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Andrzej KOSUCKI
Łukasz STAWIŃSKI
Piotr MALENTA
Jakub ZACZYŃSKI
Justyna SKOWROŃSKA

ENERGY CONSUMPTION AND ENERGY EFFICIENCY IMPROVEMENT OF OVERHEAD CRANE'S MECHANISMS

ENERGOCHŁONNOŚĆ I POPRAWA EFEKTYWNOŚCI ENERGETYCZNEJ MECHANIZMÓW SUWNICY POMOSTOWEJ

The article presents the numerical investigation of the overhead crane's energy consumption. The analysis is based on the hybrid model of the crane consisting of numerical model of drive mechanisms as bridge, trolley, hoist and also experimentally measured power consumption of each control unit. The numerical model was verified experimentally on the real crane. The investigation focuses on analyzing the energy consumption of the overhead crane in relation both to the travelled distance and also for the lifting and lowering heights of a suspended payload. Particular attention was paid on the cases straightly related to the hoist, as a main factor of improvements in the energetic efficiency of the overhead crane. Energy consumption was investigated for a variety of magnitudes of transported mass.

Keywords: *energy consumption, energy efficiency, crane, hoist.*

W artykule przedstawiono badania symulacyjne energochłonności pracy suwnicy pomostowej. Podstawą badań jest model hybrydowy bazujący na numerycznych modelach mechanizmów mostu, wózka i wciągarki oraz na eksperymentalnie zmierzonym zapotrzebowaniu mocy dla układu sterowania. Model numeryczny został zweryfikowany na rzeczywistej suwnicy. W pracy przedstawiono analizę energochłonności mechanizmów jazdy w zależności od pokonanej drogi, jak również mechanizmu podnoszenia w zależności od wysokości podnoszenia i opuszczania ładunku. Zwrócono szczególną uwagę na mechanizm wciągarki, jako na główny czynnik poprawy efektywności energetycznej. Energochłonność została zbadana dla różnych mas transportowanego ładunku.

Słowa kluczowe: *energochłonność, efektywność energetyczna, suwnica, wciągarka.*

1. Introduction

Overhead cranes are dominant pieces of handling equipment, which can be found in the majority of industrial applications. Thus, the cranes and their mechanism are a subject of interest among researchers [19, 21]. In all manufacturing and logistics systems cranes are supplied with electrical energy, which is obtained mainly by burning fossil fuels [10]. Because of this, the air pollution and greenhouse gases emission causing the greenhouse effect becomes a major problem. Hence, main stream of improvements in overhead crane operation and design are focused on reduction of energy consumption and its optimization.

The main area of the energy flow in an overhead crane is the hoist. Lifted payload buffers significant amount of the potential energy. While the payload is being lowered, the energy of gravity ineffectually dissipates as heat energy in brake resistor or brake. The European Council of October 2014 made a commitment [6] to reduce overall greenhouse gas emissions of the Union by at least 40% below 1990 levels by 2030. Many countries struggle with reducing the CO_2 emission and need to buy more carbon units and make larger contribution towards emission reductions in order to achieve desirable levels. Hence, the electrical energy obtained from coal fired power plants becomes more expensive. Regarding to a lot of industrial applications of an old – type overhead crane solutions, this phenomena raises a problem in the economical point of view. Potential savings could significantly lower the costs of crane maintenance in the field.

Currently, many articles and publications focus on the problem of cranes energy efficiency. An example would be work [2], in which the study of lifting mechanisms was discussed, among others in terms of energy overload. In addition, many articles describe various methods of reducing energy consumption for overhead cranes.

Supercapacitors are a novel energy storage device based on the principle of double layer – electrolyte capacity. They have many merits such as a long lifetime, high efficiency and fast dynamic response [4]. Hybrid supercapacitors – based propulsion systems are considered in [1, 4, 17, 11, 16]. Paper [11] faces the problem of energy loses in AC powered overhead crane by proposing the application of an auxiliary energy storing device to hoisting plants. Scientists did the investigation by numerical simulations based on the mathematical models. Simulations report that introducing hybrid storage system allows to save one third of necessary energy. Paper [4] also takes under consideration the energy – saving system also based on the supercapacitors. Authors face the problem of voltage equalization strategy in rubber tires gantry crane (RTG). It was noticed that supercapacitors used in energy storage device can be exposed to an over – voltage, which leads to shortening a life time of the system and also causes problems with the reliability. An active voltage equalization circuit based on reversible converter is proposed. Theoretical simulations have shown that the active control unit solves the problem of partial over – voltage in supercapacitors groups and can be applied in RTGs energy saving systems. The authors of paper [5] evaluate a hybrid configuration and improved management system for the 65 tones RTG driven by diesel generators. Supercapacitors, in this case constituting Energy Storage System (ESS), were connected to a DC-bus and controlled based on the voltage of the DC – bus. The undoubted advantage of the above project was the simulation of a hybrid system in the real working cycle of the RTG crane. The improvement leads to 20% decrease of fuel consumption and double the total energy efficiency of the system.

