Structure Design of Cable-Stayed Bridge Intelligent Detection Robot

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Abstract. Cables are the main load-bearing components of cable-stayed Bridges. The durability and reliability of cables are directly related to the safe operation and service life of the whole bridge. Aiming at the problem of cable detection and maintenance, a new type of cable detection robot is designed in this paper. To further enhance the stability of the robot, the structure adopts symmetrical arrangement to make the center of mass of the robot system coincide with the cable axis. According to the working condition of the robot, a flexible body spring that meets the parameter requirements is designed, which not only meets the required preload, but also meets the starting torque of the motor. The robot is simple in structure, standardized in parts, easy to assemble and disassemble, and has good obstacle clearance ability and detection efficiency.

1. Introduction
Cable-stayed bridge has the characteristics of large span capacity, strong bearing capacity, and good economic applicability. It is widely used in bridge engineering such as highway, railway and urban road construction [1]. At present, the bridge cable inspection is mainly manual inspection, which has a high-risk coefficient, high labor intensity, and low efficiency. This detection method is difficult to meet the needs of modern bridge detection and maintenance.

A lot of model research has been done on the ontology design of tether detection robots at home and abroad. A wheeled crawling robot [2] has been developed by sungkyunkwan university in South Korea, which controls the compression amount of elastic yellow through ball screw and pantograph like structure to produce adhesive force [3]. This robot has certain adaptability to the diameter of the cable [4-6]. But the structure is more complex, the weight is larger. The research group of north China university developed a pneumatic peristaltic funicular maintenance robot [7]. In the working process of the robot, the air source needs to be transported through the pressure pipe. For the relatively high cable-stayed bridge, the air is transported over a long distance. There is a pressure loss along the way, which limits the climbing speed of the robot. The weight of the pipeline makes it easy for the robot to be eccentric, limiting the movement of the cable-climbing robot. Therefore, it is of great significance to solve practical engineering problems to study the detection robot with light weight, simple loading and unloading, and adaptive cable diameter.
2. Robot overall program design

2.1. Robot performance index

Cable detection robot of cable-stayed bridge works in dangerous high-altitude environment, and it carries detection and repair equipment to maintain the cable, and there are many uncertain influencing factors [8]. The robot body mechanism is required to be lightweight, easy to disassemble and assemble, low cost, good safety and high reliability. The robot is required to be able to adapt to the change of the bar diameter, to be able to cross the small obstacles of the cable, and to have excellent obstacle crossing ability. According to the above design conditions, by comparison, the wheeled climbing mechanism is more suitable for cable-climbing environment, and the obstacle crossing performance and stability can be further improved by optimizing the body mechanism. In order to realize the stable work of the robot, the performance parameters as shown in table 1 are formulated, and the robot is designed and manufactured with this as the design objective.

| Design goals                   | parameter scale          |
|-------------------------------|--------------------------|
| Crawling speed                | 0~10m/min                |
| Battery life                  | ≥2h                      |
| Robot weight                  | ≤25Kg                    |
| Suitable for cable tilt Angle | 15°~90°                  |
| Visual detection range        | 360° no dead Angle detection around the cable |
| Adapt cable diameter          | 150~200mm                |
| Precision                     | Millimeter accuracy, accurate location of defects |

2.2. Structural design

Based on the above performance indicators, the advantages and disadvantages of various structures are analyzed [9-11], and a structural design scheme of a new tether detection robot is proposed, as shown in FIG. 1.

Figure 1. Overall structure scheme diagram of the robot.

Among them, 1- pre-tightening nut; 2- spring guide rod; 3- method blue linear bearing; 4- hollow 6061 aluminum plate; 5- motor mounting aluminum plate; 6- spring support plate; 7- driven axle; 8- driving axle; 9- horizontal shaft support base; 10- wing plate; 11- 60 stepper motor; 12- 150mm cable; 13- bearing with bearing; 14- shaft sleeve; 15- polyurethane caster.

The outer frame of the robot is a hexagonal frame structure, which is composed of hollow 6061 aluminum plates. The interior is provided with pre-tightening mechanism and gear transmission mechanism. The preload mechanism adapts to the change in cable diameter and provides stable
preload. The pre-tightening mechanism and the gear train transmission mechanism are connected to each other. The three sets of gear trains are evenly arranged on the circumference and pre-tightened on the cable, as shown in FIG. 2.

