Study on the measurement of hoisting mechanism efficiency for bridge crane

Zhihao Ge1, Yifei Tong1, Meng Zhong1, Xiangdong Li2

1School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing, People’s Republic of China
2Jiangsu Province Special Equipment Safety Supervision Inspection Institute, Nanjing, People’s Republic of China

Abstract. With the bridge crane as a research object, the problem of hoisting mechanism energy consumption and the need of detecting energy consumption are studied by using the black box theory and the serial theory. After the need of measuring reducer power is analyzed emphatically, a plan that measuring simultaneously power of reducer torque and rotational speed is finally proposed.

1. Introduction
With the development of bridge crane, energy consumption of crane transmission has attracted much attention. How to quantitatively detect the actual energy consumption of crane transmission mechanism has an important guiding significance for the crane saving design [1]. The transmission efficiency of gear coupling is studied by Qiwen Ma, which provides a theoretical basis for improving the transmission efficiency of gear coupling [2]. Michaelis, K of Munich University analyzed the effect of lubricant on the power consumption of the reducer[3]. In this thesis, the hoisting mechanism of bridge crane is taken as the research subject, and the need to detect energy consumption of the hoisting mechanism is studied by using the black box theory and the serial theory. In view of the characteristics of the transmission parts, the transmission efficiency and measurement methods are studied, especially for the reducer and the hoist system.

2. Demand analysis for measuring of hoisting mechanism efficiency
The hoisting mechanism is one of the most important transmission mechanisms on the bridge crane and the transmission efficiency is an important indicator for its energy consumption. The hoisting mechanism of a 20-5T bridge crane is studied in this paper by utilizing the serial connection and black box theories to analyze the measuring demand of transmission efficiency for each transmission component.

The input energy for entire hoisting mechanism is electricity which is applied onto both the motor and the brake. However, the mechanical energy converted from the electricity by the brake acts as the braking energy and is not transferred to transmission parts. The mechanical energy converted from the electricity by the motor during non-braking process can be transferred to transmission parts. Transmission parts of hoisting mechanism are connected with each other in series, which means if n individuals are connected with each other in series, they shall all exist concurrently to constitute their entirety. Each individual is called as a serial component of the entirety.
The mechanical energy of the hoisting mechanism is transferred to each transmission part in serial way and the transfer process of mechanical energy is shown in Fig. 1. If the entire mechanism or a single part is taken as the object to study the energy consumption, it is hard to find the solution since a lot of variables have to be studied. A method is adopted to break down and simplify the complicated problem so as to easily solve a difficult or even dissolvable problem. So the hoisting mechanism under non-braking condition is broken down into a reducer, a coupling and a suspension system, which is consisted of a drum, wire rope, a plurality of pulleys and a lifting hook. This method enables the study of mechanical transmission efficiency to be performed on each subsystem instead of the entirety.

3. Analysis for measuring of coupling efficiency

As a mechanical connecting part, the coupling not only synchronizes the driving and driven shafts for rotation, but also transmits torque. Some kinds of couplings also have functions of buffering, shock absorption and dynamic performance improving for shafting if used for power transmission under high speed/load conditions [4]. As a normal component for power transmission, its stability and high efficiency are very important.

As one of the most common transmission components, the coupling is employed in each transmission mechanism of the bridge crane to transmit torque. The coupling is characterized in low energy consumption due to high transmission efficiency.

![Fig.1. Transfer process of mechanical energy.](image)

The transmission efficiency of the coupling is very high. In particular, the transmission ratio of the gear coupling normally used in the bridge crane can reach 0.99 and vary a little under normal service conditions. It is feasible and possible to measure the efficiency of a coupling in a lab but the on-site measuring are easily affected by external factors resulting in inaccurate results, so it is meaningless to measure it on-site. Therefore the coupling is considered as a component with mechanical transmission efficiency when the transmission mechanism is studied.

4. Analysis for measuring of reducer efficiency

4.1. Demand analysis for measuring of reducer efficiency

Gear reducers are mainly used in hoisting, operating, turning and luffing mechanisms on a crane [5] and classified into soft tooth surface, medium-hard tooth surface and hard tooth surface types according to the hardness on tooth surface [6]. The most common type of reducer for bridge crane is QJ series.

As an important transmission part, the reducer plays an important role in the hoisting mechanism. The energy consumption of the reducer as shown in Fig. 2 will be comprehensively studied in the respect of structure, manufacturing, loss in service, repair and depreciation.

