The Application of Self-adaptive Design in Improvement of the Restoring Strand Operation Mechanism

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Abstract. Aiming at solving the problem that the existing restoring strand operation mechanism cannot realize self-adaption to the variation of position and shape of transmission lines, a method for self-adaptive mechanism design is introduced and summarized to meliorate the mechanism. This method is effective and practical, which can be applied to most common mechanism design: first of all, analyze the structural features of the self-adaptive mechanism; secondly, establish a universal method to determine the structure type named as initial kinematic chain which contains information of the degree of freedom (DOF), the number of links and the kinematic relations between every two of them; finally, considering the features of the existing mechanism, apply the self-adaption design to realize the required mechanism by inverting the initial kinematic chain, and build models and simulations to prove that the improved mechanism does have the ability of self-adaption to the location and shape variation of transmission lines.

Introduction

Extra High Voltage (EHV) transmission lines assume the responsibility of electric power transmission in China, so the environment of its operation has great influence on the steady development of the country’s economy [1]. However, due to the severe environment and the continuing impact of mechanical strain, electrical flashover and material aging, damages on the EHV transmission lines are produced in varying degrees. In order to prevent the expanding of the damages, patrol robots for EHV transmission lines are usually used instead of workers (reference [2] to [6]). Before repairing the broken strand, some important pretreatment should be executed, namely restoring the loose strands to the initial condition, which is called Restoring Strands Operation (RSO).

Reference [7] has designed a kind of mechanism for restoring the broken strands on EHV transmission lines, based on the principles of metamorphic mechanism, as is shown in Fig. 1. It consists of the rack, the lead screw, the screw nuts, the RSO nut, the RSO nails and so forth. The performance of RSO includes two processes: (1) process of clamping the transmission lines; (2) process of locking and unlocking. By adopting the metamorphic mechanism, the two processes of RSO can be accomplished with only one drive, which greatly reduces the total weight of the mechanism. However, two problems exist in the first process: (1) during the process of clamping lines, because of the position error, the location of the center of transmission lines may not coincide with that of RSO nut, which will produce extra force even to cause the whole mechanism deformed; (2) At the end of the first process, the tops of the RSO nails should be embedded into the gaps between every two strands. Nevertheless, sometimes, the tops of the RSO nails may not be in the gaps but against the outer diameter of lines. Thus the two parts of the RSO nut cannot fit together and neither does the second process proceed. The main reason for these two problems is that the existing RSO mechanism cannot adapt automatically to the variation of transmission lines’ position and shape. Thus, in this paper, basing on the existing RSO mechanism, improvements are made to design a self-adaptive mechanism.
Self-adaptive Mechanism

Self-adaptive Mechanism (SAM), without sensor or control, via its own design and structure, can adapt itself to the working object automatically. Reference [8] has designed a novel coupled and self-adaptive under-actuated multi-fingered hand with gear-rack-slider mechanism. The hand is able to grasp different shapes of objects dexterously and stably. Reference [9] comes up with a type of multiple fingers, passive adaptive grasp prosthetic hand, which is able to perform passive adaptive operation. References [10] and [11] make analysis of degree of freedom (DOF) of kinematic chain according to the characteristics of SAM, and synthesize all the possible kinematic chains, which propose a new method for the innovation of SAM. Reference [12] suggests a new method to synthesize kinematic chains—embryonic graph and branch chains. The metamorphic mechanisms designed by references [13] to [17] are also types of SAM. Their main feature is that the DOF can be changed during configuration transformation. Although the references above bring some comprehensive methods to design SAM, these methods are complex, cumbersome, inefficient and not practical for many common designs of mechanism.

So, in this paper, a new method of how to design SAM for common mechanism is described: firstly, analyze the features of SAM; and secondly, determine the structure of kinematic chain; finally, invert the kinematic chain into SAM which can meet the design requirements. This new scientific, rational and practical design procedure is illustrated as follows.

Structure Features of SAM. By far, SAM mainly means force-closure self-adaptive mechanism. Before touching the object, the number of DOF of SAM should equal that of the object’s sizes which may vary. When SAM touches the object, \( n_s \) pairs of internal force are produced. One pair of internal force can be regarded as one restraint, which can be replaced by an axial force link. Thus one force-closure, statically determinate or statically indeterminate structure is formed when \( n_s \) axial force links are substituted for all internal forces. Regard this closed chain as the initial kinematic chain and find ways to improve the existing RSO mechanism.

Structure of the Initial Kinematic Chain. The task of determining the initial kinematic chain is mainly to calculate the kinematic chain’s DOF, the number of links and kinematic pairs on each link. Here, all the kinematic pairs on the links are regarded as revolute pairs. And the actual kinematic pairs are determined according to the real structure when inverting the initial kinematic chain into SAM. The number of links who have \( j \) pairs is presented as \( n_j \). In most mechanical structures, the number of pairs on one link is no more than 5, so \( j=2, 3, 4, 5 \).

1) Determine the number of DOF. The number of closed kinematic chain’s DOF is related to the form of drive. When the mechanism is driven by force, one more restraint is added because drive force is also a type of internal force. Thus the DOF of the closed kinematic chain is \( F=1 \). When driven by torque, no more restraint is added. So DOF of the closed kinematic chain is \( F=0 \).

