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Research Article

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An improved metamorphosis-based scheme of configuration synthesis for feed mechanism

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Abstract: In this work, the principle of metamorphic mechanism is optimized for product design based on the variable topological structures. A metamorphic element consisting of kinematic pair and kinematic size is proposed firstly. A new configuration synthesis strategy for feed mechanism is performed in view of the translocation, inversion and duplication variation methods. The metamorphic elements are obtained by means of the decomposing the source metamorphic mechanism. A novelty configuration scheme based on constraint variation features is established by the solution of constraint relationship of metamorphic elements, and three kinds of configurations are synthesized. The comparisons of kinematic performances between source mechanism and new mechanism configurations are carried out using kinematic simulation. Results demonstrate that proposed strategy can synthesize successfully multiple types of the metamorphic mechanisms to meet the demands of functional targets.

Keywords: Metamorphic mechanism; metamorphic element; configuration synthesis; feed mechanism; kinematic simulation

1. Introduction

The metamorphic mechanism originally comes from the concept of metamorphosis in an evolutionary sense. Its variable topology characteristics contributes to the experiences a series of changes in configurations, self-reorganizations, and reconstructions varying from environments, working conditions and task requirements [1,2,3]. Based on the metamorphic mechanism principle, a new mechanism is proposed by using changing the shapes, topologies and configurations to meet the demands of the different functional tasks.

Tian et al. [4] established a method for configuration synthesis of metamorphic mechanisms based on five metamorphic modes, including the geometry, motion, force, driving joint, and combined metamorphic modes. Carbonari et al. [5] presented a reconfigurable modular parallel robot stemming from the 3-CPS under-actuated topology, and demonstrated that the robot can perform different types of motions, especially for pure translation and rotation. Aimedee et al. [6] analyzed metamorphic and reconfigurable mechanisms based on morphing types, andachieving ways, as well as categorized these morphing ways, i.e. as topological, geometrical and furcating morphings. Wang et al. [7] introduced a novel plane-space polyhedral metamorphic mechanism that governed by the edge forming principle. Moreover, evolution principles and movement conditions of the isomorphic mechanism were analyzed. Li et al. [8] proposed the structure formulation and composition methodology of planar metamorphic mechanisms using AAGs, the basic problems including mobility and synthesis of constrained metamorphic working mobility-configuration were investigated. Yan et al. [9,10] performed the mobility analysis on configuration singularity of mechanism with variable topologies. Also, and proposed a design methodology for the configuration synthesis. Goel et al. [11] proposed a study in the design, development and deployment of a knowledge-based CAD system for supporting biologically inspired design. Chen et al. [12] set up a special line and plane symmetric Bricard linkage to derived closure equations of the linkage for providing the possibility in reconfigurable structures design. Kong et al. [13] proposed a synthesis method of variable-DOF single-loop mechanisms by inserting two joints to a multi-DOF single-loop over-constrained mechanism, and reconfigured a

variable-DOF single-loop 7R mechanism. Pfurner [14] combined the two single-loop over-constrained 6 R-mechanisms to synthesize a single-loop 8 R-mechanism, and computed the arbitrary two degrees-of-freedom 8R motion modes. López-Custodi et al. [15,16] designed a method of metamorphic mechanism based on the intersection curve of two toroids, and a set of special Bricard linkage mechanisms with various reconstructed branches for plane-symmetric case was achieved. Zhang et al. [17,18] developed a methodology for synthesis and configuration design of metamorphic mechanisms on the basis of the biological modeling and genetic evolution with biological building blocks, subphase working mechanisms as well. Gan et al. [19] established a new metamorphic parallel mechanism with a reconfigurable revolute joint for investigating reconfiguration principle of the reconfigurable revolute joint. Galletti et al. [20] presented four kinemetatropic single loop linkages and a synthesis method for this kind of linkages. Padey et al. [21] deduced the extreme value distributions of robot positional errors by using the maximum entropy principle, reliability of a robotic manipulator was discussed details. Yin et al. [22] developed a gradient-based topology optimization method to synthesize mechanisms consisting of both linkages and gears. Ye et al. [23] presented a constructing reconfigurable limbs method by integrating metamorphic linkages as subchains, and provided the reconfigurable parallel mechanism in different configurations with the metamorphic linkages in different phases. Nokleby et al. [24] developed a Grashof five-bar mechanism synthesis routine based on a quasi-Newton optimization routine and Grashof criteria. Ruggiu et al. [25] analyzed the mobility of the moving platform of the parallel manipulator in the PPR and planar operational modes by via screw theory. Balli et al. [26,27] built up analytical methods of synthesis in a planar linkage mechanism with variable topology between two dead-center position and two finitely separated positions. Zhang et al. [28] proposed a unified elementary matrix operation for presentation of topological variation, and ptopological state and geometry of metamorphic mechanism in an evolutionary process were analyzed. Plitea et al. [29] presented the structural design as well as the kinematics and workspace of parallel reconfigurable robot, and structural design of an innovative parallel robot with six degrees of freedom and its configurations were established. Kang et al. [30] presented constraint equations based on the third- and fourth-order kinematics, two linearly independent relationships between joint angular accelerations at the same singular configuration were obtained. Nurahmi et al. [31] decomposed the 4-RUU PM into two 2-RUU PM, which three operation modes were utilized to change the manipulator operation mode.

As far as it concerns on the globally metamorphic mechanism, its configuration synthesis needs to be combined with its own unique working and constraint variation characteristics. An improved configuration synthesis method of metamorphic mechanism based on constraint variation characteristics is proposed in this work. The correlation-coupling among metamorphic mechanism, metamorphic element, kinematic pair and size, and variation modes of metamorphic elements are improved. By analyzing the constraint relationship and configuration scheme of metamorphic element of the feed mechanism in sewing equipment, the configuration of metamorphic mechanism is synthesized. Using kinematic simulation, the source metamorphic mechanism is compared with the new mechanism configuration in terms of displacement, velocity and acceleration. It is validated that the performances of the new mechanism synthesis are better than those of the source mechanism.

2. Characteristics of metamorphic mechanism

2.1 Composition of metamorphic element

The metamorphic mechanism can be considered as a series of kinematic chains in accompanying with continuously changes. The essence of the evolution of metamorphic mechanism is how to change the relationship of metamorphic elements. Metamorphic element is defined as: kinematic link and its kinematic pair constitute the

simplest combination in which degree of freedom is zero.

Metamorphic element includes kinematic pair and kinematic size.

Kinematic pair *Pa* in planar mechanism is divided into high pair and low pair, and its characteristics can be expressed as Table 1.

