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POWERING THE FUTURE: A CRITICAL REVIEW ON EFFICIENCY AND POWER FLOW IN CLOSED DIFFERENTIAL PLANETARY GEARS

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Abstract
The closed differential planetary gear train transmits power in multiple paths, which has large power transmission and compact structure. It is widely used in high-power occasions such as ships. However, the closed differential planetary gear train has many power flow paths and complex structure. If the structural design is unreasonable, there will be power cycle (closed power) in the system, which will seriously reduce the efficiency of the system. There are many components of closed differential planetary gear train, and the uniform distribution of load is of great significance to improve the transmission quality and service life of the system.This paper mainly summarizes the research status of ordinary planetary gears, the power flow analysis status of closed differential planetary gear transmission and the efficiency analysis status of planetary gear transmission.

Keywords: Closed differential planetary gear train; Power flow; Power cycle; Dynamic efficiency

1. Introduction

As an indispensable part of the manufacturing industry, gears play an irreplaceable role in all walks of life. Therefore, in-depth research on gears will help China accelerate into the ranks of manufacturing powers. As one of the main forms of mechanical transmission, gear transmission is widely used in automobile, ship, mining machinery and other fields. As a combined system of ordinary gears, planetary gears have the advantages of small volume, compact structure, large power transmission and strong bearing capacity compared with ordinary gear transmission. Therefore, planetary gear trains are widely used to replace ordinary gears in various transmission systems. The most special and important one is the closed differential planetary gear system. The combined transmission mechanism of single degree of freedom star gear train (closed stage) and closed two degree of freedom differential planetary gear train (differential stage) is called closed differential planetary transmission system. The transmission system uses multiple planetary gears (star wheels) to share the load and form power diversion. It has the advantages of small volume, light weight and strong bearing capacity.

2. Research status of ordinary planetary gears

Ordinary planetary gears are mainly divided into differential planetary gear train (two degrees of freedom) and single degree of freedom planetary gear train. Scholars at home and abroad have done a lot of research on ordinary planetary gear trains. They started earlier abroad. China began to study them in the 1950s, in which efficiency and dynamic characteristics have always been the focus of

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scholars at home and abroad. Single stage planetary gear transmission is mainly composed of four parts: sun gear, planet gear, inner ring gear and planet carrier. Because the theoretical installation position is coaxial, the sun gear, inner ring gear and planet carrier are generally called central components. Through reasonable arrangement, the three components can realize the input and output of the transmission system. According to the difference between input components and output components, It can be divided into six transmission forms. The most typical structural form is input by the sun gear. One of the two remaining central components of the ring gear and planet carrier is selected as the output and the other is fixed; Similarly, when the planet carrier or internal gear ring is used as the input member, one of the remaining central members is used as the output member and the remaining central member for fixation. A large number of transmission forms can be obtained by changing and combining various structural forms of planetary transmission. Based on 2K-H Planetary Transmission, two-stage and multi-stage planetary transmission after structural transformation and combination is the most widely used. For this type of structural form, the following three two-stage planetary transmission are analyzed and explained as examples.

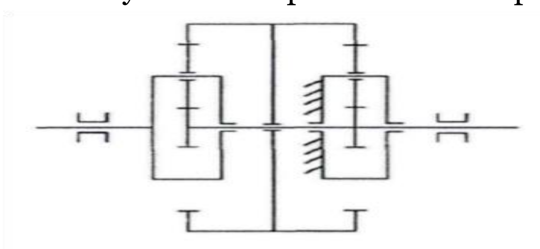

Figure 1: P lanet carrier input + sun gear output

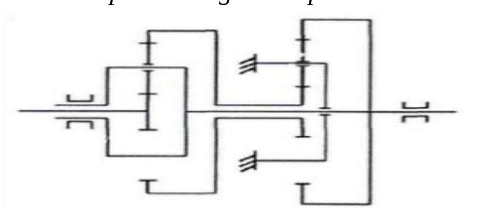

Figure 2 : S un gear input + inner ring gear output

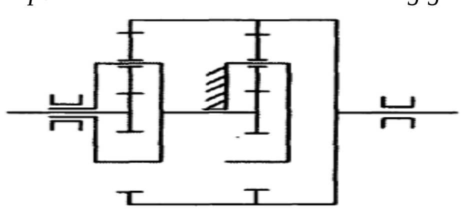

Figure 3 : P lanet carrier input + sun gear output

As shown in Figure 1, the left differential stage planet carrier is used as the input component, and the two-stage transmission sun gear is connected and used as the output component. Because it has the function of feedback compensation, it can be used to correct the transmission error. As shown in Figure 2, the left differential transmission sun gear is used as the input component, the first stage gear ring is connected with the second stage sun gear as the input of the system, and the left differential stage planetary carrier is connected with the second stage quasi star inner gear ring as the output component. As shown in Figure 3, the left differential stage sun gear is used as the input, and the ring gear of the two-stage transmission is connected and used as the output. At the same time, the first stage planet carrier is connected with the input sun gear of the second stage as the output, and the transmitted power is divided into two branches to realize power diversion.

