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A proposal research on energy-saving of gantry crane

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ABSTRACT

Construction machinery and equipment recently have been developed to be more energy-saving, however, wasting energy and low efficiency in gantry crane have become increasingly prominent. Therefore, based on existing energy-saving technology, this paper proposed an intelligent guided energy-saving method for gantry crane in terms of operation process. This method can automatically detect the optimal luffing position in the process of goods falling down to precisely direct drivers' operation so that electrical energy generated in the falling process can be used for the luffing of gantry crane to achieve energy saving. To verify this method, MATLAB/Simulinkis used to obtain a simulation platform for the whole system. According to the analysis of the simulation results, this method is demonstrated that it can significantly reduce the energy consumption of gantry crane under the best experiment condition.

KEYWORDS

Gantry crane; Energy-saving; Intelligent guided; Optimal luffing time.

INTRODUCTION

With the advance of economic globalization, port industry has developed rapidly in the world. However, the development of port transportation has brought not only advance in national economy but overwhelming energy problems. In face of high overall consumption and low resource utilization rate, it is of vital importance to establish the concept of green port and enhance technological innovation and support capabilities in energy-saving technology to promote energy saving and emission reduction and accelerate the construction of green port. The throughput of dry bulk has reached 60% compared to the total in recent years so that dry bulk terminal has a great potential in energy saving. As the general handling machines in bulk terminals, gantry cranes are widely used in various harbors and terminals. The operation process of traditional gantry crane is firstly to upgrade the goods and then lay down, while in this process a number of gravitational potential energy are produced. Generally, the gravitational potential energyis consumed by dynamic braking. It will work dramatically for the rational use of energy in bulk ports and reduce energy waste if we can convert the gravitational potential energy to electrical energy and use it during the operation of gantry cranes.

Because of the frequent starting, braking, raising, falling and variable amplitude, the operation process of gantry crane is so complex that its energy-saving technologiesare slightly lagging behind energy-saving technologies of rubber-tyred gantry crane. However,energy-saving technologies currently used in gantry cranes draw most lessons and experience of rubber-tyred gantry crane.

Iannuzzi D, ChangChunhe et.al proposed an energy-saving method based on energy recycling by AFE system[1-3]. This energy-saving technology is very similar to the method currently used intyred gantry crane. Energy produced in the process of cargo falling down is fed back to the grid, batteries or super capacitors to achieve energy saving[4-9]. Though the use of AFE system can effectively achieve energy saving, but AFE system is generally expensive. But losses may occur when using battery or super capacitor, besides, batteries and super capacitors generally have relatively short life. This method is only done at the electrical level.

Beldiajev V, Lehtla T, Liu Ganget.al proposed to achieve energy savings through frequency control[10]. The traditional method is to connect different-valuedresistors in the rotor circuit of the asynchronous motor. When the load torque of the motor is constant, the lower is the speed, the greater is the slip and the higher is the slip power. The increased slip power will be consumed through thermal energy. The frequency control changes the motor speed by changing the frequency of the power. In frequency control, the consumption of slip power remains the same no matter the level of the speed so that it has the highest efficiency to achieve energy saving. Tianjin Port test report shows that frequency control saved 23.5% in luffing mechanism and 16.7% in rotating mechanism. This energy-saving method, as described in 1, can perform a certain energy-saving effect, but remains in electrical level.

Mark M.Flynn et al proposed to perform energy recovery and release by the use of flywheel in the operation process of the crane[11-13]. Flywheel energy storage is an electromechanical energy conversion device which uses physical methods to achieve energy storage[14]. When gantry putting down the cargo, electrical energy generated by the motor is transformed to drive the motor through power converters, the motor drives the flywheel to speed up its rotation and then the energy is stored in the form of kinetic energy. When the portal crane needs electrical energy, the flywheel drives the motor to generate electricity and outputs current and voltage applied to the gate crane through power converters to complete the conversion from mechanical energy to electrical energy so as to achieve energy saving. But maintenance of energy-saving equipment is rather difficult and it requires higher security and protection features. Different from the above two methods, this method has achieve energy-saving effects in the mechanical level.