2) Determine the number of links. Firstly, the least number of axial force links \( n_{2\text{min}} \) should be determined. \( n_{2\text{min}} \) should be no less than the number of internal forces. Thus when driven by force:

\[
n_{2\text{min}} = n_s + 1
\]
When driven by torque:

\[ n_{2_{\text{min}}} = n_s \]  \hspace{1cm} (2)

And then determine the least number of executive links, transmission links and driving links (collectively called work links) \( n_{\text{wmin}} \). In most cases, the number of executive links is equal to \( n_s \); the transmission part has little necessary to be considered if there is no need to amplify the forces; the driving links, such as the motor, which are usually fixed on the base frame. So we get:

\[ n_{\text{wmin}} = n_s \]  \hspace{1cm} (3)

Finally, determine the number of base frame \( n_b \). Base frame usually refers to the relatively fixed part, such as the rack, which is nearly loaded by all the internal forces. So usually we get \( n_b = 1 \).

To sum up, the total number \( N \) \((N = n_2 + n_3 + n_4 + n_5)\) of the links should meet the inequality:

\[ N \geq n_{2_{\text{min}}} + n_{\text{wmin}} + n_b \]  \hspace{1cm} (4)

**Determine the number of pairs on links.** Since the number of pairs on axial force links is 2, here we only need to determine the pair numbers of work links and base frame. Firstly, determine the pair numbers of executive links and driving links. The number of DOF can be expressed as:

\[ F = 3(N - 1) - 2p \]  \hspace{1cm} (5)

\( P \) is the number of pairs, and also:

\[ p = \left(\sum_{j=2}^{5} n_j \cdot j\right) / 2 \]  \hspace{1cm} (6)

Take Eq.6 into Eq.5, combined with expression of \( N \):

\[
\begin{cases}
   N = n_2 + n_3 + n_4 + n_5 \\
   F + 3 = N - n_3 - 2n_4 - 3n_5
\end{cases}
\]  \hspace{1cm} (7)

According to Eq.7, we can get all possible combinations of links. Considering the purpose of task and the analysis above, the value of \( n_2 \) can be acquired. The base frame is usually the link whose pair number is larger than others, and the number of base frame is 1.

**Design of the Functional Structure.** The kinematic chain reflects the DOF of mechanism structure, the number of links and relationships between every two links. One certain kinematic chain can be designed as various mechanisms for different purposes. After the chain is figured out, invert it into mechanism that can meet the requirements of design.

**Improvement of the RSO Mechanism**

The main problem of the mechanism is that it cannot adapt to the variation of transmission lines’ position in horizontal and vertical directions. Thus the improved mechanism will have DOF of 2.

1) **Determine the DOF of the initial kinematic chain.** The improved mechanism is driven by force, just as the previous one, and thus the number of DOF of the closed kinematic chain is \( F = -1 \).

2) **Determine the number of links of the initial kinematic chain.** Firstly, because the number of variable is 2 (horizontal and vertical directions), namely \( n_v = 2 \), according to Eq.1, we get:

\[ n_{2_{\text{min}}} = n_s + 1 = 3 \]  \hspace{1cm} (8)

Secondly, Fig. out \( n_{\text{wmin}} \). There is no need to amplify the force, so the number of transmission links is 0. According to Eq.3, we get:

\[ n_{\text{wmin}} = n_s = 2 \]  \hspace{1cm} (9)
Finally, determine the base frame $n_b = 1$. So, the total number of links should meet the inequality:

$$N \geq n_{2\min} + n_{w\min} + n_b = 6$$  \hspace{1cm} (10)

3) Determine the number of pairs on links. Here we choose the minimum of the possible values, namely $n_2 = 3$, $n_w = 2$, $n_b = 1$, $N = 6$. Bring these values into Eq. 7:

$$\begin{align*}
  n_3 + n_4 + n_5 &= 3 \\
  n_3 + 2n_4 + 3n_5 &= 4
\end{align*}$$  \hspace{1cm} (11)

Because $n_j$ ($j = 2, 3, 4, 5$) are all nonnegative integers, $n_2 = 3$, $n_3 = 2$, $n_4 = 1$ and $n_5 = 0$. The base frame is loaded by all the internal forces, so it has the most kinematic pairs. Finally, the result is that the base frame has 1 link, with 4 pairs; the number of executive links is 2, with 3 pairs on each link; the number of axial force links is 3.

4) The sketch of kinematic chain of improved mechanism can be drawn according to the result above.

![Fig. 2 Sketch of kinematic chain of the improved RSO mechanism](image)

5) Design of functional structure. As shown in Fig. 2, the two executive links are connected to the base frame via two pairs, instead of 1 pair as in the previous mechanism. So the improved mechanism should gain one more DOF, which is added between the executive links and the base frame. Considering the restraints of design requirements, the improved mechanism should keep the characteristics of the previous one as many as possible. Thus the extra DOF is placed on the joint between the clamping components and the rack, while others remain the same, as is shown in Fig. 3.

![Fig. 3 Schematic diagram of improved reposition mechanism](image)

**Modeling and Simulation**

After finishing the improvement of design, model the mechanism by using Solidworks, and make simulations of its function of self-adaptation via Motion, the plug-in module of Solidworks.

Through simulation, it is demonstrated that the improved mechanism can be adapted to the variation of lines’ position and shape automatically, as shown in Fig. 4.

![Fig. 4 Self-adaption of the improved RSO mechanism](image)
Conclusion

In this paper, a new, effective and practical method of self-adaptive design is brought in to solve the problem that the existing RSO mechanism cannot adapt to the variation of transmission lines’ position and shape. Firstly, the structure features of self-adaptive mechanism are analyzed, and we get a force-closure mechanism; what’s more, determine the number of DOF, links and kinematic pairs, as well as the initial kinematic chain; Finally, apply the principles of SAM to improve the existing RSO mechanism, and combined with characteristics of previous one, invert the initial kinematic chain into mechanism which can satisfy the requirements of design. And also, build 3D model and make simulations to testify that the improved RSO mechanism can adapt to the transmission lines automatically.

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