Design of Pneumatic Cable Maintenance Robot

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Abstract. Aimed to coating, cleaning and inspection of cable for cable-stayed bridges, a pneumatic worming cable maintenance robot is presented. This paper puts forward a design method of modularizing which can simplify the design course greatly. It is composed of cable climbing mechanism, working mechanism and controlling system. The key problems of new climbing mechanisms and painting mechanism applying to cables are developed. Movement of the robot and clamping of climbing mechanism are driving by electrical and pneumatic system to identify malfunctions and make sure automation. The shortcomings such as low efficiency, high cost, less safety of artificial methods that are normally adopted in cable-stayed bridges are overcome. Furthermore, some experiments in robot lab proved this robot had perfect performances under different conditions; it was of foundation for the cable maintenance robot applying to automatic painting of cables.

Keywords: cable maintenance, robot, climbing mechanism, painting mechanism, pneumatic system.

1 Introduction

With the rapid development of our traffic field, cable–stayed bridges are more and more popular in modern middle-span bridge construction [1]. However, as main supporting parts [2], cables supported constant and fatigue loads, Since cables are exposed to the air for a long time with wind, rain and sunshine, Polyethylene sleeve on cable surface produce phenomena of hardening and crack with different extent which cause serious problems. In order to ensure security of cable's structure, it is essential to perform a series of maintenance of cables such as cleaning, painting and detecting. It is disastrous to us for safe accidents and economical loss owing to cable invalidation in the bridge fields. Traditional artificial methods [3] have some shortcomings such as low efficiency, high cost, less safety, so an intelligentized device is generated [4]. From the worldwide, the study about pneumatic cable maintenance robot (PCMR)

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is in the initial stages, but there are some special robots similar to PCMR. Hidemi Hosokai and Toshjo Fukuda [5,6] designed a series of out-pipeline diagnostic robots, Mark I-IV consisted of three modules with joint between them. These robots had capabilities of straight and spiral movement along the outside of pipeline, and of freely passing over obstacles, such as flanges, T-joints, and of moving along vertically located pipelines. Yoichiro Macda [7] developed a mobile inspection robot for power transmission lines. However, this robot couldn't climb power transmission lines with great gradient. Tian-sheng Lv professor and his fellows in shanghai Jiao tong university take the lead in study the PCMR, and obtain some practical products [8, 9]. They have developed two types of CMR. The robot is driven along the cable by an electric running mechanism held by wheels, or a pneumatic worming mechanism clamped by air cylinders, with an air spray coating mechanism or a magnetic detector. At present, the driving type of CMR is classified by an electric running mechanism held by wheels, pneumatic worming driving and hydraulic driving and so on. Among these, pneumatic worming driving has many characteristics such as clean medium, enough clamping force, strong stabilities. So adopting pneumatic driving technology, this paper puts forward a design method of modularizing. The robot is composed of cable climbing mechanism, working mechanism [10] and controlling system [11].

2 Mechanical Structure of the PCMR

A pneumatic worming cable maintenance robot is devised to coating, cleaning and inspection of cable for cable-stayed bridges. The whole system consisted of ground carried car, connected cable and robot mechanism, shown in Fig.1.

