Development of Analysis and Optimization Software for Dual Horse Head Pumping Unit with Single Arc Back Horse Head Based on GUI Editor

Wei Wu¹, Tong Xu¹ and Pengfei He¹

¹Mechanical Engineering, Xi’an Shi you University, Xi’an, Shaanxi, 710065
*Corresponding author’s e-mail: 2966300720@qq.com

Abstract. In this paper, the kinematic analysis and optimization model for the dual horse head pumping unit with single arc back horse head which has the characteristic of variable rod length are established. Using GUI editor, a motion analysis and optimization software for the dual horse head pumping unit based on MATLAB platform is developed. Realizing the kinematic analysis of dual horse head pumping unit with single arc back horse head and the optimization of installation position of rear horse head effectively reduces the torque peak, and the software has good user interface. This paper proves the validity and reliability of the software system by the simulation analysis of the CYJS6-3-18HB pumping unit.

1. Introduction

The dual horse head pumping unit has the characteristic of changing the effective rear arm length according to polished rod load to get better performance. In recent years, this special pumping unit has been used in large oil fields. However, due to its special structure, the analysis method of the dual horse head pumping unit is different from that of traditional pumping unit, so it can not be analyzed by the analysis method of traditional pumping unit. According to the different structure of back horse head, dual horse head pumping units can be divided into single arc, three arcs and Archimedes spiral type. Although the structure is different, the dual horse head pumping units belong to variable rod length pumping units, so the analysis methods are very similar. In this paper, the dual horse head pumping unit with single arc back horse head was taken as the object of analysis, and the software system of motion analysis and optimization of dual horse head pumping unit based on MATLAB platform was developed by using GUI editor. This software can calculate the polished rod displacement, velocity, acceleration and torque factor of the pumping unit accurately and quickly according to the geometric parameters of the pumping unit, can optimize the geometric parameters of the pumping unit according to the torque factor [1-3].

2. Establish The Geometric Relation Model

As shown in Fig. 1, \( \phi \) is Crank angle, \( \theta \) is swing angle of beam, \( K \) is polar distance, \( \phi_0 \) is the Angle between \( K \) and vertical direction, \( A \) is the length of the beam forearm, \( c \) is the length of the beam rear arm, \( l \) is connecting rod length, \( J \) is the distance between crank pin center and beam support center, \( H \) is the vertical distance between bracket axis and reducer center, \( I \) is the horizontal distance between bracket axis and reducer center, \( R_1 \) is the distance from the fulcrum of the back donkey head to the center of the back donkey head, \( R_2 \) is the radius of the back horse head.
Unlike conventional pumping units, because the position of tangent point $T$ is always in a state of change, the effective length of hind arm and rod length are also constantly changing, so it is impossible to use the formula of conventional pumping units to calculate. The value of tangent point $T$ must be calculated first, and determine the functional relationship between $c$, $l$ and $T$, then we can do analysis according to geometric relations.

Tangent formula for tangent point $T$:

$$\begin{align*}
(x_2 - x_{o2})(x_D - x_{o2}) + (y_2 - y_{o2})(y_D - y_{o2}) &= R_2^2
\end{align*}$$  \(1\)

Equation of circle $O_2$:

$$\begin{align*}
(x_2 - x_{o2})^2 + (y_2 - y_{o2})^2 &= R_2^2
\end{align*}$$  \(2\)

Available from formula (1):

$$\begin{align*}
x_2 &= A - By_2 + x_{o2}
\end{align*}$$  \(3\)

In the formula (3):

- $A = \frac{R_2^2 + (y_D - y_{o2})x_{o2}}{x_D - x_{o2}}$
- $B = \frac{y_D - y_{o2}}{x_D - x_{o2}}$

Bring formula (3) into formula (2) available:

$$\begin{align*}
y_2 &= \frac{B_1 + \left(B_1^2 - A_1C_1\right)^{1/2}}{A_1}
\end{align*}$$  \(4\)

In the formula (4):

