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Operating Energy Efficiency of Automatically Controlled Cranes

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Basic operation and dynamic problems of cranes, such as positioning of loads with simultaneous damping of oscillations and limitation of wheel flanges' friction, can be solved by automatic control. The energy efficiency of cranes ,controlled automatically, compared to the machines equipped with classic drives and control systems, is presented in the paper. The relative energy profit of a norm duty cycles of the overhead cranes is significant. Absolute daily values of the saved energy are not very big. This saving is not the main reason of the automatization of the cranes' control.

Keywords: operation, dynamics, kinetic energy recuperation, cranes, automatization.

1. Introduction

Research devoted to automatization of cranes, begun started at the Technical University in Lodz in the end of the 80's of the 20th century, resulted in presenting in 1994 at the international fair INPRO'94 a new technology of transport by means of cranes automatically operated. This technology, based on using both microprocessors and electro-energetic frequency convertors allowed to solve majority of operating problems of cranes [5, 6, 8, 9]. Enhancing of the operating energetic efficiency of the travel mechanisms of these machines hasn't been promoted extensively. Presently a common application of frequency convertors in the drive systems of cranes focuses on the possibility of enhancing the energetic efficiency of the travel mechanisms of cranes, in comparison to the previous drive systems and operating systems.

2. Energy analysis

Automatic operating of drives of cranes, equipped with frequency convertors, in comparison to classical drives, gives a possibility of kinetic energy recuperation in the process of electric braking. Energy savings result from the reduction of the resistance of the travelling motions by means of limiting wheel flanges' friction and due to eliminating additional movements, previously carried out for the sake of positioning the load. All that contributes to the reduction of the use of energy, necessary to transport loads, especially for overhead cranes of immense mass and wide span of tracks.

2.1. *Kinetic energy recuperation*

A fluent control of the velocity of an overhead crane's travelling (Fig. 1) enables damping of the flexibly suspended load [1, 4] after starting and braking with a parallel positioning it in a chosen point. Electric braking enables recuperation of some part of kinetic energy of all the elements in the system, including the load being motionless after braking [2, 3, 5].

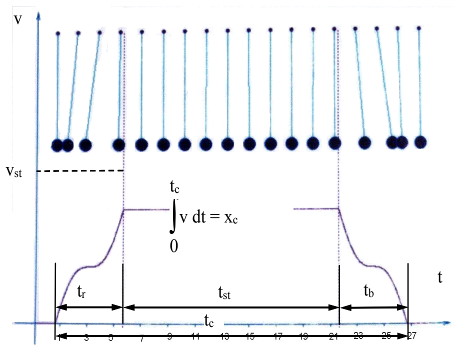

Figure 1 Damping of load oscillation after starting and braking

The recuperated energy E_b, due to electric braking of an overhead crane travelling can be determined by means of an adequate physical model of the travelling system of an overhead crane (Fig. 2).

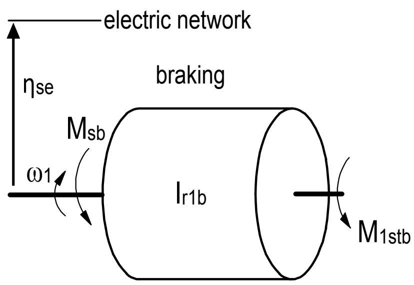

Figure 2 A physical model of electric braking of the system of an overhead crane travelling

$$E_b = \left(\frac{I_{r1b}\omega_{\mathrm{1st}}^2}{2} - M_{\mathrm{1stb}}\Phi_{\mathrm{1b}}\right)\eta_{se} \tag{1}$$

η_{se} – efficiency of an electric motor.

Inertial moment of the travelling system during braking, reduced to the drive motor shaft, is defined by the relation:

$$I_{r1b} = I_1 + I_{r1} + \frac{(m_Q + m_{lsl} + m_{br} + m_{cr})D_w^2}{4i_{gb}^2}\eta_{gb} \tag{2}$$

$I_1,\ I_{r1}$ – inertial moments of the rotational elements on an electric motor shaft and reduced to this motor shaft, $m_Q,\ m_{lsl},\ m_{br}$ and m_{cr} – masses of load, lifting sling, bridge and carriage, D$_w$ – diameter of the travelling wheel, $i_{gb},\ \eta_{gb}$ – ratio and efficiency of the gear box.

