THE RIGID-FEXIBLE COUPLING DYNAMIC SIMULATION OF MOBILE ROBOT AND OVERHANG FLEXIBE CABLE UNDER CRAWLING WORK STATE

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Abstract: - The coupling dynamics characteristic between mobile robot for working along cable and its moving path-overhead flexible cable- is simulated in ADMAS. The robot is regarded as rigid multi-body system, and its dynamic model is developed with Lagrange method; the suspension flexible cable is regarded as flexible multi-body system, then the dynamics model is formed by modal synthesis method; finally the dynamics model of the robot and the flexible cable is obtained through contact coupling. The dynamics simulation is done on the robot along flexible cable under three different kinds of motion conditions, and the law governing impact of flexible cable on dynamic performance of the robot is explored.

Key-Words: - mobile robot; flexible cable; rigid-flexible coupling; dynamics; simulation; crawling work state

1 Introduction

Overhang cable structure is widely used in mechanical and electrical equipment such as cable crane in the construction of hydropower station, overhang transmission line and suspension bridge. It is inconvenient for routine overhauling and maintenance on overhang cable, so a type of mobile technical carrier is required to perform inspection and service. The robot working along cable refers to mobile robot that is crawling or creeping along cable to accomplish failure detection and online overhauling on cable.

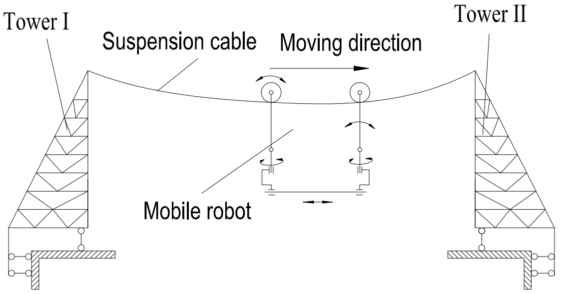


Fig.1: Flexible working path of mobile robot

As shown in Fig.1, a robot carrying detection instrument is moving along the overhang cable. As a typical flexible cable structure with large sag, span between suspension towers is as much as hundreds of meters, is of more rigid in comparison with overhang cable, and thus the mobile robot may be assumed as a multi-rigid-body system. Under environment excitation like wind loading, the flexible cable would produce various forms of vibration[12], which is transferred to the robot through coupling between the robot and the cable. Simultaneously, the mobile robot will transfer a reacting force to cable through the roller due to unstable center of gravity, and posture adjusting etc. As a result, the coupling between mobile robot and cable will influence the precision of robot motion control and signal detection. Therefore, impact of flexible moving path on robot's dynamic characteristic must be taken into account in case of dynamics and control study of the robot.

Nowadays, a large number of related research findings [1]~[6] have been available at home and abroad, most of which, however, are focusing on mechanism, motion regular and navigation. Heretofore, study on characteristic of coupling between the mobile robot and its flexible moving path has been seldom reported.

Based on ADMAS software, in combination with the modeling method of multi-flexible-body dynamics and multi-rigid-body dynamics, the coupling model of a new type of mobile robot developed by Wuhan Univesity and its moving path-flexible cable-is formed. The crawling work state of a mobile robot prototype along a 30-meters-span of cable is simulated under three different motion conditions.

2 . Coupling Dynamic Modeling for Mobile Robot and Flexible Cable

2.1 Modeling Method

Coupling dynamics modeling method for robot and its flexible work environment is shown as follows:

First, form the multi-rigid-body dynamics model for mobile robot with Lagrange equation.

Secondly, form the finite element model for one span of flexible cable first, and take several dominant models with sub-space method to describe spatial configuration of flexible cable. Solving scale is largely reduced since only modals with more contribution to dynamic response are studied with such method. The more modals are selected, the more precise the dynamics equation is. However, problems like equation numbers are over high and more time on calculation is consumed will be caused.

Then, form flexible multi-body dynamics model with Lagrange method [10]. Common flexible-body dynamics modeling methods are Newton-Euler method, Lagrange method, Guass method, Kane method, Huston method, and Hamilton method, etc. Herein Lagrange method, which is evolved on basis of virtual displacement principle and d'Alembert principle, is selected for dynamics modeling of the flexible cable.

Last, couple the rigid multi-body dynamics model of the robot and the flexible multi–body dynamics of the cable through contact coupling to obtain system dynamics model.

