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An Inspection Robot for High Voltage Power Transmission Line and Its Dynamics Study

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1. Introduction

Inspection robot for power transmission line is a new type of technical carrier for detection and inspection of mechanical/ electrical failures in high-voltage (110kV, 220kV) and extra-high voltage (500kV or above) power transmission system. The robot equipped with sensors, detection instruments and data communication apparatus, is capable of inspecting transmission system without suspending power supply. As shown in Fig. 1, an inspection robot developed by Wuhan University can autonomous move along the 220kV phase line and overcome all kinds of obstacles to carry out the inspection tasks (Wu et al., 2006: Xiao et al., 2005). Comparing with such current inspection approaches as inspectors and unmanned aerial vehicles (UAV), the robot is more efficiency and safer to assure higher detection quality, especially in severe conditions (mountain areas, river-crossing, grasslands, etc). Thus it has broad engineering application prospects.

Fig. 1. An inspection robot and its flexible obstructive working path – transmission line

Since the end of 1980s, a number of relative achievements have been carried out about inspection robot system (Montambault, 2003: Peungsungwal, 2001: Sawada, 1991: Tang & Fang, 2004: Wu et al., 2006), mechanism schematic (Wu et al., 2006: Zhou et al., 2004: Zhou et al., 2004), control system (Tang, 2004: Wang et al., 2006: Zhu et al., 2006), obstacles recognition and navigation (Fu, 2005: Li, 2007: Zhang et al., 2007).

The multi-rigid-body dynamics modeling, simulation and experimental tests were performed with an phase-line inspection robot prototype (Xiao et al., 2005). Considering the flexible obstructive working environment, the performances of the inspection robot,

especially the precision of obstacles' location and failure signals' detection, are affected by the coupling vibration of the robot and overhead transmission line. Thus, the rigid-flexible coupling dynamics modeling and simulations were studied in typical working conditions (Xiao et al., 2006, 2007 & 2008).

This chapter will introduce three generations prototypes of the inspection robot for 220kV phase line developed by Wuhan University and analyze its dynamic performances, including multi-rigid-body dynamics of the robot, coupling dynamics of the robot and flexible line.

2. Inspection robot prototypes

Since 1997, Wu et al. in Wuhan University have developed three generations of inspection robot prototypes, namely, remotely operated vehicle - ROV, auto-crawling robot - ACR, and auto-rolling/crawling robot - ARCR.

(a) ROV: The first generation prototype ROV is composed of three extension arms, three wheels and one translation rail (Wu et al., 1999). There is one rotation degree of freedom (DOF) between each extension arm and wheel, and one rotation DOF between fore/rear extension arm and robot body as well as one translation DOF between middle arm and robot body. By remotely operation, the ROV is able to travel along no-obstacle phase line by means of synchronization drive of three wheels, and overcome insulator chains, dampers and suspension clamps in manner of three arms' stepping in turn. However, it is incapable of climbing overhead line's sag and spanning tensioning tower.

(b) ACR: Since the performance limitations of ROV, an auto-crawling robot (ACR), was developed in 2000 (Wu, et al, 2006). As shown in Fig. 2, the ACR prototype is composed of two umbrella-shaped suspension wheels, two clamping jaw mechanisms, two stroke amplification mechanisms, and hydraulic servo/drive system. The three wheels, of which the angle between centerlines is 120° , can rotate around the tongue wheel together with bearing shaft. Hydraulic servo is adopted for motion controlling, including the clamps' adaptive constant force grasping, amplification mechanism's stretching motion, and coordinated crawling. A single-action cylinder is used to drive clamping jaw mechanism, while a double-action cylinder is for stroke amplification mechanism. However, the slow crawl speed and inability to span tension towers limit ACR's application.

Fig. 2. ACR prototype (by Wuhan University, 2000)

(c) ACRC: Based on the above two generations prototypes, an auto-rolling/crawling robot prototype (ARCR) was developed for autonomous online full-path inspection of 220kV

transmission phase line (Wu et al., 2006). ARCR is composed of three sub-sysytems including the inspection robot, remotely control ground station, and signal analysis/diagnosis/inspection management system software. The remotely control ground station is available for wireless data transceiver and picture capturing. The diagnosis/inspection management system software is for visual light and infrared image analysis, failure diagnosis, and inspection database management.

