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Wire in the Cable-Driven System of Surgical Robot

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Abstract. During the evolution of the surgical robot, cable plays an important role. It translates motion and force precisely from surgeon's hand to the tool's tips. In the paper, the vertical wires, the composition of cable, are mathematically modeled from a geometric point of view. The cable structure and tension are analyzed according to the characteristics of wire screw twist. The structural equations of the wires in different positions are derived for both non-bent cable and bent cable, respectively. The bending moment formula of bent cable is also obtained. This will help researchers find suitable cable and design more matched pulley.

1. Introduction

Because of its high strength, good flexibility, small diameter and other characteristics, cable has been widely used in the general industry[1]. With the continuous development of the machinery, materials and other disciplines, a variety of specifications of cables are applied to many areas. In medical applications, tungsten cable is generally selected and is highly applied in surgical robot. When cable is used, cable-driven mechanism can make the whole mechanism has the advantages of compact structure, high transmission precision. It is conducive to the realization of the lightweight design of the robot. Meanwhile, the joint driver can be arranged in the same fixed base, thus will reduce the movement of the recoil.

In the existing institutions, the use of cable as the transmission system, mostly based on practice or experience, there is no corresponding theoretical analysis as a support. Sometimes, cable-driven system is considered as a rigid member when the motion of mechanism is analysed[2, 3], sometimes, cable is just a transmitter[4]. But for the structural design including the guide pulley, cable cannot be simply equated with the spring or the rod[5]. Although the application of cable has a long history, it is not long time to analyse its dynamics. As the special structural, mechanical theories based on rigid rods cannot be applied directly to the cable-driven system.

There are many kinds of cables, but their basic structures are the same. Based on the same character of cable, the paper focuses on the dynamic analysis of wires, which twist together to form cable.

2. Cable-driven system

Just the same as chain-driven and belt-driven system, cable-driven system needs to transmit motion and force through pulleys. To make sure that cable can transmit them precisely, some important parameters are need to be analysed.

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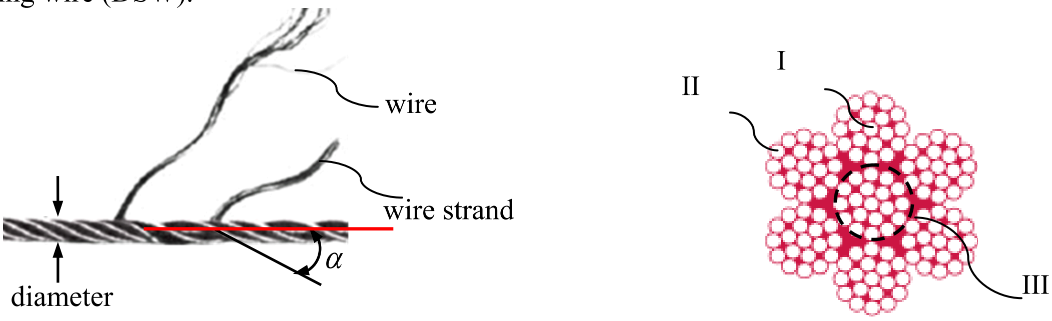
Different from belt and spring, the structure of cable is a little complicated. First, a wire strand is twisted by a number of wires, and then, cable is formed by the same method of certain number of wire strand.

To analyse the dynamic of cable, the structure of cable should be analysed firstly.

2.1. Wire of cable

Cable is twisted by wires, as shown in Figure 1. Certain number of wires comprises a wire strand. When the cable bent around the pulley, bearing tension, wires at different location will suffer different tension. To ensure that the motion and force can be transmitted precisely, every wire should be in good condition.

Figure 1(b) is the cross-section of the cable, where I is the centre wire of outer wire strand (OWS), II is the outer wire of OWS and III is the centre wire strand (CWS). According to the wire twisting method, the outer wire of III and I are named single spinning wire (SSW), the II is named dual spinning wire (DSW).



(a) Cable (b) Cross-section of the cable

Figure 1. Cable and its cross-section

To know the weak position of cable when cable is in tension, electronic universal testing machine (Model: CSS-44007) is used to do tensile failure experiment. The result shown that no matter what diameter of cable is, no matter what kind of force cable is suffered, the weakest position is the bent part, as shown in Figure 2. So it is necessary to analyse the weakest part bent cable.

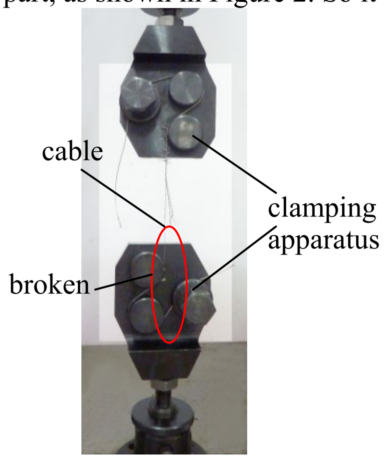


Figure 2. Tensile failure experiment

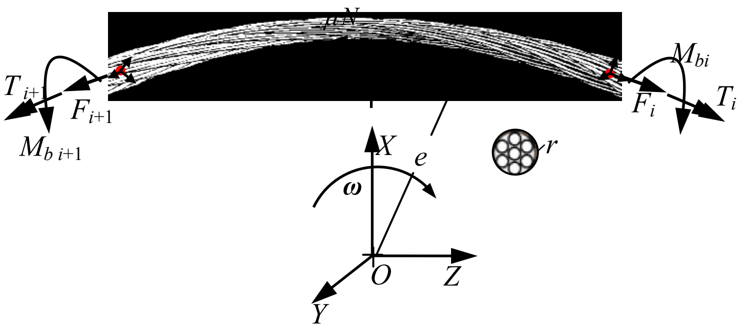


Figure 3. Bent cable

When the cable is bent around a pulley, it can be modelled as shown in Figure 3. The forces applied to the cable are pressure, friction, axial force, torsion and bending moment, which are represented by N, μN, F, T, M_b, respectively. According to the formation of cable, the mathematical equation of wire can be written as

$$\mathbf{s}(\varphi) = \left(-\left(e + r\cos n\varphi\right)\cos\varphi \quad r\sin n\varphi \quad \left(e + r\cos n\varphi\right)\sin\varphi \right) \tag{1}$$