Mo Yamei et al proposed to optimize the design of the mechanical structure of gantry cranes to avoid unnecessary energy loss in the operating process. This method took into account the special natures of gantry cranes, and proposed to improve the operation structure to achieve energy saving. But this method is still in the theoretical analysis and calculation phase, it has a long way to go to put it into practice. Moreover, this method can only be used to the new-produced gantry cranes, not the existing ones. It is unrealistic to make mechanical reformation for more than 6,000 existing large-scale gantry cranes.

All the above are the studies in their respective fields. AFE system and frequency control are relatively mature but they both use only the electrical energy-saving technologies, while flywheel and other mechanical energy-saving technologies have not yet been fully mature. For gantry crane, we can achieve energy saving through process improvement which has not been studied yet. In addition, overall study of electrical, mechanical and process technology is also almost nonexistent.

Therefore, this paper proposed an intelligent guided energy-saving method for gantry crane based on optimal luffing position while taking into account its own characteristics and operation process. Through rational guidance and integral control in electrical, mechanical and technological characteristics, the electrical energy generated in the falling process can be used for the luffing of gantry crane directly. This proposal avoids the losses when using battery or super capacitor, so high efficiency can be achieved in energy saving of gantry cranes.

CALCULATION OF THE OPTIMAL LUFFING TIME

To make the electricity generated in the process of cargo falling down use directly in the luffing mechanism, optimal luffing time should be calculated so that drivers can be informed to change the amplitude at the best time to save power.
Motor torque equation shows that torque in the weight release phase is as follows:

$$\mathbf{T = T_{st} + T_{dy}} \tag{1}$$

In which, T_{st} is the static resistance torque of the motor shaft, T_{dy} is the moment converted to the motor shaft.

And static torque of the motor shaft is the moment generated by the weight when the system is in equilibrium. The static torque of the motor can be obtained according tothe Newton's second law:

$$\mathbf{T_{st} = \frac{MgR}{mi}\eta_0} \tag{2}$$

In which, M is the mass of the cargo, R is the radius of the roll, m is the magnification of the blocks, η_0 is the transmission efficiency of the mechanism, i is the reduction ratio of the gearbox.

Dynamic moment is the moment generated by the inertial force in the process of weight releasing to achieve balance. Assuming that the total moment of inertia is J after all the rotating mass and translational mass converted to the motor shaft and angular acceleration in the rotation is ε, the dynamic moment of the motor shaft is as shown in Formula 3.

$$\mathbf{T_{dy} = J\varepsilon} \tag{3}$$

To calculate the optimal luffing time, force of the roll F_r and linear velocity V_r should be calculated first according to force on the cargo and the falling speed of the cargo, as shown in formula (4) and (5):

$$\mathbf{F_r = \frac{F}{m\eta_1}} \tag{4}$$

$$\mathbf{V_r = mv\eta_1} \tag{5}$$

In which, m is the magnification of the blocks, η_1 is the transmission efficiency of the pulley blocks, v is the falling speed of the cargo.

Assuming the process of gantry crane releasing cargo is uniform acceleration in the startup phase, the average acceleration a is calculated by the start-up time t and velocity v at time t, as shown in formula (6):

$$\mathbf{a = v / t} \tag{6}$$

According to Newton's second law and the basic dynamics, torque T_l' due to the inertia force generated on portal crane rolls can be obtained when the speed of the cargo of mass M reaches v.

$$\mathbf{T_l' = \frac{30Mv^2}{\pi nt}} \tag{7}$$

In which, n is the RPM of the rotation shaft.