Table 1. Characteristics of kinematic pair

Pa	0	1	2	3
meaning	Revolute pair	Sliding pair	Planar and planar pair	Planar high pair

Kinematic size *D* takes an effects on mechanism movement characteristics, which determined by the relative position of kinematic pairs, such as the position of revolute pair center, orientation of sliding pair and guide path. Kinematic size *D* is represented as

$$D=\begin{cases}0,1,2,\cdots d & \text{if kinematic distance is constant}\\ \ell & \text{if kinematic distance is variable}\end{cases}$$

where 0 means that kinematic size is zero, 1~*d* represents length relationship of kinematic size, and 1<2<3<...<*d*.

2.2 Variation modes of metamorphic elements

When the input motion remains constant, the variation of metamorphic elements can be detected by using kinematic pair or kinematic size.

There are three main ways of variation modes: changing the type of kinematic pair, position of kinematic pair and kinematic size.

1) Translocation operation

Translocation operation is used to change the type of kinematic pair, and identify the evolution of the metamorphic elements. The operation is recorded as

$$B_n(P_a^n \to \tilde{P}_a^n) \tag{1}$$

where, P_a^n and $\tilde{P}_a^n$ are the characteristics of the kinematic pair *n* before and after translocation operation, respectively.

The schematic diagram of translocation operation is shown in Fig. 1. The octagon represents the serial number of the kinematic pair, and the number on the bar shows the kinematic size. In Fig. 1, translocation operation $B_2(1\to 0)$ represents that characteristic of kinematic pair 2 is changed from 1 to 0, that is, varying from sliding pair to revolute pair.

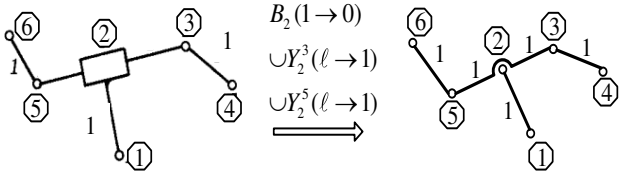


Fig.1. Translocation operation

2) Inversion operation

Inversion operation is used to rearrange the position of the kinematic pair *n*, so as to identify the evolution of the metamorphic elements. It is only utilized to rearrange of kinematic pair rather than changing quantities of kinematic pairs of metamorphic element. The operation is recorded as

$$T_{n\to i}^{n\to \tilde{i}}(D_i^n \to \tilde{D}_{\tilde{i}}^n) \quad (2)$$

where, i and $\tilde{i}$ are the serial number the kinematic pair connected with kinematic pair n before and after inversion operation, respectively; D_i^n is the kinematic size from the kinematic pair n to the next kinematic pair i along the motion transmission direction; $\tilde{D}_{\tilde{i}}^n$ is the kinematic size from n to $\tilde{i}$ after inversion operation.

In Fig. 2, inversion operation $T_{6\to 5}^{6\to 4}(1\to 1)$ represents that the kinematic pair 6 is being rearranged, and replaced the kinematic pair 5 connected to the kinematic 6 with the kinematic pair 4. Corresponding kinematic size remains to be unchanged.

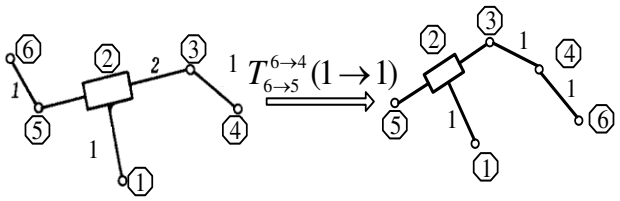


Fig.2. Inversion operation

3) Duplication operation

Duplication operation is used to increase or decrease the kinematic size D_i^n, as well as form new metamorphic element. The operation is recorded as

$$Y_i^n(D_i^n \to \tilde{D}_i^n) \quad (3)$$

In Fig. 3, duplication operation $Y_3^4(1\to 2)$ represents that kinematic size between kinematic pair 3 and kinematic pair 4 is changed from 1 to 2.

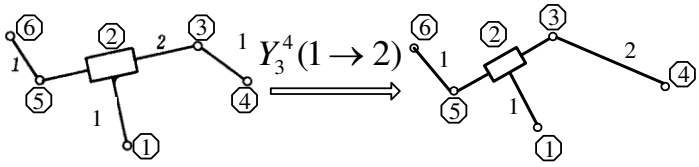


Fig.3. Duplication operation

3. Configuration synthesis method of metamorphic mechanism

The basic idea of configuration synthesis of metamorphic mechanism is illustrated as follows: 1) division scheme of each metamorphic element is obtained by disintegrating the source metamorphic mechanism; 2) constraint functions of metamorphic elements are established; 3) configuration scheme of metamorphic element based on the constraint variation is built up; 4) configuration of metamorphic mechanism is synthesized.

Specific steps of the configuration synthesis are as follows:

3.1 Source metamorphic mechanism disintegration

Lockstitch sewing machine is mainly composed of the feed mechanism, upper shaft mechanism, needle bar

rocking mechanism, and rotary hook mechanism, which the most complicated mechanism can be attributed to the structure of feed mechanism. Its function is to make the feed dog complete the periodic feeding when passing through the motion track of the closed wire ring, depicting that realize forward and backward movement and up and down movement of the feed dog during a working cycle. Fig.4 is the source metamorphic mechanism of feed mechanism, which is divided into three metamorphic elements(see Fig.5).

