Structural Synthesis and Configuration Analysis of Broken Strands Repair Operation Metamorphic Mechanism

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Abstract. Appling metamorphic mechanism to satisfy the special operation requirements of the reposition before repairing operation for broken strands of extra-high-voltage (EHV) power transmission lines, a novel structural synthesis method of metamorphic mechanism is proposed considering the forms and structures of constrained metamorphic joints. According to the metamorphic cyclogram and the equivalent resistance gradient matrix, constrained form/structure matrix of metamorphic joints is built, the relation with constraint force changes of joints and form/structure of metamorphic joints is obtained; and further all the eight corresponding structures of constrained metamorphic mechanism are synthesized by the method. One of the eight mechanisms is chosen as the broken strands reposition metamorphic mechanism, and its topological transformations of working configuration are analyzed to verify the feasibility and practicality of structural synthesis method proposed in this paper.

1. Introduction

The broken strands repairing operation of EHV power transmission lines is one of the important maintenance works of grid. At present, the most common way to broken strands repair operation of the EHV power transmission lines is still in manual by line workers on live-line with danger, high cost and inefficiency. To develop the mobile teleoperated robot repair/maintain system for live EHV power transmission lines is one of the most available ways to solve the problems with efficiency and lower cost. The study of broken strands live-line repairing operation for EHV power transmission lines is still in the development stage. The broken strands maintain robot system has been developed by IREQ in Canada 2005, and the LineScout can repair the broken strands of power transmission lines in live-line [1]. Currently, international researchers have done some work on live-line inspection robot to establish a research foundation of the broken strands repair robot system [2-3]. The broken strands repair robot system consists of mobile robot and broken strands operation mechanism. The normal strands and loose broken strands are shown as in the figure 1. The broken strands must to be reposited to the original form before repair operations. The development of broken strands reposition mechanism is one of the most important works to satisfy the special background. Metamorphic mechanism proposed a decade ago is a kind of variable mobility, changeable topology mechanism [4]. Metamorphic mechanism can change its topology to satisfy different requirements and achieve under-actuated by constrain the metamorphic joints of the mechanism alternately according to the required working stages and working sequences. A 2-DOF metamorphic mechanism is selected as the broken strands reposition mechanism. Based on the changing of resistance in the metamorphic process [5], a structural synthesis method determining the constrained forms and structures of metamorphic joints and all the corresponding metamorphic mechanisms is proposed, which provides a reference for the structural synthesis study of practical metamorphic mechanisms.

2. Operating background

For the broken strands repair robot of EHV power transmission lines, broken strands reposition

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component is a kind of repositing nut with rolling element in its inner wall, which sleeves EHV transmission lines and makes the rolling element embed into the gap between adjacent strands. The process of broken strands repositing is equivalent to the meshing course between the repositing nut pushed by a mobile robot and strands of EHV power lines, which will accomplish broken strands reposition operation of lines. Owing that EHV transmission lines are closed, the repositing nut must be made of two cut-open nuts as shown in figure 2(a), which would clamp the live-line and be locked into a unite one (figure 2(b)) to prevent the cut-open nuts from bulging open while the mobile robot pushes them move along the line during the broken strands reposition operation.

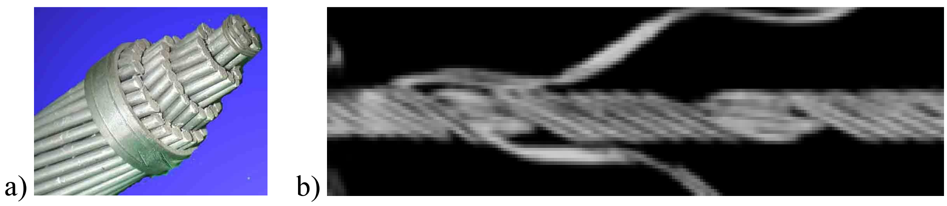

Figure 1. The broken strands.

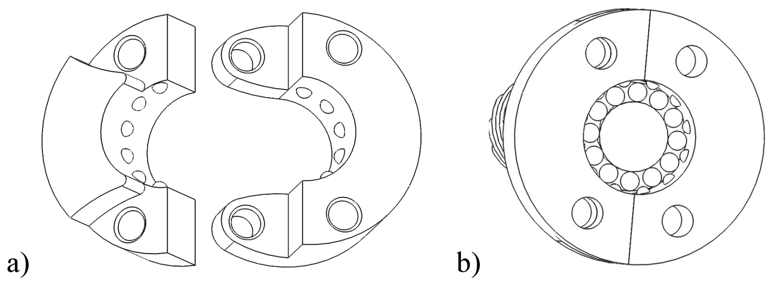

Figure 2. The cut-open nut.