Fig. 3. ARCR prototype (by Wuhan University, 2005)

As shown in Fig. 3, the inspection robot is composed of mechanism, power on-line supply, sensor and obstacles detection, navigation, image scanning and detection, data wireless transceiver, and control system. The self-governing on robot's obstacle-overcoming is realized by means of autonomous navigation of multiple electromagnetic sensors and machine visual hybrid servo. Magnetic energy of transmission conductor is converted into electric energy for power supply. Therefore, the robot can fulfill six basic functions as follows: (1) full path moving along 220kV phase line with obstacles, (2) online power supply and monitoring, (3) navigation including obstacles' detecting, identifying and location, (4) visible light/infrared image scanning and detection, (5) wireless communication, (6) robot self-position detection, grasping force detection, and motions programming.

The performance tests of ARCR was conducted on 220kV field live lines of Wuhan Power Company. The main performances parameters are listed as following: weight: 30kg; dimensions (length $\times$ width $\times$ height): 650mm $\times$ 300mm $\times$ 600mm; valid wireless communication distance: 4km; average power consumption: 40W; available power supply: 40W (as load current of phase line = 220A); rolling speed: 5km/h; maximum climbing grade: 15°; crawling speed: 200m/h; crawl grade: 75° (Wu et al., 2006).

In consideration of the obstructive working environment and the requirement on inspection tasks, ARCR prototype mechanism is designed into double-arms symmetrical and suspending structure (Fig. 4). There are nice DOF in total. There is one driving wheel on the end of each arm enabling the robot to roll along non-obstacle section of line, and a pair of claws enabling the robot to grasp/loose the line when it encounters obstacles. Each arm has two rotation degrees of freedom (DOF) to realize rotation of robot arms on two vertical axes. Between the two arms, there is an interactive translation DOF available for their interactive sliding and transposition along the slide rail.

3. Working environment analysis and obstacles-overcoming programming

3.1 Kinematics tasks

The typical structure of the transmission phase line, as shown in Fig. 1, includes suspension and tensioning angle towers, phase lines and accessories (dampers, suspension or tensioning line clamp, insulator chains, etc.). Taking the phase line as its moving path, the ACRC has to carry out three kinematics tasks as follows:

- Moving along the no-obstacle segment of the phase line:
- Overcoming the obstacles along the phase line including the suspension/tensioning tower, dampers, clamps, and insulator chains, etc.:
- Varying moving paths between phase line and jumper line.

3.2 Flexible obstructive inspection moving path

The flexibility of the transmission line is very high, because the span between two adjacent towers is usually as much as hundreds of even more than one thousand meters, and the sag is scores of meters as while.

Moreover, the environmental wind loads may excite Aeolian vibration, or galloping in the the winter (Guo et al., 2002), of which the vibration and force can be transferred to the robot. On the other hand, when the robot overcomes obstacles or change moving paths, it has to adjust postures and thus produces unbalanced force. The coupling of the robot and overhead line will force the robot to vibrate and thus decreases its performance.

3.3 Obstacle-overcoming programming

In kinematic and dynamics modeling, we only consider 6 degrees of freedom, namely, rotation Joint 2 and 3 of Arm I, and rotation Joint 5 and 6 of Arm II, translation Joint 1 and the horizontal translation Joint 4 between two arms. The axis of Joint 2 and Joint 6 are horizontal, intersecting vertical with that of Joint 3 and Joint 5, respectively.

Fig. 4. Symmetrical mechanism structure of the ACRC

As the symmetrical structure, the motion of six DOF can be abstracted into four basic sub-actions, with which the robot is able to carry out all the three required kinematics tasks. Taking damper-overcoming as an example, the four sub-actions are programmed in Fig. 5 (a)-(d). Sub-action 2, 3, and 4 are basic for obstacles-overcoming.

(a) Sub-action 1: Two wheels roll along the transmission line with two arms parallelly suspending on the line.

(b) Sub-action 2: Arm I (or Arm II) end manipulator clamps the line, while the robot rotates with Joint 2 (or Joint 6) to lift/descend the robot body by 30° .

(c) Sub-action 3: Arm I (or Arm II) end manipulator clamps the line, while another arm rotates with the axis of Joint 5 (or Joint 3) by 180° .

(d) Sub-action 4: Arm I (or Arm II) end manipulator clamps line, while another arm translates along Joint 4 the slide rail to transpose two arms.