Energy is primarily consumed by manufacturing, working and servicing of reducers and the energy consumed by manufacturing includes the energy consumption for material and the energy consumption for processing. Where in the former is evaluated through the suitability of selected material and the optimization of structure. The latter is evaluated by investigating the optimization degree of entire manufacturing process and each procedure.

The energy consumed by working mainly refers to the transmission efficiency of the reducer in service as well as the level of noise and vibration. The higher the transmission efficiency is, the lower the energy loss is. The loss of energy usually appears as vibration and noise.
The energy consumed by servicing mainly refers to the energy consumed on routine and corrective maintenance as well as depreciation. The energy consumed on routine and corrective maintenance of the reducer can be reduced but is inevitable. The energy consumed on depreciation is dependent on the years of working and the depreciation rate, which means the higher the service life is, the lower the power consumed on depreciation is.

The energy consumption of the reducer shall be comprehensively studied for the whole life cycle, which starts from the design phase and ends at the equipment recovery phase. As an important part of the energy consumption for reducer, the energy consumed by working can be measured in an indirect manner when the reducer is in service.

The transmission efficiency of the reducer is directly related to the energy consumption and influenced by load, oil temperature in housing and external environment when the reducer is in service. Therefore measuring the efficiency of the reducer in service is essential for studying the energy consumption of the hoisting mechanism on the bridge crane. The power measuring method is adopted to measure the power of both input and output shafts of the reducer so that both the energy loss within a certain time period and the instantaneous transmission efficiency of the reducer can be obtained.

4.2. Efficiency measuring for reducer

The efficiency of reducer is traditionally measured in open and closed manners, either of which corresponds to different measuring principles and equipment. However the parameters measured in both manners to calculate the transmission efficiency of reducer are the same: torques and speeds of both high speed and low speed shafts. A position has to be reserved when designing the structure of bridge crane to mount a commercially available torque sensor, in which case it is hard to carry out measuring on a working reducer. Therefore it is extremely rewarding if the efficiency can be measured when the reducer is in service. This paper investigates a torque and power meter and it is not necessary to reserve a place on the crane structure to mount this new type of meter for measuring the torque and speed. The measured torque and speed are transmitted to a host computer to calculate the power values of both low speed and high speed shafts of the reducer.

Use below equation to calculate the power:

$$P = \frac{n \times T}{9550}$$  \hspace{1cm} (1)

Where

- $T$ is the torque to be measured in N·m;
- $n$ is the speed in r/min; and
- $P$ is the power in KW.
The measured result is an instantaneous and dynamic value and the reducer power $P_{Ji}$ at any time shall correspond to the torque $T_i$ and the speed $r_i$ at the $i$th time point. The data is wireless transmitted to a host laptop nearby and the data section in each data frame comprises a torque value and a speed value in order to ensure the simultaneity of both values.

Use below equation to calculate the real-time efficiency of reducer

$$\eta_{Ji} = \frac{P_{JIi}}{P_{JOi}} \times 100\%$$

(2)

Where

- $P_{JIi}$ is the high speed shaft power of the reducer, namely the input power;
- $P_{JOi}$ is the low speed shaft power of the reducer, namely the output power.

5. **Analysis for measuring of suspension system**

The suspension system is consisted of a drum, wire rope, a plurality of pulleys and a lifting hook and it is very difficult to study the transmission efficiency of a single part. But the problem can be easily, feasibly and reliably studied if individual parts are connected with each other in series to constitute their entirety, which is to be studied on the basis of the serial connection and black box theories.

We only study the input and output power of the suspension system, which is consisted of a drum, wire rope, a plurality of pulleys and a lifting hook, instead of solving the transmission efficiency of each single part in the “Black Box”. As shown in Figures Fig.1, the input power of the suspension system is generated by the low speed shaft and can be calculated via $P_{DI} = \eta_L \times P_{JO}$, where $\eta_L$ is the efficiency of coupling and $P_{JO}$ is the output efficiency of reducer. The output power of suspension system $P_{DO}$ is physically used to lift loads.

The equation $P = F \times V \times \cos\theta$ (where $F$ is the pull force, $V$ is the load speed and $\theta$ is the angle between the pull force vector and the speed vector) can be used for the hoisting process under load. If the load is hoisted vertically, the equation turns to be $P = F \times V \times \cos\theta = mg \times \nu$ (where $mg$ is the load weight and $\nu$ is the vertical speed). Since the load weight is unknown during work, the pull force $F$ can be obtained by measuring the tension on wire rope so as to obtain the load weight.

