

Modification and Simulation of Noncircular Gear Reversing Mechanism of Pumping Unit

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Abstract. The new type of pumping unit with incomplete noncircular gear reversing mechanism can achieve automatic reversing, intermittent variable speed movement, but in the conversing prone to movement interference phenomenon. Firstly, two kinds of modification methods are proposed for the first tooth of the driver wheel on the input shaft. Secondly, using the curve integration method calculate the input shaft speed based on the demand side and simulate the reversing mechanism by ADAMS. The results show that the theoretical modification method can reduce the bending stress of the driver wheel last teeth effectively, which provides important theoretical guidance for the optimal design of noncircular gear reversing mechanism.

Introduction

Pumping unit divided into beam pumping unit and non-beam pumping unit in generally. There is a serious rigidity impact in reversing, the capacity of balance is poor and the efficiency is low. Non-beam pumping unit structure is more complex, and the higher about the cost [1]. The pumping unit of the noncircular gear could achieve intermittent motion of mechanical structure, there is a higher accuracy and reduces losses [2,3]. However, in the case of actual operation, noncircular gear motion mechanism prone to movement interference [4]. At present, most of the research on noncircular gears is the design through CAD / CAE [5,6]. In this paper, two modification methods of the tooth shape of noncircular gears are proposed for the movement interference phenomenon in reversing. The input shaft speed is determined through the curve integral method based on the demand side. Choosing the best method of the mending tooth shape under different processing conditions according to analyze the kinematics and dynamics by ADAMS.

The Work Process of Noncircular Gear Reversing Mechanism

The work principle of incomplete noncircular gear reversing mechanism. As shown in Figure 1, incomplete noncircular gear reversing mechanism of the new pumping unit combined characteristics about intermittent transmission of incomplete gear and variable speed transmission of noncircular gear. Output shaft maintain positive and negative movement with uniform acceleration, uniform, uniform deceleration periodically. The contour is symmetrical, incomplete noncircular gear II that located in the middle is the driver wheel. It is constant speed rotation, and mesh with the other two incomplete noncircular gear intermittently. Cylindrical gears III is the output shaft, which with variable speed, positive and negative movement, and drive the driven drum and sucker rod with up and down reciprocating motion. The center distance between the two cylindrical gears is exactly equal to the center distance of the incomplete noncircular gears I and III. Output shaft with variable speed reversing movement ensure the sucker rod to reciprocate pumping with up and down, and reduce the speed when the sucker rod near the hanging point, thus to reduce the reversing impact.

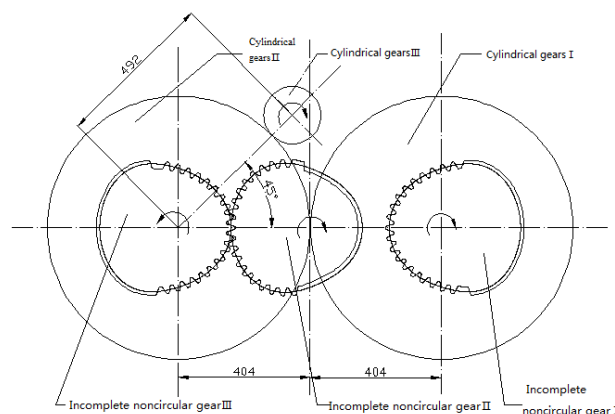


Figure 1. The work principle of incomplete noncircular gear reversing mechanism

Interference Analysis of Incomplete Noncircular Gear Reversing Mechanism. Noncircular gear reversing mechanism achieves reversing through the noncircular gear intermeshing, the time between driven incomplete noncircular gear into the engagement and exit the engagement is very short when noncircular gear reversing mechanism is reversing, and the direction of rotation change suddenly. Therefore, if the installation location is not correct, machining errors or unreasonable gear design will increase the possibility of gear stuck.

