Summary of ten innovations in the machinery field--- the analysis on material processing contrary the mechanical principles etc.

C M Li¹², X L Yin¹, Y Zhang¹³, F Sun¹, H Cao¹, Q Liu¹, X Liu¹

¹ Shengli College in China University of Petroleum, China University of Petroleum (East China), Dongying 257061, China
² School of Mechanical and Electronic Engineering, China University of Petroleum (East China), Qingdao 266580, China
³ School of Pipeline and Civil Engineering, China University of Petroleum (East China), Qingdao 266580, China
lchming@126.com; 086-18366939536

Abstract. Ten innovations in the mechanics field are summarized. For the pre-published innovations, only the results are introduced. 1) The analysis of the diamond cutting tools characteristics based on the principle of the metal outflicting the wood. We create the word “outflict”. Its affix means surpassing, suppressing, holding high, having ability to defeat, conquer and constraint. Its morpheme means conflicting and striking. 2) The concept of mechanical principle. For instance, the structure body is classified into rod, block and plate. 3) The mechanism combination analysis method instead of body group and multibody mechanism. 4) A unified moment balance equation of rigid body. 5) The harmonic composition and decomposition method for the body position angle of crank rocker mechanism. 6) Definition of kinematics bifurcation position, including dead point. 7) Indefinite application in mechanical dynamics. 8) The assembly graphic method for vector equation with too many unknown quantities. 9) The derivation process of the velocity ratio formula of the coupling. 10) Velocity zero correction method considering the characteristics of static friction.

1. Introduction
Machinery is a subject based on mechanics and mathematics. The problems in the machinery field also promote the mechanics development. Machinery is the foundation of many disciplines. Chemical industry, materials, petroleum and mining all come from this discipline, and manufacturing is one of the main research fields of this discipline.

In recent years, we have made many innovative achievements and conclusions in mechanical manufacturing, mechanism kinematics, mathematical infinity application, friction dynamics model, vector equation graphic method, mechanism combination method and universal joint velocity ratio formula. For the innovations unpublished in journals, this paper only introduces its results.

2. Analysis on material processing which is contrary the mechanical principle
We create the word “outflict”. It means “ke” in Chinese. Its affix “out” means surpassing, suppressing, holding high, having ability to defeat, conquer and constraint. Its morpheme “flict” means conflicting and striking. Diamond tools can cut general metal materials, but they can't cut high strength steel and...
ultra-high strength steel[1]. Water jet and diamond tools are suitable for cutting glass, but tools for cutting ultra-high strength steel are not.

The five elements: all substance can be divided into five kinds. It is the general name of these five kinds of substance. The five elements are the metal, the wood, the water, the fire and the soil.

Diamond: it is composed of carbon element, so it belongs to the wood in the five elements.

Metal material: composed of metal, of course, it belongs to the metal in the five elements.

The natural law of the metal outfighting the wood: The metal naturally confronts the wood. The metal can conquer and defeat the wood as well as make the wood disappear.

The reason why diamond can cut general metal materials: the hardness of diamond is much higher than that of the material to be cut. According to the nature of the metal outfighting the wood, after the resisting of two elements each other, the soft material deforms, only separates without damage.

The reason why diamond can’t cut high strength steel and ultra-high strength steel: the hardness of the material to be cut is high enough. According to the nature of the metal outfighting the wood, the cutting tool will be damaged.

Glass: it is composed of silica and belongs to the soil in five elements.

The reason why diamond tools can cut glass: the nature of the wood outfighting the soil.

The reason why the water jet can process glass crafts: the nature of the soil outfighting the water.

The reason why the cemented carbide tool can't cut glass: the tool has no wood component. It can cut glass into pieces, but can not divided the glass according to the given shape.

3. Scientific concept of mechanical principle
Mechanical principle is based on theoretical mechanics and multibody dynamics, and its concept should be consistent with that of basic disciplines. It is certainly unscientific that the same body is called swing block when drawn into a block and a track rod when drawn into a line. Therefore, the concepts of mechanical principle are supposed to be redefined and named as the following.