Fig. 5. Action programming for damper-overcoming

4. Multi-rigid-body dynamics of the robot

4.1 Dynamics modeling

The dynamics model of the robot is derived with Lagrange method. Taking E_k as the kinetic energy and E_p the potential energy of the system, the Lagrange function is defined as:

$$L = E_k - E_p \quad (1)$$

Then, the Lagrange equation of the system is :

$$\tau_i = \frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i}, \quad i = 1, 2, \dots, n \quad (2)$$

where, q_i is the generalized displacement at Joint i (m , or rad): $\dot{q}_i$ the generalized velocity at Joint i (m/s , or rad/s): τ_i the generalized force at Joint i (N , or $N \cdot m$).

With E_k and E_p represented by homogeneous coordinate, the general dynamics equation of multi-rigid body system is:

$$\tau_i = \sum_{j=1}^n D_{ij} \ddot{q}_j + I_{ai} \ddot{q}_i + \sum_{j=1}^n \sum_{k=1}^n D_{ijk} \dot{q}_j \dot{q}_k + D_i \quad (3)$$

where, n is the number of robot links; D_{ik} is the acceleration item; While $i = k$, D_{ii} is the effective inertia; while $i \neq k$, D_{ij} is the coupled inertia of Joint i and Joint j ; D_{ikm} is the inverse torque item imposing on joint i generated by the acceleration of joint k ; while $k = m$, D_{ikk} is the Centripetal Force coefficient caused by velocity of Joint j at Joint i ; while $k \neq m$, D_{ikm} is the Coriolis Force coefficient caused by velocity of Joint j and k at Joint i ; D_i is the gravity at Joint i .

$$D_{ik} = \sum_{j=\max i,k}^n Trace\left(\frac{\partial T_j}{\partial q_i} J_j \frac{\partial T_j^T}{\partial q_k}\right) + I_{ai} \delta_{ik} \text{ where } \delta_{ik} = \begin{cases} 1, i = k \\ 0, i \neq k \end{cases} \tag{4}$$

$$D_{ijk} = \sum_{p=\max i,j,k}^n Trace\left(\frac{\partial^2 T_p}{\partial q_j \partial q_k} J_p \frac{\partial T_p^T}{\partial q_i}\right) \tag{5}$$

$$D_i = \sum_{p=1}^n -m_i \vec{g}^T \frac{\partial T_p}{\partial q_i} \vec{r}_p \tag{6}$$

Fig. 6. The links coordinates setting of the ACRC Prototype

Link i	θ_i	α_{i-1}	a_{i-1}	d_i
1	0°	0°	0	d_1 (variable)
2	θ_2 (variable)	-90°	a_1	$d_2 (-l_1)$
3	θ_3 (variable)	90°	a_2	$d_3 (-l_2)$
4	180°	90°	a_3	d_4 (variable)
5	θ_5 (variable)	-90°	a_4	$d_5 (l_5)$
6	θ_6 (variable)	-90°	a_5	0

Table 1. Link Parameters of ACRC prototype

Considering the six joints defined in section 3, the coordinates of each link were formed in Fig. 6. Based on D-H method robot link parameters were obtained (Table 1). α_i, a_i, d_i stand for the link twist angle, link length, and the link offset, respectively.

The initial value of the six variables are listed as follows:

$$d_1 = 0; d_4 = l_4; \theta_2 = -90^\circ; \theta_3 = 90^\circ; \theta_5 = -90^\circ; \theta_6 = 0^\circ$$

Then we can obtain link transformation matrix T_i , and derive D_{ik} , D_{ikm} , D_i and pseud-inertia matrix J_i from Equ. (4)-(6), which were detailed in paper (Xiao, 2005). The effective inertia items are listed in Equ.(7) - (12),

$$D_{11} = \sum_{p=1}^6 \text{Trace} \left(\frac{\partial T_p}{\partial q_1} J_p \frac{\partial T_p^T}{\partial q_1} \right) = m_1 + m_2 + m_3 + m_4 + m_5 + m_6 \quad (7)$$