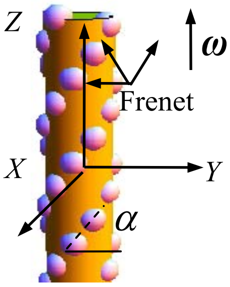
where e is the bending radius, n is the twisting number and r is the radius of wire.

2.2. Bending moment of wire

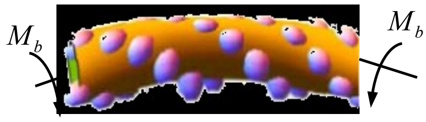
Set a Frenet coordinate system[6] at the *i*th infinite element, as shown in Figure 4. It is easy to know that the base point of Frenet coordinate system can be written as

$$(\tau_0, \quad \upsilon_0, \quad \beta_0) = (s\alpha c\alpha / r_0, \quad c^2\alpha / r_0, \quad 0) \tag{2}$$

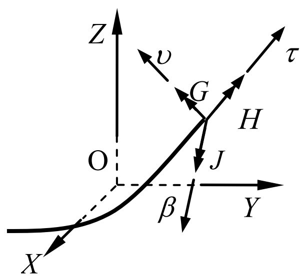
where $c = \cos$, $s = \sin$, r_0 is the distance from the base point of Frenet coordinate to that of the fixed coordinate.



(a) Straight wire



(b) Bent wire



(c) Wire in Frenet coordinate

Figure 4. Infinitesimal element of wire

Decomposing the torsion and bending moment of the infinitesimal element wire into the Frenet coordinate system. G and J are the torsion at the direction of υ and β, respectively, while H is the bending moment at τ direction. Then, according to the torsion and bending moment formula, the following equations can be obtained:

$$G = EI_\upsilon(\upsilon' - \upsilon_0) \tag{3}$$

$$J = EI_\beta(\beta' - \beta_0) \tag{4}$$

$$H = C_p I_p(\tau' - \tau_0) \tag{5}$$

where $C_p I_p$ is torsional rigidity,

E is the elastic modulus of cable,

I_υ and I_β are the moments of inertia of the two axes, which are $I_\upsilon = I_\beta = (\pi r^4/4) + \pi r^2 r_0^2 = \pi r^2(r^2 + 4r_0^2)/4$,

$I_p = I_\upsilon + I_\beta$ is polar inertia,

$C_p = E/2(1+\rho)$ is the shear modulus,

ρ is Poisson ratio.[7]

Let the fixed coordinate at the centre of the pulley, so the bending moment equation of the wire can be obtained as:

$$m_b = \frac{\pi r^2 \left(r^2 + 4{r_p}^2 + 4e^2 \right) E\phi}{4l} \tag{6}$$

where ϕ is bending angle,

l is the arc length of cable curved part,

r is the radius of cable,

r_p is the distance from the centre of cable to the pulley centre,

e is the radius of pulley.

2.3. Result

Using the equation (6), the weakest wire is known. According to the surgical instrument, a pulley with 5mm radius, 15mm arc length of cable curved part is chosen. The cable with 0.6mm radius produced by SAVA Company is taken as an example. Its elastic modulus is 460N/mm^2. The result of different wires is shown in Figure 5. From the result, it is easy to know that the centre wire of CWS is the most likely broken wire.

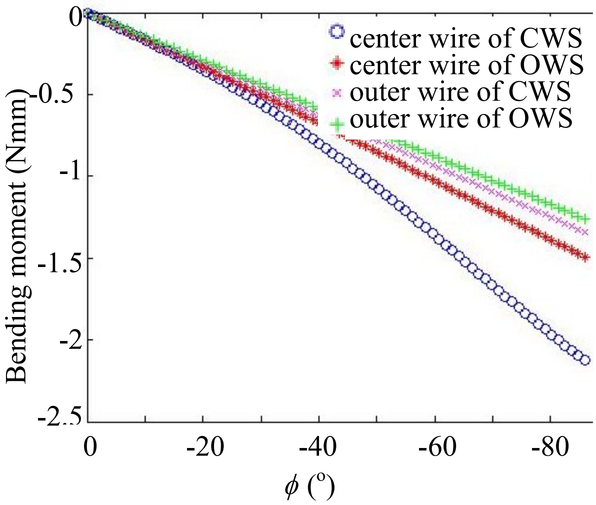


Figure 5. Bending moment of different wires

3. Conclusion

The structure of cable is very complicated, which is formed by twisting wires. A plurality of wires twist into strands, and a plurality of strands twist into cable. For better analysis of cable, according to the twisting method, the structural equation of wire is obtained, including the unbent centre wire and the outer wire, and bent centre wire.

In surgical operation, safety is of primary importance. Therefore, the choice of the appropriate cable, to ensure the safety of wire transmission system is the primary problem. According to the characteristics of cable structure, this paper put forward the bending moment formula, which provides a theoretical support for the design of cable-driven system in surgical robot.

Acknowledgments

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