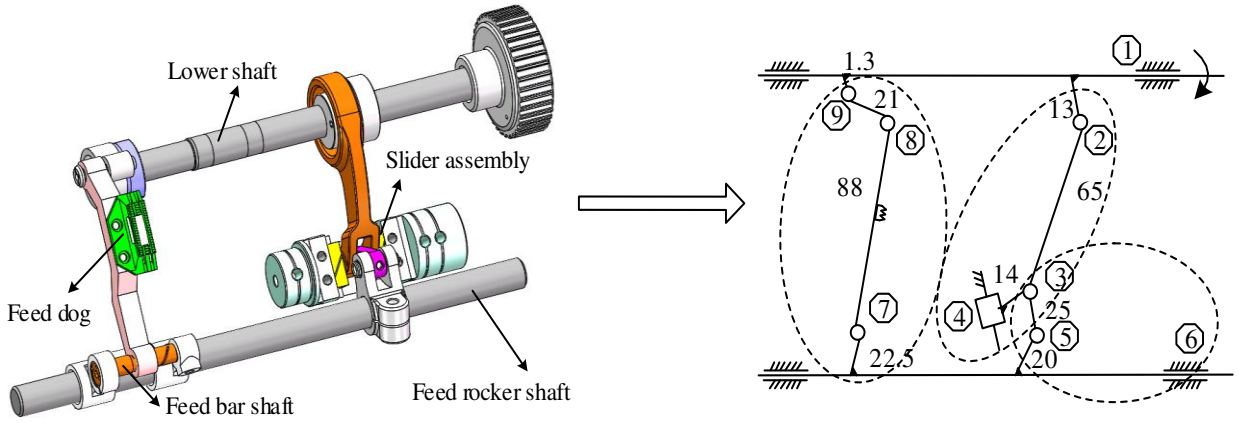
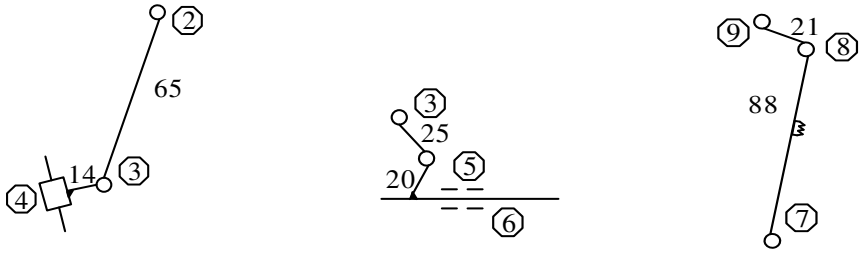


Fig.4. The source metamorphic mechanism of the feed mechanism

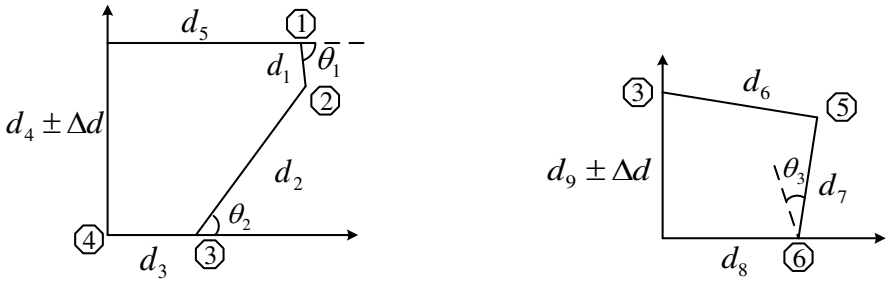


(a) The metamorphic element 1 (b) The metamorphic element 2 (c) The metamorphic element 3

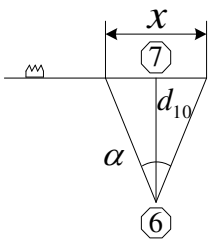
Fig.5. The source metamorphic elements of the feed mechanism

3.2 The constraint functions of metamorphic elements

As seen from the Fig. 6, the constraint relationships of the feed mechanism belongs to the closed vector polygons based on the different views. Using the matrix method, the sum of vectors in the closed vector polygons is equal to zero, and the following constraint relationships of the metamorphic elements are acquired.



(a) The constraint relationship diagram 1 (b) The constraint relationship diagram 2



(c) The constraint relationship diagram 3

Fig.6. The constraint relationship diagrams of the feed mechanism

$$\bar{d}_1 + \bar{d}_2 - \bar{d}_3 - \bar{d}_4 - \bar{d}_5 = 0 \tag{4}$$

$$\bar{d}_6 + \bar{d}_7 - \bar{d}_8 - \bar{d}_9 = 0 \tag{5}$$

$$d_2^2 = (d_5 - d_3 + d_1\cos\theta_1)^2 + (d_4 + \Delta d + d_1\sin\theta_1)^2 \tag{6}$$

$$\tan(\frac{\theta_1}{2}) = \frac{2d_1(d_4 \pm \Delta d) \pm \sqrt{4d_1^2(d_4 \pm \Delta d)^2 + 4d_1^2(d_3 - d_5)^2 - (d_2^2 - (d_5 - d_3)^2 - d_1^2 - (d_4 \pm \Delta d)^2)^2}}{2d_1(d_3 - d_5) - d_2^2 + (d_5 - d_3)^2 + d_1^2 + (d_4 \pm \Delta d)^2} \tag{7}$$

$$\tan(\frac{\theta_3}{2}) = \frac{2d_7d_8 \pm \sqrt{4(d_7d_8)^2 + 4(d_7(d_9 \pm \Delta d))^2 - (d_6^2 - (d_9 \pm \Delta d)^2 - d_8^2 - d_7^2)^2}}{2d_7(d_9 \pm \Delta d) - d_6^2 + (d_9 \pm \Delta d)^2 + d_8^2 + d_7^2} \tag{8}$$

where, d_i is the kinematic size between kinematic pairs, Δd is the displacement of the kinematic pair 4, θ_j is the rotation angle of each component.

$$\alpha = \theta_4' - \theta_4'' \tag{9}$$

$$x = 2\tan(\frac{\alpha}{2})d_{10} \tag{10}$$

where, θ'_4 and θ''_4 are the rotation angles of the feed rocker shaft under the limit displacement state of the kinematic pair 4, respectively, α is the relative rotation angle of the feed rocker shaft, x is the displacement of forward and backward movement of the feed dog.

The common needle pitch of high-speed lockstitch sewing machine is -5~5 mm, implying that takes the displacement of forward and backward movement of the feed dog x=0~10 mm. Let set it to the target value, and take d_2, d_3 and d_6 that affecting the target value to some extents, as the variables, relationships between the target value and the variable can be obtained through the mentioned- above equations.

The relationship between d_2 and x is shown in Fig. 7. The displacement x is directly proportional to d_2. In order to make the displacement x large enough, d_2 should not be too small, but when $d_2 \geq 74$ mm, the solution of the constraint relationship is invalid, so the variation range of d_2 is ranging from 65 to 73 mm.

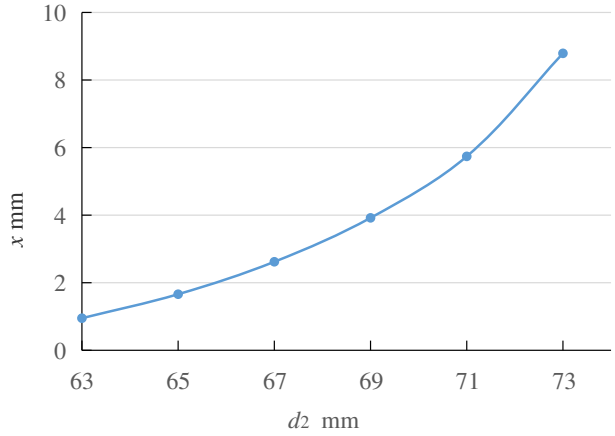


Fig.7. The relationship between d_2 and x

Fig. 8 shows the relationship between d_3 and x. Increasing d_3 results in the increasing displacement x within a small range, depicting that the change of variable d_3 is not sensitive to the displacement x. When d_3 increases from 13 to 16 mm, x increases by less than 5%. Therefore, the variation range of d_3 is ranging from 14 to 16 mm.