2.2 Multi-rigid-body dynamics modeling of mobile robot

In consideration of the suspension cable structure and the requirement on working, a type of mobile robot prototype is designed into double-arms symmetrical structure. Either of the two robot arms has one roller on their ends enabling the robot to roll along non-obstacle section of flexible cable; and there is a relative-motion degree of freedom between two arms available for their interactive sliding along guide rail. Each robot arm has two rotation degrees of freedom to realize rotation of robot arms on two axes. Through motion programming, full path moving along flexible cable can be realized, including rolling along straight non-obstacle cable and surmounting all kink of obstacles. Structural of such robot and setting of link coordinates is shown in Fig.2.

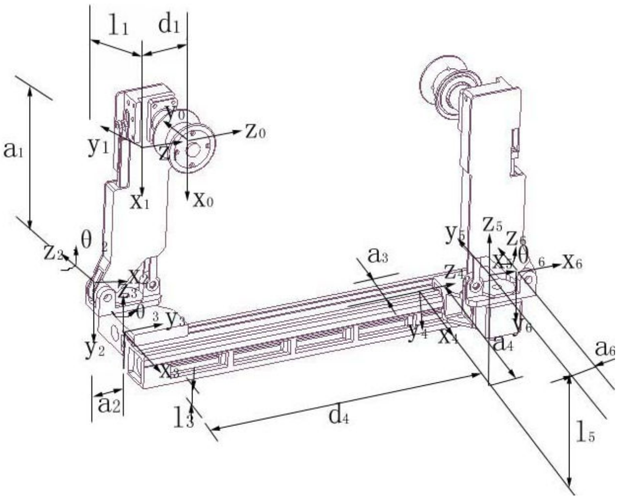


Fig. 2: Link Coordinates of Mobile robot

The multi-rigid-body dynamics model of the mobile robot prototype is formed, and the dynamics equations of six links, including items of inertia, coupling inertia, Coriolis acceleration, centripetal acceleration and gravity are derived[7]. As text length limited, they are not listed here.

2.3 Multi-flexible-body dynamics modeling of the overhang flexible cable

To form the finite element model of overhang cable, initial sag of cable must be considered. There is a considerable interval between two suspension points and rigidity of cable material has less impact on geometry of flexible cable, therefore it is assumed that the cable can only bear tensile force, instead of bearing bending moment, and all tensile forces will point to one and the same direction and will subject to uniform distribution along cable length. It can be deducted that overhang cable between suspension point A and suspension point B will take on "Catenary" state[8], as shown in Fig.3, then,

$$y=\frac{H}{w}ch\frac{w}{H}x-\frac{H}{w} \qquad (1)$$

wherein,

H: Horizontal tensile force of cable(N);

w : Self-gravity in unit length of overhead cable (N/m);

x: Horizontal distance from any point P to lowest point O of the span(m).

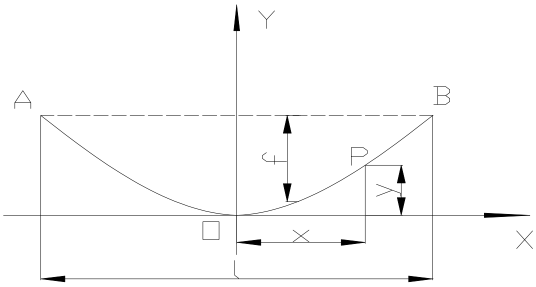


Fig. 3 Catenary Overhang Cable

The cable density is 4.7×10^3kg/m^3 and elastic modulo is 74,000Mpa. With catenary's formula of flexible cable adopted, coordinates of key points on the centerline of a span of overhang cable could be attained. Create the finite element model for a 30-meters-span of overhang cable in ANSYS, and then solve low order modal parameters with subspace method. Natural frequencies of first six orders are shown in Table 1. In vibration shape of first 5 orders every vibration shape is in vertical plane except that third order is in horizontal plane.

Table 1: Natural frequencies of the first 5 orders model of one span of cable

Ordering	Frequency (Hz)
1	0.5
2	0.7
3	0.7
4	1.2
5	2.1

Spatial configuration of flexible cable is described with first 5 dominant orders modal vectors and corresponding modal coordinates. Then physical coordinates vector {x (t)} of system can be indicated by superposition of dominant system modal, quota of which is represented by modal coordinates, i.e.:

$$\{x\,(t)\}=[X]\{q\,(t)\} \qquad (2)$$

Coordinates {q (t)} defined by Formula (2) is referred to as "modal coordinates" of a system, and [X] is referred to as "select modal matrix" of a system.

2.4 Contact modeling of the cable and the robot crawling roller

According to the finite element analysis method [9], it is necessary to realize contact modeling between flexible cable and roller through discretizing the actual continuous contact modeling. We simplified the flexible cable and roller model reasonably, and equalized their contact force to two dimensional contact between central node group of flexible cord FEA model and rigid roller edge.

