dynamics relation of the flexible cable drive parallel mechanism in the finite constraint space, the mathematical model of flexible cable drive parallel mechanism is derived, which includes the constraints of shape size, force and cable weight. The maximum effective working space of flexible cable drive parallel mechanism is calculated, and the dimension parameter value of flexible cable drive parallel mechanism is obtained. It provides the basis for fast and accurate design of key dimension parameters for flexible cable drive parallel mechanism.

1. INTRODUCTION

Compared with the traditional rigid parallel mechanism, the flexible cable drive parallel mechanism has the advantages of large working space, simple re-configuration and fast moving speed. It is widely used in lifting, workpiece assembly, large stadium camera, astronomical telescope feed and wind tunnel simulation load support [1-3].

How to ensure the maximum effective working space of the mechanism under limited space constraints is a technical problem to be solved in the design of mechanism. The existing mechanical structure design method needs to be finished after the target material processing to determine whether the designed mechanical structure performance index meets the use requirements, which can not control the performance index in the design process, and it is difficult to obtain the optimal solution of the structural size parameters. For this reason, some scholars put forward the model-based design method. The basic idea of the model-based design method is to establish the mathematical model of the design object, the designed mechanism is predicted by means of numerical simulation analysis, and the structural parameters are further modified and perfected by feedback of the obtained prediction results to the structural design link. The whole design link is a closed loop process. The model-based design method is widely used in many mechanical structure design processes, such as fast mirror, two-link robot operating arm, plane two-link manipulator, space deployable antenna servo mechanism [4-6].

At
the same time, it has been applied in the design of flexible cable drive parallel mechanism [7]. Based on
the previous research, the method of model-based design for flexible cable driven parallel mechanism is
further studied in this paper.

2. BASIC DESIGN IDEAS

2.1 Introduction of design object
The flexible cable drive parallel mechanism is a kind of mechanical device which converts the motion
and force of the drive into the moving platform with the flexible cable. Its main components include
support frame, flexible cable, moving platform, pulley, composite joint, winding mechanism, servo
motor and load. The schematic diagram of 4 flexible cable drive parallel mechanism is shown in Fig.1.

Dimensional parameter design of flexible cable drive parallel mechanism mainly includes
mechanism configuration, flexible cable diameter and shape size. The objective of the design is to find
the optimal parameters under the condition of limited tension and suspension force.

2.2 Design ideas
The basic design ideas for dimensional parameters of flexible cable drive parallel mechanism is shown
in Fig.2. Firstly, the design objective is established, and the maximum effective working space is
established under the condition of size constrain. Secondly, the configuration of the mechanism is
determined and the mathematical model including kinematics and dynamics is established. Then, the
constraint equations including the dimensions of the mechanism, the length of the flexible cable, the
pulling force and the drape force are established. Finally, the size parameters of the mechanism are
solved by numerical calculation, including the diameter of the flexible cable, the size of the shape.

Figure 1. The schematic diagram of 4 flexible cable drive parallel mechanism
3. MODEL BUILDING

3.1 System simplification
Taking the design of the dimension parameters of the 4 cable drive parallel mechanism as an example, the key dimension parameters are obtained by using the model-based dimension parameter design method. The basic structure configuration of the 4 cable drive parallel mechanism is shown in Fig.1. The load can move freely in a certain 3D space.

In the process of system model simplification, the following conditions should be satisfied: The flexible cable is rigid without considering its elastic deformation; The moving platform size is small enough relative to the overall size of the system to be ignored as a particle; The friction of the motion joints is ignored; The support cable frame is equal in height and is arranged in a rectangle on the ground, any deformation can be ignored during the movement.

3.2 Mathematical model building
As shown in Fig.1, a cartesian coordinate system is established based on $B_3$. The load and the moving platform are regarded as particles, and their position coordinates are $P(x, y, z)$. Cable tension is $T_i(i=1,2,3,4)$, pulley center coordinates are $B_i(x_i, y_i, z_i)$, the distance from the center of the pulley to the load is $L_i(i=1,2,3,4)$.

