

Innovative Design of Cam-Controlled Planetary Gear Trains

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Abstract

The objective of this paper is to perform the innovative design for the new structures of cam-controlled planetary gear trains (CCPGTs), based on the creative mechanism design methodology. Firstly, the design requirements and design constraints are summarized according to the kinematics characteristics of existing CCPGTs. Then, the (4, 5) and (5, 7) graphs are generated by the theory of number synthesis. After that, the atlas of feasible specialized graphs is obtained. Finally, the atlas of new designs is obtained through the particularization process. In addition, an illustrated example is given, and the feasibility of the design is verified by computer simulation using ADAMS software. The result indicates that news design can produce a more wide range of non-uniform motion than the existing design, therefore they are better alternatives for driving a variable speed input mechanism.

Keywords: planetary gear train, cam, innovation design, variable speed mechanism

1. Introduction

Cam-controlled planetary gear trains (CCPGT) are planetary gear trains with cam pairs. Chironis [1] illustrated a CCPGT in his book, as shown in Fig. 1. It is composed of a cam groove (the frame), a sun gear (the output), a planetary gear, and an arm (the input), and its exploded view is shown in Fig. 2. In general, the arm rotates at constant speed, and drives the planetary gear to revolve around the sun gear and to spin around itself simultaneously. At the same time, the planetary gear produces an oscillatory motion through the contact of the attached roller and the cam groove. Therefore, the sun gear can produce a non-uniform motion by engaging with the planetary gear. The main advantage is that it can produce a wide range of non-uniform output motion. In addition, it has the advantages of higher reliability, lower cost, faster response, and higher power transmission due to its mechanical nature. It is now at work in film drives. However, the design and analysis of the CCPGT are not easy due to its complex structure. In addition, few studies on the CCPGT can be found in literature or references.

Hsieh [2-3] proposed the method of kinematic design and control for the CCPGT. A CCPGT can be applied to drive a mechanism at a non-uniform speed. This kind of mechanism is called a variable speed input mechanism. And it was seldom investigated before 1990. Hsieh [4] firstly presented a novel approach to improve the state of the motion of the follower by varying the input speed using a servomotor. After that, Yan et al. [5-6] contributed to improve the output motion characteristics of a mechanism by a servomotor solution. Although the method is effective, there are still some disadvantages exist due to the utilization of a servo motor, for instance, higher cost, a specially designed servomotor required, slow response, and limited output power. A new way to drive the variable speed input mechanism is an open topic to be investigated.

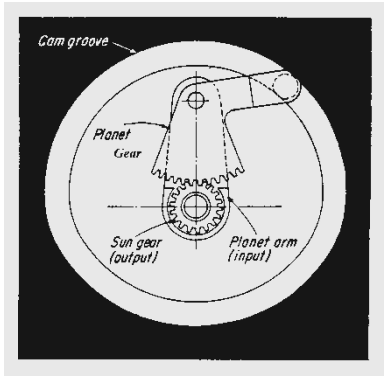


Fig. 1 CCPGT [1]

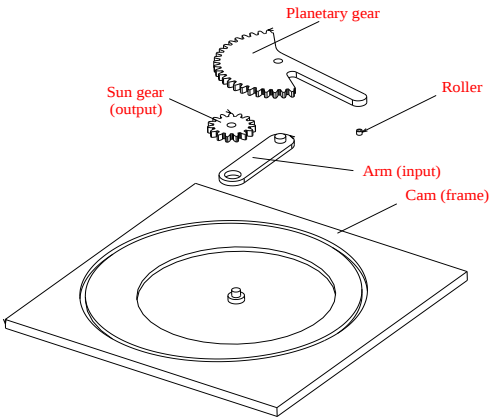


Fig. 2 Exploded view of a CCPGT

The purpose of this paper is to perform the innovation design of cam-controlled planetary gear trains with one degree of freedom. The atlas of new designs with 4 and 5 links will be generated. The feasibility of new designs will be illustrated with an example, and verified by kinematic simulation.

