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Design of Five-Bar Screw-Lever Manipulator and Optimization of its Output Link Path of Motion

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Abstract

This study presents novel findings on design and analysis of spatial screw-lever manipulators. It is offered to introduce a screw kinematic pair with variable pitch instead of a classical screw-and-nut connection with a fixed pitch in the manipulators. Using this kinematic pair, we have developed a novel model of manipulator based on the structure of five-bar screw-lever mechanism. This manipulator has a single drive input and allows reproducing complex screw movement in the shape of spatial trajectory having variable pitch and curvilinear axis. The potential application of such manipulator that has a complex reproducible trajectory is for internal contouring cutting, as well as for mixing processes. The novel manipulator as distinct from known screw-lever mechanisms allows easy changing of the output link for reproduction of new trajectories. This property is essential for cutting different internal surfaces by the same manipulator.

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Keywords: mechanism; kinematic pair; trajectory; internal surface.

1. Introduction

For a complex internal surfaces cutting process, the output links of manipulators have to move along with spatial paths, providing efficient movements of their processing elements [1-7]. Determination of the end-effector trajectory is the most important task for such applications [8-17]. This study presents screw-lever models of spatial manipulators as processing mechanisms with output links moving on the complex helical paths with curvilinear axes [18,19].

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The peculiarity of these manipulators bases on having one input degree-of-freedom (DoF), i.e. input movement is given to only a single link when an output link has four DoF (reproducing four relative movements according to the axes of Cartesian coordinates) [20-23]. The mobility of these mechanisms is calculated by the following structural formula [24-26]

$$W_2 = 4n - 3p_5 - 2p_4 - p_3, \tag{1}$$

where indicated W_2 - mobility of a kinematic chain that determines the number of its DoF, n - number of movable links, p_5, p_4 and p_3 - one-, two- and three-DoF kinematic pairs.

2. Kinematic Model of Manipulator for Internal Contouring Cutting with Singular DoF

Discuss manipulator for internal contouring cutting shown in the Fig. 1a [27]. Its mobility can be calculated by (1) and with four movable links (n=4) and five one-DoF kinematic pairs (p_5=5) it will be equaled to one (W_2=1). The input link of this manipulator is crank, when the output link is nut (shown in red) where processing tool is set. Movement from crank passes through screw coupler to the nut which have complex screw motion. Configurable parameters in this mechanism are lengths of links and parameters of screw kinematic pair. It is possible to provide different end-effector trajectories by changing of these parameters, this is quite important for cutting of internal surfaces with different curvatures and shapes. The Fig. 1b and 1c show trajectories reproduced by processing tools set on the output links of the manipulator for internal contouring cutting with same dimensions of links, but with different pitches of screw. The Fig. 1b provides pitch 140 mm, the Fig. 1c includes pitch 200 mm, when the length of screw part of coupler in both models equals 280 mm.

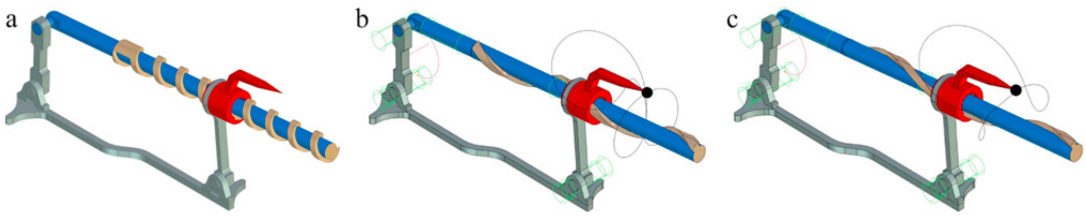

Fig. 1. (a) Kinematic model of the manipulator for internal surfaces cutting;
(b) manipulator with pitch 140 mm and its reproducible curve; (c) manipulator with pitch 200 mm and its reproducible curve.

It is obvious from the Fig. 1b and 1c that trajectories have principal differences and can describe diverse surfaces. Variation of geometrical parameters can give an opportunity to additionally change trajectory of nut for a required surface. These differences are explained more by kinematic diagrams shown in the Fig. 2 and 3 as dependences of coordinates X, Y, Z of processing tools on time t. Diagrams X (t) presented in the Fig. 2 and 3 are completely different, as well as diagrams Y (t) and Z (t) for the same structure of the mechanism.