The consecutive contact between robot roller and flexible cable is subject to discretization, which is equivalently simplified as follows during modeling:

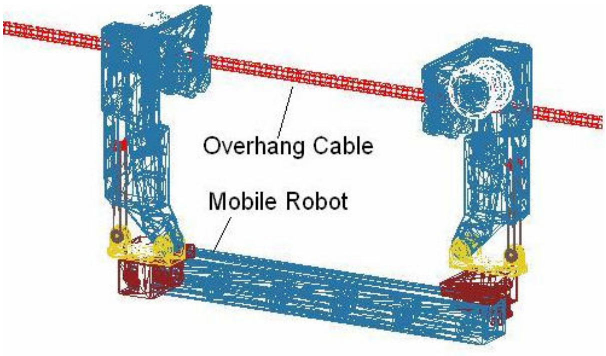
1) Make the contact between robot roller and flexible cable equivalent to the bidimensional contact between rigid roller edge and central node group of FEM of flexible cable through interactive use of "Macro" and "ADAMS/View" Commands provided by ADAMS and rational simplification of flexible cable and roller models. Make the contact between roller and flexible cable equivalent to the contact

between roller edge and centreline of flexible cable;

2) Contact flexible cable via a pure circle adhering to mass centre of roller, radius of which is equal to the radius of roller;

3) As ADAMS/View provides no support to contact on FEM, thus the contact between flexible cable and roller shall be simplified as the contact between every node on centreline of flexible cable and roller. A dumb, an object, both quality and inertia of which are zero, adheres to every node mentioned above, for rigid coupling with finite element model of flexible cable.

In this way, the contact model between the rigid roller and the flexible cable is formed, which is shown in Fig.4.



.Fig.4：Coupling model of the robot and the overhang flexible cable

3. Coupling dynamics Simulation

Motion function of the rotating joint between roller and its axis is defined by means of STEP [11] function. The STEP functions of the three simulation conditions is shown as follows:

Condition 1:

3×360d×(step (time,0,0,1,1)- step (time,4,0,5,1))

Condition 2:

3×360d×(step (time,0,0,0.5,1)-step (time,4.5,0,5,1))

Condition 3:

3×360d×(step (time,0,0,0.3,1)-step (time,4.7,0,5,1))

In motion STEP function of simulation condition 1(unit: deg/sec), acceleration time was 0~1 second, deceleration time was 4~5 seconds. Total simulation time is 5 seconds and the solving step length is 0.01 second.

Given the above-mentioned joint movement functions, perform dynamics simulation and solve motor driving moment and dynamics response parameter. The simulation results are shown as Fig.5, where there are response curves in three kinds of line color to represent simulation results in such three job condition as Condition 1 (in red), Condition 2 (in blue) and Condition 3 (in brown) respectively. Within simulation time of 5s, the robot runs about 2800mm along the cable. As shown in Fig. 3, x direction is the moving direction, pointing from suspension point A to B; y direction is plumb.

4. Analysis and Conclusion

On basis of simulation under three motion conditions as well as comparative analysis of the results, conclusions as follows can be made:

1) In the flexible work environment, the mobile robot could fulfill preset motion target under crawling work state.

2) In the flexible work environment, the motion displacement and velocity of the robot will fluctuate at certain frequencies.

3) Under coupling action with mobile robot, the overhang flexible cable will produce co-frequencies vibration.