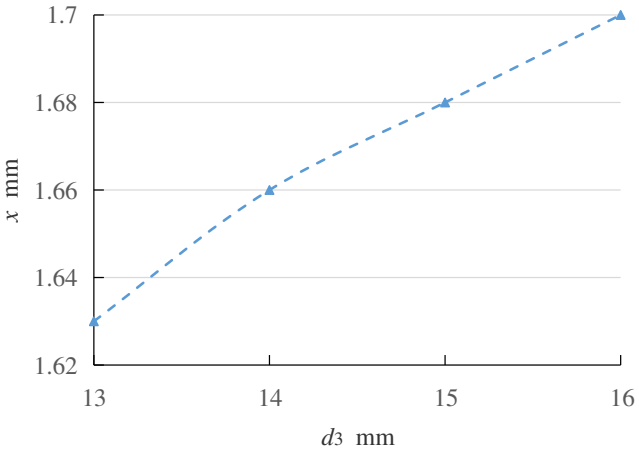


Fig.8. The relationship between d_3 and x

Fig. 9 shows the relationship between d_6 and x. The curve is a parabolic with a minimum value. With the increase of d_6, the displacement x gradually decreases. When d_6 continues to increase, the displacement x gradually increases beyond the minimum value, but the increasing trend is slowly, when d_6 increases from 29 to 39mm, x increment is less than 1mm as a result of the cost of too much increase in the size of the mechanism. Therefore, the variation range of d_6 is ranging from 23 to 25 mm.

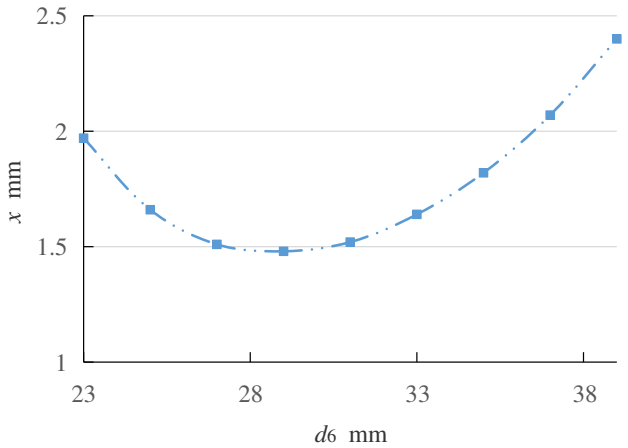


Fig.9. The relationship between d_6 and x

3.3 Metamorphic element configuration scheme

It can be seen from the Fig.5, the feed mechanism is decomposed into the three source metamorphic elements belonging to Assur group II. According to the principle of similarity, the configuration design of metamorphic elements is also mainly based on Assur group II. Fig.10 shows the configuration scheme set of Assur group II and the corresponding variation modes.

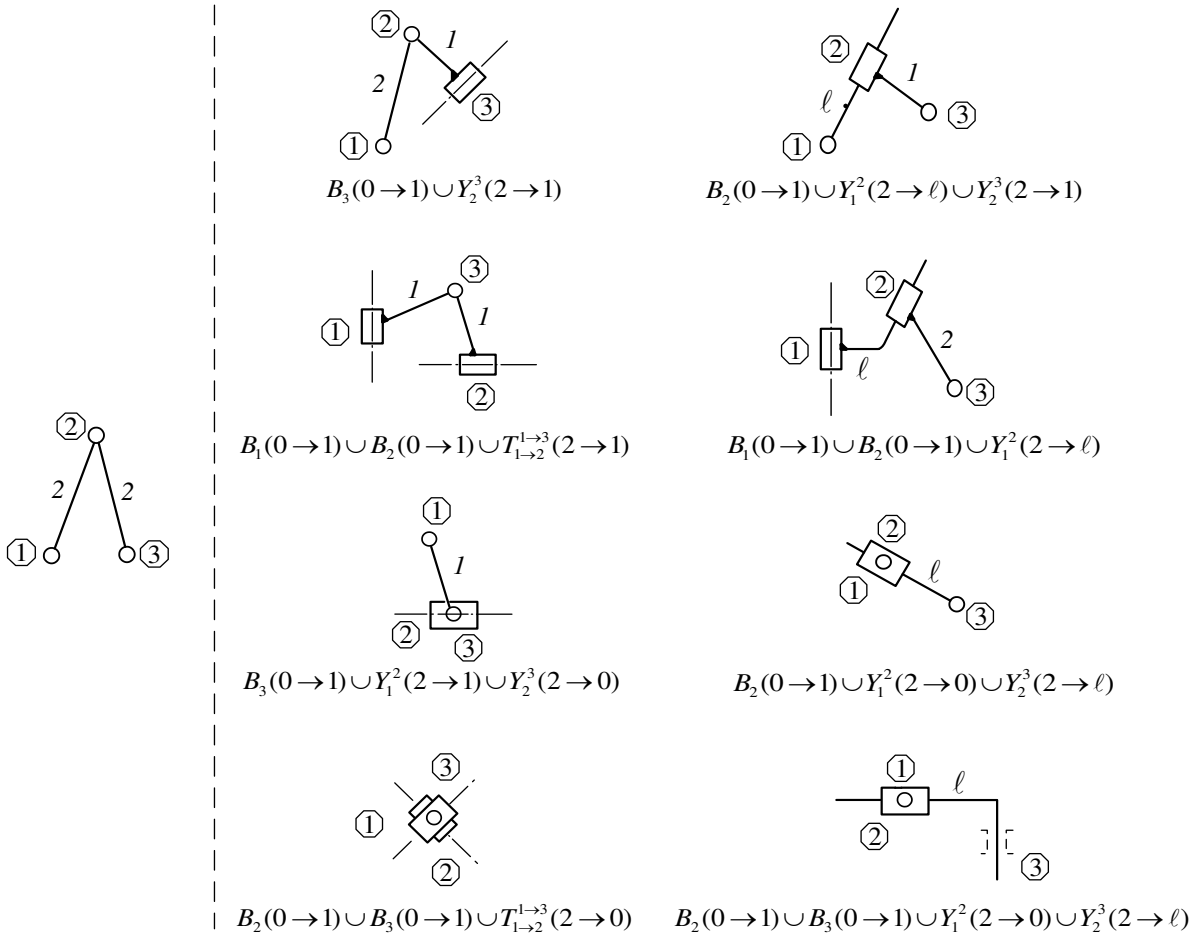
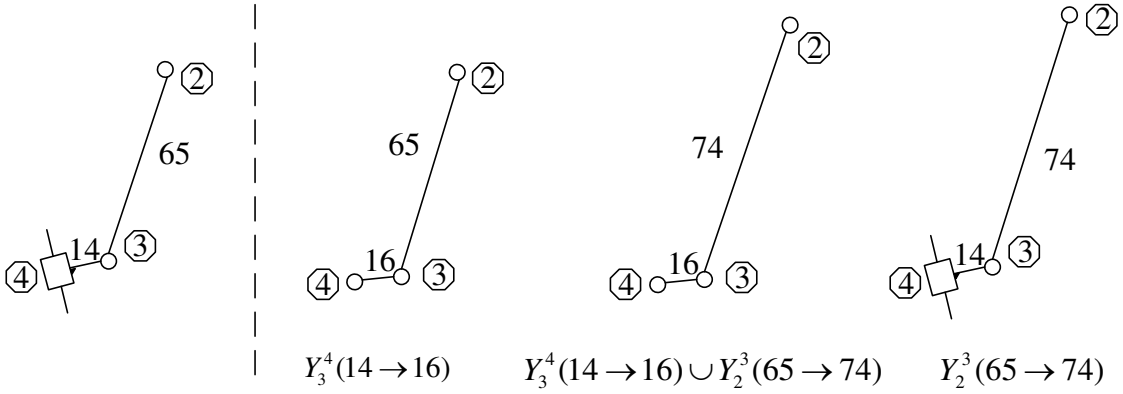
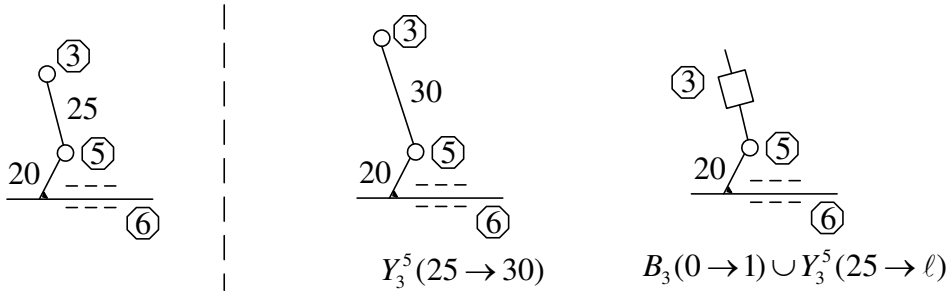