The relationship between the length of each cable and the load position can be expressed as [8]

$$
\begin{align*}
L_1 &= \sqrt{(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2} \\
L_2 &= \sqrt{(x-x_2)^2 + (y-y_2)^2 + (z-z_2)^2} \\
L_3 &= \sqrt{(x-x_3)^2 + (y-y_3)^2 + (z-z_3)^2} \\
L_4 &= \sqrt{(x-x_4)^2 + (y-y_4)^2 + (z-z_4)^2}
\end{align*}
$$

Equation (1) is the inverse kinematics solution of the 4 cable drive parallel mechanism. The length of the flexible cable can be obtained by finding the inverse kinematics solution, which is the basis for the position motion control. The position of the load $P(x, y, z)$ is obtained, the forward kinematics solution can be expressed as
The length of 4 flexible cables can be satisfied as
\[ L_i^2 + L_j^2 = L_k^2 + L_l^2 \] (3)

The dynamic equation of the 4 cable drive parallel mechanism can be expressed as (4) [8].

The calculation of the effective working space is to determine whether a specific point in space meets the following constraints, if satisfied, it is a point in the effective working space, and the set of points in all the effective working space is the effective working space of the 4 cable drive parallel mechanism under the current size and load conditions.

\[
\begin{bmatrix}
\begin{pmatrix} x_1 - x \over L_1 \\
 y_1 - y \over L_1 \\
 z_1 - z \over L_1 \\
 m \ddot{x} \\
m \ddot{y} \\
m g + m \ddot{z}
\end{pmatrix}
- F_x - F_y \\
T_i
T_2 \\
T_3 \\
T_4
\end{bmatrix} = 0
\] (4)

### 3.2.1 End moving platform workspace range constraints
End moving platform workspace must be in a closed cuboid space composed of 4 follower supports, so the position coordinate \( P(x, y, z) \) satisfies the following constraints

\[
\begin{cases}
0 < x < x_1 \\
0 < y < y_1 \\
0 < z < z_1
\end{cases}
\] (5)

### 3.2.2 Length constraints
The length of the flexible cable can not exceed its maximum limit length, assuming that the flexible cable 1, 2, 3 as the driving input, the length range satisfies the following constraints

\[
\begin{cases}
0 < L_i < \sqrt{x_i^2 + y_i^2 + z_i^2} \\
L_i^2 = L^2 + L^2 - L^2 > 0
\end{cases}
\] (i = 1, 2, 3)

(6)

### 3.2.3 Force constraint
Each cable is subjected only to tension, and its force range satisfies the following constraints

\[
T_{\text{min}} < T_i < T_{\text{max}} \quad (i = 1, 2, 3, 4)
\] (7)
where $T_{\text{min}}$ is the cable subjected to the minimum tensile force, and $T_{\text{max}}$ is the cable subjected to the maximum tensile force, and the maximum tensile force is calculated by the cable subjected to the failure condition.

### 3.2.4 Length constraints by cable weight

When the weight of the cable cannot be ignored, the relationship between the tensile force and the elongation of the cable can be analyzed by the catenary theory, which is shown in Fig.3.

Define the following variables: $T$ is the cable tension; $H$ is the horizontal component of the cable tension; $V$ is the vertical component of the cable tension; $h$ is the vertical height distance of the A and B points; $l$ is the horizontal distance of the A and B points; $s$ is the length of the cable. The length of elastic elongation is not taken into account for the $s_0$. $\Delta s$ is the elongation; $g$ is the acceleration of gravity; $E$ is the elastic modulus of the flexible cable; $A$ is the cross-sectional area without considering the effect of elastic deformation; $\rho$ is the cable density.

![Cable catenary model](image)

Figure 3. Cable catenary model

Cable elongation can be calculated as [9]

$$
\Delta s = H / (2EA) \sqrt{l + H / \rho g [\sinh (\rho gl / H) + (\rho gh / H)^2 \cosh (\rho gl / 2H) / \sinh (\rho gl / 2H)]}
$$

The elongation constraint caused by the weight of the cable is as follow

$$
\Delta s_{\text{ub}} \leq \Delta s \leq \Delta s_{\text{up}}
$$

where $\Delta s_{\text{ub}}$, $\Delta s_{\text{up}}$ are the upper and lower bound values of the elongation constraint, respectively.

### 3.2.5 Maximum tensile damage constraints

The wire rope safety factor calculation formula is as follow

$$
[n] = \frac{F_d}{F} \geq 3.5
$$

where $F_d$ is the breaking tensile force of the wire rope, $F$ is the rated tensile force of the wire rope, $[n]$ is the minimum safety factor of the wire rope, the value is 3.5. The diameter parameter constraint for the wire rope can be expressed as

$$
d \geq f \sqrt[4]{F_d}
$$

where $f$ is the engineering selection coefficient, and the value is 0.071.

