Journal of Applied Sciences

ISSN 1812-5654

Journal of Applied Sciences 13 (10): 1828-1832, 2013
ISSN 1812-5654 / DOI: 10.3923/jas.2013.1828.1832

Mechanical Conceptual Design Based on Kinematics Characteristic

[1]J.J. Qin, [2]Y.A. Yao and [1]Y.F. Liu
[1]Department of Mechanical-electronic and Vehicle Engineering,
Beijing University of Civil Engineering and Architecture, 100044 Beijing, China
[2]School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, 100044 Beijing, China

Abstract: This study discusses the conceptual design process based on kinematics characteristic and proposes how to analyze the feasible design scheme combinations on the basis of kinematics characteristic analysis. The possible kinematics characteristic of target scheme can be expressed by the possible typical form in the intermediate process from initial state to target state. The scheme solving process means the process in which function conversion element can generate the state of satisfying output. Function conversion generator, which relates to structural forms, can work out the overall scheme that meets design requirements through the combinational computation between mechanisms.

Key words: Conceptual design, scheme innovation, kinematics characteristic, user participation

INTRODUCTION

Different from ordinary daily necessities, mechanical products are designed based on the core which aims to present structural design scheme for satisfying the output of special kinematics characteristic. It turns out that natural structure characteristic and kinematics characteristic constitute the core of innovative design of mechanical products. At an early stage, the design methods of mechanical products stemmed from theory of mechanism, such as, the study on mechanical structure and function made by Freudenstein and Maki (Freudenstein and Maki, 1979). Based on the thoughts of graph theory, Freudenstein (Erdman, 1993) devoted pioneering efforts to mechanical innovative design and studied synthetic algorithms of various typical mechanisms based on the degree of freedom and the quantity of components. On this basis, Cai Longwen started with the functional characteristics of mechanical devices, as well as proposed calculating, analyzing, synthesizing and innovating on the actual practice of the projects such as automobile gearbox. Professor Yan Hongsen from National Cheng Kong University presented regenerative kinematics chain for innovative design of mechanisms on the basis of graph theory(Yan, 1998), with structural characteristics of mechanisms as major focus in the early research. Kota et al. firstly put forward automatic synthetic theory for conceptual design of mechanical device, with automatic synthesis methods composed of two approaches. The first approach obtained the independent functional unit by means of decomposition and then figured out overall design methods by dint of synthetic scheme, which was called synthetic method. Another approach preset the functional parameters of every functional module and worked out the final design scheme through motional conversion between input/output force and displacement characteristic, which was called elimination method. It is proved that the latter is more suitable for computer calculation.

Sauders *et al.* (2011) classified innovations of mechanical products into five categories, including functional innovation, structural innovation, external interaction, user interaction and cost, among which user interaction means that compared with rival's products, the products can be used more easily. The major improved contents comprise the improvements of physical demand, feeling demand and spiritual demand.

This paper analyzes how to figure out the complete and feasible schemes through the scheme combinations of mechanisms based on the analysis about kinematics behavior and characteristic. Then, it achieves the optimal user experience process by making improvements and optimizations from the perspective of ease of use.

PRODUCT'S EASY OF USE AND STATE DESCRIPTION

Products aim to meet special requirements or corresponding functions. However, initial requirements are required to be further decomposed and classified, because at the initial phase, design requirements are often obscure. At the early design stage, it is only necessary to

Corresponding Author: Jianjun Qin, Department of Mechanical-electronic and Vehicle Engineering,
Beijing University of Civil Engineering and Architecture, 100044 Beijing, China Tel :86-10-68322420

analyze the specific behavioral state characteristic of design scheme, which can be expressed by the relationship between time and kinematics characteristic. State analysis should mainly give consideration to the kinematics characteristics including displacement change and angle change and borrow an insight from the description methods of the pose in robotics to describe the state to be solved (Kurfess, 2010), with *S* representing motion output end.

First, let $_P S$ be the location of S. In a rectangular coordinate system {A}, motion output location can be expressed in the form of column vector:

$$ {}_P^A S = [x_s, y_s, z_s]^T \tag{1} $$

Concerning motion forms, motion output end S has a translational displacement along three coordinate axes respectively, including T(x, Δx), T(y,Δy) and T(z,Δz). Concerning the azimuth of S, let another rectangular coordinate system {B} be fastened to the components; then, the azimuth of S can be expressed by the matrix constituted by the direction cosines of X_B,Y_B,Z_B relative to {A}, where X_B,Y_B,Z_B are {B}'s three principle unit vectors. See below:

$$ {}_B^A S = [\theta_x, \theta_y, \theta_z]^T \tag{2} $$

The common rotation form is to rotate around three coordinate axes based on a certain angle θ. The angles θ based on which S rotates around three coordinate axes are respectively expressed as R(x,θ), R(y,θ) and R(z,θ).