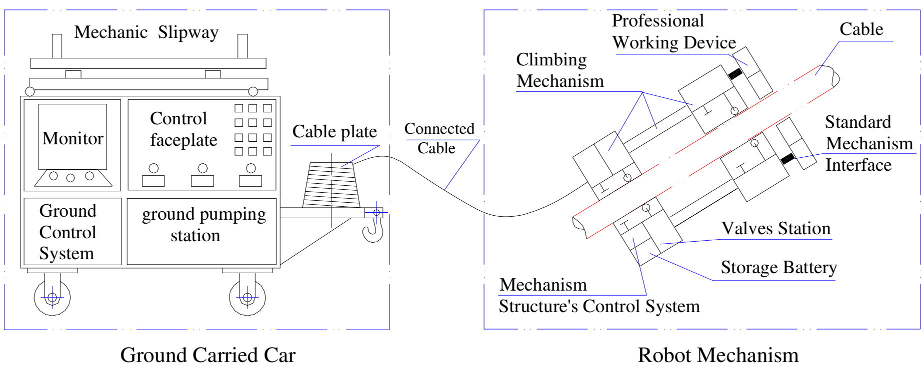


Fig. 1. Diagram of cable robot system

The mechanism structure is the most important part, we put forward the suited method of modularize design. According to this designing idea, the PCMR is designed separately in two modules, including the climbing module and the maintenance modules such as cleaning, painting, and detecting modules which can be integrated by standard mechanical interface, shown in Fig.1. When using the same climbing mechanism we can change different maintenance modules with different functions of cleaning, painting and detecting cables. Based on all kind of mechanisms adapting for climbing out-pipeline, trunk, power transmission lines and so on, we designed a new climbing mechanism (shown in Fig.2) which can climb not only arbitrary gradient cables with diameter range of F80-F200, but also a certain extent flexible cables.

The control system in which electrical system controls electromagnetic valve of pneumatic system through PLC and MCS-51 singlechip's logically control to make robot climbed up and down and painted cables. In addition, the sample has a brake apparatus which can safeguard PCMR to brake when PCMR's acceleration is at some value. When power failure and other unexpected condition happen in high altitude, the clamping mechanism can clamp cable by clamping cylinder supplied gas through gas storage holder. The brake apparatus takes effect. So the robot can return back safely with loads from high-altitude cable.

3 Design of Climbing Mechanism

3.1 Structural Model of Climbing Mechanism

There are some kinds of climbing mechanisms at home and abroad, for example, continuity climbing , pneumatic clamping and worming climbing [12], helix climbing [13], Adsorption climbing and so on. When the section of cable is rotundity or almost rotundity, Adsorption climbing mechanism is difficult to come true in practice. Owing to the clamping force of pneumatic clamping climbing mechanism is bigger, this mechanism is fit for various cables. So Climbing Mechanism is developed.

Due to large gradient, long distance, its weight and natural condition of stay cables, Sectional shapes of most cables in cable-stayed bridges are spiral hexed-prisms, so the center of mechanism structure and cable must be set in rotation along axis of cable because of deflection produced by gravity and forced condition. Otherwise it will influence the working quality of PCMR on the stay cable. Therefore, the climbing mechanism is divided into two components between which have a lead axis and moving cylinder, and can climb on a large range diameter stay cable by reliable moving, clamping and leading cylinders, controlled by a PLC. All of these consist of mechanism structure, Shown in Fig.2. Each component respectively comprises supporting board, parallel and automatic center clamping mechanism, various rigidity and elasticity leading mechanism.

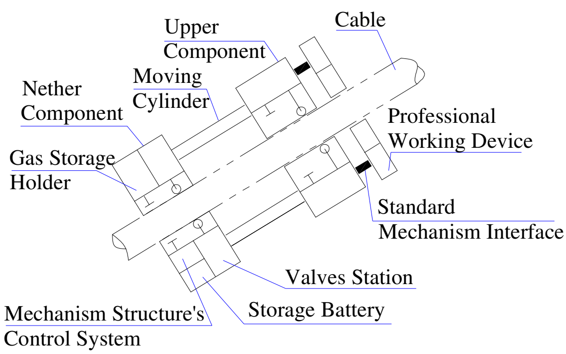


Fig. 2. Sketch diagram of cable robot's climbing mechanism

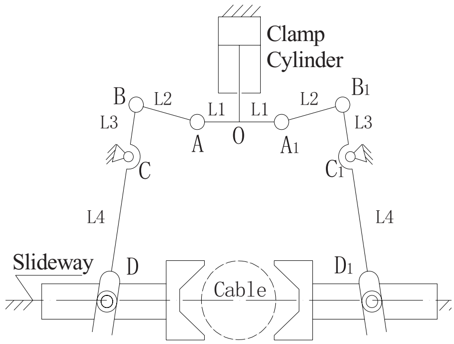
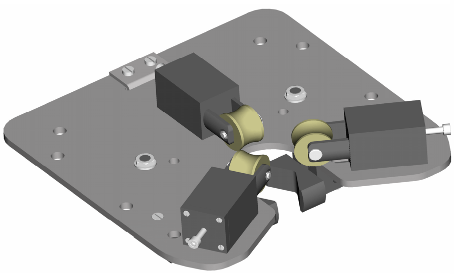