Mechanical motion: the motion of one objects can be obtained from the motion of other object, and there is a certain relationship among the motion of all objects. Such a motion is called mechanical motion.

Machinery: the main tool to replace or reduce human labor and increase labor productivity. It is a theoretical model or objective device composed of several parts with definite mutual motion and with certain functions. Machine: a movable objective device that performs mechanical motion. Mechanism: a theoretical model for performing mechanical motion.

Structure body (component): An independent object moving in a mechanism or machine.

The characteristics of the structure body in the mechanism: it is rigid and can be abstracted as the body formed by the rigid connection of each motion pair element.

Three freedoms (independent motions) of a body moving in the plane: 2 mutual vertical moving motions and 1 rotating motion. Kinematic pair: the connecting part between every two bodies.

Rotating pair: Two bodies connected with a cylindrical surface. If one body rotates relatively to the other, its two moving freedoms are constrained. Such a motion pair belongs to the biconstraint pair, which is called the low pair before. Moving pair: Two bodies connected with a plane or two points or lines on the track. If one body moves relatively to the other along the track, its one moving freedom and one rotating freedom are constrained. It also belongs to the biconstraint pair.

Pure Rolling pair: Two bodies connected with a point or line. If one body can only roll relatively to the other, its two moving freedoms are constrained. It also belongs to the biconstraint pair.

Rolling and sliding pair: Two bodies connected with a point or line. If one body is rolling and sliding relatively to the other, its moving freedom perpendicular to the sliding direction is constrained. Such a motion pair belongs to the monoconstraint pair, which is called the high pair before. Rod: structure body with two or more rotating pairs, including crank, rocker, connecting rod, multi pair rod, etc. Block: a structure body with one rotating pair, including slider, track rod, swing block, etc. Plate: structure body without rotating pair. The slider of crank slider mechanism: this block can be regarded as an infinitely long rod which is perpendicular to the track path and from the rotating pair C to...
infinity far. The slider track: the straight / curve line parallel to the motion track when passing the rotating pair. Freedom degree: Freedom number is the independent motion number.

4. Mechanism combination analysis method instead of body group and more-bodies mechanism

It is a classic content of mechanical principle to analyze complex mechanism with body group and multibody mechanism. With more knowledge points, it is more difficult. Mechanism combination design is one of the classic contents of mechanical innovation design. The analysis of some complex mechanisms is ambiguous, and the former definitions of four combination types overlap, so it is difficult to analyze complex mechanisms.

Composed of four structure bodies, the crank rocker mechanism can be considered as the most basic mechanism. The plane quabody mechanism can be considered the result of the crank rocker mechanism changing the length of some bodies. The cam mechanism can be considered as the result of quabody mechanism replacing one body and two two-constraint motion pairs by one one-constraint motion pair. Gear mechanism and worm mechanism can also be considered as the evolution of quabody mechanism. Intermittent motion mechanism can be regarded as the deformation of basic mechanism. In the belt transmission mechanism, there is a pure rolling pair between the belt and wheel, which belong to the biconstraint pair. The engagement of the chain and wheel in the chain drive mechanism is also a biconstraint pair.

Fig.1 Four types of mechanism combination

On the basis mechanism, two-freedoms mechanism is evolved by adding a body, adding a freedom of motion pair or releasing a fixed body constraint. The combination of several basic mechanisms according to certain rules is called mechanism combination. Every time a basic mechanism is added, a freedom will be added. And every time two bodies are consolidated, a freedom will be subtracted. There are mainly four types (in Figure 1): 1) Serial connection. One output of the front mechanism is the input of the back mechanism, and both have one pair of body consolidating. 2) Parallel connection. The motion of the two basic mechanisms has the form of parallel connection with one or more pairs of body consolidating. For complex mechanisms with the same structure, if the driving part is different, the combination type may be different. 3) Closed connection. The basic mechanism has two freedoms and the additional has one. Their motion route can form a ring. 4) Loading connection. The fixed body of the paddle mechanism is consolidated with an movable body of the boat mechanism.