According to the analysis of the theory corner relationship between the driver and driven wheel, noncircular gear reversing mechanism will work stuck before the reversing. As shown in Figure 2, the last teeth of driver incomplete noncircular gear II and the driven incomplete noncircular gear III are not disengaged fully, and the first teeth of driver incomplete noncircular gear II and the driven incomplete noncircular gear I have begun to contact. As the radial position of the two gears fixed, when the driver wheel continues to rotate, the first teeth of the driven wheel I and the driver wheel II interfere and stuck. This situation must be prohibited in practical applications, otherwise, it will cause very serious consequences. It is necessary to design the tooth shape of the driver wheel first tooth properly.

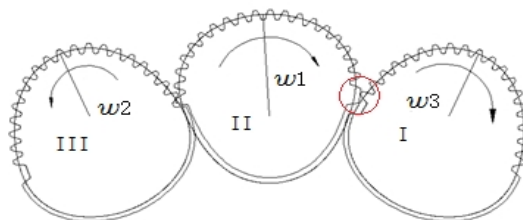


Figure 2. The interference diagram of noncircular gear mechanism first tooth in reversing

The Tooth Top Modification of Noncircular Gear Reversing Mechanism Driver Gear

Theory modification. In order to avoid stuck, need to modify the tooth shape of the incomplete noncircular gear first tooth reasonably. According to the theory angle relationship of driver and driven wheel, the top tooth interference point between the driver and the driven incomplete noncircular gear first tooth at reversing is determined. As shown in Figure 3, point A, point B ... point F, connect these points to form the line that is the first tooth modification line of driver wheel. The theoretical modification line L1 as shown in Figure 3, which is connected through the theoretical interference point directly. If using the theoretical modification line, when the driver wheel teeth and the engagement driven wheel is not disengaged completely, the first tooth of the driver wheel and the driven wheel which meshed with the driver wheel after reversing are already in contact. And the first tooth of the driven wheel across along the driver wheel first tooth modification line.

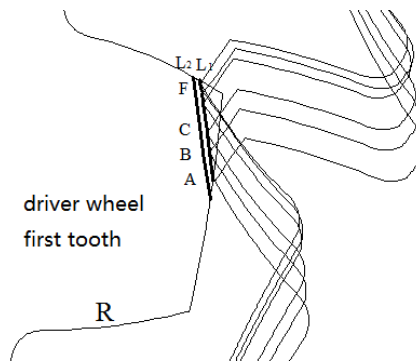


Figure 3. Modification of driver wheel first tooth

Un-contact Modification. Un-contact modification line L2 as shown in Figure 3, which formed by moving the theoretical modification line to the internal of gear with 1 mm. When using the un-contact modification line, the first tooth of the driver wheel and the driven wheel that meshes with the driver wheel after reversing are not in contact before reversing.

The Simulation and Analysis of Noncircular Gear Reversing Mechanism

Model establishment. Import noncircular gear reversing mechanism model into ADAMS, after the completion of noncircular gear reversing mechanism model in SOLIDWORKS. After the simulation and analysis of the characteristics of incomplete noncircular gear reversing mechanism about two kinds of modification methods for the first tooth of the driver wheel, choose a reasonable modification program through contrast.

Material characteristics of parts. In actual operation, factors that affect the performance of incomplete noncircular gear reversing mechanism are complex. In order to facilitate the study, manufacturing and installation error of incomplete noncircular gear is negligible. Parts of the reversing mechanism are regarded as rigid bodies. Influence about the deformation of gear meshing and axial displacement on the performance of institutions are not considered. The density, elastic modulus, and Poisson's ratio of the alloy steel, which used for each gear and shaft are equal respectively. Selecting 20CrMnMo as gear material, with carburizing quenching, which Poisson's ratio is 0.25, and elastic modulus is $2.07 \times 10^5 \text{ N/mm}^2$.

Constraints and contact parameter settings. In order to facilitate the establishment of simulated model, the noncircular gear and shaft made of gear shaft. We can't add gear pair on the meshing place between incomplete noncircular gears, and in order to simulate the gear teeth impact better when the noncircular gear reversing mechanism is reversing, meshing motion between noncircular gears is set to contact-impact mode, noncircular gear contact stiffness is $8.48 \times 10^5 \text{ N/mm}$.