2. Creative Mechanism Design Methodology

The structural synthesis of CCPGTs will be performed based on the creative design methodology process [7-8]. Fig. 3 shows the flow chart for the approach. The process consists of six steps:

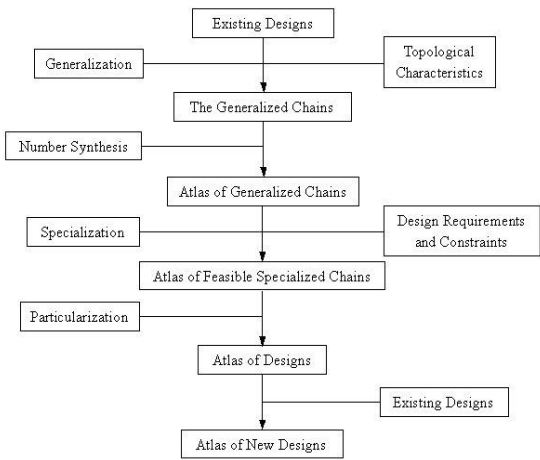


Fig. 3 Creative design methodology

2.1. Existing designs (or original designs)

To search existing design models or study an available new design model with required specifications and to establish

the topological structure of these models are the first step of the methodology. The goal of this step is to select some of these models for researching their equivalent mechanism skeleton and kinematic chain for developing the new designs.

2.2. Generalization

The above original designs are transformed individually into their corresponding generalized chains (kinematic chains). The generalized chain will be involved in various types of members (edges) and joints (vertices, or said kinematic pairs) for all possible assembly in the following steps.

2.3. Number synthesis

The atlas of generalized chains and kinematic chains, respectively, with the required numbers of links and joints, are synthesized for obtaining all possible generalized chains that have the same number of links (N) and joints (J) as the original generalized chain.

2.4. Specialization

Specialization is to assign specific types of members and joints to every available generalized chain subject to certain design requirements to obtain the specialized chains. Among, design requirements are determined based on the concluded topological structure of the original designs.

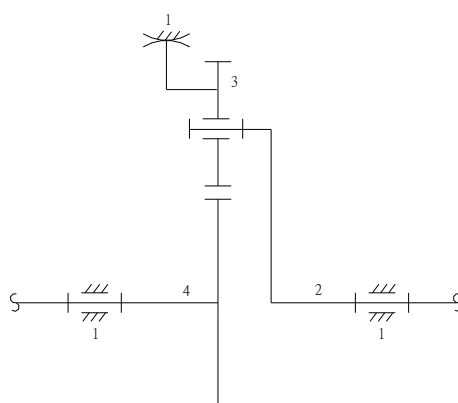
2.5. Particularization

Particularization is the reverse process of generalization. Once a feasible specialized chain is obtained, it is particularized into its corresponding mechanical device in a skeleton drawing.

2.6. Atlas of new designs

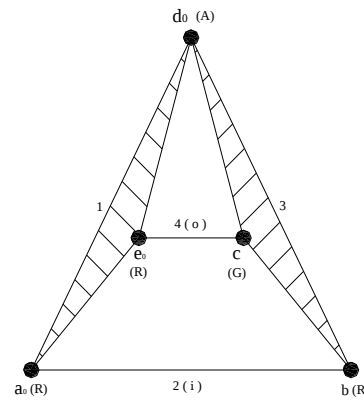
Every feasible specialized chain is particularized into its corresponding mechanical device in a skeleton drawing. Therefore, the last step is to identify all non-existing designs from the atlas of designs as the new designs.

3. Existing Mechanism



(a) Structure sketch

Fig. 4 The existing design



(b) Generalization chain

Fig. 4 The existing design (continued)

The CCPGT in Chironis's book [1], shown in Fig. 1, is selected as the existing Mechanism for structural synthesis. Fig. 4(a) shows its structural sketch. Fig. 4(b) is the corresponding kinematic chain. It consists of 4 links and 5 joints, denoted as (4, 5) chain, including 3 revolute pairs, 1 cam pair, and 1 gear pair. The design requirements and design constraints are summarized based on the characteristics of the mechanism.

3.1. Design requirements

- (1) It has one degree of freedom, therefore one input.
- (2) It is a planar mechanism with four links or more.
- (3) It has at least one cam pair to generate a non-uniform output speed.
- (4) It has at least one gear pair to change the uniform output speed.
- (5) It has a ground link to support or constrain other links.
- (6) It has one output link.

