Analysis and optimization of detection curve of BLTD cementing mud flowmeter

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Abstract: Cementing slurry flow meter testing curve accuracy directly affect the measurement precision of the cementing slurry flow meter, through collecting BLTD cementing slurry type flowmeter in actual data in the process of project operation, study the inner link, thus obtains the actual test curve in the process of operation. The working principle of BLTD flow meter is studied and the testing curve of its theoretical model is obtained. Check the consistency of the theoretical curve and the actual testing curves, through the analysis of the characteristics of flow testing curve, from the perspective of numerical calculation with the method of nonlinear correction are given for testing curve optimization strategy, and carries on the verification, and measure the lower limit is lower, wider range of cementing slurry flow meter testing model, solved the cementing slurry flow meter testing curve of nonlinear optimization problem.

1. Introduction
In cementing operation, mud flow detection is very important for cementing quality[1-4].Existing flowmeters are generally used for the detection of pure substances. For the detection environment with high flow rate and special medium, the general flowmeter is too fragile in material and cannot bear the mud with high flow rate and a lot of impurities in structure. The cementing mud flow meter needs to work normally in the complex environment of high pressure, high temperature, high velocity and high impurity. BLTD cementing mud flowmeter is designed with tangential impeller and installed with vertical insertion type, which can effectively reduce the damage of mud impurities to the mud flowmeter and reduce the accuracy. If the measurement error cannot be corrected, the cementing quality will be affected[5-8].Based on the actual detection data collected by BLTD type cementing mud flow meter in a drilling company in liaoning province, this paper obtains the flow detection curve of the flow meter through curve fitting for various types of data, and analyzes the characteristics of the detection curve. Test the consistency between the theoretical curve and the actual curve; The original curve is modified by numerical method[9], The optimization strategy of testing curve of cementing mud flow meter is given.

2. BLTD type cementing mud flow meter test curve

2.1. Establish the flow meter mathematical model
The basic governing equation of cementing mud flowmeter is obtained according to the theorem of moment of momentum[10].
\[
J \frac{d\omega}{dt} = M_r + \sum_{i=1}^{n} M_{ri}
\]  

(1)

Where \( J \) is the moment of inertia of the impeller (which is only related to the mass of the impeller), \( \omega \) is the rotation angular velocity of the impeller, \( \frac{d\omega}{dt} \) is the rotation acceleration of the impeller. \( M_r \) is the driving torque of fluid to impeller blade, \( M_{ri} \) shows all resistance moments of impeller blades.

Under the quantitative normal flow condition, the impeller of the cementing mud flow meter is in a stable and uniform rotation state, and the angular acceleration of the impeller is 0.

\[
J \frac{d\omega}{dt} = 0
\]  

(2)

At this point, the driving torque of the impeller blade is balanced with all the resistance moments of the impeller. Because the mechanical frictional resistance moment between the impeller shaft and the bearing and the electromagnetic resistance moment of the magneto-electric induction amplifier to the impeller are far less than the viscous frictional resistance moment of the fluid to the impeller (related to the actual measured fluid density), the driving torque of the impeller under stable operation is equivalent to the viscous resistance torque generated by the fluid flowing through the impeller blade.

According to the momentum theorem, the driving moment of a single impeller blade is analyzed, and the relationship between the rotational speed of the impeller and the fluid velocity under ideal conditions is deduced by combining (1) and (2):

\[
Q = \left( \frac{S_e \cdot 2\pi r^2}{r_0} \cdot n \right)
\]  

(3)

Where: \( Q \) is the volume flow rate of the fluid; \( n \) turbine revolutions; \( r \) is the radius of the impeller blade; \( r_0 \) is the distance from the axis of the effective fluid area at the inlet of the flow cavity to the center of the impeller. The cross-sectional area of exit aperture of \( S_e \) fluid cavity.

2.2. Fit the flow meter engineering test curve

The collected test data is the process log of each cementing operation. Each acquisition interval is 12 seconds. Existing data types include monitoring time (unit: hour/minute/second), number of pulses (unit: Hz), fluid velocity (unit: L/min), fluid density (unit: g/cm³), external pressure (unit: Mpa), etc. The mud used in the record is a high-density mud with a density of more than 1.25 g/cm³ used in the actual cementing work and mixed with unquantifiable solid impurities. The workflow log with obvious data changes and less abnormal data was selected from multiple groups of actual monitoring data. By analyzing the collected flow data information, and using MATLAB software to summarize and analyze various data by curve fitting, exploring the curve characteristics of the flow meter monitoring data in the process of work.