- $A_1 = B^2 + 1$
• \( B_1 = y \omega_2 + AB \)
• \( C_1 = y \omega_2^2 + A^2 - R_2^2 \)

Bring (4) back into (3) to get the value of \( x_2 \), it is a complex trigonometric function equation and cannot be solved directly. So I use the iteration method to determine the values of \( \phi \) and \( \theta \). Extend \( O_1, O_2 \) to the point \( M \) of back donkey head arc, available from Fig. 1, \( \overline{MT} = R_2 \times \delta \), \( \delta \) is arc wrapping angle between Point \( T \) to point \( M \), available from the cosine theorem:

\[
\delta = \cos^{-1}\left( \frac{R_2^2 + R_1^2 - c^2}{2 \times R_1 R_2} \right)
\]

And:

• \( l = \left( (x_2 - x_0)^2 + (y_2 - y_0)^2 \right)^{1/2} \)
• \( L = \overline{MT} + l \)

Available from Fig. 1, the sum of arc \( \overline{MT} \) and connecting rod \( l \) is the length of driving rope \( L \), so \( \overline{MT} \) and \( l \) are dependent variables with \( \phi \) and \( \theta \) as independent variables. Therefore, given a set of values \( \phi \) and \( \theta \), a set of values \( \overline{MT} \) and \( l \) can be obtained. Find the difference between \( \overline{MT} + l \) and the length \( L \) of the driving rope, if the difference is within the allowable accuracy, the values \( \phi \) and \( \theta \) are considered to be available.

3. Establish The Mathematical Model of Motion and Dynamics

The polished rod displacement formula:

\[
S = \theta A
\]

The velocity \( \omega_T \) at point \( T \) can be obtained by analytic method:

\[
\omega_T = \frac{1}{c} r \omega \frac{\sin \alpha}{\sin \beta}
\]

In the formula (6), \( \omega \) is the average rotation angular velocity of crank, \( \omega = \frac{n \pi}{30} \) rad/s, \( n \) is the stroke rush.

The polished rod velocity \( V_S \) can be obtained from formula (6):

\[
V_S = A \omega_T
\]

The formula of the polished rod acceleration can be obtained by analytic method:

\[
a_s = -\frac{A}{c} r \omega^2 \frac{\cos \alpha}{\sin \beta}
\]

The torque factor \( \overline{TF} \) is the ratio of polished rod load to crankshaft torque, which reflects the bearing capacity of pumping units in normal operation. The formula is as follows:

\[
\overline{TF} = \frac{Ar \sin \alpha}{c \sin \beta}
\]

4. Design of The Analysis and Optimization Software

The motion analysis and optimization system of dual horse head pumping unit with single arc back horse head is developed on the basis of MATLAB platform and GUI Editor under Windows system[4]. The software display interface, input area and function buttons are simple and intuitive. By inputting the geometric parameters of the pumping unit, the result can be obtained by clicking the corresponding
function button. Fig. 2 and 3 are the system schematic illustration and the button function schematic illustration.

![System Schematic Illustration](image1)

![Button Function Schematic Illustration](image2)

5. Kinematic Analysis of The CYJS6-3-18HB Pumping Unit

We use the CYJS6-3-18HB pumping unit as the object of this analysis. The geometric parameters of the CYJS6-3-18HB pumping unit are as follows: $A = 3000 mm$, $I = 1900 mm$, $H = 3785 mm$. The crank radius, stroke and stroke rush date of CYJS6-3-18HB pumping unit are shown in Table 1.

| Crank Radius (mm) | Stroke Rush (r/min) | Stroke (m) |
|-------------------|---------------------|------------|
| 600               | 5                   | 2          |
| 740               | 7                   | 2.5        |
| 880               | 9                   | 3          |