The article [17] discusses the issue of ultracapacitors in the context of the practical application of NZEB (Nearly Zero-Energy Buildings) systems. Such systems use almost only locally produced energy (often from renewable sources). The use of ultracapacitors allows them to store excess energy generated.

Parallel to the energy saving systems, scientists have investigated other field of energy savings. The article [18] focuses on the energetic efficiency of hoisting mechanisms in industrial applications. A typical duty cycle of the hoist is periodically intermittent. Simultaneously there are pauses during the work. Cranes, the majority of time, work at partial load. When a sequential run with constant load takes place, the hoisting mechanism has to be driven by motors designed for S3 duty cycle [12]. Authors of paper [18] investigate the influence of motor's rotor material on the energetic efficiency for a few stack lengths. The conclusion is that because of low operating hours and major share of partial loads, increasing efficiency does not provide notable energy or cost savings.

Paper [22] considers energy efficiency in a proposed control approach. To minimize energy consumption the authors employ planning an optimal trajectory, tracked in real time. The study focuses only on horizontal transportation considered as a linear movement of the trolley with swing of the suspended payload. Two steps are key to minimizing energy consumption: planning and tracking the trolley's trajectory (so called Model Predictive Control MPC). An air resistance was also and the load was treated as point mass. The investigation notes that thanks to the elaborated method energy savings can be obtained, but the authors do not give a quantity of potentially saved energy.

Increasing energy efficiency by reducing energy consumption can also be achieved through nonlinear crane control schemes during load's skew rotation [7]. The use of an electromechanical clutch allows the engine to be disconnected from the load, which can only rotate under certain circumstances due to inertia forces. In the above work, ways of solving the control problem of such a system were proposed: with and without switching.

Energy efficiency can also be ensured by properly configured and calculated machine construction. In article [20] the finite element method was used to design an energy – efficient crane construction, and the previously developed transmission design was used as input. Therefore, the presented research on energy – saving crane design can be divided into three parts: energy-saving metal construction, energy-saving transmission design and energy-saving electrical system design. The result of the research is the improvement of a crane's parameters affecting its energy efficiency, such as crane weight, while maintaining all basic requirements related to safety.

A lot of papers concerning energy efficiency deal with the issue of the use of flywheels. Due to the fact that when the crane load is lowered, the energy from the engine is wasted on generating heat - the possibility of using flywheels that could store energy so that it does not dissipate was investigated [8, 9]. Thanks to that, it is possible to achieve a lower fuel consumption for diesel engines in RTG cranes.

In article [1] the advantages of flywheels over the previously mentioned supercapacitors were considered. Features of supercapacitors such as high efficiency, longer life span for flywheels are even more noticeable. The above work also discusses one way of controlling an energy storage system based on a flywheel.

Paper [2] lists other advantages of the flywheel used in overhead cranes for increased energy efficiency. First of all, the ability to work under overload is greater than in the case of supercapacitors. In addition, there is no risk of explosion with flywheels. An important aspect is also their lower price.

The literature studies lead to the conclusion that there is lack of investigations assessing the magnitude of energy consumption for cranes. Hence, the authors of this article decided to address this problem. A simulation of overhead crane's energy consumption was carried out in this paper.

The basis for the simulation studies is a hybrid model of crane drives and control systems consisting of experimentally verified mathematical models of the bridge, the hoist and the trolley and actual data covering energy consumption of the control and energy supply systems. The calculations refer to the typical overhead crane duty cycle including the possibility of energy restoration while lowering of the payload and braking of the whole system.

A new approach presented in this paper is developed by engaging numerical simulations with an experimentally measured amount of the energy consumed by the drives control system and also energy necessary for releasing the brakes. This approach gives a comprehensive view of energetic relations between each of mechanism in cranes, what provides the possibility of the energy recuperation or more rationally energy management. As an example can be the system presented in this publication, enabling both the supply of more drive systems from one intermediate circuit (DCLink) with the possibility of energy return to the power grid, or the exchange of energy between drives connected to DCLink.