The data of impeller speed and time, fluid flow data and time data in each group of workflow logs were extracted, and the following curves were drawn:

![Figure 1. Testing time-Rotate speed relation schema](image1)

![Figure 2. Testing time-Rate of flow relation schema](image2)

As shown in figure 1, in the initial stage of work, the rotating speed of the cementing mud flow meter impeller is in a rapidly increasing range. Later, when the flow field in the cavity of the cementing mud flow meter and the force on the impeller tend to be stable, the speed of the impeller enters a stable
range, within which the speed of the impeller remains within a stable numerical range. Finally, with the gradual decrease of the measured flow body, the rotational speed of the impeller presents a stepped decline and enters a rapid reduction range. As shown in figure 2, it is obvious that the relationship between time and flow is similar to that between time and the rotating speed of impeller, and the law of motion of fluid flow and impeller at the same time tends to be consistent.

The data of fluid flow and impeller speed were extracted, and there was a linear relationship between the flow and impeller speed. However, in the early and late stages of detection, some abnormal data existed. That is, when the impeller is in the process of driving and deceleration, it does not maintain a stable speed, which results in the partial data not having a more obvious linear relationship similar to the stability interval data. See figure 3.

The discrete data of impeller speed and fluid flow were fitted to a quadratic curve, and the least square method was applied. The fitting results were shown in formula (4), and the fitting curve was shown in figure 4:

\[ f(x) = 836.6x + 1858 \]  

According to the actual test data of a drilling company in Liaoning province, the correlation and consistency between the fluid volume flow of the actual test data and the fluid volume flow calculated by the model are compared.

As shown in figure 5, the established cementing mud flow meter detection model still has some errors. However, the error distribution range is small, and the error distribution is obvious only when the impeller speed is large.
The correlation between the calculated fluid flow data and the actual detected fluid flow data was analyzed by using the statistical principle: The correlation coefficient between the two groups was 0.999885693. And the covariance is greater than 0. Therefore, it can be considered that the cementing mud flow meter detection model is consistent with the actual detection model of BLTD type cementing flow meter, and this detection model is reasonable, stable and practical.

3. Optimization strategy for testing curve of cementing mud flowmeter

3.1. derivation of instrument coefficient of cementing mud flow meter

In order to uniformly evaluate various cementing mud flow meters, the coefficient K of volume instrument is usually adopted to describe the detection characteristics of different flow meters[10]. The calculation formula is as follows:

$$K = \frac{f}{Q}$$

Where f is the pulse frequency and Q is the fluid flow rate. Take the pulse frequency into the expression:

$$K = \frac{N \cdot n}{Q}$$

Where N is the number of impeller blades and n is the number of rotation cycles per unit time measured by the impeller.

According to comprehensive formulas (3) and (6), the calculation formula for the instrument coefficient of BLTD type cementing flowmeter is as follows:

$$K = \frac{N}{2 \pi r^2} \left( \frac{r_0}{S_e} - C \right)$$

The linear characteristic curve of the cementing mud flow meter sensor is expressed by volume flow q and instrument coefficient K. In engineering measurement, due to the influence of fluid characteristics, impeller inertia and rotational friction, the actual characteristic curve is different from the ideal one.

The instrument coefficient of the sensor is verified by the flow calibration device, and the conversion coefficient is determined according to the frequency of input flow and output pulse signal. However, this instrument coefficient is conditional, and its inspection condition is the reference condition. If the use deviates from this reference condition, the coefficient will change, and the changing condition will depend on the type of sensor, installation condition of pipeline and physical parameters of the fluid. Therefore, in the design of turbine flow timing, it must be measured within its linear range to ensure the accuracy of measurement. The linear range mentioned here generally refers to the flow range corresponding to the variation value of the instrument coefficient within the range of ±1%.

3.2. An optimization strategy for correcting nonlinear segments

For turbine flowmeters, due to the universal non-linear relationship between the instrument coefficient K and the flow rate Q at a small flow rate, K is difficult to be guaranteed to be a constant even within the range of linearity, which brings great difficulties to describe the relationship between them with mathematical formulas. Interpolation method can solve this problem well. According to the verification regulations of velocity flowmeter, the detection point $Q_i (i=0,1,...,n)$ can be taken as the node of interpolation function, and the function value $K_i (i = 0,1,...,n)$ corresponding to each node is the instrument coefficient corresponding to each flow point. The instrument coefficient is corrected by linear interpolation method.

The linear interpolation method is to connect every two adjacent detection points with a straight line. When the frequency signal f of an instantaneous flow is collected, the if and else statements are
used to determine the interval segment corresponding to \( f \). In other words, the frequency \( f \) sampled by the intelligent detection and analysis system is compared with the preset frequency \( f_i \). When the following inequality is satisfied:

\[
f_{i-1} < f < f_i
\]  

(8)

The frequency \( f \) is considered to meet the judgment condition. At this time the following four cases to be considered:

When \( i=1 \), that is, \( f < f_i \), let \( K = K_i \), instantaneous flow is:

\[
q_v = \frac{f}{K} = \frac{f}{K_i}
\]  

(9)

According to the characteristics of the turbine flowmeter, the actual instrument coefficient \( K_a \) corresponding to the frequency \( f \) is less than \( K_i \), the calculated instantaneous flow is smaller than the actual instantaneous flow, i.e., \( q_v < q_{va} \), at which time the fitting error of instrument coefficient is positive.