3. Design of source metamorphic mechanism

3.1. Operational requirements

According to the operating requirements, the reposition mechanism to be designed must have 2 DOFs, one of which is the motion of making two cut-open nuts clamp EHV power lines and the other of which is the motion of locking the two cut-open nuts into a united one through pins. Because of the special operation background, it is needed to reduce the weight of repair mobile robot, to simplify the control system, and to save the carrying energy (usually lithium battery). Therefore, 2-DOF constrained metamorphic mechanism is designed as the reposition mechanism which accomplishes two motions above with only one driver.

3.2. The design of source metamorphic mechanism

According with the kinematic requirements and operating background, the metamorphic mechanism to be designed has 2 DOFs and two rotational constrained joints. Finally, the metamorphic cyclogram of 2-DOF reposition metamorphic mechanism is got shown in figure 3 [5]. In figure 3, J denotes the working conditions of joints J in corresponding working configuration ($J = R$ for revolute joint, $J = P$ for prismatic joint etc.); θ denotes the displacement (turning angle or moving distance) of the driver. Suppose the driving link obtains translational motion of screw driven by motor, a kind of corresponding planar 5-bar mechanism i.e. source metamorphic mechanism is designed shown in figure 4.

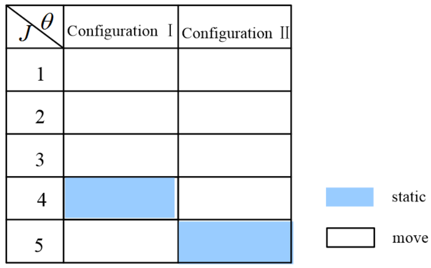

Figure 3. Metamorphic cyclogram of the metamorphic mechanism.

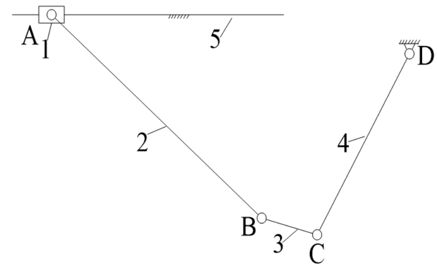

Figure 4. The source metamorphic mechanism of broken strands reposition.

4. Structural synthesis method of constrained metamorphic mechanism

4.1. Equivalent resistance gradient sketch of metamorphic joints

Based on figure 3 and equivalent resistance gradient model proposed in reference [5], the equivalent resistance gradient sketch of working stroke of constrained metamorphic mechanism is obtained shown as in figure 5, in which f_e denotes equivalent resistance coefficient.

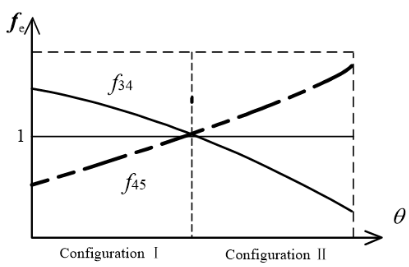

Figure 5. Equivalent resistance gradient sketch.

The equivalent resistance gradient sketch of metamorphic joints can be described as matrix i.e. the equivalent resistance matrix:

$$\boldsymbol{F} = \begin{bmatrix} 0 & f_{45} \\ f_{34} & 0 \end{bmatrix} \quad (1)$$

where, working configurations are shown in columns of the matrix and constrained status of metamorphic joints with different working configurations are shown in rows, and f_{ij} denotes metamorphic joint R_{ij} keeps constrained and 0 means R_{ij} keeps working.