G Is the gravityof the rolls, J_r is the moment of inertia and D is the diameter of the moment. When the rotation speed is $n(r/\min)$,inertial torque T_r' generated by the rotation of the cylinder is:

$$\mathbf{T_r' = J_r \frac{d\omega}{dt} = \frac{G}{g}(\frac{D}{2})^2 \frac{\pi n}{30t} = \frac{GD^2}{375t} n} \tag{8}$$

When the gantry crane ratio is $i = \frac{n_d}{n}$ and the efficiency is η_2, T_l' and T_r' can be converted to the shaft at the speed $n_d (r/\min)$:

$$\mathbf{T_l = \frac{T_l'}{i}\eta = \frac{30Mv^2}{\pi t n_d}\eta_2} \tag{9}$$

$$\mathbf{T_r = \frac{T_r'}{i}\eta = \frac{GD^2 n_d}{375ti^2}\eta_2} \tag{10}$$

The average starting torque T of the motor can be obtained:

$$\mathbf{T = \frac{MgR}{mi}\eta_0 + \frac{1}{t}[\frac{30Mv^2}{\pi t n_d}\eta_2 + \frac{GD^2 n_d}{375ti^2}\eta_2](kgf \cdot m)} \tag{11}$$

The starting torque of the motor should be smaller than the maximum starting torque $T_{\max}$ and the rated torque T_n. For wire-wound AC motor, the starting torque $T \approx (1.5 \sim 1.6)T_n$; while for squirrel cage motor $T \approx (0.7 \sim 0.8)T_{\max}$.

There is some rotating mass existing in the transmission process of the hoisting mechanism, but the inertia moment of it will decrease along with the increase of the transmission ratio of transmission shaft, which leads to inertia force of rotating membersaccounting for the main part. To simplify the calculation, the inertia moment of the main rotation mass is selected as the inertia moment of the motor shaft generated by all other shafts in the hoisting mechanism.

$$\mathbf{\sum \frac{GD^2}{i^2}\eta_2 \approx 1.15(GD_m^2 + GD_c^2) + \eta_2 \sum GD_r^2 \cdot \frac{1}{i^2}} \tag{12}$$

The optimal luffing time can be obtained according to formula (11) and (12):

$$\mathbf{t}=\frac{\frac{30Mv^2}{\pi n_d}\eta_2+\frac{n_d}{375}\cdot 1.15(GD_m^2+GD_c^2)}{T-\frac{MgR}{mi}\eta_0} \qquad (13)$$

According to formula (13), v, T and n_d should be calculated first before t can be calculated. v is determined by the power relation between hoisting mechanismand luffing mechanism, which is to say, when the power generated in the cargo falling process is enough to provide the power needed in luffing mechanism, the speed is regarded as the critical speed.

According to $P = Fv$, the power generated in the lifting process P_{Hoist} is shown in (14), in which, v is the falling speed of the cargo and $\dot{v}$ is the acceleration at v. The power of luffing mechanism P_{Amp} is shown in (15), in which, $\overline{U}$ is the average resistance of the rack and v_r is the average speed of the rack.

$$P_{Hoist}=M\cdot v\cdot \dot{v} \qquad (14)$$

$$P_{Amp}=\overline{U}v_r \qquad (15)$$

As the arm swing, the luffing loads is constantly changing so that average value should be calculated after the resistance and speed are calculated in sections, which is shown in formula (16) and (17)

$$\int mvdv=\int \overline{U}v_r dt \qquad (16)$$

$$v=\sqrt{\frac{2\overline{U}}{m}v_r t} \qquad (17)$$

The torque T and the speed n_d of the motor can be obtained by electromagnetic torque equation, as shown in (18) and (19).

$$T=K_t\Phi I_2\cos\varphi_2 \qquad (18)$$ (**K_t is a constant only concerned with the motor**)

$$n_d=\frac{3E_2I_2\cos\varphi_2-3I_1^2R_1}{2\pi M} \qquad (19)$$

The above derivation is the whole process of solving the optimal luffing time. In the cargo falling process, the energy can be used directly in luffing mechanism according to the calculated time so that energy is saved and devices are simplified. In order to verify the effectiveness and reliability of the proposed method, we conducted the simulation study through MATLAB/ Simulink simulation platform.