Determination of input shaft speed. The output shaft speed of the pumping unit of noncircular gear reversing mechanism changes with the transmission ratio in real time. The output shaft speed calculated by the traditional method is the ideal average speed, but it does not match the actual conditions, this can't guarantee requirements of the output shaft roller speed, and then can't guarantee the design requirements of the sucker rod with up and down.

In this paper, incomplete noncircular gear reversing mechanism is designed according to the needs of an oilfield. It is known that the load of the pumping unit is $120 \text{ kN} \cdot \text{m}$, add the balance block which weight is 70% of this mechanism. Drum diameter is 596 mm, the transmission ratio about spur gear III and spur gear II is 4.59, and the transmission ratio is largest when the output shaft moves at a constant speed. The maximum transmission ratio of noncircular gear is 1.5, Output shaft acceleration time is equal to the deceleration, and the sum of acceleration and deceleration running time is equal to the running time at constant speed. So the load torque of the reversing mechanism is: $120 \times (1 - 70\%) \times (0.596/2) = 10.72 \text{ kN} \cdot \text{m}$

Pumping stroke is 6 m, and pump speed is 2 times / min, so the number of revolutions of the drum for one stroke is: $6 / (\pi \times 0.596) = 3.20446 \text{ r}$

And the rotating speed is: $3.20446 \times 2 \times 2 = 12.8178$ rpm

Take drum speed for 13 rpm, so the ideal average speed of the output shaft is 13 rpm.

This paper presents that the maximum output shaft speed is determined by curve integral method according to the ideal curve and the actual speed curve (Figure 4) of output shaft average speed in the case of unknown output shaft speed curve. And the input shaft speed is determined according to the transmission ratio of the noncircular gear mechanism at this moment. The actual speed curve of output shaft changes as piecewise linear.

The description function is:

$$n_{out} = f(t) = \begin{cases} kt & 0 \leq t \leq 0.25T \\ n_{out_{max}} & 0.25T \leq t \leq 0.75T \\ -kt + b & 0.75T \leq t \leq T \end{cases} \quad (1)$$

We can see from the actual speed curve:

$$k = \frac{n_{out_{max}}}{0.25T} \quad (2)$$

$0 \leq t \leq T$, the curve integral of theoretical average speed is equal to the actual speed, then through the curve integral:

$$\int_0^T f(t) dt = 13T \quad (3)$$

So: $n_{out_{max}} = 17.33$ rpm

And the input shaft speed: $n_{in} = 17.33 / (4.59 \times 1.5) = 2.6$ rpm

In theory, the input shaft speed is taken for calculation convenience: $n_1 = 3$ rpm

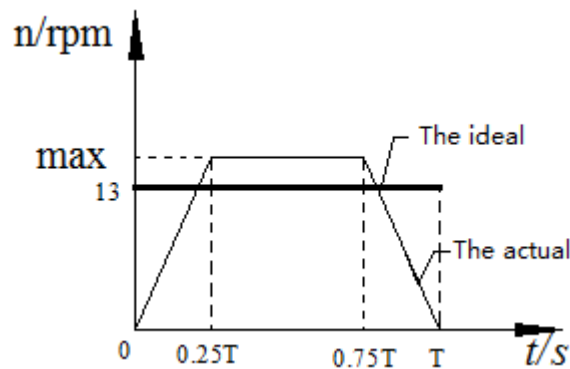


Figure 4. The relationship between speed and time of the Output shaft

In order to avoid that there is a greater impact on the simulation results in sudden start of the reversing mechanism, add a driver of Step function to the rotation pair between the incomplete noncircular gear II and the earth [10], and period $T = 20$ s. Add the load torque by IF function, as shown in Figure 5. In order to rule out the sudden start-up of the reversing mechanism on the simulation results, the simulated time is set to 25 s, and the number of steps is 2,500 steps. Observed movement of noncircular gear reversing mechanism in a cycle (5 s-25 s).