The results of motion analysis under different crank radius and stroke rush are given below. Fig. 4, 5 and 6 correspond to the results of displacement (stroke), velocity and acceleration analysis under three geometric sizes $r = 0.6n = 5$, $r = 0.74n = 7$ and $r = 0.88n = 9$ respectively. The results of analysis in Fig. 4, 5 and 6 are consistent with the data given in the table 1.
6. Torque Factor Analysis and Calculation of The CYJS6-3-18HB Pumping Unit

The torque factor is the ratio of crank torque to polished rod load, so as long as the crank torque is given, the polished rod load can be obtained. Cause the crank torque value is not given in the geometric size, we only calculate the torque factor. From the formula (9), we can get the torque factor curve Fig. 7.
7. Optimization of Geometric Parameters of Pumping Units

7.1 Selection of Target Parameters
In this paper, the torque peak $TF_{\text{max}}$ is selected as the optimization objective. Reducing the peak value of pumping unit torque factor can reduce the root mean square torque of the reducer output shaft, thus achieving the goal of energy saving and high efficiency. Moreover, $TF_{\text{max}}$ is only related to the geometric parameters of pumping units, which avoids the interference of complex actual working conditions on the optimization results and makes the results more universal[5-6].

7.2 Selection of Design Variables
The design variables are generally composed of multiple variables. Independence should be considered among the variables, and the minimum variables should be used to reflect all the characteristics of pumping units[6]. In this paper, the geometric parameters of pumping units have been given, the installation size $R_1$ and radius $R_2$ of the back donkey head are selected as design variables. By calculating $TF_{\text{max}}$ of different $R_1$ and $R_2$ values, we can find the minimum $TF_{\text{max}}$ corresponding to $R_1$ and $R_2$.

7.3 Establishing Constraints
Establish constraints based on the design variables selected above:
- $c \cdot r \cdot K \cdot l$ meet rod length and crank existence conditions;
- $0 \leq R_1 \leq H$
- $0 \leq R_2 \leq I$
- $TF_{\text{max}} \geq 0$

Taking $r = 0.6, \ n = 5$ as an example, after calculating the torque factor curve, click the button of automatic optimization to optimize. From Fig. 8, it can be seen that the torque peak after optimization has become more gentle than that before. It shows that when $R_1 = 0, \ R_2 = 1.9$, the pumping unit is in a better state of operation.
8. Conclusion

According to the special geometric structure of dual horse head pumping unit with single arc back horse head, the kinematic analysis and optimization software based on MATLAB platform is developed by GUI editor, which is suitable for all dual horse head pumping units with single arc back horse head. This software realizes the kinematic analysis of dual horse head pumping unit and the optimization of the installation position of the back horse head, and effectively reduces the torque peak of the double horse head pumping unit. The torque factor parameters of the CYJS6-3-18HB pumping unit are optimized with back horse size and installation position as design variables, which further verifies the validity and reliability of software analysis and optimization function.

References

[1] Dai, Y., Lu, L., Gao, X. S. (2004). Analysis of Motion and Dynamic Characteristics of Double Donkey Head Pumping Unit. Journal of Machine Design, Vol 21: 26-28.

[2] Nie, Y. G., Liu, J., Xiao, S. H., Wang, Z. W. (2001). Analysis of Motion and Dynamic Characteristics of Double Donkey Head Pumping Unit. J. OIL Field Equipment. J. Vol 30: 24-28.

[3] Li, Z. W., Wu, X. D., Zhou, C. F. (2001). Solution Method of Motion Parameters of Special-Shaped Beam Pumping Unit. J. China Petroleum Machinery. J. Vol 29: 14-16.

[4] Xie, L. R. (2014). Man-machine interface design of asynchronous motor based on matlab/GUI. Experimental Technology and Management. J. Vol 31: 50-53.

[5] Lian, Y. (2007). Dynamic Analysis and Optimum Design of Double Donkey Head Pumping Unit. NanJing. pp. 41-43.

[6] Chen, A. M., Yuan, D. Z., Huang, W. T., Zheng, P. B., Wu, X. Z. (1998). Optimum Design of Double Donkey Head Pumping Unit. China Petroleum Machinery. J. Vol 26: 2-4.