SIMULATION RESULTS

This paper built the mechanical module, motor module and control module by using MATLAB/Simulink. This three modules were combined into a complete simulation platform. Theentire simulation platform is established based on parameters of a 40t-30m gantry crane as shown in the TABLE 1.

TABLE 1 : The key parameters of the simulation platform

Designation		Parameter			Unit
Elevating capacity		25(grab)	30.5(spreader)	40(hook)	t
Working range			R10-35		m
Classification grade		A8		A6	
Working speed	Lifting mechanism	60/75(no load)		30	m/min
	Slewing mechanism		1.3		r/min
	Luffing mechanism		50/30		m/min
Motor	Lifting mechanism		YZP-335M2-8 2*200Kw		
	Slewing mechanism		YZR-280M-8 2*55Kw		
	Luffing mechanism		YZP2-280M-8 55Kw		
Lifting height	Above rail	18(grab)		28(hook)	m
	Below rail		16		m
Install capacity			635		Kw

Figure 1 is the diagram between power and height of a 40tons gantry crane with different loads of 10 tons, 20 tons, 30 tons and 40 tons.

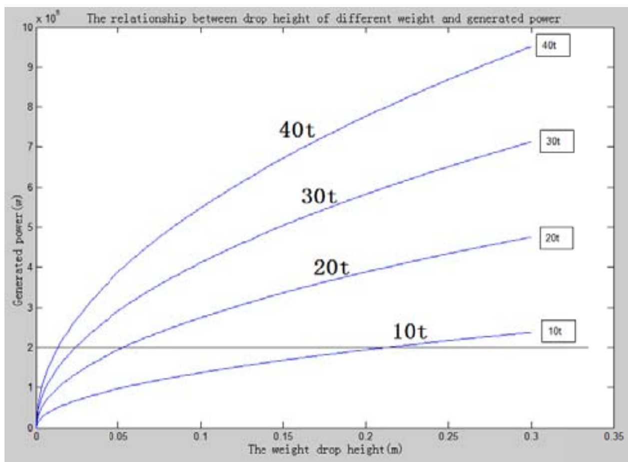

Figure 1 : Power diagram of hoisting mechanism

Seen from the diagram, the power is proportional to the mass of the load and proportional to the square of the height, which is $P \propto m\sqrt{h}$. It can be from the ordinate that power willincrease in a short time at first, but gradually level off with the height keeping increasing. Intersections of straight lines and curves in the diagram are the needed heights under the required power with different loads.

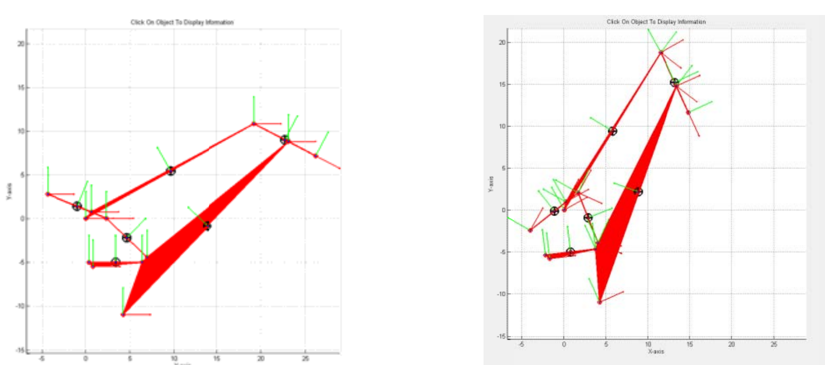

Figure 2 : The maximum and minimum luffing of gantry crane

As shown in figure 2, running states underthe maximum and minimum luffing can be observed in the simulation platform. In the luffing process, motion path can be observed by the sensors installed on the nose. Figure 3-3 is the motion path of nose of gantry crane under the load of 32 tons.