Fig.10. The configuration scheme set of Assur group II

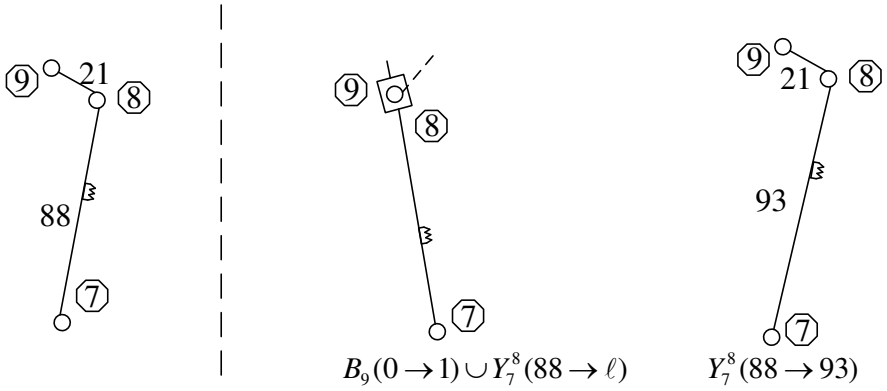
Based on motion requirements of the feed mechanism, configuration design of each metamorphic element is carried out: 1) kinematic sizes of the metamorphic element are determined by the constraint relationship from the variable value range accordingly; 2) configuration schemes of each metamorphic element should have the similar structures, functions and features. The configuration sets of each metamorphic element are shown as Fig. 11.



(a) The configuration set of metamorphic element 1



(b) The configuration set of metamorphic element 2



(c) The configuration set of metamorphic element 3

Fig.11. The configuration scheme sets of each metamorphic element of the feed mechanism

3.4 Configuration synthesis of metamorphic mechanism

The configuration synthesis of metamorphic mechanism is obtained by aggregating the kinematic pairs in connections with multiple metamorphic elements, as well as driving link and frame in turn. The following rules are responsible for the aggregation process, they are

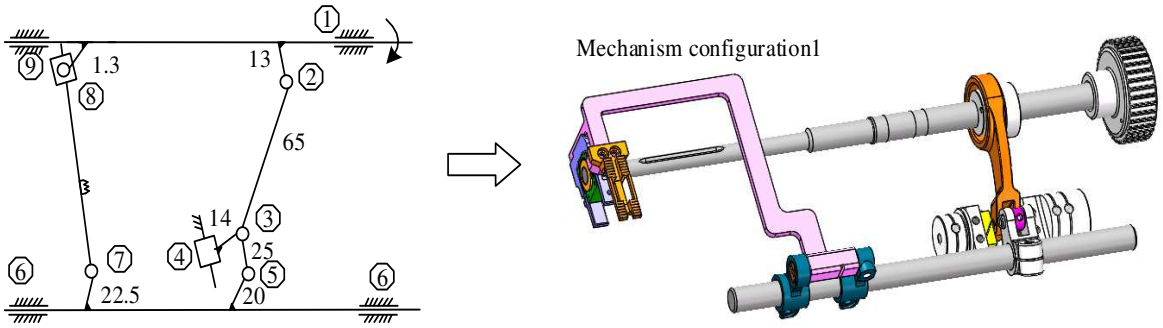
1) The aggregated two metamorphic elements have the same motion directions.

2) The characteristics of aggregated kinematic pair are consistent.