Fig. 3. Diagram of Parallel and Automatic Center Clamping Mechanism



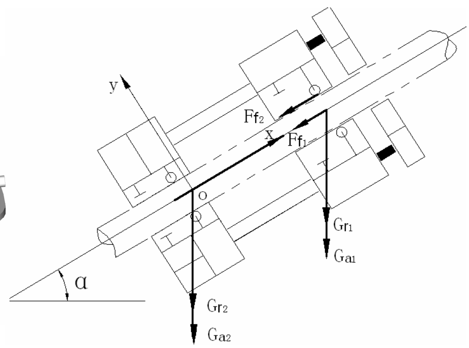


Fig. 4. The leading mechanism of PCMR **Fig. 5.** Force analysis of PCMR when it's working

The clamping mechanism is comprised of a cylinder, a cylinder holder, a link, a slideway and so on. It is easy to control and has bigger clamping force for different cable diameters (Shown in Fig.3).

To keep robot mechanism structure's center on the same line with the cable center axis when robot is moving along the stay cable, it is necessary to design the various rigidity and elasticity leading mechanism which consists of three springs and leading cylinders and three leading wheels (Shown in Fig.4).

3.2 Kinematics Equation of Climbing Mechanism

When PCMR climbs on the cable, Clamp force produced by clamp cylinder must be bigger than the slip force which arises from robot gravitation. Furthermore, when the cable is vertical with the ground, the slip force is the biggest. So it is very important to certain clamp force for making sure robot's safe when it's working.

Based on force analysis in Fig.5, we can build a kinematics equation of PCMR:

$$m\mu_1\eta\frac{\pi}{4}(D_1^2 - d_1^2)P_1 \geq (G_{r1} + G_{a1} + G_{r2} + G_{a2})sin\alpha + F_{f1} + F_{f2} \tag{1}$$

where m is multiple coefficient of added-force mechanism; u_1 is the biggest friction coefficient between clamper and cable; P_1 is the work pressure of clamp cylinder(Mpa); η is cylinder efficiency; G_{r1} is the upper component's weight(N); G_{a1} is the robot's load(N); G_{r2} is the nether component's weight(N); G_{a2} is the force between electrical cable and PCMR(N); D_1 is the piston diameter of clamp cylinder(mm); d_1 is the piston pole diameter of clamp cylinder(mm); F_{f1} is the wind load(N); F_{f2} is the leading wheel resistance(N); α is the angle between cable and horizontal plane (Rad.).

Equ.1 expresses the relations among climbing ability, robot gravitation, load, resistance force, climbing angle and so on.

4 Design of Painting Mechanism

One of jobs for the robot is to coat antiseptic paint on the cable. We must know that painting cable requires not only painting fully the cambered surface of cables, but also uniform coat. So realizing circular painting for the cable in high-altitude is relatively difficult.

The mechanism (shown in Fig.6) adopts hybrid four-bar linkage mechanism to rock painting guns by rocker BO_1 back and forth. The upper groove link to upper component of climbing mechanism, nether groove on which four spray guns symmetrically fix is fixed on the Painting mechanism. That is Painting motor make crank turn, then via linkage make rock back and forth at an angle of 30 to nether groove. The nether and upper grooves are linked by vertical bearings and horizontal bearings rolling smoothly for reducing their friction force. If the rotating angle is too large, it's very easy to destroy the groove. To avoid of this condition happening, it is necessary to design a restrained mechanism, its lubrication system and adjusted force mechanism to ensure that the spray guns fix on the nether groove symmetrically can guarantee realizing painting on the cambered surface of cables. Scattered angle which can be varied by changing the length of crank OA is relative to spray quality.