Angular velocity ω_{1st} before braking, rotational angle Φ_{1b} of the motor shaft, torque M_{1stb} deriving from travelling resistance W_{tb}, calculated excluding wheel flanges' friction is determined by the following relations:

$$\omega_{\mathrm{1st}} = \frac{2v_{tst}i_{gb}}{D_w} \tag{3}$$

$$\Phi_{\mathrm{1b}} = \frac{\omega_{\mathrm{1st}}t_b}{2} \tag{4}$$

$$M_{\mathrm{1stb}} = \frac{W_{tb}D_w\eta_{gb}}{2i_{gb}} \tag{5}$$

v_{tst} – travelling velocity in the steady motion,
t_b – time of braking.

While taking into account $m_Q = 0$, the energy recuperated due to braking in a duty cycle without load can be calculated in a similar way.

2.2. *Limitation travelling wheel flanges' friction*

The resistance of the cranes' travelling for the previous drive systems was defined by the known relation:

$$W_t = (1 + \Psi_{br})(m_Q + m_{lsl} + m_{br} + m_{cr})g\frac{2f + \mu d}{D_w} \tag{6}$$

The coefficient of the wheel flanges' friction ψ against travel tracks is of crucial importance as a possibility for the reduction of the energy consumption during travelling. The values of this coefficient, at the ball bearing of axe wheels, oscillated between$\psi_{cr} = 1,0 \div 1,3$ for carriages and $\psi_{br} = 1,3 \div 1,5$ for bridges, depending on the span of the tracks. The entire elimination of wheel flanges' friction would mean a significant reduction of the calculated value of the travelling resistance. One should emphasize that the dependence (6) was used to determine the dimension of the drive motor and the wheel flanges' friction during exploitation didn't necessarily occur continually. An overhead crane moved on the track with periodical wheel flanges' friction at the bevelling of the bridge. The recuperated energy resulting from the limiting of the wheel flanges' friction calls for determining the coefficient

$k_{x\psi}$ which marks the way on which the friction occurred. Coefficient $k_{x\psi}$ has been assumed as equal 0,2 which means the incidence of the wheel flanges' friction on 20 per cent of displacement of an overhead crane in a duty cycle.

Automatic operation by means of frequency convertors enables eliminating of chamfering of an overhead crane bridges and limitation of the wheel flanges' friction. A simplified scheme of this system is presented in the picture 3.

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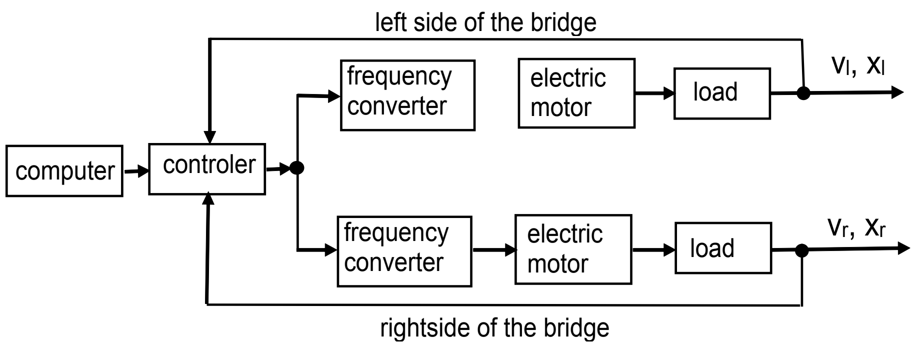

Figure 3 A scheme of supplying and controlling motors of end-carriages of an overhead crane bridge

A simultaneous motion of end-carriages results simply mainly from supplying their motors with current of the same frequency from the frequency convertors. It implies equal rotational velocity of end-carriage motors, independent of different load of each of these motors. A feedback of this system calling for measuring of displacements of the end-carriages is an additional protection for accurate functioning of the system.

Before frequency convertors appeared, for overhead cranes with a wide span of tracks, mechanic or electric shafts were used in order to protect overhead cranes' chamfering. It should be noted that bevelling of bridges can be eliminated. However, a limited wheel flanges' friction of the bridge may temporarily result from the motion of the carriage travelling along the bridge of an overhead crane.