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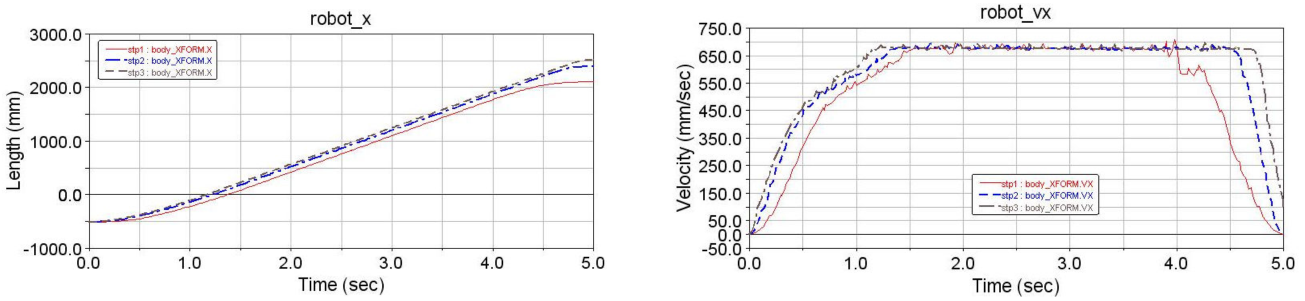
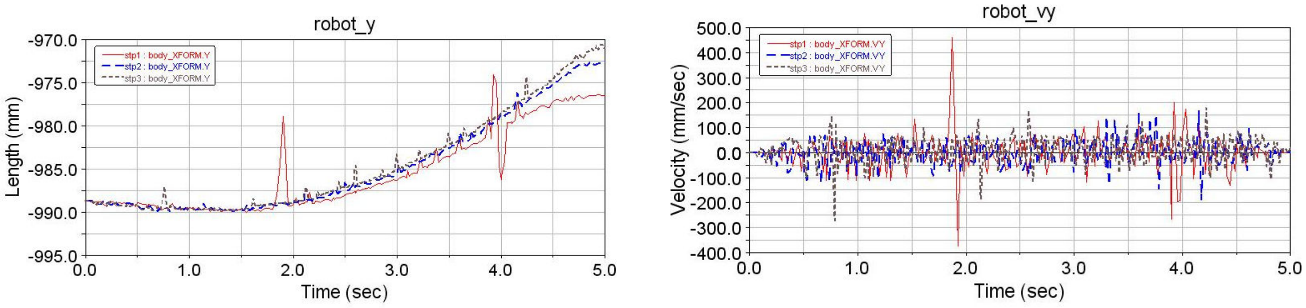


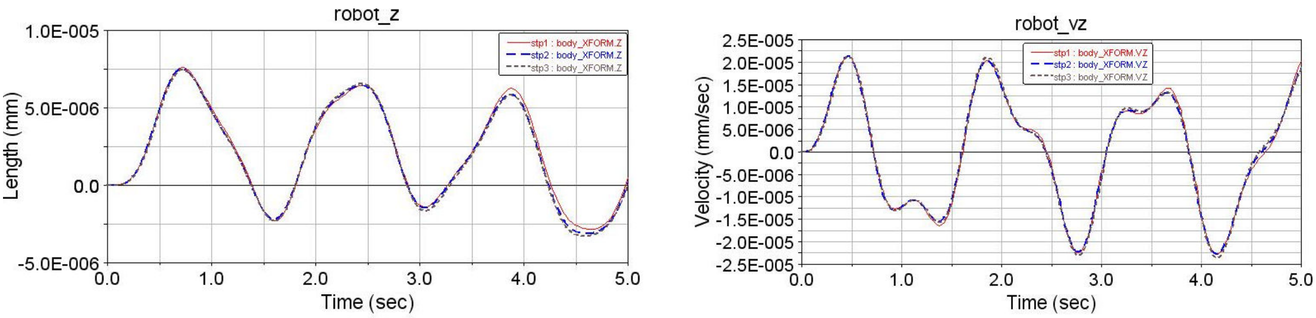
x-direction displacement-time curve of the robot centroid

x-direction velocity-time curve of the robot centroid



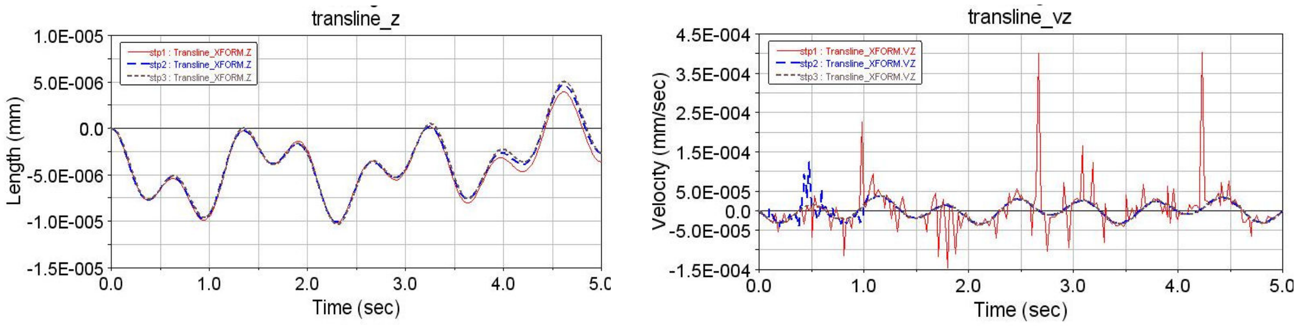
y-direction displacement-time curve of the robot centroid

y-direction velocity-time curve of the robot centroid



z-direction displacement-time curve of the robot centroid

z-direction velocity-time curve of the robot centroid



z-direction displacement-time curve of the cable span center

z-direction velocity -time curve of the cable span center

Fig. 5 Simulation results of robot's rolling along the 30-meters-span of cable

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