5. Moment balance equation of rigid body rotation

Theoretical mechanics introduces the moment balance equation of rigid body rotating around a fixed point. In dynamics simulation, most of times, the moment balance equations of rigid body rotating around the mass center is used. Both of them have the same form. Does the moment balance equation of rigid body rotating around a moving point have the same form?

Based on Fangyan equation[2] of 40 years ago, the moment balance equation of rigid body rotating around general point B[3] is derived along its research idea route as the following.

\[ J_B \ddot{\theta} + J_B \dot{\theta} = \sum (r_{B \rightarrow j} \times F_j) - m(r_{B \rightarrow C} \times \dot{r}_B) \]  

(1)

Where, \( J_B \) is the inertia moment around point B. \( \theta \) is the position angle of the rigid body. \( r \) is the vector diameter. \( F \) is the external force. \( m \) is the mass of the rigid body. \( C \) is the mass center.

Equation (1) is the unified moment balance equation of rigid body rotating around mass center, instantaneous velocity center, instantaneous acceleration center, fixed point and moving point. When the rigid body rotates around the mass center, \( r_{B \rightarrow C} \) is the zero vector, and then the second term on the
right side of the equal sign is a zero vector. When the rigid body rotates around the instantaneous acceleration center or a fixed point, \( \dot{r}_B \) is a zero vector, and then the second term is also a zero vector.

6. The programming obtaining method of the follower angle of the crank rocker mechanism

This angle need to be obtained by solving a trigonometric function equation. Now, there are cosine theorem method, numerical integration method, half angle unified method, sine (cosine) function substitution method, hinge point coordinate method, etc. All of them has the problem of angle choice and is not easy to be programmed. For the basic mechanism, if each rod is regarded as a vector determined by two rotation pairs, all vectors are connected head to tail one by one. According to the geometric meaning of the vector equation, the position vector equation can be established.

\[ l_1 + l_2 + l_3 = l_4 \]  

(2)

The equations can be obtained by projecting the above equation to the coordinate axis of the rectangular coordinate system. Then we can get the equation about the position angle of body 2.

\[ 2l_2 \left( l_4 \cos \theta_4 - l_3 \cos \theta_2 \right) \cos \theta_2 + 2l_2 \left( l_4 \sin \theta_3 - l_3 \sin \theta_1 \right) \sin \theta_2 = l_2^2 + l_3^2 + l_4^2 - 2l_2 l_4 \cos (\theta_4 - \theta_1) \]

(3)

Equation (3) can be regarded as the trigonometric expansion of the sum of \( \theta_2 \) and \( \theta_6 \).

\[
\begin{align*}
\sin (\theta_6 + \theta_2) &= \frac{l_2^2 + l_3^2 + l_4^2 - 2l_2 l_4 \cos (\theta_4 - \theta_1)}{\sqrt{(2l_2)^2 \left[ l_2^2 + l_3^2 - 2l_2 l_4 \cos (\theta_4 - \theta_1) \right]}} \\
\sin \theta_6 &= \frac{l_4 \cos \theta_4 - l_3 \cos \theta_1}{\sqrt{l_2^2 + l_3^2 - 2l_2 l_4 \cos (\theta_4 - \theta_1)}} \\
\cos \theta_6 &= \frac{l_4 \sin \theta_3 - l_3 \sin \theta_1}{\sqrt{l_2^2 + l_3^2 - 2l_2 l_4 \cos (\theta_4 - \theta_1)}} \\
\end{align*}
\]

(4)

According to the installation position, the formula of each angle can be determined and the programming can be realized. This is the harmonic composition and decomposition method[4].

7. Research on stuck position (dead point) based on motion characteristics

When the mechanism is still in a position, no matter how much driving force can not drive the mechanism to move. Such a mechanism position can be called stuck position, which is dead point originally. If it is used for clamping device, the stuck position is a favorable position. If it is used for power machinery, it is the position that needs to be assisted to leave.