Compared with ordinary fixed shaft transmission, planetary transmission has the characteristics of high transmission efficiency, so its transmission efficiency has been studied as an important performance index. Scholars at home and abroad have analyzed and deduced this transmission performance index respectively.

In the 1990s, G. mantriota and L. mangialardi[1] found that the transmission efficiency of CVT equipped with planetary gear system was the highest by comparing the efficiency of CVT. The efficiency of two different types of toroidal traction drives (full torus and half torus) is estimated to indicate which one has higher mechanical efficiency. According to the results of elastohydrodynamic lubrication theory, the immersion isothermal contact model is used to evaluate the sliding and rotation losses and the mechanical properties of the transmission. The results show that the method is feasible, and the semi toroidal traction drive provides higher efficiency and higher maximum transmission torque. The calculation results of the friction loss of the planetary transmission system in 2001 are closer to the actual friction loss of the planetary transmission system. The dynamic power loss of planetary gear transmission consists of meshing loss, wind resistance loss and bearing loss. Through the dynamic analysis of planetary gear transmission, the dynamic motion law and dynamic load of each component are obtained, and the dynamic power loss of planetary gear transmission is calculated. On this basis, a calculation method of planetary gear transmission based on dynamic power loss is proposed, and the obtained efficiency is called dynamic efficiency. The dynamic efficiency of an aviation planetary gear transmission is calculated by this method. By comparing the results with the conventional efficiency calculation method and the experimental data, it is concluded that the efficiency calculated by this method is more in line with the actual situation of planetary gear transmission.

In 2003, referring to the power method to calculate the transmission efficiency of planetary transmission system, Yao Jiucheng[2] deduced and gave the efficiency calculation formula of fixed shaft gear train through further analysis and improvement. The translational gear mechanism is different from ordinary gear mechanism. It not only has large transmission ratio, but also has high mechanical efficiency. However, using the existing efficiency calculation method, For example, when the meshing power method is used to calculate its efficiency, the result deviates greatly from the actual situation. Starting with the study of the relative sliding between tooth profiles during the meshing of translational gear mechanism, the calculation method of meshing efficiency of translational gear mechanism is discussed according to the average sliding speed method, and the corresponding calculation formula is deduced.

3. Current situation of power flow analysis of closed differential planetary gear transmission

At present, scholars at home and abroad have conducted a lot of research on the closed planetary transmission mechanism. In terms of power flow analysis, Dong Wanfu and Lu Cunguang [3] adopted the method of deriving the diagram of the relationship between the structure and power of the closed planetary gear train, which increased the convenience of the design. The diagrams reflecting the relationship between the structure and power flow of the closed planetary gear train are deduced and drawn. Using these diagrams to analyze the power flow direction of the existing gear train, or design and combine the new gear train according to the required power flow, which is clear, intuitive, convenient and fast. The design and power flow analysis of closed planetary gear train are no longer difficult.

Xue Huiling and others applied the virtual power theory to analyze[4] the power flow and transmission efficiency of composite differential gear train and closed planetary gear train. Firstly, the power flow and virtual power flow diagrams of gear train without gear meshing power loss and considering gear meshing power loss are established respectively, and the flow directions of power and virtual power are analyzed. Then, the equation is established to solve the meshing power loss of gear pair, and the expression of gear train transmission efficiency is obtained. Li Qingkai and others applied bond graph theory to the power flow analysis of closed planetary gear trains. In order to judge the power flow of closed planetary gear trains more simply and clearly, using the characteristics of energy conservation and power flow of bond graph, bond graph theory was applied to the power flow analysis of this kind of gear trains.

In 2001, Wang Sanmin and Shen Yunwen included the factors such as meshing friction loss and bearing rotation friction loss into the dynamic efficiency solution of planetary transmission, and verified through experiments that the calculation result of the efficiency calculation formula deduced is closer to the actual transmission efficiency of planetary transmission system when considering the power friction loss and rolling bearing friction power loss. The dynamic power loss of planetary gear transmission consists of meshing loss, wind resistance loss and bearing loss. Through the dynamic analysis of planetary gear transmission, the dynamic motion law and dynamic load of each component are obtained, and the dynamic power loss of planetary gear transmission is calculated. On this basis, a calculation method of planetary gear transmission based on dynamic power loss is proposed, and the obtained efficiency is called dynamic efficiency. The dynamic efficiency of an aviation planetary gear transmission is calculated by this method. By comparing the results with the conventional efficiency calculation method and the experimental data, it is concluded that the efficiency calculated by this method is more in line with the actual situation of planetary gear transmission.