The description of working state mainly gives consideration to the relationship between two adjacent states. The approach of state transition is associated with degree of freedom or the quantity of the mechanical devices that work independently. Assuming there are two kinetic units working independently, the change of state with the times can be expressed by Fig. 1.

The innovative design of the scheme is aimed at finding the solution that satisfies specific state transition to finally satisfy the change of pose and azimuth from initial to target locations, as well as output end's requirement on target location. Besides, within specific constraints, the design satisfies the time and displacement characteristics of locus. Taking motion locus of two-dimensional plane for example, Figure 2 shows several states from initial location to target location. Figure 2a and b have no rotary motion. Figure 2a has a displacement according to linear relationship and Fig. 2b has a displacement or rotates around the axis which is perpendicular to *xoy* plane according to non-linear relationship. When rotating, Fig. 2c moves according to non-linear relationship.

For convenience, the motion locus can be expressed in the form of locus matrix. The process from initial state S_0 to target state S_T is accomplished by one step. State locus matrix can be expressed as below:

$$ {}_T^0 S = [\Delta x, \Delta y, \Delta z, \Delta\theta_x, \Delta\theta_y, \Delta\theta_z] \tag{3} $$

If the process is accomplished by various steps, state locus matrix, with two-step displacement as an example, can be expressed as below:

$$ {}_1^0 S + {}_T^1 S = {}_1^0[\Delta x, \Delta y, \Delta z, \Delta\theta_x, \Delta\theta_y, \Delta\theta_z] + {}_T^1[\Delta x, \Delta y, \Delta z, \Delta\theta_x, \Delta\theta_y, \Delta\theta_z] \tag{4} $$

In the stage of conceptual design, consideration should be only given to the macroscopic property of variables in state locus matrix. Several figures in variable relation can be defined as below:

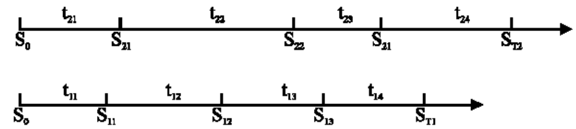

Fig. 1: The work state transformation and the time interval indicates

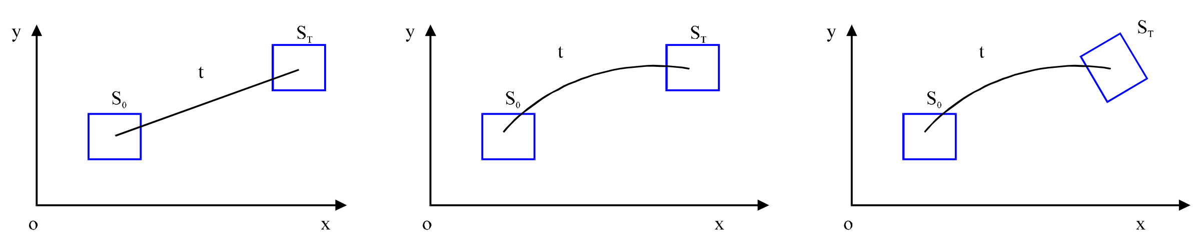

Fig. 2: Time and displacement characteristics of the initial state to the target state

- 0 means that there is no displacement in this direction
- 1 means the displacement in this direction is of some significance, which indicates that there is a linear relationship between displacement motion and time t, or the relationship between them can be simplified as linear relationship
- -1 means displacement in this direction shows some significance and moves to the opposite direction as defined, which suggests that there is a linear relationship between displacement motion and time t, or the relationship between them can be simplified as linear relationship
- 2 means the displacement in this direction is of some significance, which suggests that there is a linear relationship between displacement motion and time t^2 or the relationship between them can be simplified as linear relationship
- 0.5 means that the displacement in this direction is of some significance, which indicates that there is a linear relationship between displacement motion and time $\sqrt{t}$ or the relationship between them can be simplified as linear relationship