In the parallelogram mechanism shown in Fig. 2, when the connecting rod and the driven crank are collinear, the driven crank can rotate clockwise or anticlockwise. Such a mechanism position with motion bifurcations can be called the kinematics bifurcation position. The stuck position belongs to kinematics bifurcation position. In the rocker slider mechanism shown in Fig. 3, when the connecting rod is perpendicular to the slider track, if the mechanism is still, the driving rocker can pull the connecting rod to move. Such a kinematics bifurcation position can’t stuck.

8. Application of infinitive in mechanical dynamics

In the mechanical dynamics simulation, if divided by zero, the calculation will be forced to end, or even lead to the calculation system collapse. Before the calculation, the empirical value or the previous moment’s value can be used to avoid the calculation failure. Most of times, such a phenomena meets a 0 / 0 type infinitive. L’Hôpital’s rule is a mathematical tool to calculate infinitives.

In basic mechanism, the angular velocity and acceleration of connecting rod 2 and driven crank 3 are respectively as the following:
\[
\begin{bmatrix}
\dot{\theta}_2 \\
\dot{\theta}_3
\end{bmatrix} = \frac{\dot{\theta}_3 l_3}{l_2 l_1 \sin(\theta_2 - \theta_3)} \begin{bmatrix}
- l_2 \sin(\theta_2 - \theta_3) \\
- l_2 \sin(\theta_2 - \theta_3)
\end{bmatrix}
\]

In the kinematics bifurcation position, the denominators of formula (5) and formula (6) are equal to zero. According to the graphic analysis method, the molecule of formula (6) is also equal to zero[5]. The above infinitives can be calculated by L’Hopital’s rule. In Fig. 3, one parameter of dynamics simulation in the kinematic bifurcation position is also an infinitive[6].

\[
B_2 = \left(\frac{m_2 l_2^2}{12}\right) \ddot{\theta}_2 \left[ (l_2 F_{ib} + (l_2 - l_2a) F_{ic}) \sin \theta_2 \right]^{-1}
\]

It can be calculated by L’Hopital’s rule as the following:

\[
B_2 = \left(\frac{m_2 l_2^2}{12}\right) \left[ 12 (l_2 - l_2a) \dot{\theta}_2 \sin \theta_2 \right]^{-1} + \left( l_2 F_{ib} + (l_2 - l_2a) F_{ic} \right) \left[ (l_2 - l_2a) \dot{\theta}_2 \right]^{-1}
\]

Although the third derivative of position angle and displacement to time does not have the same theoretical equation as Newton's second law, it still has certain theoretical significance.

9. The assembly graphic method of vector equation

Vector equations exist in various research fields. According to the geometric meaning of the vector equation, the graphical method can be used to find the unknown length of location quantities which is no more than \( n \) for a \( n \)-dimensional vector equation. However, the analytic method of vector equations is not limited by the number of unknown quantities per equation. As long as \( m \) independent vector equations have no more than \( n \times m \) unknown quantities, they can be solved.

In some complex mechanisms, each vector equation that can be established contains more than \( n \) unknowns, which cannot be solved directly by vector equation graphic method. All vector diagrams of equations should be drawn respectively. The undetermined vector should be drawn by dotted line. All diagrams should be put together. According to the kinematics relationship between different points on the same body, the undetermined line can be determined[7].