4.2. The structural topology matrix of constrained metamorphic mechanism

4.2.1. Constrained metamorphic joints Typical constrained structures and constrained matrixes of metamorphic joints are shown as in figure 6. Figure 6(a) are turning joint and prismatic joint with geometric constraint. Figure 6(b) are turning joint and prismatic joint with spring force constraint. Figure 6(c) are turning joint and prismatic joint with geometric constraint controlled by spring. Figure 6(d) are turning joint and prismatic joint with geometric constraint and spring force constraint respectively, Figure 6(e) are turning joint and prismatic joint with geometric constraint and geometric constraint controlled by spring respectively. In constrained matrixes, 0 denotes metamorphic joint R_{ij} which keeps moving and 1 denotes R_{ij} which keeps static. Suppose $g = r, p$, which denotes revolving or prismatic metamorphic joints with geometric constraints. $s = rk, rt, pk, pt, rk, rt$, denote revolving metamorphic joints with spring force constraint and geometric constraint controlled by spring respectively, and pk, pt denote prismatic metamorphic joints with spring force constraint and geometric constraint controlled by spring respectively, $sg = rkg, rtg, pkg, ptg$ denotes metamorphic joints (revolving or prismatic) with spring force constraint and geometric constraint, and with geometric constraint and geometric constraint controlled by spring .

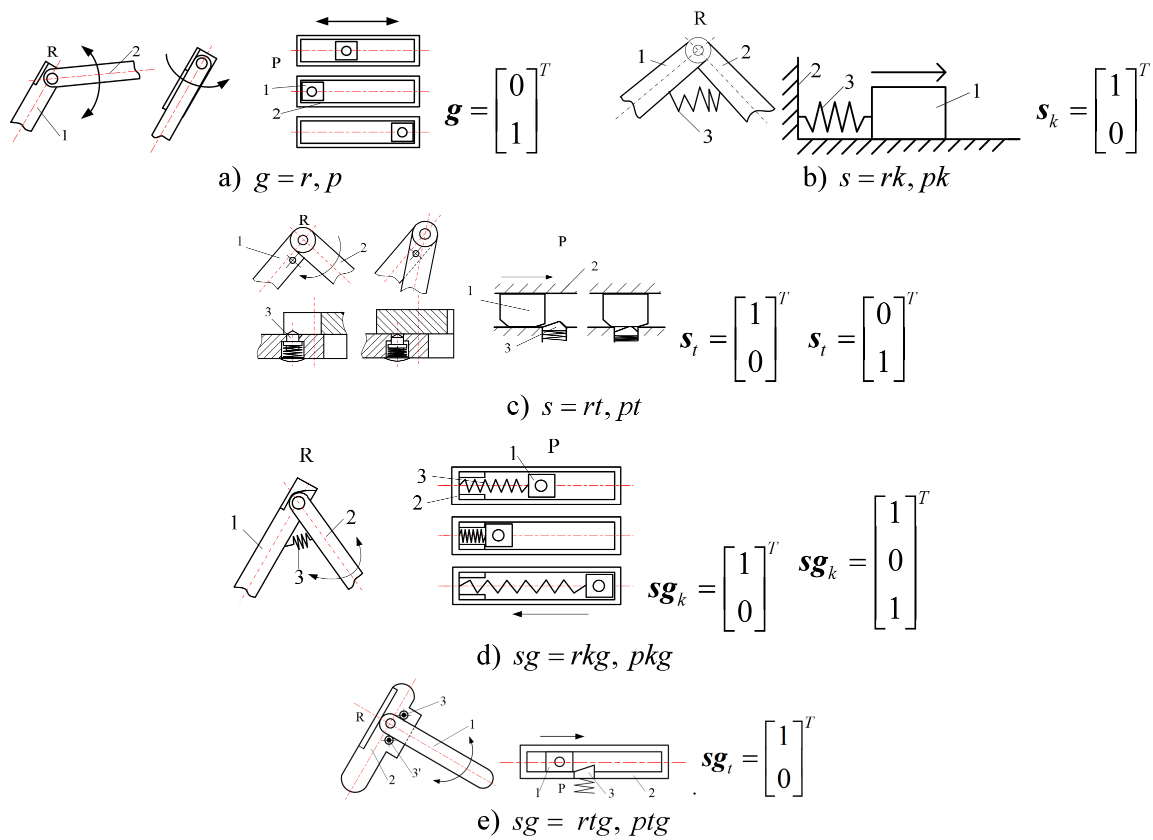

Figure 6. Typical constrained structures of metamorphic joints.