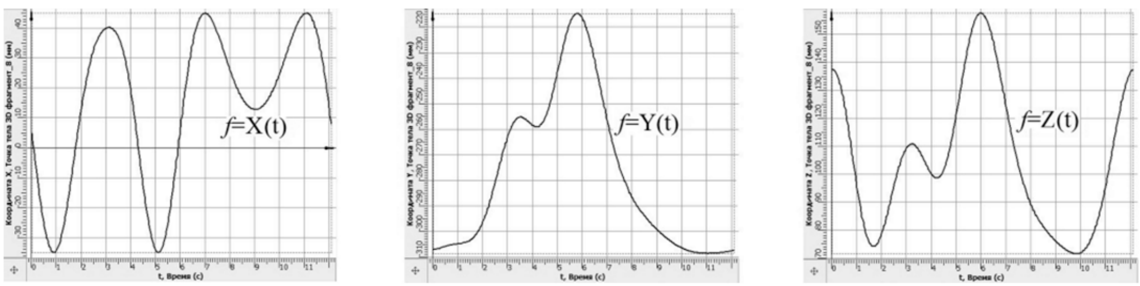

Fig. 2. Coordinate (X, Y, Z) - time (t) curves of manipulator with pitch 140 mm.

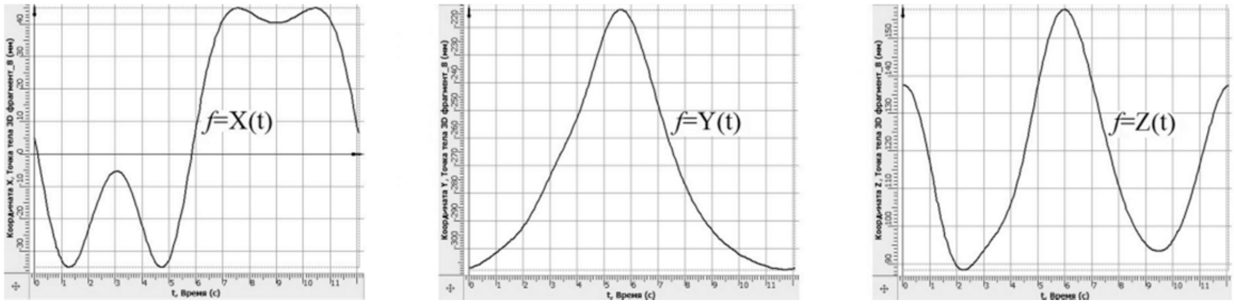

Fig. 3. Coordinate (X, Y, Z) - time (t) curves of manipulator with pitch 200 mm.

Thus, we have changed only one parameter in the mechanism (screw pitch) and got absolutely different coordinates of output link. This property can make this mechanism be applied to cut surfaces with various curvatures and shapes.

3. Design of Novel Manipulator with Variable Pitch in Screw Kinematic Pair

However the structural scheme of manipulator shown in the Fig. 1 can be developed more to the particular surface. Pitch of screw is fixed in this manipulator and can not be changed for a variable one. This means that each mechanism can be applied only for specific surface as the reproduced curve can not be changed with fixed parameters of the manipulator. This fact seriously reduces its technological application. Change of screw kinematic pair to reproduce different curves is costly operation. Therefore this mechanism allows to reproduce singular curve or to cut concrete surface. Using variable pitch in screw kinematic pair allows to increase application of this manipulator for different surfaces, and to control velocity of nut rotation depending on cutting areas of machine elements. All of this would allow to increase practical opportunities of this type of mechanisms.

To provide variable pitch it needs to introduce additional contact into screw kinematic pair, i.e. to make it double-contact. Such pair can be realized as a connection of two-DoF cylindrical and five-DoF dotted pairs realizing surface and dotted contacts [28,29]. This modernization allows to retain holdability of both links in this pair and assumes a reversal motion through both its links. The Fig. 4a provides female link made as closed cylindrical gutter with curvilinear groove. Male link is made as circular cylinder with finger set on its surface. Axial axes of cylinder and finger intersect at the angle 90º. Screw groove is made with variable pitch at the areas t_1, t_2 and t_3, matching to elevation angles of screw line. Thus, links contact in screw pair is provided by surface contact of cylinder with gutter and point contact of finger with groove.

The Fig. 4b shows a five-bar manipulator with screw kinematic pair having variable pitch. This manipulator is structurally similar to that which is shown in the Fig. 1 as it has the same number and types of links and kinematic pairs. However its reproducible curve is principally different from that are shown in the Fig. 1b and 1c reproduced by manipulators with fixed pitch. New manipulator (Fig. 4b) provides to control velocity of nut rotation through the angle of curvilinear groove as well as to replace different types of nuts having various curvilinear grooves and variable pitches without changing any other link in the mechanism.