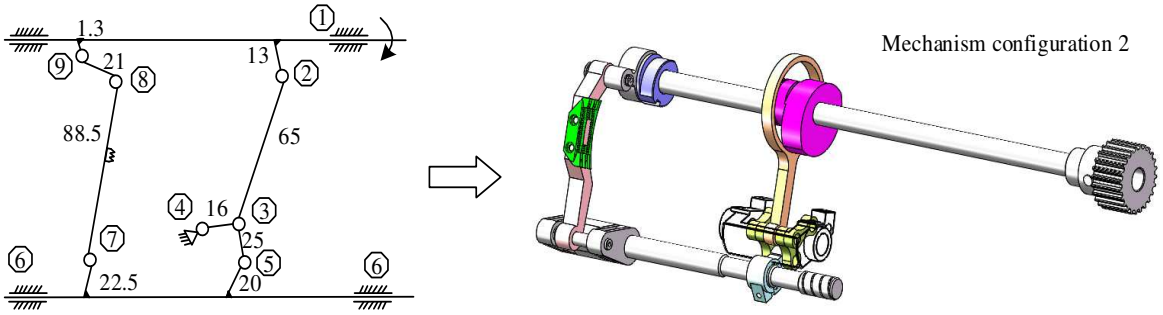
3) When the metamorphic elements are aggregated, the kinematic pairs of a metamorphic element cannot be connected to the same metamorphic element.

4) Relative position of other kinematic pairs keeps invariant.

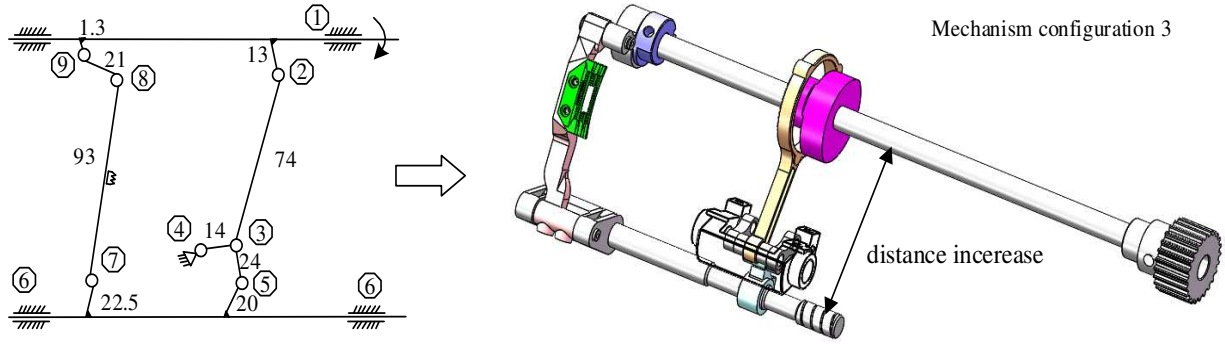
The mechanism configuration schemes of the feed mechanism are obtained in the light of the aggregation of metamorphic elements, and the corresponding 3D digital models are constructed (see Fig. 12).



(a) The mechanism configuration 1



(b) The mechanism configuration 2



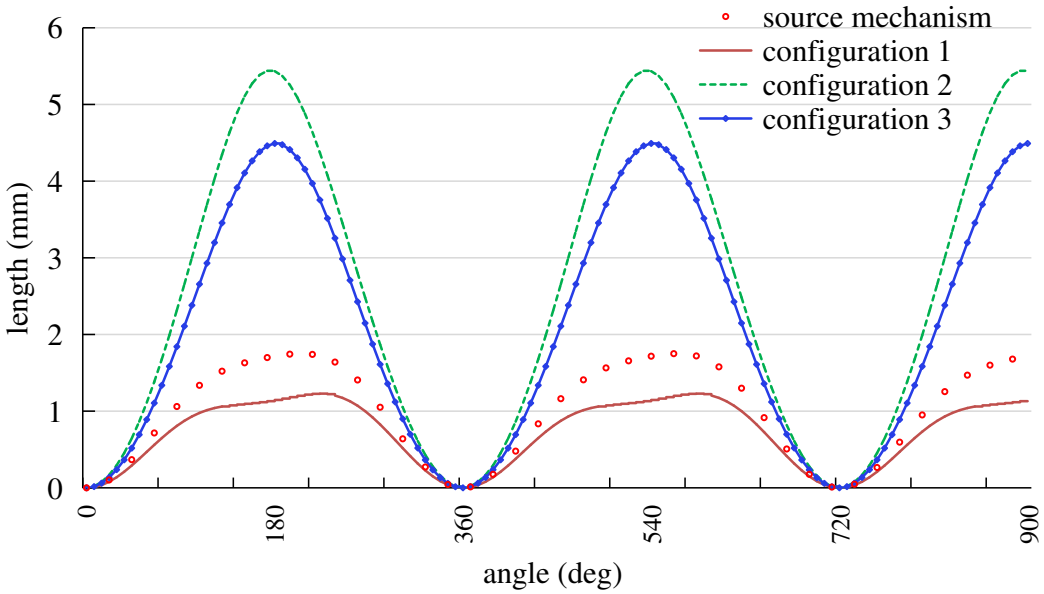
(c) The mechanism configuration 3

Fig.12. The mechanism configurations of the feed mechanism

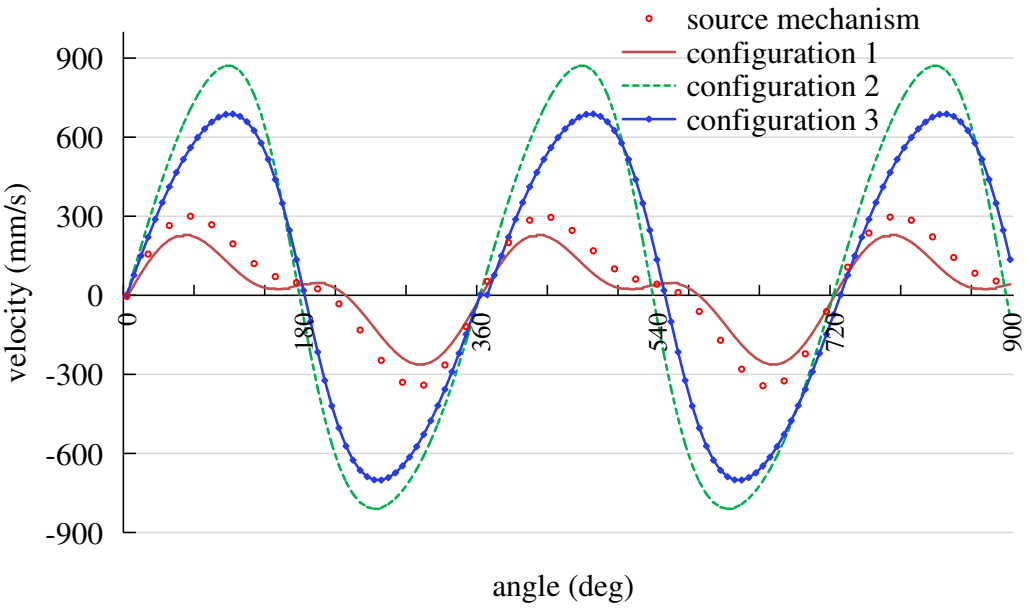
4. Comparison of the mechanism configurations

Feed dog is a kind of the end-effector of lockstitch sewing machine, which motion parameters can be used for representing performance indexes for evaluating the lockstitch sewing machine. By means of kinematics simulation with rotor speed of 3,000 r/min, the curves of displacement, velocity and acceleration of the feed dog are acquired.