In an automatically controlled system, with the assumption that the coefficient $\psi = 0$, the energy savings E_t coming from the minimalized resistance of the travelling motion W_t on the way $k_{x\psi}l_t$ in a duty cycle are determined by the relation:

$$E_t = \Psi(m_Q + m_{lsl} + m_{br} + m_{cr})g\frac{2f + \mu d}{D_w}\frac{k_{x\Psi}l_t}{\eta_{gb}\eta_{em}} \tag{7}$$

2.3. *The energy of extra movements for the positioning of the load*

In the present system of automatic control of cranes there is no necessity to carry out extra movements during positioning of the load, which was the case in the previous drive systems. Hence, there are no losses, caused by these movements. In the previous solutions the operator switched on the travelling drive for a short time, while positioning the load, before placing it on the ground. Estimating the energy losses, connected with these movements, calls for determining the velocity, which was achieved by travelling system. In case of suspending load on ropes whose length reaches the maximum value for the extra movements the kinetic energy of the load may be omitted. Taking into consideration only kinetic energy, the energy losses E_{lp}, for the number of additional switches are in this case determined by the relation:

$$E_{lp} = n_{lp} \frac{I_{r1lp}\omega_{1\mathrm{lp}}^2}{2\eta_{em}} \tag{8}$$

where:

$$I_{r1lp} = I_1 + I_{r1n} + \frac{(m_{lsl} + m_{br} + m_{cr})D_w^2}{4i_{gb}^2\eta_{gb}}(9)\omega_{1lp} \approx 0,1\omega_{1\mathrm{st}} \tag{9}$$

For the additional movements, the losses resulted from the travelling resistance, in case of minimal displacements of these movements can be omitted.

2.4. *The energy of extra movements for the positioning of the load*

For the sake of comparison, the energy $E*$, used in a duty cycle of the travelling drive, without frequency convertors, can be calculated from the relation:

$$E* = (1 + k_{x\Psi}\Psi)(m_Q + m_{lsl} + m_b + m_{cr})g\frac{2f + \mu d}{D_w}\frac{l_t}{\eta_{gb}\eta_{em}} + \frac{I_{r1}\omega_{1\mathrm{st}}^2}{2\eta_{em}} + E_{lp} \tag{10}$$

The inertial moment, reduced to the drive motor shaft, can be determined by the relation:

$$I_{r1} = I_1 + I_{r1n} + \frac{(m_Q + m_{lsl} + m_b + m_{cr})D_w^2}{4\ \ i_{gb}^2\eta_{gb}} \tag{11}$$

For a duty cycle without load, mass of the load should be assumed as equal 0 ($m_Q = 0$) in the calculations.

3. Examples of calculations and conclusions

For the sake of an approximate estimation of the energy profit which follows after introducing automatic control, the calculations for the two overhead cranes with load capacity 5 and 50 t. have been carried out.

The classification group A6 of the crane which corresponds to the norms of exploitation classes of the cranes U5 and the state of load Q3 has been assumed. The maximal number of duty cycles for this exploitation class U5 equals $C_{Tmax} =$ 500000. It should be mentioned, that according to the norm the duty cycle of the crane begins as soon as the load is ready to be hoisted [7]. It implies two duty cycles, one with the load and the other without it during one norm cycle. The assumed load state Q3 means that the nominal coefficient of load distribution K_{pn} = 0,5. The duty cycles of overhead cranes, with load mass m_Q = 2,5 and 25 t, with the assumed displacement of the bridge travelling l_{tb} = 20 m and the carriage travelling l_{tcr} = 10 m, with a coefficient of the wheel flanges' friction ψ_{cr} = 1,1 for the carriage and ψ_b = 1,35 for the bridge, have been calculated.

The energy profit E_{cn}, coming from automatic control for a norm cycle consists of the energy recuperated by braking ($_b$) and saved on the resistance of the travelling motions ($_t$) and on eliminating additional movements ($_{lp}$) in duty cycles of the bridge travelling ($_{br}$) and the carriage travelling ($_{cr}$), by the nominal loading ($_Q$) as well as without loading.

$$E_{cn} = E_{bcrQ} + E_{bcr} + E_{bbrQ} + E_{bbr} + E_{tcrQ} + E_{tcr} + E_{tbrQ} + E_{tbr} + E_{lpcrQ} + \\ + E_{lpcr} + E_{lpbrQ} + E_{lpbr} \tag{12}$$

The Fig. 4 presents the diagram with energy savings E_{cn}, in the norm cycle for overhead crane, with load capacity 5 and 50 tons.