The paper is organized in the following order. Chapter 2 defines the energy consumption of the mechanism. Chapter 3 describes a hybrid model engaged to assess the energy consumption of each mechanism. The experimental stand where the measurements were carried out is presented in chapter 4. Results of the investigation are provided in chapter 5. Finally, the conclusions drawn from the investigation and also discussion can be found in chapter 6.

2. Definition of the energy consumption

Driving system based on electric motor characterized by certain power consumption in each part of duty cycle. Fluctuations in power consumption depend on movement resistance of the mechanism and velocity of the movement. Both of these parameters are variable while the movement. Therefore, calculating an energy consumption can be done according to the following formula:

$$E = \int_0^{t_k} F \cdot v \cdot dt \tag{1}$$

where:

F - driving force [N],
v - instantaneous velocity [m/s].

Usually it is impossible to directly assess the driving force. An example could be driving mechanisms of the bridge and the hoist. Hence, estimation of the energy consumption can be calculated basing on magnitudes related directly to the electric motors. Mentioned magnitudes are both mechanical torque on the motor's shaft (or motor's current) and also shaft's angular velocity. Thanks to those data there is a possibility of assessing the instantaneous power as follows:

$$N = M_s \cdot \omega_s \tag{2}$$

where:

M_s - motor's torque [Nm],

ω_s - angular velocity of motor's shaft [rad/s].

Power is derivative of the work (and the energy also) in a definition of time. Hence, to estimate the energy consumption the integration of the motor's power function was conducted according to the following formula:

$$E = \int_0^{t_k} N \cdot dt = \int_0^{t_k} M_s \cdot \omega_s \cdot dt \tag{3}$$

Necessary data for above calculations can be obtained by measurement of parameters directly on the electric motors. Therefore, there is need to install appropriate sensors to obtain necessary data. The other way to assess the energy consumption and also energy efficiency is a computer simulation using verified numerical model of the crane, where costs in comparison to laboratory tests are negligible. This article presents the investigation of crane, where the maximum loading and maximum range are 50 kN and 10 m, respectively.

3. Hybrid model of crane's mechanisms

The hybrid model of the overhead crane is based both on the numerical simulations of drive mechanisms and on the measurement of the values of energy consumed by the drives control system.

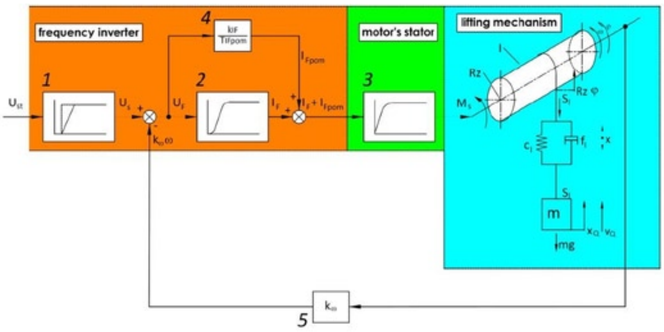

Figure 3.1. The model of the hoist and the inverter – motor's stator [13]

Numerical model of the lifting mechanism fed by inverter is widely discussed in the paper [14]. Figure 3.1 shows model of the hoist driven by an asynchronous motor fed by an inverter, developed basing on the model described in [13]. The dual mass model of mechanical part is defined by typical dynamic equations and kinetic relations. Drive system inverter – stator is described using typical equations of dynamic element, where: element 1 – integrating controller (installed in the inverter to prevent the overstoring oh the entry signal U_{st}, element 2 – second order delay element, element 3 – first order delay element and element 4 – integrator. Element 5 is an angular velocity feedback of the motor shaft. Magnitude of velocity is transformed to the voltage.

Basing on dependencies developed in [13] both systems were described in space of state variables as follows:

a) hosting mechanism:

$$\frac{d\omega}{dt} = \frac{1}{I_z} \cdot M_s - \frac{c_l}{I_z} \cdot x - \frac{R_z f_l}{I_z} \cdot \omega + \frac{f_l}{I_z} \cdot v_Q \tag{4}$$

$$\frac{dx}{dt} = R_z \cdot \omega + v_Q \tag{5}$$

$$\frac{dv_Q}{dt} = \frac{c_l}{m} \cdot x - \frac{R_z \cdot f_l}{m} \cdot \omega + \frac{f_l}{m} \cdot v_Q - g \tag{6}$$

a) inverter – stator system:

$$\frac{dU_s}{dt} = \frac{1}{T_c} \cdot U_{sz} \tag{7}$$

$$\frac{dI_F'}{dt} = \frac{k_{IF} \cdot k_{wzm}}{T_{F_1}^2} \cdot \left(U_s - k_\omega \cdot \omega\right) - \frac{T_{F_2}}{T_{F_1}^2} \cdot I_F' - \frac{1}{T_{F_1}^2} \cdot I_F \tag{8}$$

$$\frac{dI_F}{dt} = I_F' \tag{9}$$

$$\frac{dM_s}{dt} = \frac{k_{M_s}}{T_{M_s}} \cdot \left(I_F + I_{F_{pom}}\right) - \frac{1}{T_{M_s}} \cdot M_s \tag{10}$$

$$\frac{dI_{F_{pom}}}{dt} = \frac{k_{I_F}}{T_{I_{F_{pom}}}} \cdot \left(U_s - k_\omega \cdot \omega\right) \tag{11}$$

where the state variables are:

x - elongation of the wire ropes

v_Q - velocity of the payload

ω - angular velocity of the motor

I_F - current of the stator

I_F' - additional variable - current

I_{Fpom} - stator supply current,

M_s - torque of the stator,

U_s - voltage of the control system

parameters are defined as follows:

I_z - moment of inertia reduced to the motor shaft

m - mass of the payload

R_z - effective radius of the mechanism

c_l - equivalent rigidity of the ropes

f_l - damping of the ropes

T_{F1}, T_{F2} - time constants of element 2,

k_{IF} - conversion factor of element 2 and 4,

k_{wzm} - gain factor,

T_{IFpom} - time constant for element 4,

k_ω - factor of angular velocity conversion,

k_{Ms} - gain factor for element 3,

T_{Ms} - time constant for element 3.

Verified model of driving mechanisms for bridge and trolley is described in details in the paper [15]. Figure 3. 2 shows the model of overhead crane treated as a rigid body moving by planar motion with a trolley and hanged payload.

Thanks to mathematical transformations the following description of the overhead crane bridge and the trolley movements using the space of state variables notation was obtained:

$$\frac{dv_w}{dt} = \frac{\frac{M_{sw}}{R_{zw}}}{\left(m_w + \frac{I_{ow}}{R_{zw}^2}\right)} - \frac{W_w}{\left(m_w + \frac{I_{ow}}{R_{zw}^2}\right)} - \frac{H_w}{\left(m_w + \frac{I_{ow}}{R_{zw}^2}\right)} \tag{12}$$

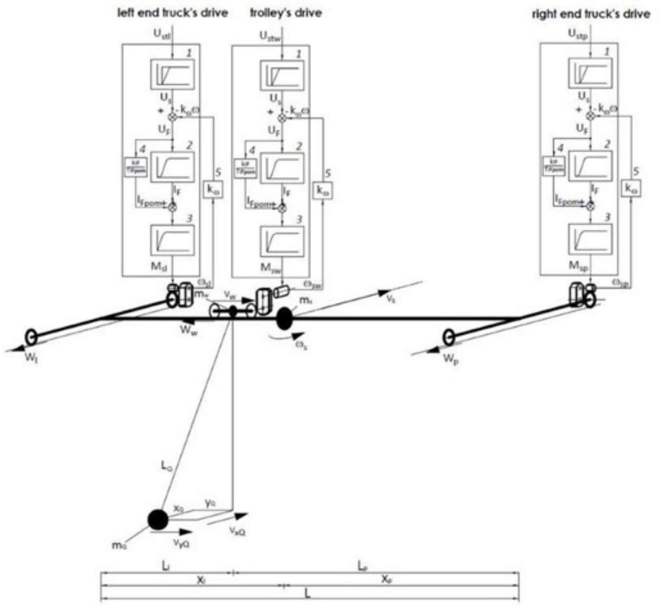

Fig. 3.2. The model of overhead crane drive system with a suspended payload

$$\frac{dx_w}{dt} = v_w \tag{13}$$

$$\frac{dv_s}{dt} = \left(\frac{1}{R_z \left(m_s + \frac{2 \cdot I}{R_{zr}^2} \right)} + \frac{R_{zr} - x_l}{R_z \cdot I_{zast}} \cdot R_{zr} \right) \cdot M_{sl} + \left(\frac{1}{R_z \left(m_s + \frac{2 \cdot I}{R_{zr}^2} \right)} + \frac{R_{zr} + x_p}{R_z \cdot I_{zast}} \cdot R_{zr} \right) \cdot M_{sp} + \tag{14}$$