3.2. Design constraints

- (1) The number of links must be 4 or 5 links.
- (2) The frame must be a link with three joints or more in order to have a firm support.
- (3) At least one cam pair must be incident to the frame.
- (4) The input link must be adjacent to the frame with a revolute joint.
- (5) The input link, the output link, and the frame, must be assigned on different links.
- (6) The input link must be assigned to the arm in order to drive the planetary gear to move around the sun gear.
- (7) The arm must be adjacent to a planetary gear with a revolute joint to produce a uniform output rotation.
- (8) The output link must be adjacent to the frame with a revolute joint to produce a rotational output motion.
- (9) The input link and the output link must be in different loops.
- (10) Apart from the input and the output link, all the other links must be a link with 3 or more joints.

4. Generalization and Number Synthesis

Based on the theory of generalization theory [7-8], the generalized kinematic chain of the existing design, shown in Fig. 4(b), is transformed from Fig. 4(a). According to design requirements (1)-(2) and constraint (1), hence the new designs are planar mechanisms of one degree of freedom and with 4 or 5 links. The equation of the degree of freedoms can be obtained by

$$F=3(N-1)-2J_1-J_2 \quad (1)$$

105 where F is the degree of freedoms, J_1 is the number of joints with i degree of freedom. The link assortments can be found by

106
$$J=J_1-2J_2$$
 107 (2)

108 When F and N are specified, then their corresponding kinematic chains are found and denoted as (4, 5) and (5, 7) chains,
109 respectively, based on the theory of number synthesis. Since a graph is more concise to represent the topology structure and
110 easier to distinguish isomorphs than a kinematic chain, it is adopted here for synthesis. Furthermore, Fig. 5 shows the
111 corresponding graphs of (4, 5) and (5, 7) chains generated by Hsu [9], therefore it is not necessary to generate their atlas of
generalized graphs by number synthesis. In addition, the number of graphs for the atlases of (4, 5) and (5, 7) generalized graphs
are 3 and 13, as shown in Fig. 5(a) and (b), respectively.

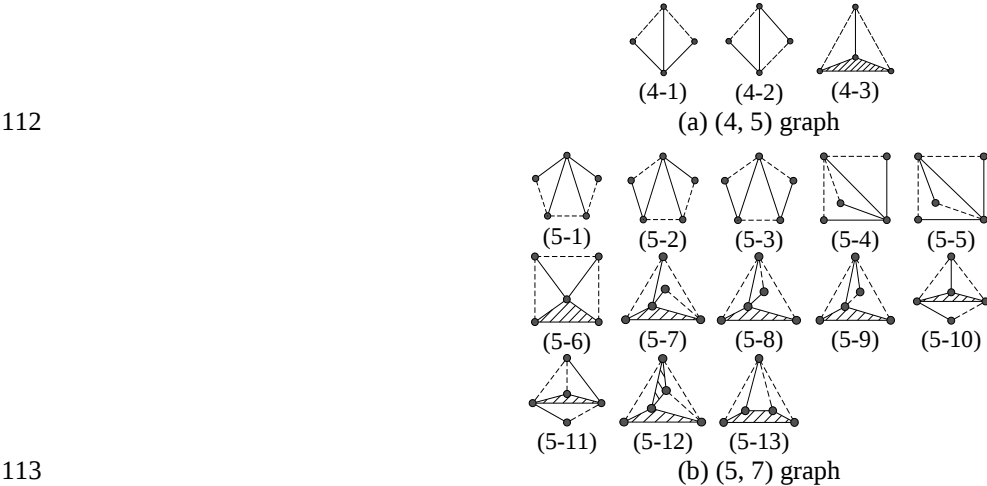


Fig. 5 Atlas of graphs of geared kinematic chains

115 **5. Specialization**

116 The objective of specialization is to obtain the whole atlas of specialization chains (graphs) by assigning various types of
117 members and joints to each available generalized chain (graphs) subject to the design requirements and design constraints
118 specified above.