10. Velocity ratio formula of universal joint

This mechanism is widely used in mechanical transmission. When the driving shaft rotates at a constant velocity, the driven shaft rotates at a variable velocity.
Universal joint is shown in Fig. 4. The fixed coordinate system \( Oxyz \) is established with \( O \) as the origin. The distances from point \( O \) to point A, B and C are unit length respectively. The body 1 rotates \( \beta \) angle around \( z \) axis to form a new coordinate system \( O' \). Then it rotates \( \phi_1 \) around its own axis to form a new coordinate system \( O'' \). The coordinates of A, B and C, and the coordinate transformation matrix \( A \) are shown respectively as the following.

\[
\begin{bmatrix}
    x_A^{(0)} \\
    y_A^{(0)} \\
    z_A^{(0)}
\end{bmatrix} =
\begin{bmatrix}
    1 \\
    0 \\
    0
\end{bmatrix}, \quad
\begin{bmatrix}
    x_B^{(0)} \\
    y_B^{(0)} \\
    z_B^{(0)}
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    1 \\
    0
\end{bmatrix}, \quad
\begin{bmatrix}
    x_C^{(0)} \\
    y_C^{(0)} \\
    z_C^{(0)}
\end{bmatrix} =
\begin{bmatrix}
    0 \\
    0 \\
    1
\end{bmatrix}, \quad A =
\begin{bmatrix}
    \cos \beta & -\sin \beta & \cos \phi_1 & \sin \beta \sin \phi_1 \\
    \sin \beta & \cos \beta & \cos \phi_1 & -\cos \beta \sin \phi_1 \\
    0 & \sin \phi_1 & \cos \phi_1 & 0
\end{bmatrix}
\]

Since OC and OB are perpendicular to each other, then:

\[
x_B = 0, \quad -\cos \beta \sin \phi_1 \cdot y_B + \cos \phi_1 \cdot z_B = 0, \quad \tan \phi_3 = \frac{z_B}{y_B} = \tan \phi_1 \cos \beta
\]

The derivation of equation (11) can be obtained as the following.

\[
\frac{1}{\cos^2 \phi_3} \phi_3 = \frac{1}{\cos^2 \phi_1} \phi_1 \cos \beta
\]

The square of the equation (11) can be obtained as the following.

\[
\frac{1-\cos^2 \phi_3}{\cos^2 \phi_3} = \tan^2 \phi_1 \cos^2 \beta, \quad \cos^2 \phi_3 = \frac{1}{\tan^2 \phi_1 \cos^2 \beta + 1}
\]

Substituting equation (13) into equation (12), we can get:

\[
\phi_3 = \frac{\cos \beta}{\sin^2 \phi_1 \cos^2 \beta + \cos^2 \phi_1} = \frac{\cos \beta}{1 - \sin^2 \phi_1 \left(\cos^2 \beta - 1\right)} = \frac{\cos \beta}{1 - \sin^2 \phi_1 \sin^2 \beta}
\]

If the body 3 is taken as the research object and the corresponding coordinate system is established, the sign of angle \( \beta \) is opposite, and the relation formula is obtained as the following.

\[
\frac{\phi_3}{\phi_1} = \frac{\cos(-\beta)}{1 - \sin^2 \phi_3 \sin^2 (-\beta)} = \frac{\cos(\beta)}{1 - \sin^2 \phi_3 \sin^2 \beta}
\]

The derivation process[8] of vector calculation method is as the following.

1) \( \omega_1 \cdot e_1 \) is set as the angular velocity of body 2 (cross axis) relative to body 1. According to the composition theorem of angular velocity, the angular velocity of body 2 can be expressed as the following.

\[
\omega_2 = \omega_1 i + \omega_1 \cdot e_1 = \omega_1 \left(\cos \beta i + \sin \beta j \right) + \omega_1 \cdot e_1
\]

2) \( \omega_3 \cdot e_3 \) is set as the angular velocity of body 2 relative to body 3, the angular velocity of body 2 can be expressed as the following.

\[
\omega_2 = \omega_3 i + \omega_3 \cdot e_3
\]

3) Since \( e_1 \perp e_3, e_3 \perp i \) and \( e_3 \cdot j = \sin \phi_3 \), if multiplying equation (16) and equation (17) by \( e_3 \) respectively, we can get:

\[
\omega_3r = \omega_3 \sin \beta \sin \phi_3
\]