4.2.2. The structural topology matrix of constrained metamorphic mechanism In order to build the connection-ship of constrained structures of metamorphic joints and its equivalent resistance matrixes in corresponding working stages, structural topology matrix $\boldsymbol{C}$ of constrained metamorphic mechanism and constrained structures matrix $\boldsymbol{R}_{ij}$ of constrained metamorphic joints are built:

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{R}_{45} \\ \boldsymbol{R}_{34} \end{bmatrix} = \begin{bmatrix} 0 & c_{45} \\ c_{34} & 0 \end{bmatrix} \tag{2}$$

Compared the rows of (2) with constrained structures of figure 6, constrained structures matrix of metamorphic joints can be deduced:

$$\begin{cases} \boldsymbol{R}_{45} = [g / st] \\ \boldsymbol{R}_{34} = [sk / st / rkg / rtg] \end{cases} \tag{3}$$

Take (3) into (2), structural topology matrix of constrained metamorphic mechanism is got:

$$\boldsymbol{C} = \begin{bmatrix} \boldsymbol{R}_{45} \\ \boldsymbol{R}_{34} \end{bmatrix} = \begin{bmatrix} 0 & c_{45} \\ c_{34} & 0 \end{bmatrix} = \begin{bmatrix} 0 & r / rt \\ rk / rt / rkg / rtg & 0 \end{bmatrix} \tag{4}$$

According to (4) and permutations and combinations theory, all the eight structural topology matrixes can be calculated.

$$\boldsymbol{C}_1 = \begin{bmatrix} 0 & r \\ rk & 0 \end{bmatrix};\ \boldsymbol{C}_2 = \begin{bmatrix} 0 & r \\ rt & 0 \end{bmatrix};\ \boldsymbol{C}_3 = \begin{bmatrix} 0 & r \\ rkg & 0 \end{bmatrix};\ \boldsymbol{C}_4 = \begin{bmatrix} 0 & r \\ rtg & 0 \end{bmatrix};$$

$$\boldsymbol{C}_5 = \begin{bmatrix} 0 & rt \\ rk & 0 \end{bmatrix};\ \boldsymbol{C}_6 = \begin{bmatrix} 0 & rt \\ rt & 0 \end{bmatrix};\ \boldsymbol{C}_7 = \begin{bmatrix} 0 & rt \\ rkg & 0 \end{bmatrix};\ \boldsymbol{C}_8 = \begin{bmatrix} 0 & rt \\ rtg & 0 \end{bmatrix}.$$

There are eight constrained structures of metamorphic joints together, which means eight corresponding constrained metamorphic mechanisms can be designed theoretically to satisfy broken strands reposition operation.

5. Structural design and working configurations analysis

5.1. Design of the practical reposition metamorphic mechanisms and its topological transformations

Because of simple structure and reliable operating, constrained structures of metamorphic joints were selected as the one corresponding with C_3, which means one metamorphic joint is with spring force constraint and geometric constraint and the other is with geometric constraint. Finally the practical broken strands reposition metamorphic mechanism designed is shown in figure 7.

This mechanism mainly consists of 2 parts, a main clamping metamorphic mechanism and a locking mechanism. The main clamping mechanism is a 5-bar metamorphic mechanism, comprised of screw nut 1, link 2, link 3, clamp 4 and the frame 0 in x-y plane, as is shown in figure 7. Cut-open nut 11 is embedded in clamp 4, and spring 10 and a kind of geometric structure constrains joint C, and the geometric limitation (strand 12) constrains pair D. This mechanism can provide 2 motions, one for carrying two cut-open nuts clamping EHV power lines, and the other for providing driving motion (link 3) for the locking mechanism bellow.

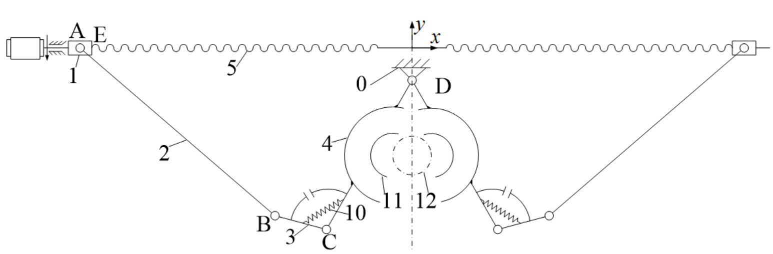

Figure 7. The main 2-mobility clamping metamorphic mechanism.

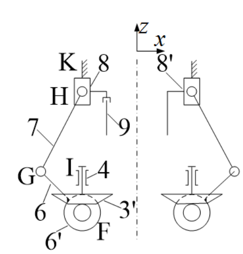

Figure 8. The locking mechanism.