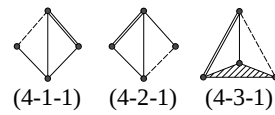
119 According to these design requirements, the specialized joints and members include cam pairs, gear pairs, the frame, the
120 input, and the output. Their symbols and representations are listed in Table 1. The whole process proceeds according to the
121 follows:

Table 1 Graph representations

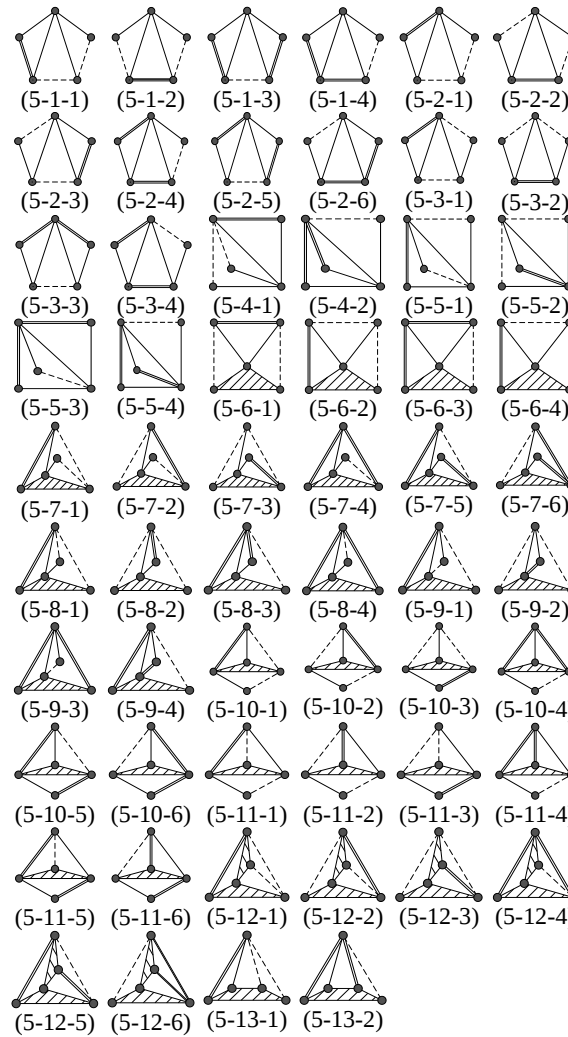
Symbols	Definitions
—	Revolute pair
—	Cam pair
—	Multiple joint
—	Gear pair
(f)	The frame
(i)	The input
(o)	The output

124 **5.1. Assigning cam pairs and gear pairs**

125 As indicated in design requirements (3) and (4), there must be one or more cam pairs, and the same for gear pairs. By
126 assigning them to Fig. 5, 3 and 58 specialized graphs for (4, 5) and (5, 7) graphs are obtained, respectively, shown in Fig. 6(a)
127 and 7(b).



(a) (4, 5) graph

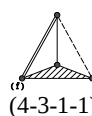


(b) (5, 7) graph

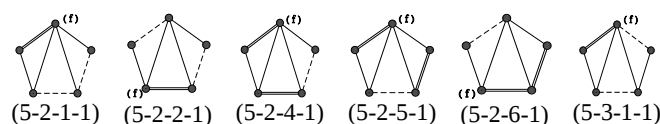
Fig. 6 Atlas of specialized graphs – assigning cam pairs & gear pairs

5.2. Assigning the frame (member f)

Since there must be a frame as indicated in design requirement (5), and the frame must be a link with three joints or more, and incident to a cam pair, as stated in design constraints (2) and (3), respectively. By specifying the frame to Figs. 7(a) and 7(b), 1 and 75 specialized graphs for (4, 5) and (5, 7) graphs that meet the above requirement and constraints, are obtained and shown in Fig. 8(a) and Fig. 8(b), respectively.