Sometimes, the required mechanical devices are comparably complicated, which thus cannot be easily described through the first layer of kinematics characteristics. As a consequence, it will be difficult for the later scheme designs to find a solution and therefore, the design requirements will be required to be decomposed to make every design requirement more clear and provide more conveniences for finding a solution. Decomposition can help to get more specific requirements of kinematics characteristics, which can be expressed as below:

$$S_0 = \{S_1, S_2, S_3, \ldots\} \quad (5)$$

$$S_1 = \{S_{11}, S_{12}, S_{13}, \ldots\} \quad (6)$$

where S_0 means the first layer and S_1, S_2 the second layer. Besides, the expressions of other corresponding layers can be extended on the basis of the previous layer. Similar requirements can be decomposed and extended as below:

$$\begin{aligned} S_0 &= \{S_1, S_2, S_3, \cdots\} \\ &= \{\{S_{11}, S_{12}, \cdots\},\ \{S_{21}, S_{22}, \cdots\},\ \cdots\} \\ &= \cdots \end{aligned} \quad (7)$$

FUNCTION CONVERSION ELEMENT

The design process of mechanical devices is to find the solution that satisfies design requirements and work out the internal logical relation of scheme solutions. A certain mechanical device should comprise one or more basic mechanisms, which cannot be decomposed into other units that work independently, such as slider-crank mechanism and level-1 spur gear mechanism. Function conversion element can be viewed as a state generator, which achieves state change through the motion conversion between input and output and then realizes a certain function of a product. Besides, it can also realize the conversion of a certain kinematics characteristic between input and output, such as linear displacement and angular displacement.

A function conversion element can fulfill one or more design requirements. The function conversion element set that can fulfill all design requirements can be integrated as an overall scheme of mechanical devices. Therefore, function conversion element is the bridge between design requirements and specific design scheme. A function conversion element is consisted of input, serial number and output modules. A particular function conversion element may have one or more motion input modules, which can be power unit or other function conversion modules. Function conversion element can directly satisfy design requirements through motion output or output them to other function conversion elements.

If a certain motion output is accomplished by several function conversion elements, then these function conversion elements might maintain a relationship in parallel, in series or in parallel and series at the same time. Similarly, if a certain function conversion element is equipped with various input or output modules, then these modules could cross each other.

Basic mechanism can be expressed as type of mechanism, input, output and corresponding characteristics, among which input and output can be expressed as kinematics characteristics.

For the users, the output rotation behaviors comprise unscrew, twist, turn, swing, pedal, etc; the output movement behaviors include press, lift, pull, etc; the behaviors of output curve consist of dig, raise, stamp, kick, etc. For a mechanical device, motive force often moves in a rotary way or in line. The input of a mechanism may be the output of motive force or the output of other mechanisms and the output of mechanism can be a curvilinear motion. See Figure 3 for the common combinational algorithms of the motions.

Design requirements can be expressed by the output of function conversion element and besides, basic mechanisms and units can be integrated as the mechanical device that realizes the conversion between input and output motions. Chiou and Sridhar classified basic motion function modules into four categories (Kota and Chiou,

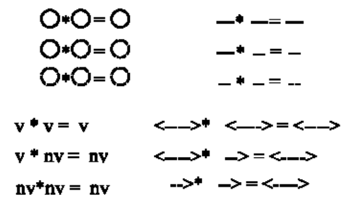

Fig. 3: Logical operations of the movement characteristics

1992), including translation to translation, rotation to rotation, rotation to translation and rotation to spiral. The mechanisms corresponding to these four categories can be classified and collated. Analysis on kinematics of mechanism mainly gives consideration to the motion forms including translation and rotation. If function conversion element is perceived as a comparably interdependent module, its input and output would be more special, which may involve the motion types of input and output, rather than the specific conversion process. As a result, the forms of curvilinear motion will be increased. In the process of mechanism design, basic mechanisms are usually combined into complicated mechanism forms. Though an independent basic mechanism has complicated input and output forms, translation and rotation are the general motive force input forms of the whole mechanical device.

For ordinary designers, it is easy to understand the translational and rotational motions, whereas the composite motion is comparably complicated, which can be expressed as the superposition of translation and rotation. Plane curvilinear motion is related to the translation and rotation of two dimensions, while space curve motion may be associated with the translation and rotation of three dimensions. According to motion conversion forms, functions can be divided into night forms. Meanwhile, based on this Table, more subtypes can be extended. Mechanism can realize the motion conversion from input to output and the corresponding motion conversion needs to clearly describe the conversion forms.