$$\left(\frac{R_{zr} \cdot (x_l - L_l)}{I_{zast}} - \frac{1}{m_s + \frac{2 \cdot I}{R_{zr}^2}} \right) \cdot H + \left(\frac{R_{zr} \cdot x_l - R_{zr}^2}{I_{zast}} - \frac{1}{m_s + \frac{2 \cdot I}{R_{zr}^2}} \right) \cdot W_l + \tag{15}$$

$$- \left(\frac{R_{zr} \cdot x_p + R_{zr}^2}{I_{zast}} - \frac{1}{m_s + \frac{2 \cdot I}{R_{zr}^2}} \right) \cdot W_p \tag{16}$$

$$\frac{d\omega_s}{dt} = \frac{R_{zr} - x_p}{R_z \cdot I_{zast}} \cdot M_{sl} + \frac{R_{zr} + x_p}{R_z \cdot I_{zast}} \cdot M_{sp} + \frac{R_{zr} + x_l - L_l}{I_{zast}} \cdot H + \frac{R_{zr} + x_l}{I_{zast}} \cdot W_l + \frac{R_{zr} - x_p}{I_{zast}} \cdot W_p \tag{17}$$

where:

- v_w - velocity of the trolley,
- x_w - position of the trolley
- M_{sw} - torque of the trolley's motor
- R_{zw} - effective radius for trolley's mechanism,
- W_w - friction of the trolley,
- H_w - horizontal force caused by the payload oscillations, parallel to the axis of the trolley
- m_w - mass of the trolley,
- I_{ow} - moment of inertia for all parts of the trolley reduced to the motor's shaft
- M_{sp}, M_{sl} - driver torques of both sides of the bridge,
- W_p, W_l - friction of both sides of the bridge,
- H - horizontal force caused by the oscillations of the payload
- R_z - effective radius of end truck
- L - range of the bridge,
- L_p, L_l - position of the trolley related to both left and right end truck
- x_p, x_l - position of the center of the mass related to both left and right end truck
- I - moment of inertia of all rotating parts reduced to the motor's shaft
- I_{zast} - effective moment of inertia.

Both end trucks and the trolley are driven by induction asynchronous motor described similarly as for the lifting mechanism. There are additional subscripts *l* and *p* for left and right end truck, and *w* for the trolley.

$$\frac{dx_s}{dt} = v_s \tag{18}$$

$$\frac{d\varphi_s}{dt} = \omega_s \tag{19}$$

$$\frac{dU_s}{dt} = k \tag{20}$$

$$dI_f' = \frac{k_{IF} \cdot k_{wzm}}{T_{F_1}^2} \cdot \left(U_s - k_\omega \cdot \omega_s \right) - \frac{T_{F_2}}{T_{F_1}^2} \cdot I_F' - \frac{1}{T_{F_1}^2} \cdot I_F \tag{21}$$

$$\frac{dI_f'}{dt} = I_F' \tag{22}$$

For presented mechanisms of the bridge and the trolley the following state variables were assumed:

- v_w - velocity of the trolley,
- x_w - position of the trolley
- v_s - velocity of the bridge's center of the mass
- ω_s - angular velocity of the bridge related to the center of the
- x_s - position of the bridge's center of the mass,
- ϕ_s - angular position of the bridge related to the center of the mass
- $I_{F(l,\,p,\,w)}$ - current of the stator,
- $I_F'{}_{(l,\,p,\,w)}$ - additional variable - current,
- $I_{Fpom(l,\,p,\,w)}$ - additional current,
- $M_{s(l,\,p,\,w)}$ - torque of the motor,
- $\omega_{s(l,\,p,\,w)}$ - angular velocity of the motor's shaft,
- $U_{s(l,\,p,\,w)}$ - control voltage

With assumption of no slip between the wheel and the trail velocities of motors were defined as follows:

$$\frac{dI_{F_{pom}}}{dt} = \frac{k_{IF}}{T_{I_{fpom}}} \cdot \left(U_s - k_\omega \cdot \omega_s \right) \tag{23}$$

$$\frac{dM_s}{dt} = \frac{k_{M_s}}{T_{M_s}} \cdot \left(I_F + I_{Fpom} \right) - \frac{1}{T_{M_s}} \cdot M_s \tag{24}$$

$$v_l = \frac{v_s - x_l \cdot \omega_s}{R_z} \tag{25}$$

$$v_p = \frac{v_s - x_p \cdot \omega_s}{R_z} \tag{26}$$

A constant value of energy consumed by the drive control system was measured using an intermediary system plugged between the power grid and the crane. The system, shown in the Figure 3.3 , consists of the three – phase current transformer and the programmable transducer. These two devices are governed by the software installed in the notebook.