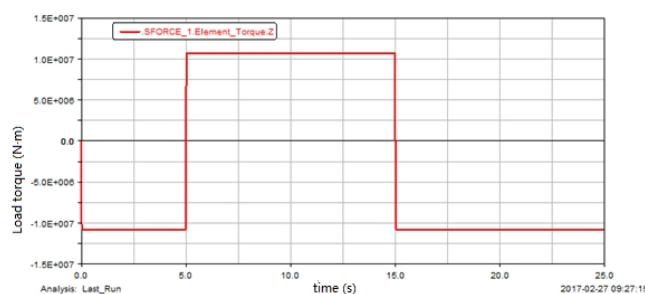
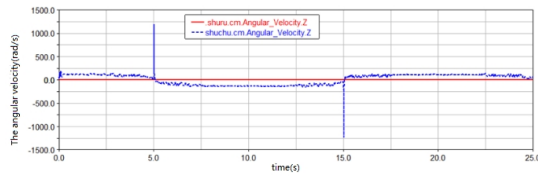


Figure 5. Load torque diagram

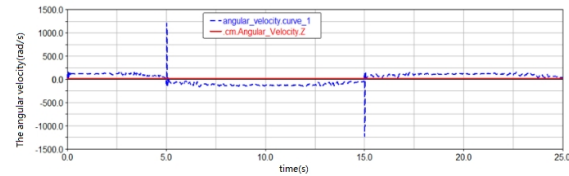
The Simulation and Analysis of Noncircular Gear Reversal Mechanism. The models of noncircular gear reversing mechanism about two kinds of modification methods of driver wheel first

tooth are simulated respectively. After the normal operation of the mechanism, viewing the simulation results, and getting curve about the angular velocity, angular acceleration and contact force of each part.

Comparison of Two Kinds of Modification Methods on Angular Velocity Curve of Output Shaft.



a. Non-contact modification



b. Theoretical modification

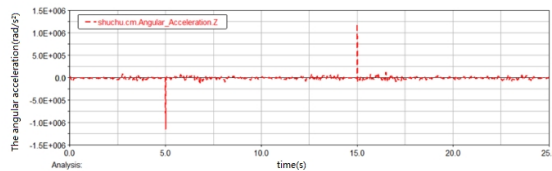
Figure 6. Input shaft and output shaft angular velocity about two modification programs

From Figure 6, we can see, in the two modification programs, there are a greater volatility for output shaft speed in reversing instantaneous, and Table 1 shows the maximum speed. In addition to reversing moment, the maximum output shaft speed is at the constant speed, and the average is $122.97^\circ/\text{s}$, it is close to the theoretical maximum speed. The output shaft speed changes consistent in the two programs. And the difference between the maximum speed of reversing moment is small, regardless of the first tooth of the driver wheel is theoretical modification or non-contact modification, there is no effect on the maximum speed of the output shaft in reversing moment.

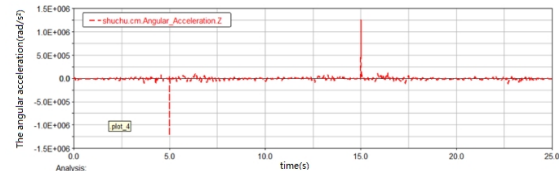
Table 1. The maximum speed of two modifications programs in a moment

Time[s]	15.0	15.01
Un-contact modification[$^\circ/\text{s}$]	1218	1228
Theoretical modification[$^\circ/\text{s}$]	1212	1232

Comparison of curves about output shaft angular acceleration of two modification methods.



a. Non-contact modification



b. Theoretical modification

Figure 7. Output shaft angular acceleration

From Figure 7, we can see, the angular acceleration of the output shaft fluctuates around 0, and fluctuates greatly when reversing. The maximum acceleration shown in Table 2. Comparing the curves of angular acceleration of the two modified methods, it is found that there is almost no effect on the angular acceleration of the output shaft with different modification schemes in driver wheel first tooth.