The preload mechanism is assembled by spring guide bar, spring, preload nut, horizontal shaft support and spring support plate. The spring is preloaded between the aluminum plate and the spring support plate, which is guided by the guide bar, and the spring guide bar is fixed on the spring support plate by the horizontal shaft support seat. The preload of the spring is adjusted by using the nut, and the guide bar moves relative to the method blue linear bearing mounted on the outer frame surface, so as to adjust the preload of the spring. The gear train transmission mechanism is composed of aluminum plate, wing plate, belt wheel, 60 motor, belt bearing, active wheel shaft and polyurethane caster. The preload force generated by the spring compacts the gear train transmission mechanism above the cable surface, and the preload mechanism can adapt to the variation of cable diameter (150~200mm) within a certain range. The three camera brackets of the tether detection robot are arranged in a ring of 120°. In the groove plate of the outer frame, the camera is fixed by an extended bracket, and the camera attitude is adjusted to achieve the best detection effect.

![Figure 2](image)

*Figure 2. (a) Schematic diagram of 3D robot model. (b) Robot physical prototype.*

Combined with the above analysis, the structure of the tether detection robot studied in this paper has the following characteristics:

(i) Use six frame board outside around the synthesis of hexagonal framework, using the hexagon framework is symmetric shape, can effectively reduce the frame system of mass center and the cable's axis misalignment eccentric, external surface of the plate and frame are easily to electronic components for installation, frame plate use the aluminum plate, able to work fast heat conduction, the parts which is caused by heat conduction with the external environment, quickly cooling effect.

(ii) Two springs are designed to be arranged on the guide bar in a symmetrical way, which can balance the excessive effect of single spring thrust on a single point and stress concentration, so as to reduce the increment value of positive pressure on the driving wheel and the cable surface and enhance the obstacle passing ability of the cable detection robot.

(iii) Three controllers are controlled by computer to achieve the effect of synchronous driving of three driving motors, which not only improves the power of the robot to climb the cable, but also forms a multi-drive transmission structure, which greatly improves the ability of the robot to climb the cable and enhances the stability of the robot. The vibration problem caused by the unsynchronized driving wheel of the prior art is avoided, and the phenomenon of robot sticking and slipping in the high air is reduced.

3. Design of key parts of robot

Spring is the main force component of the cable detection robot studied in this paper. If the spring force is too large, the motor drive torque increases, the overall structure and weight increases. If the spring force is too small, the robot may slip, spiral motion and so on. So the spring force has to be in
the right range. Spring design, according to the spring maximum load, maximum deformation and structural requirements to determine the spring wire diameter, spring diameter, the number of working cycles and length.

According to the spring working conditions, the use of high strength, good processing performance of small size 65Mn spring steel wire. According to the installed space, the spring middle diameter \(D=30\text{mm}\), the winding ratio \(C=6\). Estimate the spring wire diameter \(d\) from the winding ratio \(C\), try to calculate the diameter \(d'\), and Find the number of spring operating turns \(n\) based on the deformation conditions. According to the spring installation requirements, check the spring size \(H_0, D_2, D_1\), if not, modify the primary value of the relevant parameters to redesign. The spring design formula is:

\[
d = \frac{D}{C} \quad (1)
\]

\[
d' \geq 1.6 \sqrt{\frac{F_{\text{max}} KC}{[\tau]}} \quad (2)
\]

\[
H_0 = pn + (1.5 \sim 2)d \quad (3)
\]

\[
n = \frac{Gd}{8F_{\text{max}} C} \lambda_{\text{max}} \quad (4)
\]

In equations (1) ~ (4): \(F_{\text{max}}\) is the maximum load of the spring; \([\tau]\) is the allowable shear stress of the spring material; \(P\) is the spring pitch; \(G\) is the shear modulus of the spring material; \(\lambda_{\text{max}}\) is the maximum deformation of the spring.

Considering the spring stability problem, the spring of the cable detection robot is installed in the guide bar to overcome the spring instability problem, so the spring stability check calculation meets the requirements.