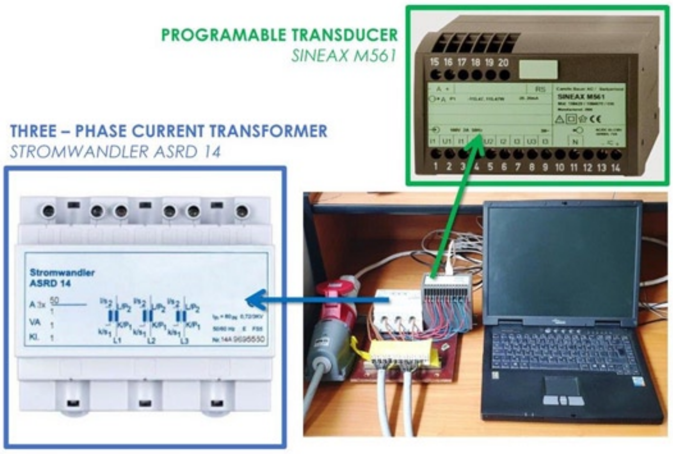

Fig. 3.3. Intermediary measuring system plugged between the crane's drive control and the power grid

4. Experimental stand

The experimental stand, shown in the Figure 4.1., considered in this article, is based on the overhead crane, where main parts of the crane as bridge, trolley and hoist, are an inverter – fed mechanisms. All inverters are supplied by the DC Link, where the voltage fluctuates from 560 to 780 V. To return the energy, which is gained from change the potential energy during lowering of a payload or during braking another mechanisms, to the grid, all drives are supplied using the regenerative power supply unit. The system is governed by the PLC controller, which allows control all crane mechanisms and also monitors some parameters of system's operation using software installed on the portable computer. Measurements of the actual energy demand of the crane is provided by using a power measuring system, plugged between the overhead crane system and the power grid.

5. Results of duty cycles investigation

Numerical models of the crane mechanisms and drives allow for a wide inspection of the overhead crane for example by investigating the payload trajectory while taking into account existing obstacles and also for analyzing the energy consumption.

Maximum range of the overhead crane displacement in the direction of movement of bridge and the trolley are 20 m and 8 m, respectively. The trajectory of the payload was determined by the application calculating safe path for the payload in the hall. The application is widely described in paper [15].

Using the energy measuring system, which is depicted in the Figure 3.3, the power consumption was investigated in a few cases of the overhead crane's operation. Results of this investigation can be observed in the Figure 5.1. The measurement cycle was divided into phases of standby of the crane and also phases when each mechanism

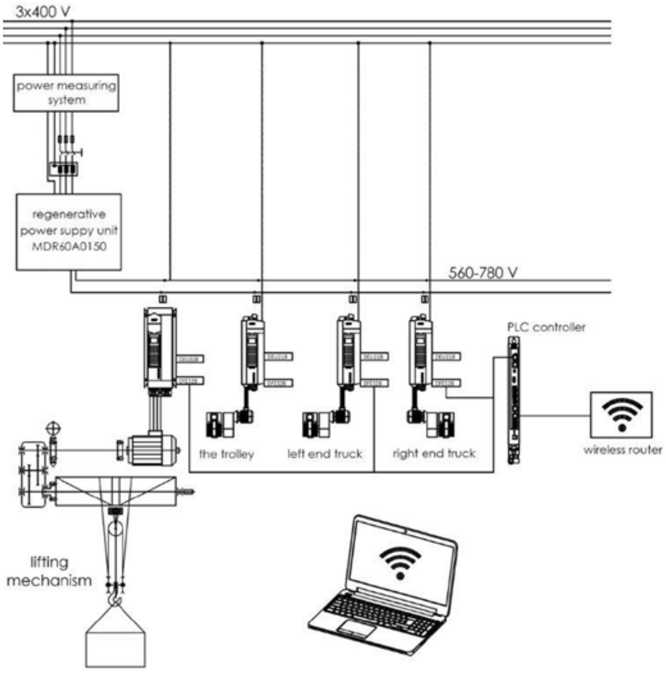

Fig. 4.1. The experimental stand based on the overhead crane

is activated. This means that the inverter is turned into *run allowed* mode with a simultaneous release of each brake. Green solid line shows actual power consumption of the crane, which was recorded during the operation. Violet solid line represents an average value of the actual power for individual phases of operation. Red solid line represents a power demand necessary for release the brakes of each mechanism taken from the catalog data.