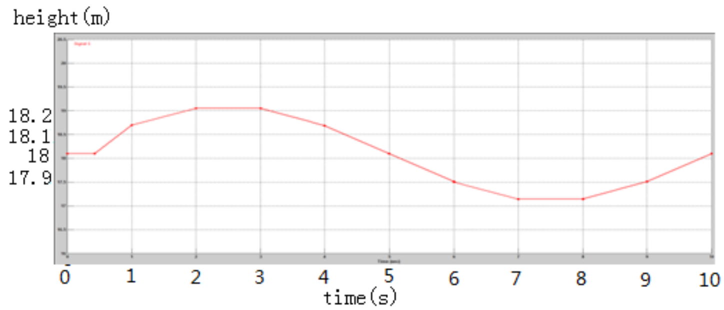

Figure 3 : Luffing curve of gantry crane

Through calculation, gantry crane with a load of 32 tons can provide enough power for the luffing mechanism at the time of 0.427s and then it starts luffing. If the height difference is in the range of 0.02* (maximum amplitude - minimum amplitude), it is accordant with the practical situation.
TABLE 2 is the optimal luffing time and saved energy with the method proposed in this paper in one operation cycle with different loads of 10 tons, 20 tons, 30 tons and 40 tons.

TABLE 2 : The optimal time and saved energy under different loads.

Mass (ton)	10	20	30	40
Time (second)	3.548	1.491	0.5022	0.2468
Saved energy (kJ)	195.4	82.005	27.621	13.574

The saved energy in TABLE 1 is the production of rated power and the optimal luffing time. If it doesn't change amplitude in the best luffing time, this energy will waste. Note that the saved energy in the table is the extra energy by this method in addition to the existing technologies. It doesn't mean as the load increases, the overall energy saving effect is deteriorated.

Figure 4 is energy-saving power comparison diagram. P_o is power curve without power saving technology, P_D is power curve with this power saving technology and P_{sum} is power curve in the process.

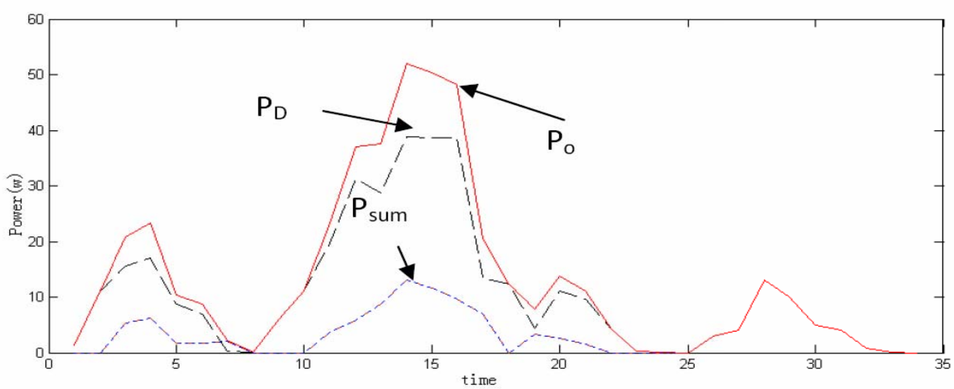

Figure 4 : Energy-saving power comparison diagram

In summary, through the simulation analysis, it can be found that huge potential energy can be generated in the operation. According to the power relation between hoisting mechanism and luffing mechanism, the method to determine the optimal luffing time can further save a lot of energy on the basis of the original energy-saving technologies.

CONCLUSION

This paper studied the energy relationship between hoisting mechanism and luffing mechanismand proposed an intelligent guided energy-saving method by calculating the optimal luffing time. This method observed the cargo loaded on the gantry crane which would generate power and when the power satisfied the luffing operation, it would be used for the luffing operation. This method will not only save the super capacitorand batteries, but avoid the energy loss during storage.

This paper also established a simulation platform in MATLAB/Simulink according to the study of mechanical structures, drive modes and motions of gantry crane. Through simulation, intelligent guided energy-saving method proposed in this paper can perform well in the ideal experimental conditionsandachieve good social and economic benefits.

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