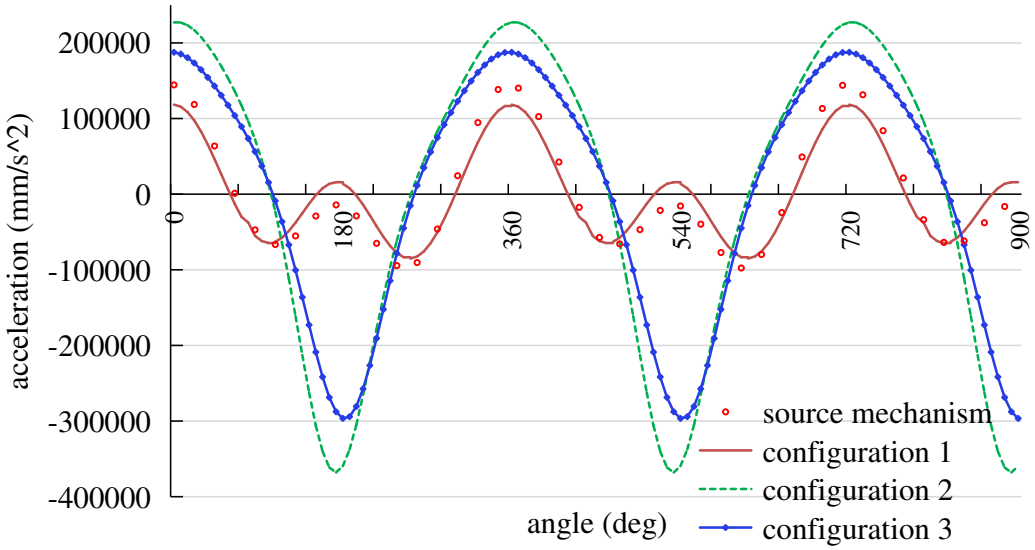
Fig. 13 and Fig. 14 show the forward and backward, up and down movement curves of the feed dog. Curves of velocity and acceleration are continuously changed without suddenly changing, denoting that there is no impact during the movement of the feed dog.



(a) forward and backward movement displacement of the feed dog



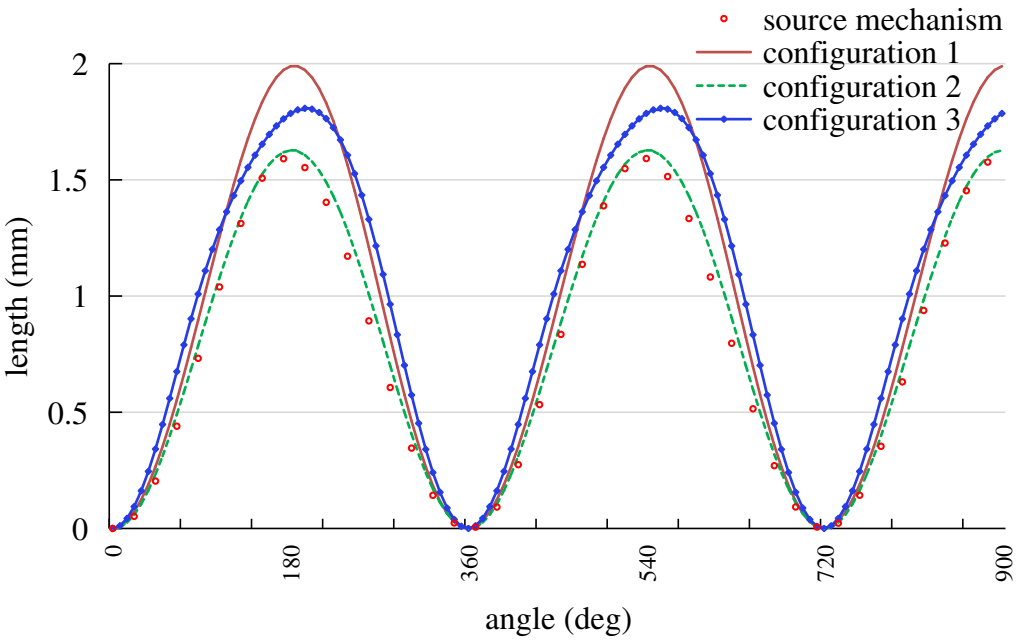
(b) forward and backward movement velocity of the feed dog



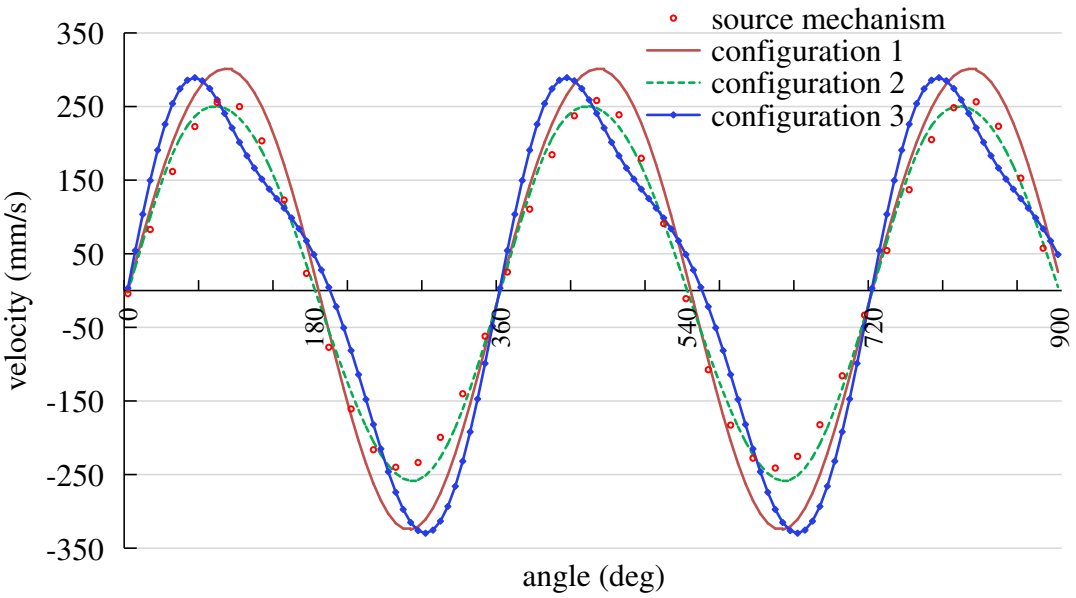
(c) forward and backward movement acceleration of the feed dog

