AN INSPECTION ROBOT FOR HIGH VOLTAGE POWER TRANSMISSION LINE

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Abstract - The procedure used for inspection and verification of damages in cables is highly dependent on the experience of a skilled technician who, using binoculars, covers the transmission lines in a helicopter, and is able of visualizing points where seems to exist damaged spots in the wires and in insulators of the transmission lines. After this previous identification, teams are sent to verify, with greater detail, if the imperfection is relevant. To confirm the relevance of imperfections, the lines are de-energized and the repair or substitution can be carried out. With the objective of complementing the service of inspection in transmission lines and making it less dependent of the technician skill, the development of a system of services in lines of energy transmission that includes the automation as an auxiliary tool in the identification of imperfections and as a mechanism of diminishing the lines disconnection time. In this work, a mobile robot is presented as a tool to automate the operations of inspection. This robot, currently teleported, while travelling upon the wires, gathers cable images, through cameras, and sends them to an operations base.

I. 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.

II. 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 limitaions 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 120º, 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 limite ACR’s application.

Fig. 2. ACR prototype (by Wuhan University, 2000)
c) ACRC: Based on the above two generaions 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-systems 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.

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×width×height): 650mm×300mm×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).

III. WORKING ENVIRONMENT ANALYSIS AND OBSTACLES-OVERCOMING PROGRAMMING

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:

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

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.

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
(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. 4. Symmetrical mechanism structure of the ACRC

Fig. 5. Action programming for damper-overcoming
III. 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.

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 = 3.473×10³ kg/m³, elastic module = 7,600 Mpa, 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).

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:

Simulation results:
The joint’s kinematical function was defined with STEP function in ADMAS. The form of STEP is:STEP ( t , t₀ , x₀ , t₁ , x₁ ) where, t is the independent variable; t₀ , t₁ the initial and final value of t, respectively; x₀ ,x₁ 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 □ 360 □ ( STEP(t ,0,0,1,1) –STEP(t ,4,0,5,1)) ( deg )
STEP 2: 3 □ 360 □ ( STEP (t ,0,0,0,5,1) –STEP (t ,4,5,0,5,1)) ( 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. 7).

![Fig. 7. Simulation results of Sub-action 1]

IV. CONCLUSION AND FUTURE PLANS

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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REFERENCE