The locking mechanism is made up of crank 6, link 7, slider 8 and the frame 0 in x-z plane, which actually is a crank-slider mechanism, as is shown in figure 8. It can provide the motion of locking the two half cut-open nuts into a united one through pins. The main clamping mechanism and locking mechanism are connected through a pair of bevel gears 3’ and 6’, which are respectively fastened to link 3 and crank 6 rigidly. Pin 9 is a joining pin used to lock the two half cut-open nuts, while the pin on the other side is just part of slider 8’ used to disassemble the united nut after the repair operation.

5.2. The working configurations analysis of metamorphic process

The reposition metamorphic mechanism proposed will be carried by a mobile robot and mounted onto the EHV power line. In its initial working configuration as shown in figure 9, link 3 and clamp 4 are fixed together by spring 10 and a special geometrical constrain. When the operating starts, screw 5 rotates driven by the motor, and screw nut 1 moves towards the symmetrical center which drives clamp 4 swing around D to carry the cut-open nut 11 to clamp and tighten the EHV power line 12, as shown in Fig. 9.

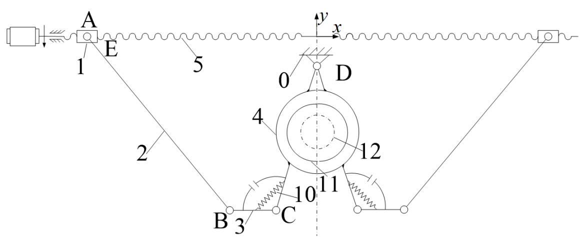

Figure 9. The configuration of changing work stage.

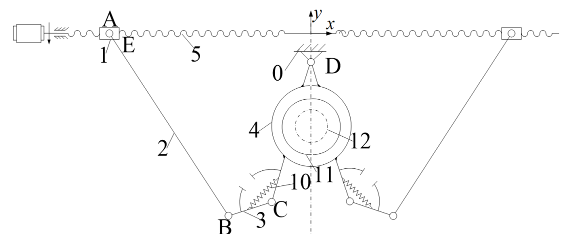

Figure 10. The locking configuration.

After the cut-open nuts' clamping operation finished, clamp 4 will be fixed as a part of the frame. Along with the motion of screw nut 1, link 3 begins to rotate around joint C after overcoming the spring resistance to provide a driving motion for the locking mechanism as shown in figure 10. Beginning to rotate around joint C, link 3 drives bevel gear 3' rotate relative to clamp 4 in x-z plane. Through the bevel gears 3' and 6', movement and power are delivered to the locking mechanism which moves along with crank 6, and makes slider 8 move toward the cut-open nuts. Pin 9 connects the two cut-open nuts into a united one.

6. Conclusions

A practical structural synthesis method for metamorphic mechanism is presented according to the special operation requirements and application background of the broken strands repair mobile teleoperated robot used in EHV power transmission lines. Applying the method, all the eight theoretical structures of the reposition metamorphic mechanism and forms/structures of constrained metamorphic joints are obtained. Finally, the reposition metamorphic mechanism designed can achieve multi-mobility with single-drive, which leads to reduce weight of the robot and save the energy carried. The results of the research indicates that the method provides a new way for designing broken strands repair operation mechanism of EHV power transmission lines, as well as for similar design requirements of under-actuated mechanisms.

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References

[1] Toussaint K, Pouliot N and Montambault S 2009 Journal of Field Robotics **26** 477–499
[2] Montambault S and Pouliot N 2006 *LineScout Technology: Development of an Inspection Robot Capable of Clearing Obstacles While Operating on a Live Line 11th Proc. Int. Conf. on Transmission & Distribution Construction Operation and Live-Line Maintenance* (Albuquerque NM: IEEE) 1–9
[3] Zhu X L, Zhou J P, Wang H G, Fang L J and Zhao M Y 2009 Journal of mechanical engineering **45** 119–125
[4] Dai J S and Rees J 1999 Journal of Mechanical Design **121** 375–382
[5] Li S J and Dai J S 2012 The Equivalent Resistance Gradient Model of Metamorphic Mechanisms and the Design Approach *ASME/IFToMM Proc. Int. Conf. on Reconfigurable Mechanisms and Robots* (Tianjin China:IEEE) 53–62