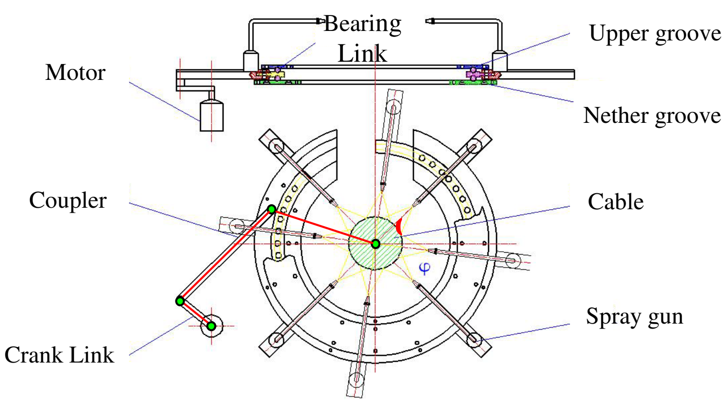


Fig. 6. Structure diagram of painting mechanism of PCMR

When cable maintenance robot is painting cable, painting must satisfy continuity condition. In other word, there should be no missed area between areas of guns some a painting and area of guns next painting. Now we can calculate the continuity condition of painting according to the requirement.

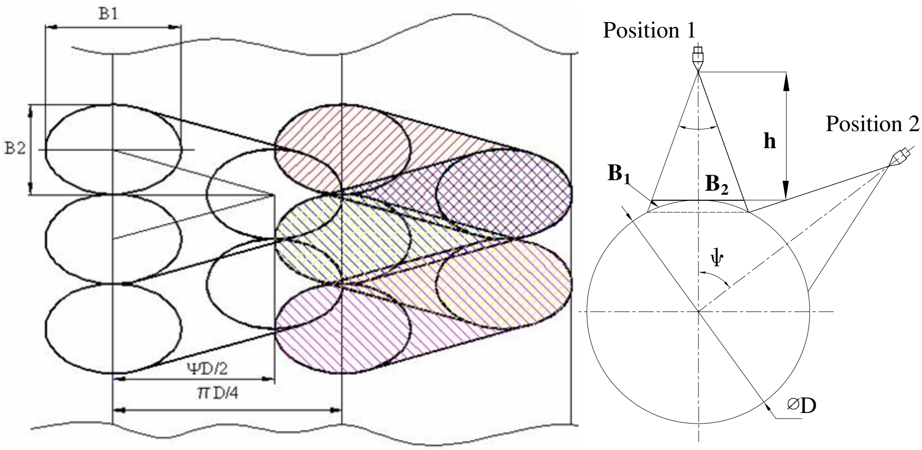


Fig. 7. Painting range expansion drawing of per spray gun

Given that the distance between nozzle of spray gun and surface of cable is h , scattered angle is φ ,shown in Fig.7.We can know from above mentioned that rock back and forth of paint gun and robot's climbing are driven by different motors, then the continuity condition of painting is as follows:

$$n \geq \frac{120Q}{\pi({D_H}^2 - d^2)h\tan\frac{\varphi}{2}} \tag{2}$$

$$\psi \geq \frac{\pi}{2} - \arcsin(\frac{D_L + 2h}{D_L}\sin\frac{\varphi}{2}) + \varphi \tag{3}$$

where n is rotational speed of painting motor, D_L is cable's diameter, Q is gaseous flow rate of each moving cylinder, D_H is piston diameter of moving cylinder, d is piston pole diameter.

Therefore, when we choose painting motor, its rotational speed must be satisfied with inequation (3), which can guarantee continuity of painting. φ must be satisfied with inequation (2). At the same time, for the sake of influence of high-altitude wind, we design wind-proof cover outside the painting mechanism.

5 Design of Pneumatic System

Pneumatic system (shown in Fig.8) is one of parts control system; another part is electric system which adopted remote supervisory control type. Electric system