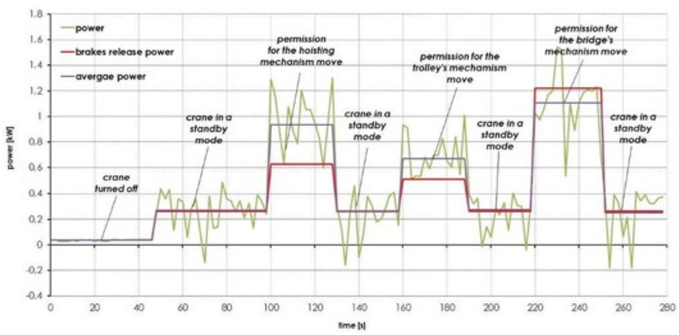

Fig. 5.1. Power demand of the overhead crane.

Based on the numerical investigation, and also on the inspection with real energy consumed, an energetic demand of the overhead crane for a few types of motion while the duty cycle was estimated. Results of the simulation presented in the Figure 5.2 shows the energy consumption related to the travelled distance for bridge and trolley mechanism. The investigation was carried out for motions with an empty hook and also with 5 ton weight payload. Dashed lines show a theoretical energetic demand of the overhead crane as a result of numerical simulation. The solid lines (with _C suffix) show a theoretical energetic demand corrected by the average value of the energy consumed by the control unit and brakes.

Thanks to the consideration of the hybrid model, it can be concluded that the energetic demand of the overhead crane increases significantly in comparison to theoretical simulations. The biggest change in the energy consumption can be observed in the case of the trolley's move with an empty hook, where energetic demand raises from 6 kJ to 18,5 kJ.

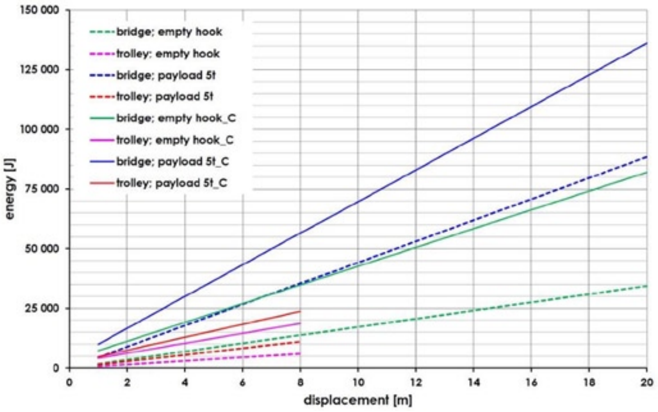

Fig. 5.2. Energy consumption of the overhead crane for the bridge and trolley mechanisms related to the travelled distance for different loading conditions

The presented above research allows estimate the real energy consumption of mechanisms responsible for horizontal displacement of payload. It is visible that the energy necessary for the operation of the control system and brake release can exceeds the energy consumed directly by drives. Performing research on energy consumption of drives equipped with motors with brakes fed by inverters should consider additional power demand which in real systems exist and are necessary to its operation and this applies not only to overhead cranes.

Next step of analysis was an investigation of the hoisting mechanism. It is the main part of an overhead crane's energetic optimization because of the huge with respect to other mechanisms amount of energy demand . Charts presenting energy consumption in the function of hoisting/lowering distance are shown in the Figure 5. 3. The investigation also includes energy consumption of the drive control system and brake release system.

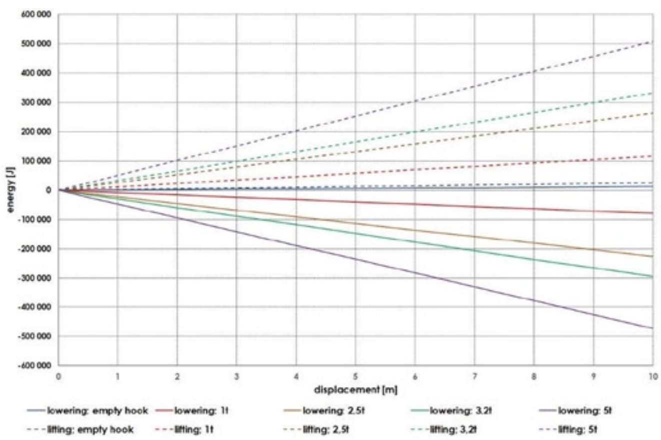

Fig. 5.3. Energy consumption of winch mechanism in relation to the travelled distance (lifting and lowering) for different loading conditions.