Fig.13. Forward and backward movement curves of the feed dog

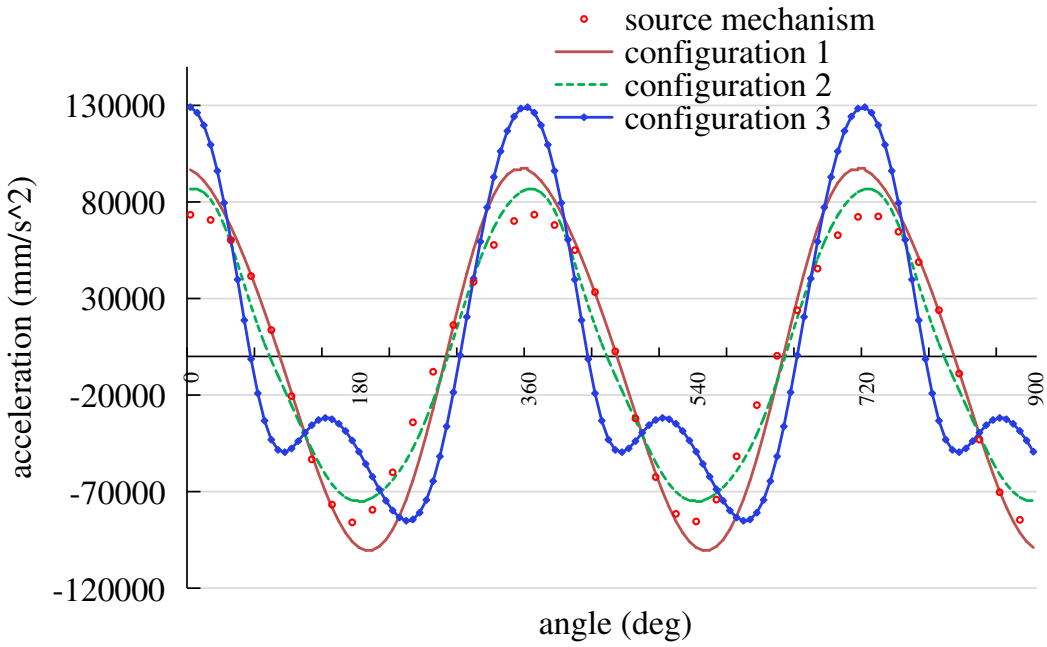
The amount of forward and backward movement of the feed dog is the sewing needle distance. For a lockstitch sewing machine, the increasing needle distance leads to the decreasing the rising slope and the pressure of the presser foot, however, it increases the sewing efficiency. In Fig. 13(a), the forward and backward displacement of the mechanism configuration 1 is the smallest, indicating the sewing needle distance is the smallest, and the displacement of the mechanism configurations 2 and 3 are relatively larger. It can be explained that slider assembly was used for source mechanism and mechanism configuration 1, and link assembly was used for the mechanism configurations 2 and 3. The slider drives the feed rocker shaft to rotate at an angle smaller than that of the link, leading to a small forward and backward movement. In Fig. 13(b), the velocity curves of the source mechanism and the mechanism configuration 1 are similar, the fluctuations are approximately 180°, 540°, etc. Velocity curves of the mechanism configurations 2 and 3 are closely to a sine wave, and the velocity changes are relatively stable. In Fig. 13(c), the acceleration curves of the source mechanism and the mechanism configuration 1 fluctuate significantly approximately 180°, 540°, etc. Those curves of mechanism configurations 2 and 3 are similar to the cosine waves, and the acceleration changes are relatively stable. This is due to the reciprocating motion of the slider in the source mechanism and mechanism configuration 1 resulting in velocity and acceleration fluctuations.



(a) up and down movement displacement of the feed dog



(b) up and down movement velocity of the feed dog



(c) up and down movement acceleration of the feed dog

Fig.14. Up and down movement curves of the feed dog

The amount of up and down movement of the feed dog is the lifting height. The more larger lifting height, the more greater the feed force, which is suitable for thick material sewing. In Fig. 14(a), the displacement of mechanism configuration 1 is the largest as a result of common influence of both the eccentric wheel on the lower shaft and the feed bar slide block assembly at the same time. In Fig. 14(b), the velocity curve of each mechanism is sine wave, but the velocity of the mechanism configuration 3 fluctuates slightly. In Fig. 14(c), except the acceleration curve of the mechanism configuration 3, all are cosine waves. The acceleration curve of the mechanism configuration 3 is similar to a cosine wave, but fluctuates greatly approximately180°, 540°, etc. The reason is that mechanism configuration 3 has a larger distance between lower shaft and the feed rocker shaft than the other mechanism configurations, which changes the initial angle of the feed bar shaft relative to the lower shaft, and the angle is offset by 10.15°, incurring the movement of the mechanism to change. As a result, the more acceleration motion fluctuates, and the more motion inertia force changes greatly.

It demonstrates that the lifting height of the feed dog in the mechanism configuration 1 is larger and more suitable for thick material sewing. Moreover, needle distances of the mechanism configurations 2 and 3 are larger and more suitable for high-efficient places. Overall movement of the mechanism configuration 2 is significantly stable.

5.Conclusions

In this paper, an improved mechanism-configuration synthesis method is proposed based on the principle of metamorphic mechanism, in which feed mechanism is considered as the source metamorphic mechanism. The kinematic performances of source mechanism and mechanism configurations are analyzed. The following conclusions are given as below:

1) The three-layer coupling relationship of metamorphic mechanism, metamorphic element, kinematic pair and kinematic size is established. Most importantly, three variation modes of metamorphic element, such as translocation, inversion and duplication, are optimized.

2) Metamorphic elements are obtained by decomposing the source feed mechanism, its constraint equations

are established, and three mechanism configurations of the feed mechanism are synthesized successfully.

3) Scheme 1 of mechanism configuration is suitable for sewing thick materials, schemes 2 and 3 are suitable for high-efficiency place. Regarding overall movements, scheme 2 exhibits the more stability behavior, indicating that the proposed mechanism is better than source mechanism.

4) This research provides the guidance designation for the lockstitch sewing machine with differently functional requirements.

Author contribution：

Li Zhang and Yang Liu contributed significantly to the compilation of experimental results and organized the manuscript.
Li Zhang, Yang Liu and Yongju Zhang contributed to data analysis and writing.

Declaration of Competing Interest

None.

Declarations

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