Figure 3. Diagram of spring state: (a) Instability. (b) Install guide bar.

As the spring is subject to variable load, the spring constantly changes in the cycle between the initial load \(F_1\) and the maximum load \(F_2\), so it is necessary to perform fatigue check on the spring:

\[
\tau_{\text{max}} = \frac{8KD}{\pi d^4} F_2 \quad (5)
\]
In equations (5) ~ (7): $\tau_{\text{max}}$, $\tau_{\text{min}}$ is the maximum and minimum cyclic shear stress respectively. $\tau_0$ is the pulsating cyclic shear fatigue limit of the spring material; $S_F$ is the design safety factor of spring fatigue strength.

The 65Mn spring with the size of 5x35x150mm was selected to meet the performance requirements of the cable robot structure by calculating the maximum load, minimum load, stability and reliability checking parameters of the spring.

4. Conclusion

In the work, we design a new cable-stayed bridge cable intelligent detection robot structure. Mainly reflected in the following aspects:

(i) A new design structure of cable detection robot is presented, which USES spring to generate preload and can adapt to the change of cable diameter in a certain range (150 ~ 200mm). Because the designed spring meets the requirements of pre-load, no dangerous phenomena such as sliding and falling will occur in the state of system power failure.

(ii) The robot adopts three sets of wheels to drive synchronously, forming a multi-drive transmission structure, which avoids the phenomenon of spiraling, flutter, jamming and skidding due to the different speed of the wheels.

(iii) The robot reduces the weight of the robot structure by hollowing out aluminum plates. The mechanical parts are arranged symmetrically to make the center of mass of the robot system coincide with the cable axis. The robot studied in this paper is simple in structure, standardized in parts, easy to assemble and disassemble, and has good obstacle clearance ability and detection efficiency.

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References

[1] Yangzi Lin. “Special detection and maintenance and reinforcement technology of bridge cable system”, Beijing: people's transportation press, 2016.

[2] H.M.Kim, K.H.Cho, F.Liu, H.R.Choi, “Development of Cable Climbing Robotic System for Inspection of Suspension Bridge”, in Proc.IEEE International Symposium on Automation and Robotics in Construction, pp.1422-1423, June/July. 2011.

[3] H.M.Kim, K.H.Cho, Y.H.Jin, F.Liu, J.C.Koo, H.R.Choi, “Development of Cable Climbing Robot for Maintenance of Suspension Bridges”, in Proc. IEEE International Conference on Automation Science and Engineering, pp.602-607, August. 2012.

[4] Cho K H, Jin Y H, Kim H M, et al. “Caterpillar-based cable climbing robot for inspection of suspension bridgehanger rope”, Automation Science and Engineering (CASE), 2013 IEEE International Conference on. IEEE, 2013: 1059-1062.

[5] Cho K H, Jin Y H, Kim H M, et al. “Development of multifunctional robotic crawler for cable inspection (MRC 2 IN)”, International Conference on Ubiquitous Robots & Ambient Intelligence. IEEE, 2013.

[6] Cho K H, Jin Y H, Kim H M, et al. “Development of novel multifunctional robotic crawler for inspection of hanger cables in suspension bridges”, Robotics and Automation (ICRA), 2014 IEEE International Conference on. IEEE, 2014: 2673-2678.

[7] Jianyong Li, yunlong wang, xiaoyong liu, et al. “Research on continuous traveling pneumatic
cable maintenance robot”, Chinese hydraulics & pneumatics, 2012 (12): 82-86.

[8]  Xuetao Qin. “Design and implementation of tether detection robot system” [D]. 2017.

[9]  Xiang Li. “Structural design and analysis of four-drive cable-climbing robot” [D]. 2016.

[10] Guozhi Wang, xiang li, bin deng, et al. “Analysis of obstacle surmounting ability and clamping mechanism of a new cable-climbing robot”, Mechanical design and manufacturing, 2016 (6): 30-33.

[11] Bin Deng, xiang li, wenhai wu, et al. “Structure and dynamics analysis of four-drive cable-climbing robot”. Science, technology and engineering, 2015 (32): 165-167.