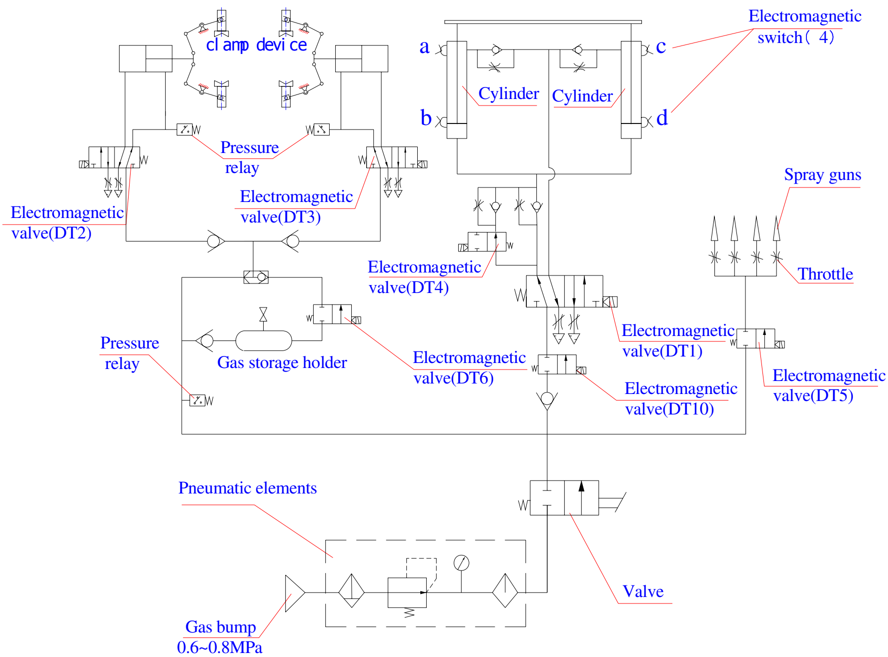


Fig. 8. Principle diagram of pneumatic system for PCMR

consists of ground supervisory system and mechanical body's control system, PLC can logically control electromagnetic valve's on or off to make robot move, clamp and work along the cable.

Pneumatic System (shown in Fig.8) of PCMR consisted of gas pump, pneumatic elements, control valves, cylinders and accumulator and so on. Some pneumatic loops are made up of above basic pneumatic elements, such as decompression loop, throttle timing loop, security loop, synchronization loop and so on.

The main job for Pneumatic System is to clamp, move, paint and be safe the robot. The gas bump supplies gas for three circuits to complete Pneumatic System's work, such as clamping, climbing up the cable, climbing down the cable, and painting. Through PLC can logically control electromagnetic valve's on or off to make robot climb up, clamp and climb down along the cable.

6 Application

PCMR can be applied to painting, cleaning, and detecting cables of cable-stay bridges. Painting experiments were done in the robot lab, and test result is much better than manual work with their higher quality, higher efficiency, lower cost and more safety. Experiment in the lab is shown in Fig.9.

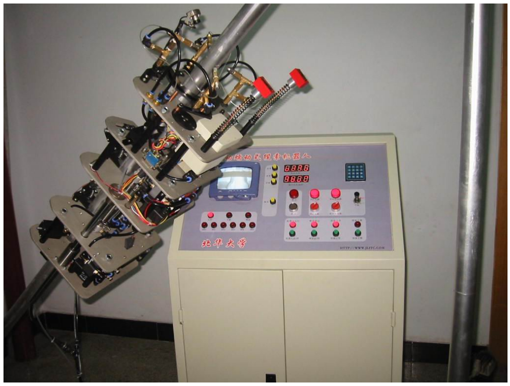


Fig. 9. Photo of PCMR painting cable

7 Conclusions

The cable maintenance robot developed in this paper is electromechanical and pneumatic integrated system in which the robot is driven along the cable by a pneumatic worming mechanism clamped by air cylinders, with PLC and MCS-51 singlechip to control climbing mechanism and painting mechanism. It has advantages of fitting to many cables, a simple structure, feasible, low cost and so on.

Ⅰ. Climbing mechanism can climb along different gradients and diameters with the velocity of 5 meter/second and load over 1.2 multiple of mechanism structure.

Ⅱ. Painting mechanism with a hybrid four-bar linkage mechanism is credible in construction, stabilized, perfect atomization. In the meanwhile, the continuous spray coating equations are deserved.

Ⅲ. Pneumatic system is introduced in this paper with the characteristics of strong ability of adapting and credible. When PCMR is troubled in high altitude, on the one hand, the clamping mechanism can clamp cable by clamping cylinder supplied gas through gas storage holder. on the other hand, a brake apparatus takes effect when PCMR's acceleration is at some value. It is able to return back safely with loads.

Acknowledgments

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