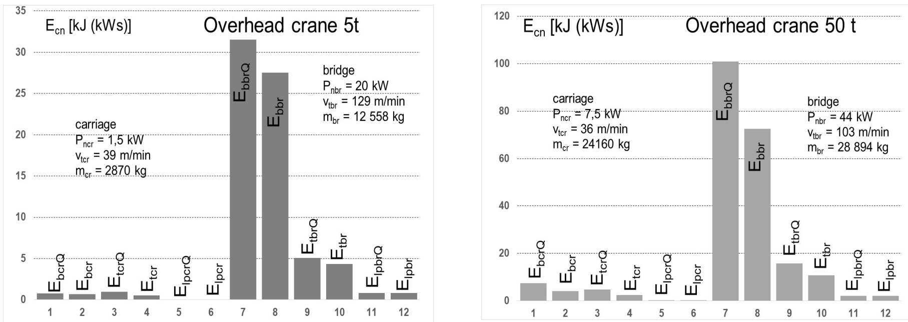

Figure 4 Distribution components of the energy profits in a norm cycle of overhead cranes

The diagrams imply that the highest share in the energy profits has the kinetic energy recuperation E_h, regained while braking the bridges of overhead cranes. Energy savings E_t, coming from the limitation of the wheel flanges' friction and calculated with the assumption that the friction occurs on the part of the road of the duty cycle, are of minor significance. The share of the single components of the energy E_{cn} is similar for the both overhead cranes, although they differ significantly as far as their load capacity is concerned.

The added components of the energy, saved in the norm cycle for carriages and bridges of overhead cranes are presented in the picture 5. The diagram in the picture 6 presents the energy $E*_{cn}$, used in the norm cycle of overhead cranes, equipped with the drives without frequency convertors and the energy saved E_{cn}, of overhead cranes with frequency convertors, automatically controlled.

The added energies, saved in the norm cycle (Fig. 5) for the bridges are significantly higher than those for the overhead cranes of the carriages. The energy profit E_{cn} in the norm cycle (Fig. 6) equals for an overhead crane 5t - 51% and for the an overhead crane 50t - 47,4%, in relation to the energy use $E*_{cn}$ of the drives without frequency convertors.

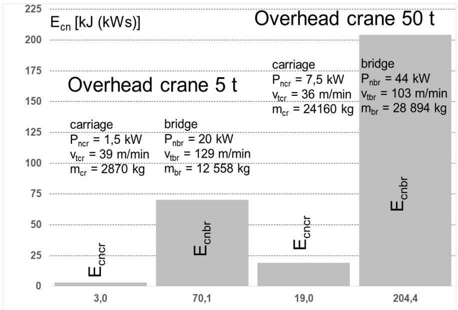

Figure 5 Energy profits in a norm cycle of overhead cranes

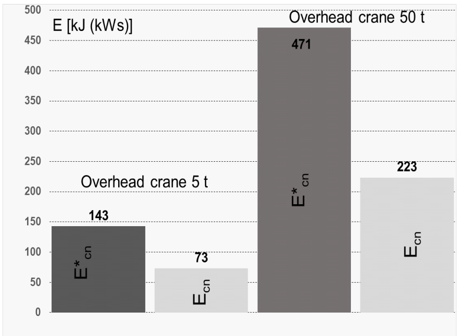

Figure 6 Energy profits E_{cn} in a norm cycle in comparison to the energy use E^*_{cn} of the drives without frequency convertors

The energy profit E_{zCT} during the whole period of the norm exploitation is determined by the relation:

$$E_{zCT} = E_{cn} C_{T\max} \tag{13}$$

The energy profits, calculated in kWh during the whole exploitation for an overhead crane with the load capacity 5t equals 10 153 kWh, and for an overhead crane with the load capacity 50t equals 31033 kWh. Assuming that an overhead crane accomplishes about 100 norm cycles per day during exploitation, the daily savings for a 5t overhead crane equals 2,03 kWh and for a 50t overhead crane equals 6,21 kWh.

The relative energy profit of a norm duty cycle is significant. It implies a significant raising of energetic capacity of the exploiting mechanisms of an overhead crane travelling, achieved due to automatic control.

Absolute daily values of the saved energy are not very big. This saving is not the main reason for the automatization of the cranes' control. It results from the minimal velocity of the bridge and carriage, compared to the velocity of cars or trains. For the analysed examples of overhead cranes, the velocities do not exceed 6,2 km/h , and the recuperation of the kinetic energy is the main component of the saved energy.

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