$$\begin{aligned} D_{22} = \sum_{p=2}^6 \text{Trace} \left(\frac{\partial T_p}{\partial \theta_2} J_p \frac{\partial T_p^T}{\partial \theta_2} \right) = & I_{2xx} + c_3^2 I_{3xx} + c_3^2 I_{4xx} + c_{35}^2 I_{5xx} + (c_6^2 c_{35}^2 + s_6^2) I_{6xx} + I_{2yy} \\ & + s_3^2 I_{3yy} + I_{4yy} + s_{35}^2 I_{5yy} + (s_6^2 c_{35}^2 + c_6^2) I_{6yy} + I_{3zz} + s_3^2 I_{4zz} + I_{5zz} + s_{35}^2 I_{6zz} + m_3 l^2 + m_4 l^2 \\ & + m_4 d_4^2 s_3^2 + m_5 d_4^2 s_3^2 + m_6 d_4^2 s_3^2 + 2m_4 d_4 Z_4 s_3^2 - 2m_6 \bar{y}_6 d_4 s_3 s_6 c_{35} \end{aligned} \quad (8)$$

$$\begin{aligned} D_{33} = \sum_{p=3}^6 \text{Trace} \left(\frac{\partial T_p}{\partial \theta_3} J_p \frac{\partial T_p^T}{\partial \theta_3} \right) = & I_{3xx} + I_{4xx} + I_{5xx} c_6^2 I_{6xx} + I_{3yy} + I_{5yy} + s_6^2 I_{6yy} + I_{4zz} + I_{6zz} \\ & + 2d_4 \left(m_4 \bar{Z}_4 + m_6 \bar{y}_6 S_5 S_6 \right) + d_4^2 (m_4 + m_5 + m_6) \end{aligned} \quad (9)$$

$$D_{44} = \sum_{p=4}^6 \text{Trace} \left(\frac{\partial T_p}{\partial d_4} J_p \frac{\partial T_p^T}{\partial d_4} \right) = m_4 + m_5 + m_6 \quad (10)$$

$$D_{55} = \sum_{p=5}^6 \text{Trace} \left(\frac{\partial T_p}{\partial \theta_5} J_p \frac{\partial T_p^T}{\partial \theta_5} \right) = I_{5xx} + I_{5yy} + c_6^2 I_{6xx} + s_6^2 I_{6yy} + I_{6zz} \quad (11)$$

$$D_{66} = \sum_{p=6}^6 \text{Trace} \left(\frac{\partial T_p}{\partial \theta_6} J_p \frac{\partial T_p^T}{\partial \theta_6} \right) = I_{6xx} + I_{6yy} \quad (12)$$

Wherein, c_i and s_i stand for cosine θ_i and sine θ_i respectively, c_{jk} and s_{jk} stand for $\cos(\theta_j + \theta_k)$ and $\sin(\theta_j + \theta_k)$, respectively.

4.2 Experimental tests and simulation

The experimental tests were performed with the III ACRC prototype in the simulative 220 kV 1: 1 overhead transmission line laboratory, Wuhan University. The experimental test system is detailed in Fig. 7. A 20-meters model with three spans and two towers was set up for full-path inspection tests. The test variables include motor drive current, angular displacement, velocity and acceleration of each joint. The angular motion sensors are embedded in the robot control system. The motor current test system was composed of 6 hall-effect current transducers, a 6-channel amplifier, INV360D data acquisition instrument, and a computer with data analysis software. The tests were performed under 4 sub-actions. The experimental results were listed in the paper (Xiao et al., 2005).

Fig. 7. Experimental test system scheme (Xiao et al., 2005)

Fig. 8. Simulation results (Xiao et al., 2005)

Based on the dynamic model in section 4.1, we performed forward dynamics simulations of 4 sub-actions in MATLAB. Fig. 8 shows the simulation results of Sub-action 2 and Sub-action 4. Comparing with the experimental results, the angular displacement and velocity in simulation are more stable, because we didn't consider the flexibility of the transmission line in dynamics modeling.

5. Rigid - flexible coupling dynamics of robot and transmission line

To explore the influences of the flexible path on the robot's dynamic performance, coupling modeling and simulation were conducted based on multi-flexible body dynamics theories. First, a finite element model (FEM) of one span of line was built to obtain its dominant modals for spatial configuration. Second, a multi-flexible-body dynamics model of the line was obtained with Lagrange method. Third, the multi-rigid-body model of the robot and the multi-flexible-body model of the line was coupled to conduct coupling dynamics simulation.