4) Since \( i' \perp e_1, i' \cdot e_3 = \sin \beta \sin \phi_3 \) and \( i \cdot i' = \cos \beta \), if multiplying equation (16) and equation (17) by \( i' \) respectively, we can get:

\[
\omega_3 = \omega_3 \cos \beta + \omega_3 \cdot e_3
\]

5) Substituting formula (18) into equation (19), we can get:
\[ \omega_3 \cos \beta + \omega_3 \sin^2 \beta \sin^2 \varphi_3 = \omega_1, \quad \frac{\omega_1}{\omega_3} = \frac{\cos \beta}{1 - \sin^2 \varphi_3 \sin^2 \beta} \]  \hspace{1cm} (20)

11. The influence of friction model in dynamics simulation

Since Leonardo da Vinci described the friction phenomenon, the friction phenomena studied mainly include Coulomb friction, viscous friction, Striebeck effect, pre-sliding friction, variable static friction and friction memory effect. There are dozens of friction models[9].

The friction has the following characteristics. If the relative movement direction changes, the friction direction also changes. The static friction changes within a certain range. The static friction is greater than the sliding friction. The rolling friction belongs to the static friction[10].

When the resultant force of an external force on one body is less than the maximum static friction with another body, the resultant force is balanced with the static friction between the two bodies, and the two bodies continue to remain relatively static. Therefore, the relative velocity and acceleration are corrected to zero. The above correction is called the velocity zero correction. Set the following status variables:

\[ V_s = -1 \quad \text{subject to} \quad \dot{x} < 0 \quad \text{at reverse motion stage} \]  \hspace{1cm} (21)

\[ V_s = +1 \quad \text{subject to} \quad \dot{x} > 0 \quad \text{at forward motion stage} \]  \hspace{1cm} (22)

\[ V_s = 2 \quad \text{subject to} \quad \dot{x} = 0, x < 0 \quad \text{on back limit position} \]  \hspace{1cm} (23)

\[ V_s = 3 \quad \text{subject to} \quad \dot{x} = 0, x > 0 \quad \text{on front limit position} \]  \hspace{1cm} (24)

Acknowledgments

Online course construction project of Shengli College in China University of Petroleum [XJKC201804], Natural Science Foundation of Shandong Province of China under Grant ZR2018PEE009.

References

[1] C M Li 2016 Study on the curriculum system of new technology of modern machining Value Engineering in China 35(03)253-254

[2] Fangyan 1982 Rotation equation of rigid body to instantaneous center University Physics in China 1(1) 23-25

[3] C M Li, X L Yin, P L Yun, Y Guo, Y J Cui 2019 Crank slider mechanism dynamics and its related problem of a machine Chinese Journal of Dezhou University 35(6) 40-46

[4] X L Yin, C M Li 2021 On the programmed kinematics computation of crank rocker mechanism based on harmonic composition and decomposition J. of Gansu Sciences 33(1) (Preprint gr-qc/20190326)

[5] X L Yin, C M Li 2020 On the programmed kinematics computation of crank rocker mechanism based on the stuck position analysis Applied Mathematics and Mechanics 41(4) 367-375

[6] C M Li, H Cao, Q Liu, X Liu 2020 Kinematics of planar quabody mechanism with more kinematics bifurcation positions Proceedings of 4th International Conference on Advanced Technologies in Design, Mechanical and Aeronautical Engineering, Malaysia 1-6

[7] C M Li, X L Yin, Q Liu2020An assembly graphic method for kinematics vector equation of combination mechanism abandoning the bar group concept J. of Gansu Sciences 32(4) 1-6

[8] C M Li 2010 On the dynamics of bull-nose plane six-rod mechanism considering some practical factor Key Engineering Materials 426-427 65-69

[9] L L Liu, H G Liu, Z Y Wu, et al. 2008 An overview of friction models in mechanical systems Chinese Journal of Advances in Mechanics 38(2) 201-213

[10] C M Li 2015 The new conception of the friction classification and the stressed pole failure Manufacturing automation in China 37(12) 85-86+91