\( i = 2, 3, ..., N \) (in this case, \( N \) is the number of detection points), that is, there is \( f_{i-1} < f \leq f_i \) within the range of range. According to the theorem that two points on the plane determine a straight line, we can get:

\[
K = \frac{K_i - K_{i-1}}{f_i - f_{i-1}} \times (f - f_{i-1}) + K_i
\]  

(10)

Where \( f \) is the instantaneous frequency; \( K \) is the instrument coefficient corresponding to the instantaneous frequency; \( f_{i-1} \) is the frequency of the previous detection point in the appropriate range; \( K_{i-1} \) is the instrument coefficient of the previous detection point in the appropriate range; \( f_i \) is the frequency of the latter detection point in the appropriate range; \( K_i \) is the instrument coefficient of the last reference point in the appropriate range.

The instrument coefficient \( K \) value corresponding to \( f \) can be obtained through formula (10). Then according to the formula:

\[
q_v = \frac{f}{K}
\]  

(11)

The instantaneous flow rate of the turbine flowmeter is calculated. At this time, the fitting error of the instrument coefficient can be positive or negative.

When \( f > f_N \), that is, the cementing mud flow meter works at the upper limit of the flow range, let \( K = K_N \). At this moment, the instantaneous flow is:

\[
q_v = \frac{f}{K} = \frac{f}{K_N}
\]  

(12)

According to the working characteristics of the cementing mud flow meter, the actual instrument coefficient \( K_a \) corresponding to the frequency \( f \) at this time is slightly greater than \( K_N \). The calculated instantaneous flow is smaller than the actual instantaneous flow, namely \( q_v < q_{va} \).

(4) When \( f = f_i (i = 1, 2, ..., N) \), that is, the frequency of the cementing mud flowmeter happens to be the inspection point, that is, \( K = K_i \). Obviously, the fitting error at the inspection point is zero.

3.3. optimization results of nonlinear segment correction

After the nonlinear correction of the instrument coefficient of BLTD type cementing flowmeter by the intelligent monitoring and analysis system, the actual flow test is carried out again, and the average instrument coefficient and frequency data of each point within the full range before and after the nonlinear correction are compared.

Taking a group of test data, the calculation shows that the linearity of the instrument coefficient is 1.63% before the nonlinear segment correction. The data of BLTD cementing flowmeter before nonlinear segment correction are shown in table 1.
Table 1 BLTD cementing flowmeter data before modification

| traffic (m³/h) | Average instrument coefficient | frequency (Hz) |
|---------------|-------------------------------|----------------|
| 169.62        | 12904.13866                   | 608            |
| 169.74        | 12937.43372                   | 610            |
| 169.86        | 12970.68174                   | 612            |
| 169.98        | 13003.88281                   | 614            |
| 170.16        | 13032.44006                   | 616            |
| 170.4         | 13056.33803                   | 618            |
| 171.9         | 13068.06283                   | 620            |

Through experimental test and data comparison, the widening effect of nonlinear segment correction on range ratio is studied. After nonlinear section correction, the linearity of the instrument coefficient is 0.32%. The linearity was effectively controlled within 0.5%. The data of BLTD cementing flowmeter after nonlinear segment correction are shown in table 2.

Table 2 BLTD cementing flowmeter data after modification

| traffic (m³/h) | Average instrument coefficient | frequency (Hz) |
|---------------|-------------------------------|----------------|
| 169.62        | 13026.47732                   | 608            |
| 169.74        | 13034.58794                   | 610            |
| 169.86        | 13038.81128                   | 612            |
| 169.98        | 13045.98406                   | 614            |
| 170.16        | 13050.49311                   | 616            |
| 170.4         | 13056.33803                   | 618            |
| 171.9         | 13068.06283                   | 620            |

K-qv curves before and after nonlinear correction are shown in figure 6:

Figure 6. The K-qv curve of BLTD cementing flowmeter before and after modification

4. conclusion
In this paper, the mathematical model of BLTD type cementing mud flow meter is established. Based
on the field test data of the cementing mud flow meter in a certain place of liaoning province, MATLAB software is applied. The curve fitting method was used to fit the time scatter data. According to the fitting results, the possible variation rules and physical characteristics of each variable were predicted. At the same time, the linear relationship between the impeller speed and the fluid velocity is analyzed. Its accuracy was tested by consistency. In this paper, based on the nonlinear correction, the optimal strategy of BLTD type cementing mud flow meter detection curve is given. By means of numerical calculation, the original intelligent detection and analysis system is improved, and the data comparison before and after correction is given. By using this optimization strategy, the calculation method of converting original measurement coefficient into measurement data is improved, and the range ratio is widened to enhance the measurement accuracy.

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