(a) (4, 5) graph



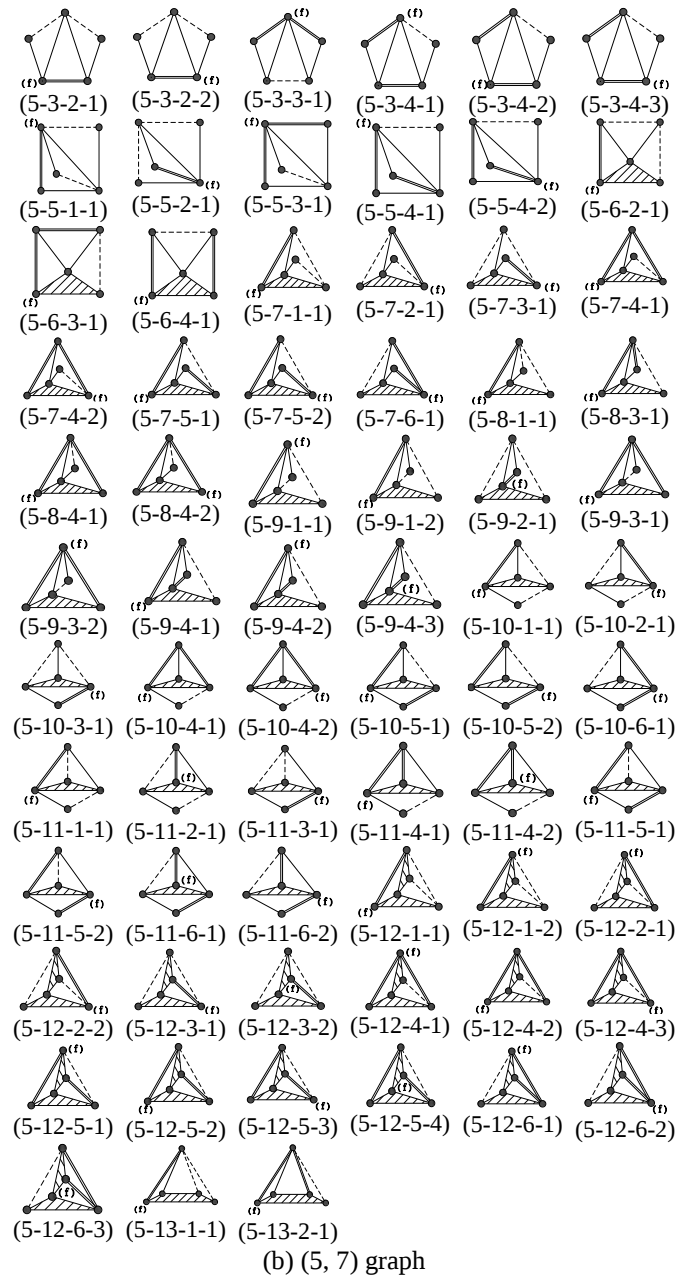
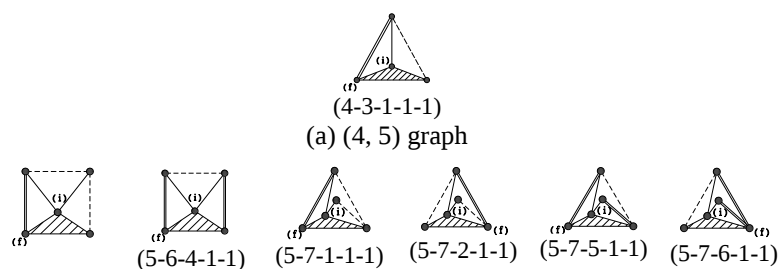


Fig. 7 Atlas of specialized graphs – assigning the frame

5.3. Assigning input link (member i)

According to design requirement (1) and constraints (4)-(5), respectively, there must be an input link, it must be adjacent to the ground link with a revolute pair, and it must be a different link with the ground link. Moreover, from design constraints (6)-(7), the arm must be the input link, and incident to a planetary gear with a revolute pair. 1 and 26 specialized graphs for (4, 5) graphs and (5, 7) graphs, as shown in Fig. 8(a) and Fig. 9(b), are obtained by assigning the input link to Fig. 8(a) and Fig. 8(b), respectively.