The matrices for motion's input and output characteristics are M_{input} and M_{output}. Let $\{P_i\}$, i>0 be the target mechanism set that satisfies the requirements of input and output characteristics. The scheme solving based on kinematics characteristics is to work out the scheme $M_{output}=P_i(M_{input})$ that satisfies the conversion from motion input to output in target mechanism. That is, input and output motion characteristics (M_{input}, M_{output}) can be expressed in the matrix form of motion characteristics:

$$M_{input} = \left[R_x^{in}, R_y^{in}, R_z^{in}, T_x^{in}, T_y^{in}, T_z^{in}\right] \tag{8}$$

$$M_{output} = \left[R_x^{out}, R_y^{out}, R_z^{out}, T_x^{out}, T_y^{out}, T_z^{out}\right] \tag{9}$$

MATRIX OPERATION OF INPUT AND OUTPUT

Kota and Chiou presented a qualitative matrix operation method of input and output kinematics transformation, which was associated with output state matrix, input state matrix, Motion Transformation Matrix (MTM) and basic constraint matrices. For basic characteristic matrix, the operational rule is shown as below:

$$\{M_{output}\} = \{M_{MTM}+M_{BCM}\}\ \{M_{input}\} \tag{10}$$

The kinematics transform matrix from input state to output state can be expressed as below:

$$MTM = [S_{in}]\bullet[S_{out}]^T = \begin{array}{c} \\ R_x^{out} \\ R_y^{out} \\ R_z^{out} \\ T_x^{out} \\ T_y^{out} \\ T_z^{out} \end{array} \begin{array}{c} \begin{array}{cccccc} R_x^{in} & R_y^{in} & R_z^{in} & T_x^{in} & T_y^{in} & T_z^{in} \end{array} \\ \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} & x_{16} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} & x_{26} \\ x_{31} & x_{32} & x_{33} & x_{34} & x_{35} & x_{36} \\ x_{41} & x_{42} & x_{43} & x_{44} & x_{45} & x_{46} \\ x_{51} & x_{52} & x_{53} & x_{54} & x_{55} & x_{56} \\ x_{61} & x_{62} & x_{63} & x_{64} & x_{65} & x_{66} \end{bmatrix} \end{array} \tag{11}$$

in which rows show the input motion forms; columns show output motion forms. If x_{ij} to which i row and j column correspond is 1, then function conversion element could realize the motion output from this row to this column. Otherwise, x_{ij} is 0.

Basic constraint matrix includes all 6 types of constraint elements involved in the table. Along the same diagonal of the matrix, they can be expressed as below:

$$BCM = \begin{bmatrix} \bigcirc & 0 & 0 & 0 & 0 & 0 \\ 0 & \pm & 0 & 0 & 0 & 0 \\ 0 & 0 & \text{-->} & 0 & 0 & 0 \\ 0 & 0 & 0 & v & 0 & 0 \\ 0 & 0 & 0 & 0 & p & 0 \\ 0 & 0 & 0 & 0 & 0 & c \end{bmatrix} \tag{12}$$

If the mechanical devices are obtained from the combinations of the basic function conversion element, then their constraints could satisfy product formula as below:

$$BCM = BCM_i \cdot BCM_j \tag{13}$$

CONCLUSIONS

The analysis on product state in application process and its kinematics characteristics can help to figure out the feasible mechanism forms. For one thing, it follows the basic analysis rules that start with the analysis about user's requirements for products and for another, it contributes greatly to deepening engineers' understanding on design. In this way, engineers can not only come up with innovative solutions with more ease, but also work out specific scheme that can meet operating requirements through combining with the constraint of actual operating condition and structural optimization.

ACKNOWLEDGMENTS

This work is supported by the supported by National Natural Science Foundation of China(Project number: 51175030), Funding Project for Academic Human Resources Development in Institutions of Higher Learning Under the Jurisdiction of Beijing Municipality(Project number: 201106125) and by Open Research Fund Program of Beijing Engineering Research Center of Monitoring for Construction Safety (Beijing University of Civil Engineering and Architecture).

REFERENCES

Erdman, A.G., 1993. Modern Kinematics: Developments in the Last Forty Years. John Wiley and Sons, New York, USA., ISBN-13: 9780471554592, Pages: 604.

Freudenstein, F. and E.R. Maki, 1979. The creation of mechanisms according to kinematic structure and function. Environ. Plann. B, 6: 375-391.

Kota, S. and S.J. Chiou, 1992. Conceptual design of mechanisms based on computational synthesis and simulation of kinematic building blocks. Res. Eng. Des., 4: 75-87.

Kurfess, T.R., 2010. Robotics and Automation Handbook. CRC Press, Boca Raton, FL., USA., ISBN-13: 9780849318047, Pages: 608.

Saunders, M.N., K. Holtta-Otto and C.C. Seepersad, 2011. The characteristics of innovative, mechanical products. J. Mech. Des., Vol. 133, No. 2.

Yan, H.S., 1998. Creative Design of Mechanical Devices. Springer-Verlag,Singapore,ISBN-13:9789813083578, Pages: 242.