Refer to the kinematic analysis of this novel mechanism in particular to its end-effector trajectory calculation. Discuss two cases when mechanism has different length of links and pitches in screw kinematic pair with the aim to compare coordinates of reproduced curves.

Case-study 1. Introduce following geometric parameters of links: crank length l1=65 mm, length from axis of revolute joint of coupler to its finger l2=195 mm, rocker arm length l3=70 mm, fixed link length l4=290 mm, sections of variable pitch as t1=55 mm, t2=25 mm, t3=70 mm. In accordance with the mentioned parameters, the end-effector trajectory of manipulator has been calculated and the change of coordinates X, Y, Z depending on time is shown in the Fig. 5 as diagrams X (t), Y (t), Z (t).

Case-study 2. Change manipulator parameters for the following values: crank length l1=110 mm, length from axis of revolute joint of coupler to its finger l2=365 mm, rocker arm length l3=81 mm, fixed link length l4=500 mm, sections of variable pitch as t1=25 mm, t2=75 mm, t3=145 mm. Based on these parameters we have got diagrams describing the change of coordinates X, Y, Z depending on time, they are presented in the Fig. 6. Comparison of diagrams X (t), Y (t) and Z (t) shown in the Fig. 5 and 6 based on the case studies 1 and 2 demonstrates principal distinctions in movement character of output links of five-bar screw-lever manipulators having identical structure and operation principle.

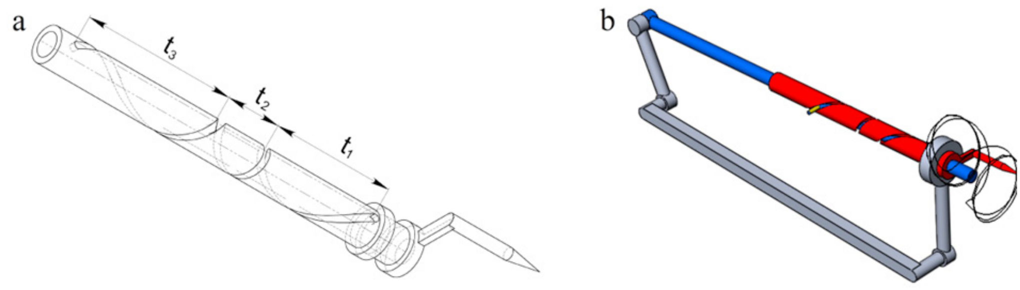

Fig. 4. (a) Geometry of the female link in double-contact screw kinematic pair with variable pitch; (b) kinematic scheme of the five-bar screw-lever manipulator and its reproducible curve.

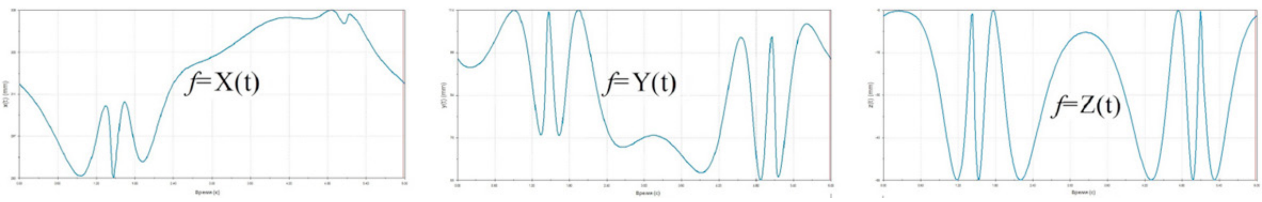

Fig. 5. Coordinate (X, Y, Z) - time (t) curves of the manipulators from case-study 1.

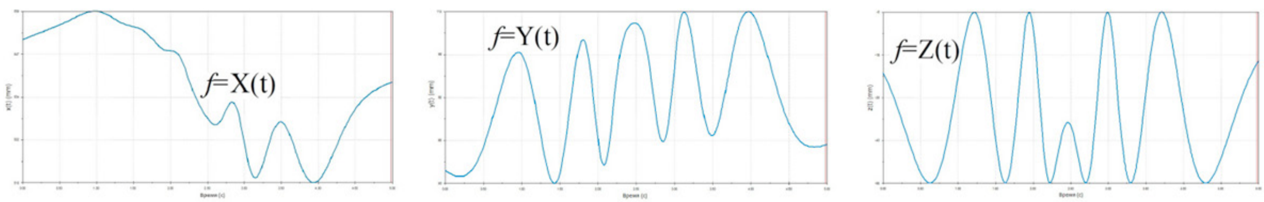

Fig. 6. Coordinate (X, Y, Z) - time (t) curves of the manipulators from case-study 2.

