A new design and optimization analysis of tunnel inspection equipment’s luffing mechanism

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Abstract. The inside space of railway tunnel is complex and enclosed. The maintenance for internal lines and tunnel itself always requires lots of time, and the inspectors need to climb ladders, which is unsafe and cannot reach blind side [1]. In this paper, a new luffing mechanism of tunnel inspection equipment is designed, and the joint of luffing mechanism is optimized. The interference is solved, and the joints load of luffing mechanism is decreased. Combined with finite element analysis, the stiffness and strength fully meet the demand. The analysis results could provide the theory guidance for the design and production of railway inspection equipment.

1. Introduction

The inside space of railway tunnel is complex and enclosed. The maintenance for internal lines and tunnel itself always requires lots of time, and the inspectors need to climb ladders, which is unsafe and cannot reach blind side [1]. In this paper, a new tunnel inspection equipment, which has three working platforms, is designed. The luffing mechanism is installed on one of these platforms, and the maintenance of full section inspection demand can be satisfied.

Luffing mechanism is widely used in construction machinery because of its compact structure, stable operation, and can effectively expand the scope of operation. And with it, the working range of construction machineries can be extended significantly. Sheng et al. [2] analyzed the simplified four-linked structure of garbage compressed station by commercial software, ADMAS, and the max driving power is set as the objective of dynamic optimization. The extreme working condition of garbage compressed station is obtained by the optimization results. Gao et al. [3-5] established the crank structure’s dynamic model of aerial working platform. All components of the crank structure are statically analyzed in full range. Liang et al. [6] simulated the multiple DOFs luffing mechanism of large drilling rig, and a new automatic luffing mechanism is designed. Considering the narrow space, the luffing mechanism needs to be compact and has long range and large coverage area. In this paper, a new luffing mechanism of tunnel inspection equipment is designed and the finite element analysis is carried out. Then the optimization is studied based on dynamic analysis. The results could provide theory guidance for production of tunnel inspection equipment.

2. Railway tunnel inspection

2.1 railway tunnel
Railway tunnels are usually distributed underground, underwater or in the mountain. The structural size and space of tunnel is determined strictly. The single and multiple lines tunnel are shown in Fig. 1 respectively. When conducting full section inspection, inspectors can reach the top of tunnel by using conventional equipment. But to reach the side part of tunnel, i.e. blind side, as is shown as Fig. 2b, workers need to climb ladders, which is inefficient and unsafe.

2.2 A new type of railway tunnel inspection equipment

In this paper, a new model of railway tunnel inspection equipment is designed to assist the maintenance. With the new equipment, workers could make the best of no traffic time and inspect multiple positions in the same time. The new model consists of three work platforms, two of them can stretch in and out, vertically and horizontally. The rest one has the function of rotation, stretch and luffing. The layout is shown as Fig. 3.

3. The design of luffing mechanism
The requirement of railway tunnel inspection’s luffing mechanism is reaching the blind side, which other conventional platform cannot reach. It means that, the ability of stretching to bottom directly in single line tunnel, luffing and extending horizontally to side part in multiple tunnel is needed simultaneously. The variable amplitude operating platform needs a compact overall structure and the range of motion must be large and the coverage of the area should be wide because of the narrow space in the tunnel. In the design procedure, kinematics analysis and optimization is applied, the design process is shown as Fig. 4.

First design (Fig. 4a), which consists of top, bottom connecting rod and luffing arm, cannot avoid luffing blind side. Through modeling and analyzing by commercial software, Hyperworks, the load of connecting rod changed dramatically and the maximum load is 5362kN, which has exceeded material’s yield strength. The bottom connecting rod bear tensile and pressure stress repeatedly during luffing, but compressed slender rod has unstable problem.

Second design (Fig. 4b), which is improved based on the first design, added a top connecting rod and deleted the bottom connecting rod, and the bended design is applied. But the large range and two luffing cylinders are needed. Two bound cylinders design has unstable problem.

Third design (Fig. 4c), which is improved based on the second design, added two connecting rods at the bottom of luffing cylinder. The range of cylinder is decreased but luffing angle is increased. As a result, the range of luffing is increased with no large stress occurred.

4. Dynamic optimization for luffing mechanism

When conducting prototype experiments, the interference occurred between the new model and railway carriage. The three joint points is considered as design variable and the height of railway carriage, h, is set as objective. The optimization is performed by commercial software, ADAMS. The result has no interference and shorter cylinder, which is facilitated to manufacture.

The further optimization for other eight joint points is performed based on previous results, which is
shown in Fig. 6. The optimization results are shown in Tab. 1. The max decrease rate of joint load is 81%.

| joints | Joint1 | Joint2 | Joint3 | Joint4 | Joint5 | Joint6 | Joint7 | Joint8 |
|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Before (kN) | 156.4 | 96.4 | 143.1 | 44.8 | 152.3 | 99.4 | 135.8 | 144.5 |
| After (kN) | 53.1 | 33.2 | 42.5 | 27.1 | 29.6 | 39.6 | 25.4 | 28.1 |

5. The finite element analysis of luffing mechanism

The finite element analysis of optimized luffing mechanism is performed to verify validity of the new model and ensure the structural stiffness and strength.

The new luffing mechanism of railway inspection equipment is modeled, and material properties and contacts are applied. The material of luffing mechanism is Q550. The boundary condition is set as reality: railway inspection equipment and railway carriage are fixed by multiple bolts, which is considered as full constraint. In working condition, the vertical load on the three platforms, simulating workers and carried equipment, is 250kN identically. The horizontal load pressure, simulating wind pressure, is 90N/m², which is referred to GB/T3811-2008 design rules for cranes. The safety factor is set to 1.5.

The two most dangerous conditions are luffing platform fully extended to lowest point and horizontally respectively by analysis results.
The stress of luffing mechanism

The displacements of fully extended horizontally and extended to lowest point are shown in Fig. 7 respectively. The max displacements are 31.8mm and 28.7mm respectively, which are much smaller than the railway carriage displacement.

The stress of 80% structure is less than 30MPa, which is satisfied to steel yield strength. In extreme condition, the max stress, which is 157MPa and 149.6MPa, is occurred around joint 3 and joint 1 respectively. Since the Q550 steel is applied, the safety factor is 5.2, which is satisfied to design standards.

6. Conclusions.

In this paper, a new railway tunnel inspection equipment with new luffing mechanism is introduced, which has the ability of rotation, expansion and luffing. The efficient full section inspection for railway tunnel can be realized by the new model.

(1) Three prototypes of luffing mechanism are designed, the last one, improved from the previous designs, with lower cylinder displacement and bigger angle has larger luffing range.

(2) The optimization with kinematics of mechanism for each joint is applied by commercial software, ADAMS. The best positions of each joint are obtained, and the interference problem is solved. In the meanwhile, the stress of each joint is satisfied to design standards.

(3) The stiffness and strength of the new luffing mechanism is checked through finite element analysis and the result is satisfied to design standards.

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