In 2003, white G[5] studied the relationship between the internal power flow direction of the closed planetary gear and the unit transmission ratio, deduced the general formula of the total transmission ratio and unit transmission ratio of the closed power split planetary gear, obtained the unit transmission ratio selection map to avoid power cycle, and investigated the power and torque boundary between the components of the coaxial two-stage planetary gear. A method to identify only the layout

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mode to avoid power internal circulation is proposed. This method is a necessary condition to ensure the minimum loss and the maximum bearing life. Sixteen possible coaxial gear interconnects for dividing input power are derived, their speed ratio regions are listed, and their applications in automobile transmission and turboprop reducer are pointed out.

Based on the calculation of the efficiency of planetary gear train, Salgado[6] et al. Proposed a graphical representation method to compare the planetary transmission structures with different number of components; Nelson and others analyzed the power flow and efficiency of bevel gear planetary gear train based on graph theory and spinor theory respectively. Lin Hongyun calculated the power loss of closed differential planetary gear train through empirical formula, and optimized the closed differential planetary gear train with the goal of minimum system volume and maximum transmission efficiency.

Cheng W, Cui h, y use a simple algorithm to determine the direction of power flow, determine the existence of circulating power according to the transmission ratio between various components of differential planetary gear, and calculate the planetary gear transmission. He believes that transmission efficiency is the main index to evaluate the performance of 2K-H closed cycle gear train. As shown in Figure 4, in order to calculate the transmission efficiency, it is necessary to first determine the direction of power flow in the deformed gear train and verify whether there is power cycle in the closed epicyclic gear train. In this paper, a simple algorithm based on differential gear train and changing the transmission ratio of basic links of gear train is proposed to determine the direction of power flow and estimate whether there is power cycle.

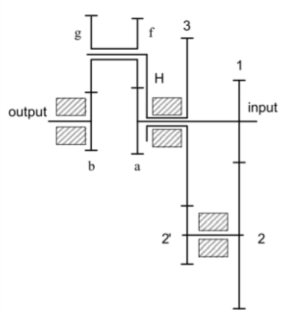

Figure 4: Closed epicyclic gear train

4. Fficiency analysis and present situation of planetary gear transmission

In 2012, Jiao Wanming[7], Ma Fei and Yang Yaodong first calculated the transmission ratio of the system according to the structural characteristics of planetary gears, and then calculated the transmission efficiency of the system by using the transmission ratio method (kleinius method) based on the relationship between transmission ratio and characteristic coefficient, so as to provide some reference for the calculation of planetary gear efficiency. In 2015, according to the meshing characteristics of high coincidence gear, Hu Mingxin established the calculation model of power loss of high coincidence planetary gear transmission system; The transmission efficiency of high coincidence planetary gear system is calculated and compared with that of ordinary planetary gears; The influence of parameters on the coincidence degree and transmission efficiency of planetary gears under the condition of changing the design parameters or system working conditions of a gear is analyzed, and the corresponding analysis curves are obtained.

In 2016, Wang Cheng deduced a simple method for calculating the transmission efficiency of 2K-H Planetary Gears Based on the meshing power method. This method does not need to know the direction of power flow. As long as the transmission ratio and torque are calculated, the efficiency of the system can be calculated, which provides theoretical guidance for the design and selection of planetary gears.

It is concluded that the transmission efficiency of planetary gears increases with the increase of the number of teeth and modulus, and the increasing trend of transmission efficiency is gradually stable with the increase of the number of teeth and modulus. The efficiency of planetary gear transmission increases first and then decreases with the increase of input power and input speed. The transmission efficiency will reach a maximum at a certain input power and input speed under a certain set of specific parameters of the system.

5. Conclusion

Although scholars at home and abroad have done a lot of research on the transmission efficiency and power flow characteristics of planetary mechanisms and achieved many results, most of the proposed power flow judgment and calculation methods are cumbersome, and due to the complexity of structure, there is a lack of systematic analysis of closed differential planetary transmission mechanisms. Therefore, it needs to be further explored in this field.

The closed planetary gear transmission system reduces the load on each component through double path transmission. Therefore, under the condition of transmitting the same load, its structure is more compact. Due to the above advantages of closed planetary gear transmission, it is widely used in modern mechanical transmission fields such as industrial machinery, hoisting machinery, construction machinery, metallurgical machinery and aviation machinery. However, if the transmission ratio of each branch of the closed planetary gear transmission system is not selected properly, there will be a large circulating power (closed power) in it. The existence of circulating power increases the load on the components, intensifies the wear, produces large vibration and noise, and seriously reduces the performance of the transmission system. Therefore, the research on the efficiency of closed differential planetary transmission will be of great significance.

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