(5-6-2-1-1)

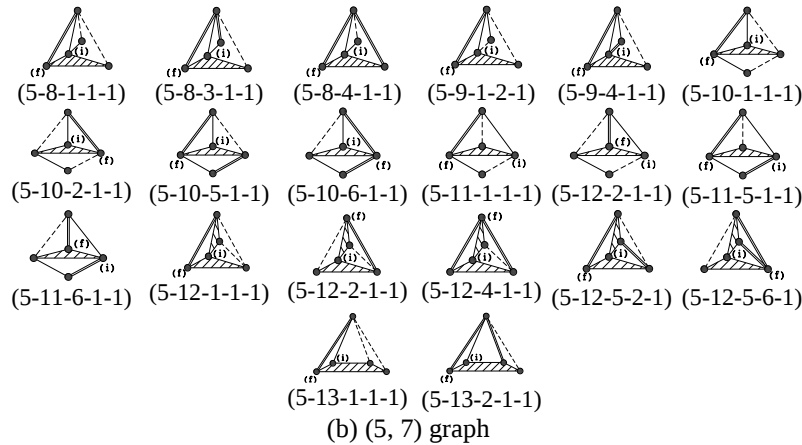


Fig. 8 Atlas of specialized graphs – assigning the input

5.4. Assigning Output link (member o)

Based on design requirement (5), there must be an output link. Furthermore, the input link, output link, as well as ground link, must be assigned on different link, the output link must not be adjacent to the ground link with a revolute joint, the input link and the output link must be in different loops, according to design constraints (7)-(9), respectively. In addition, according to design constraint (10), all the other links, except the input and the output links, must be a link with three joints or more. 1 and 3 specialized graphs for (4, 5) and (5, 7) graphs, as shown in Figs. 10(a) and 10(b) are generated by assigning the output link to Figs. 9(a) and 9(b), respectively.

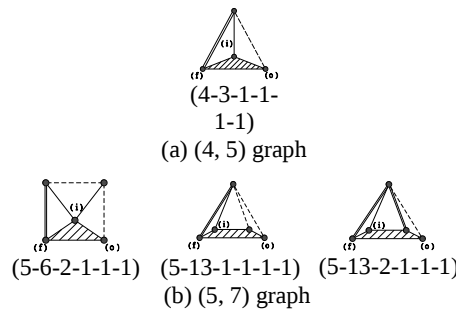


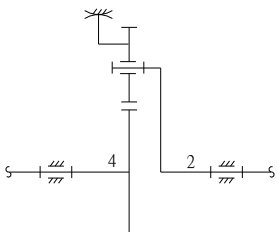
Fig. 9 Atlas of specialized graphs – assigning the frame

6. Particularization

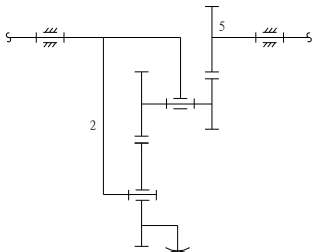
The next step of the creative design methodology is to particularize each feasible specialized graph, by applying the generalizing rules backwards to obtain the corresponding schematic diagram of the CCPGT. Moreover, the atlas of corresponding mechanisms shown in Figs. 11(a) and (b)-(d) is generated from the feasible specialized graph, shown in Figs. 10(a) and 10(b). The input link and the output link are denoted as link 2 and link 4 in Figs. 11(a), but link 2 and link 5 for Figs. 11(b)-(d).

7. Atlas of New Designs

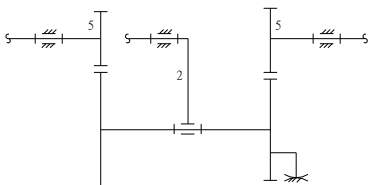
The atlas of new designs can be obtained by subtracting the existing mechanism from the feasible schematic diagram. The design configuration shown Fig. 10(a) is the same as the existing design in Fig. 4. Therefore, only 3 new designs are synthesized from (5, 7) graph, but none for (4, 5) graph.