Table 2. the maximum instantaneous acceleration of two modified methods

Time[s]	5.01	15.01
Un-contact modification[$^\circ/\text{s}^2$]	1.2012×10^6	1.2127×10^6
Theoretical modification[$^\circ/\text{s}^2$]	1.2037×10^6	1.262×10^6

Comparison of Noncircular Gear Contact Force about Two Types of Modification Methods.

In Figure 8, a and b represent resultant contact force diagram of the driver wheel in two modification methods of driver wheel first tooth. It can be seen from the figure that in the two modification methods, the contact force curves are the same basically, and the maximum force of the first teeth of the driver wheel in the reversing is the same basically, as shown in Table 4. In the stage of uniform movement of output shaft, contact force is stable at about $3.25 \times 10^5 \text{ N}$. After reversing, the force of the first gear of the driving wheel gradually increases, and the fluctuation of the contact force in the acceleration and deceleration stage is larger than that in the uniform movement stage.

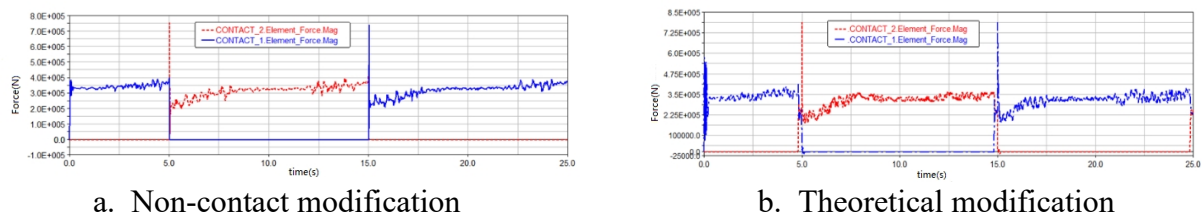


Figure 8. Resultant contact force in different modification methods

Confirmation of Modification Method about the First tooth of the Reversing Mechanism.

Theoretically, the theoretical modification program is better relatively, which helps to reduce the force exerted by the driver wheel last tooth when the driver wheel and the driven wheel are about to exit from engagement, so as to reduce the root bending stress of the driver wheel last teeth. However, this requires a higher precision for the manufacturing of non-circular gears, otherwise it is easy to get stuck. Therefore, in practical applications, what kind of modification program the driving wheel first tooth is adopted depending on the manufacturing cost and processing conditions. In the research of this subject, a theoretical modification method is adopted to modify the driver wheel first tooth of the noncircular gear reversing mechanism. In the course of work, the pumping unit is running well, there is no interference phenomenon of gear movement.

Conclusions

In this paper, two kinds of modification methods are proposed for the first tooth of the driver wheel in view of the motion interference. Selecting the best application in different methods for the scene. Based on the demand side, the integral method of the average rotational speed curve of the output shaft is proposed to determine the actual rotational speed curve of the output shaft. This ensure the pumping rod stroke of up and down to meet the design requirements, and the output shaft speed curve and simulation of the speed curve is the same basically. Increasing the buffer device or optimize the gear and other methods is the next study to improve the device, so there is an important guiding significance in the research of this paper for future research.

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References

- [1] ZHANG Qiang. Study on system dynamics of rack pumping unit [D]. Southwest Petroleum University, 2014.
- [2] Guan Yu Ming, Zhang Wenya, Xiao Yanchun. Incomplete gear-the design and application of incomplete gear [J]. Machinery Design & Manufacture. 2009(7):59-61.
- [3] YANG Cun. Kinematics and dynamics of non-circular gear [D]. Lanzhou University of Technology, 2014.
- [4] CHAI Shifeng, ZHANG Xiling, LI Yulan. Design and kinematics simulation of non-circular gear [J]. Journal of Military Transportation Institute, 2014 [9]: 36-40.
- [5] Wu Junfeng, Lv Xiaobo, Li Chuan. Three-dimensional design and motion analysis of non-circular gear [J]. Journal of Hubei University of Technology, 2014 [4]: 69-72
- [6] LIU Yong-ping, YANG Cun, SUN Xuan. Kinematic simulation analysis of non-circular gear based on ADAMS [J]. Mechanical Transmission, 2014 [6]: 106-109.