The tension sensor applied on the wire rope is designed according to the principle “Bending at 3-point”, as shown in Fig.3. The sensor is clamped on the rope during measuring and tensioned when a force is applied on the rope. The moveable pulley $C$ presses down on the rope in this process while pulleys $A$ and $B$ are fixed to generate the displacement signal $\delta$, which is controlled by a distance sleeve, and the pressing signal $P$ (as shown in Fig.3), which is measured by a force sensor. The rope tension $T$ is determined by the displacement signal $\delta$ and the pressing signal $P$ and embodied by $T = f(P, \delta)$. So it is possible to use the tension sensor to measure the rope tension.

![Fig.3. Schematic for measuring rope tension](image)

Using tension sensors to measure the rope tension is shown in Fig.4. The rope tension is shown in Fig.4, where $T$ is the tension value measured by the tension sensor. Providing number $N$ of tension sensors are arranged, $F_1 = T \times \sin\theta$, so the total pull force is $F = N \times F_1$.

Since the pull force has the same direction with the speed, the power of suspension system is

$$P_D = F \times V = N \times T \times \sin\theta \times V$$

(3)

Where

- $N$ is the number of tension sensors;
- $T$ is the value measured by the tension sensor; and
- $V$ is the value measured by the speed sensor.
θ increases with the increase of load but changes a little, so it’s considered as a constant to facilitate the calculation.

The efficiency of suspension system is expressed via

\[
\eta_D = \frac{P_D}{P_D \times P_{JO}} \times 100\% \quad \text{and since both } P_0 \text{ and } P_D \text{ are instantaneous values, } \eta_D \text{ has to be calculated from the perspective of power. Use below equation to calculate the input power } W_I \text{ of the suspension system:}
\]

\[
W_I = \eta_L \int_0^{t_0} P_{JO} \, dt = \eta_L \sum_{i=0}^{n} \Delta P_{JOi} \cdot \Delta t_1 = \eta_L \sum_{i=0}^{t_0 \times f_1} \Delta P_{JO} \cdot \frac{1}{f_1}
\]

\[
W_O = \int_0^{t_0} P_D \, dt = \sum_{i=0}^{n} \Delta P_{DI} \cdot \Delta t_2 = \sum_{i=0}^{t_0 \times f_2} \Delta P_{DI} \cdot \frac{1}{f_2}
\]

Where

\[ t_0 \text{ is the hoisting time;} \]
\[ f_1 \text{ is the data acquisition frequency of reducer power measuring system;} \]
\[ \Delta t_1 \text{ is the time interval between adjacent torque or speed values and expressed by } \Delta t_1 = \frac{1}{f_1}; \]

\[ f_2 \text{ is the data acquisition frequency of tension sensor and speed sensor; and} \]
\[ \Delta t_2 \text{ is the time interval between adjacent tension or speed values and expressed by } \Delta t_2 = \frac{1}{f_2}. \]

The suspension system efficiency can be obtained by combining the reducer power equation and Equations (1) to (5):

\[
\eta_D = \frac{W_O}{W_I} \times 100\% = \frac{\sum_{i=0}^{t_0 \times f_2} \Delta P_{DI} \times \frac{1}{f_1}}{\eta_L \sum_{i=0}^{t_0 \times f_1} \Delta P_{JO} \cdot \frac{1}{f_1}} \times 100\%
\]

\[
= \frac{\sum_{i=0}^{t_0 \times f_2} \Delta P_{DI} \times \frac{1}{f_2} \times \frac{\eta_{JOi} \cdot T_{JOi} \times 9550}{f_2}}{\eta_L \sum_{i=0}^{t_0 \times f_1} \Delta P_{JO} \cdot \frac{1}{f_1} \times 100\%}
\]

Where

\[ N \] is the rope tension sensor;
\[ T_i \] is the rope tension at each time point;
\[ V_i \] is the load speed at each time point;
\[ t_0 \] is the load hoisting time;
\[ T_{JOi} \] is the torque on the low speed shaft of reducer at each time point;
\[ n_{JOi} \] is the speed of low speed shaft on the reducer at each time point;
\[ f_1 \] is the reducer torque and speed acquisition frequency;
\[ f_2 \] is the suspension system tension and speed acquisition frequency;
\[ 9550 \] is a constant; and
\[ \theta \] is the angle between the rope and the horizontal plane.
6. Conclusion
In this paper, the hoisting mechanism is taken as the research object, the issues of energy consumption, and the relationship between energy consumption and efficiency are analyzed. First, the method of calculating the transmission efficiency of the parts of the lifting mechanism is analyzed by using the theory of serial and black box. Then, the measurement requirements of each transmission component are put forward. Through the study of the reducer, the detection index and detection scheme of the reducer are determined.

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