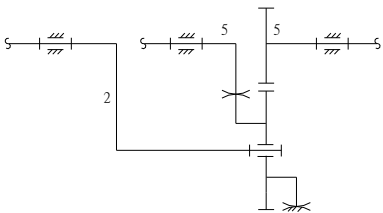
(a) (4-3-1-1-1-1)



(b) (5-6-2-1-1-1)



(c) (5-13-1-1-1-1)



(d) (5-13-4-1-1-1)

Fig. 10 New designs

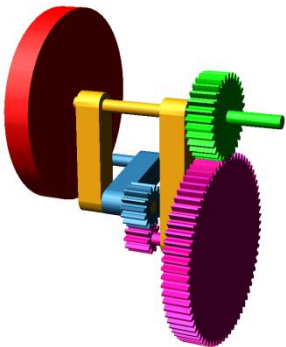


Fig. 11 Solid model

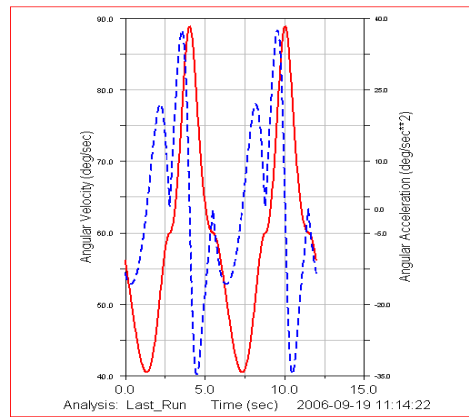


Fig. 12 Kinematic simulation

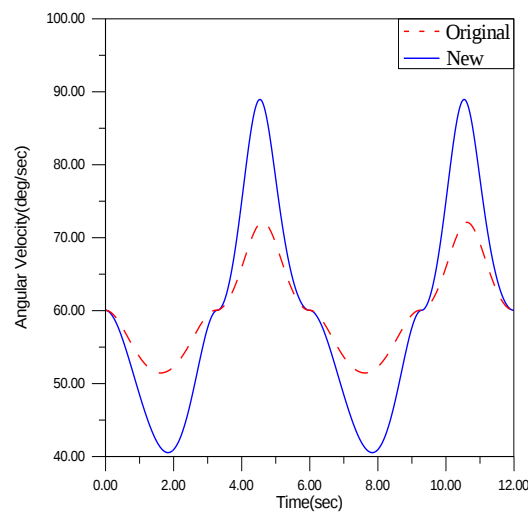


Fig. 13 Comparison

8. Design Example

After the atlas of new designs is obtained, a detailed design can be carried out by selecting one from the atlas. Here, Fig. 10(b) is selected as a design example, and its solid model is drawn and shown in Fig. 11. Compared to the exist design, the design example has an additional compound gear, therefore much larger speed reduction cam be obtained. Moreover, the numbers of teeth of the sun gear and the planetary gear are set as 30 and 15, respectively, for both the existing design and the design example. The numbers of teeth of gears meshing with the sun gear and the planetary gear is 70 and 10, respectively. And the cam profiles of both designs are identical. After that both designs are introduced into ADAMS software for kinematic simulation. Fig. 12 shows the angular velocity (solid line) and the acceleration (dashed line) of the design example. Fig. 13 shows their comparison. It is found that the maximum angular velocity can be increased about 125%, compared to the existing design.

9. Conclusions

In this paper, the new designs of CCPGT have been generated in a systematic methodology. Firstly, the design requirements and design constraints are summarized based on the characteristics of the existing CCPGT. Then, the atlas of new designs are obtained through the process of the creative mechanism design approach, and 3 new designs synthesized from (5, 7) graph have been obtained. Finally, the feasibility of the new designs is verified by conducting kinematic simulation. The result has shown that the new designs can produce a more wide range of non-uniform output motion than the existing design, and are better alternatives for driving a variable speed input mechanism.

Conflicts of Interest

Authors must identify and declare any personal circumstances or interest that may be perceived as inappropriately influencing the representation or interpretation of reported research results. If there is no conflict of interest, please state "The authors declare no conflict of interest."

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Author Contributions

Author **X** contributed to the conceptualization, methodology, investigation, data curation, formal analysis, and preparation of the original manuscript draft. Author **Y** contributed to software development, validation, visualization, and critical review and editing of the manuscript. Author **Z** supervised the research, managed project administration and resources, and critically reviewed and approved the final version of the manuscript. All authors contributed substantially to the research, have read and approved the final manuscript, and agree to be accountable for all aspects of the work.

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