Note that the developed manipulator shown in the Fig. 4a can also reproduce curves with permanent pitch. For this purpose groove on the nut should be formed with fixed pitch. It is also possible to have the groove created by the function of a curve. For example, the Fig. 7a provides manipulator where nut has parabolic groove (Fig. 7b), which is created based on the ground of parabolic function shown in the Fig. 8 and described by the following equation

$$y = \frac{x^2}{136}, \tag{2}$$

where coefficient $\frac{1}{136}$ has been empirically chosen according to the length of the groove (L=160 mm). Number of turns of curvilinear groove depends on this coefficient. Its increase will lead to appear more turns of the groove and decrease of the pitch, alternatively decrease of this coefficient allows to increase pitch and decrease numbers of turns of the groove. So the groove angle as well as its pitch and numbers of turns can be included in the function. Note, that parameters L and H in the Fig. 8 are equaled 160 mm and 47 mm, when the full length of the nut is 190 mm.

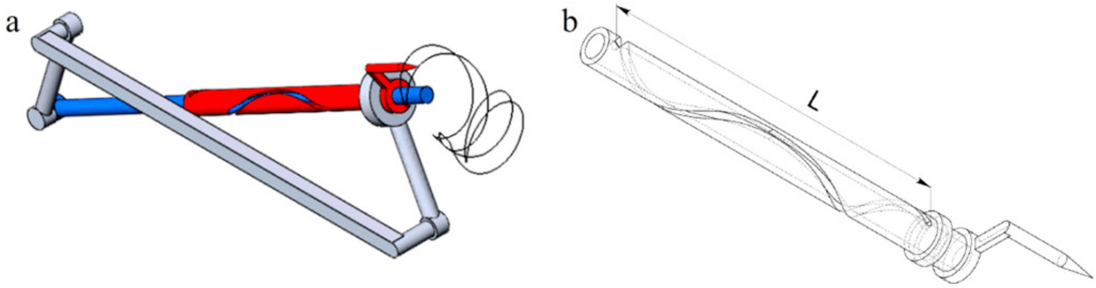

Fig. 7. (a) Screw-lever manipulator with parabolic groove and its end-effector trajectory; (b) nut with the parabolic groove.

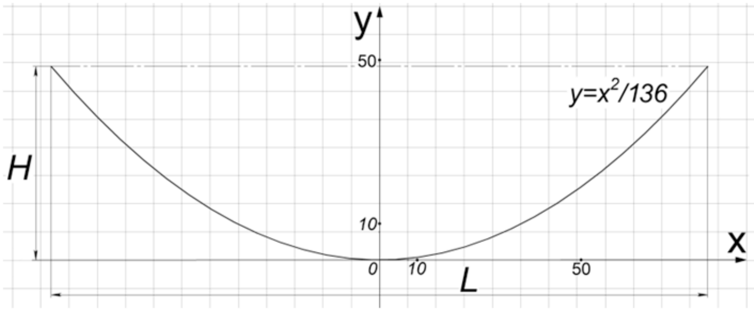

Fig. 8. Parabolic curve prototyping groove in the nut.

Thus, functional capabilities of double-contact kinematic pair allow to make the groove with various geometry. This gives a possibility to correct a reproduced spatial trajectory. The absence of screw on the male link, cylindrical coupler, allows to use various types of nuts with different curvatures of groove.

4. Conclusions and future works

This study proposes new models of single drive input screw-lever manipulators for internal contouring cutting of machine elements. The complex character of output motion also allows to use them for other applications, such as alimentary mixers, deep groove machines or bulk-handling machines. The presented manipulators have simple structure as they include only four movable linear links connected by five kinematic pairs, and at the same time allow to reproduce complex spatial end-efficient trajectories. These trajectories are based on screw curves with curvilinear axes. The idea to use double-contact screw kinematic pair instead of classical single contact screw-and-nut connection greatly expands opportunities for reproduction of different types of curves. Using this pair allows to provide screw trajectories with variable pitch and gives an opportunity to change output links with different curvilinear grooves thus to reproduce various trajectories without changing any other links. Other properties of this pair include possibility to control velocity of output link that is essential for specific areas during cutting processes. These effects became possible after introduction of novel screw pair with variable pitch. In the future, model of screw-lever manipulator (Fig. 4b) will be developed with the opportunity to have output motion in completed Cartesian space with six DoF.

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