### 4. Model-based parametric design

Suppose that the shape profile size (length × width × height) of the 4 cable drive parallel mechanism is 23 m×14 m×11 m, with a load of 1000 kg ~ 8000 kg as shown in Fig.4. The maximum effective
working space (length × width), the diameter of the flexible cable, the length of a single flexible cable, and other dimension parameters are designed.

![Figure 4. Schematic diagram of the effective working space of 4 cable drive parallel mechanism](image)

The numerical calculation flow of the effective workspace of 4 cable drive parallel mechanism is shown in Fig.5.

![Figure 5. The numerical calculation flow of the effective workspace](image)

The effective workspace of the 4 cable drive parallel mechanism in a two-dimensional plane with a height of 9 m is calculated according to Fig.5. The results are shown in Fig. 6(a). The distribution of each flexible cable pull in a two-dimensional plane is shown in Fig.6 (b), and the distribution of each flexible cable length in a two-dimensional plane is shown in Fig. 6(c).

As shown in Fig.6(a), the maximum effective working space of 4 cable drive parallel mechanism on the two-dimensional plane with a height of 9 m is 20 m×10 m. The middle part of the Y direction near X=0 or X=14 region, which the cable tension is larger than the other region. The cable tension range is 5000 N~5.75×10^5 N, which is shown in Fig.6 (b). The distribution of cable length in Fig.6(c) shows that the length of cable is increasing with the position of pulley as the center point, and the length range of cable is 0.81 m~26.8 m. At this time, the diameter range of cable is 40 mm~44 mm.
(a) Effective workspace of the 4 cable drive parallel mechanism (Red-load is 8000 kg, Blue-load is 1000 kg, the black rectangle is the workspace boundary)

(b) Distribution of tension in each cable ($T_{\min} = 5000\text{N}$, $T_{\max} = 5.75 \times 10^5\text{N}$)
5. CONCLUSIONS
Based on the design of the dimension parameters for the 4 cable drive parallel mechanism, the following conclusions are obtained:

- A mathematical model for the design of structural dimension parameters including kinematics, dynamics and constraints is established.
- The model-based method is used to design the dimension parameters. The numerical results show that the maximum effective working space (length \times width) is 20 m\times 10 m, the diameter of cable is 44 mm, the maximum length of single flexible cable is 26.8 m.
- The design method can be used to design the exact size parameters of the flexible cable drive parallel mechanism in the theoretical design stage.

ACKNOWLEDGMENT
The authors sincerely appreciate the valuable suggestions and comments from editors and anonymous reviewers.

REFERENCES
[1] J. Albus, R. Bostelman, and N. Dagalakis, “The NIST RoboCrane. Journal of Robotic Systems”, vol. 10, pp. 709–724, 1993.
[2] Philipp Tempel, Fabian Schnelle, Andreas Pott. et al. “Design and Programming for Cable drive Parallel Robots in the German Pavilion at the EXPO 2015”, Machines, vol. 3, pp. 223-241, 2015.
[3] R. Nan. “Five hundred meter aperture spherical radio telescope”, Science in China G, vol. 49, pp. 129–148, 2006.
[4] PARK J H, ASADA H. “Concurrent design optimization of mechanical structure and control for high speed robot”, ASME Journal of Dynamic Systems, Measurement, and Control, vol. 116, pp. 344-356, 1994.
[5] REVICHANDRAN T , WANG D , HEPPLER G. “Simultaneously plant-controller design optimization of a two-link planar manipulator”, Mechatronics, vol. 16, pp. 141-242, 2006.
[6] Su Yu, QiuYuanying, Liu Peng. “Optimal cable tension distribution of the high-speed redundant driven camera robots considering cable sag and inertia effects”, Advances in Mechanical Engineering, pp. 1-11, 2014.
[7] Zi Bin, Cao Jianbin, Qian Sen. “Integrated design of hybrid-driven-based cable parallel manipulator system”, Journal of Mechanical Engineering, vol. 48, pp. 28-35, 2012.
[8] Yang Yuta. “Research and implementation of control system of camera robot with flexible cable traction”, Xidian University, 2014.
[9] Jin Mingjun, Zhang Zhiguo. “Computation of the length of flexible cable of catenary curve”, Railway Standard Design, vol. 5, pp. 9-10, 2004.