5.1 Multi-flexible modeling of the transmission line

For the rigidity of the large span of flexible line has little impact on its spatial configuration, we can assume that the line takes on "Catenary state" to calculate the coordinates of the key points (Li, 2001). Considering the general condition in 220 kV high-voltage transmission system, we chose the conductor's type LGJ-185/30: diameter = 18.88 mm, density = $3.473 \times 10^3 \text{ kg/m}^3$ elastic modulo = 7,600Mpa, tensile force of the line = 500 N.

A FEA model was built in ANSYS with the key points data. The modal frequencies and modal shape are obtained with subspace method. Then, the spatial configuration of overhead line can be described with selected modal vectors and corresponding modal coordinates, namely, the physical coordinate vectors of the line can be indicated by superposition of the selected dominant models (Xiao et al., 2007).

5.2 Coupling contact model under sub-action 1

In ADMAS, the contact model of flexible line and the rigid robot wheel was built via discretizing the actual continuous contact modeling. We simplified the model of the robot and line, and equalized their contact force to two dimensional contact between central node group of flexible line FEA model and rigid edge circle of the robot wheel. Dynamics model for inspection robot rolling on non-barrier segment of transmission line contained 300 contract force units in total as shown in Fig.9, where 1 is transmission line finite element model; 2, dumb object; 3, fixing pair; 4, contract force unit; 5, wheel of Arm "I"; 6, two-dimensional circle; 7, kinematical input; 8, robot body; 9, rotating pair; 10, co-planer restraint:

Fig. 9. Contact mode of one robot wheel and flexible transmission line

5.2 Simulation results

The joint's kinematical function was defined with *STEP* function in ADMAS. The form of *STEP* is:

$$STEP(t, t_0, x_0, t_1, x_1) \quad (13)$$

where, t is the independent variable ; t_0 , t_1 the initial and final value of t , respectively; x_0 , x_1 the initial and final function value of $STEP$, respectively.

According to the parameters of the robot prototype, the joint $STEP$ functions are set as follows.

Taking 5s for simulation time, and 1s, 0.5s, and 0.3s for accelerate/decelerate time, respectively, the simulation of sub-action 1 was conducted with three different $STEP$ functions.

$STEP$ 1: $3 \times 360 \times (STEP(t,0,0,1,1) - STEP(t,4,0,5,1))$ (deg)

$STEP$ 2: $3 \times 360 \times (STEP(t,0,0,0.5,1) - STEP(t,4.5,0,5,1))$ (deg)

$STEP$ 3: $3 \times 360 \times (STEP(t,0,0,0.3,1) - STEP(t,4.7,0,5,1))$ (deg)

The dynamics simulation results of the robot rolling along a 30-meters-span of overhead transmission line are shown in Fig. 10, where x-axis is horizontal direction between two adjacent towers, and y is the vertical direction. Fig. 10 shows that the vibration amplitude in XY plane is much higher than that in Z direction, which is corresponding with the overhead line’s wind-deduced vibration characteristics. The robot can carry out the preset kinematic target in flexible working environment. And, the coupling between the robot and line forces the robot vibrate, thus the fluctuation of the robot body with flexible moving path are larger than that with rigid path(Fig. 8).

Fig. 10. Simulation results of Sub-action 1

6. Conclusions and future plan

Through kinematic analysis, dynamics modelling, simulation and tests, we can conclude as follows:

1) The proposed double-arms inspection robot prototype can fulfill full-path kinematic target, including moving along the no-obstacle segment, overcoming the obstacles, and varying moving paths.

2) The flexible working path decreases the performance of the robot, but the robot is capable of carrying out the preset kinematic target along flexible path.

More detailed dynamics analysis can refer to other papers (Xiao et al., 2005, 2006, 2007 & 2008). The model proposed in this chapter are far from fully demonstrating the actuality and those nonlinear factors in flexible obstructive inspection work environment. Further research is conducting to improve the robot's dynamic performance, such as: considering the flexibility of the joints and robot arm on dynamic model improvement, simulation for obstacle-overcoming in flexible working environment, and the effects of natural wind loading, etc.

The chapter proposed an inspection robot for 220kV phase line, and detailed the three generation prototypes developed in the past decade. Under the support of "863 Plan" and NSF in China, the research is now performing in further perfect of the robot prototype and reliability for field application. The future plan is to expand mobile robot technical platform in inspection robot to the application of icebreaking and repairing on transmission.

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