Analyzing results of the experiment it is easy to observe that the energy consumption changes for different loading conditions. he energy consumption during hoisting rises up with increasing payload mass. The energy necessary to lift an empty hook is 10 kJ and increases to the magnitude over 500 kJ while lifting the 5 ton mass payload. Negative values of the energy prove that there is a possibility to recover the energy of gravity stored in the payload, which now is dissipated as a heat into resistors installed in the crane. The graph does not show symmetry about the horizontal axis due to the additional energy necessary for the operation of control systems.

The value of recoverable energy Er in relation to the energy put in hoisting a payload Eh was determined. This proportion changes with the change of mass mQ of the payload what is visible in Figure 5.4. The changes range is from 0.5 for an empty hook to -0.93 for a nominal payload mass. Negative values mean, that energy recuperation, proportional to energy consumption for hoisting the particular payload, is possible. Positive values appeared when for properly operation of the system, energy must be supplied. In presented figure, the limit point , when recovery becomes possible, is 7% of the weight of the payload.

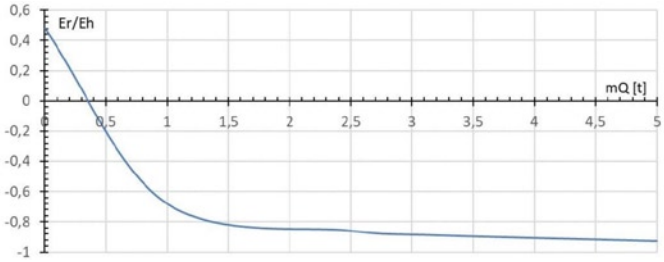

Fig. 5.4. The possibility of energy recuperation during lowering with respect to energy consumption during hoisting.

Due to the fact of buffering of significant amount of the energy in a suspended payload, the investigation was carried out for a typical duty cycle, which was compared to the similar one with possibility of energy recovery. Figures 5. 5 and 5.6 depict both of duty cycles.

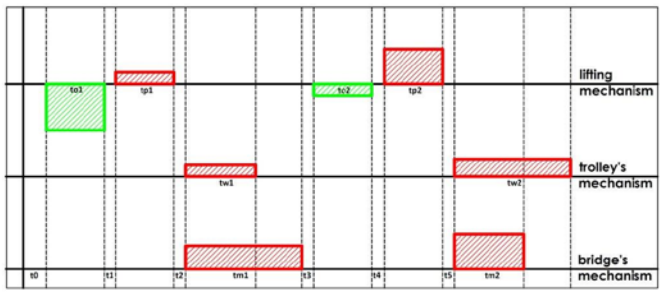

Fig. 5.5. Crane's duty cycle with possibility of restoring the energy

Presented typical duty cycle consists of lowering the payload from highest transportation level to the ground, next the hoisting the empty hook at the same level. Then simultaneous movement of trolley and bridge to the loading point and lowering empty hook. Next hoisting full load at transportation level and then return to the unloading point.

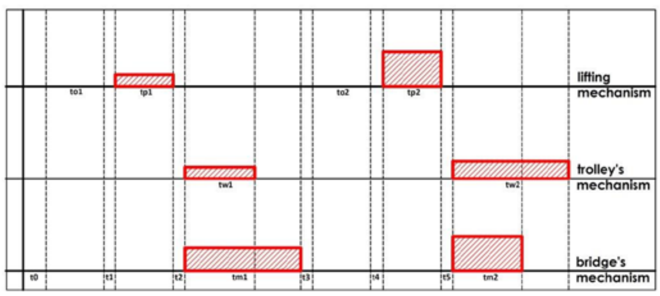

Fig. 5.6. Crane's duty cycle without possibility of restoring the energy

Comparison of energy consumption for both cycles is presented in the Figure 5. 7. Negative values show the possibility of energy restoration and potential savings as a consequence.

Analyzing the data in the Figure 5. 7 it could be observed that significant amount of the energy can be restored in the hoisting mechanism during the lowering of the suspended payload. The energetic demand in a standard cycle is about 610 kJ of the electrical energy.

Energy consumption of the system with the possibility of its restoration is about 360 kJ which gives a potential energy savings of 40%.

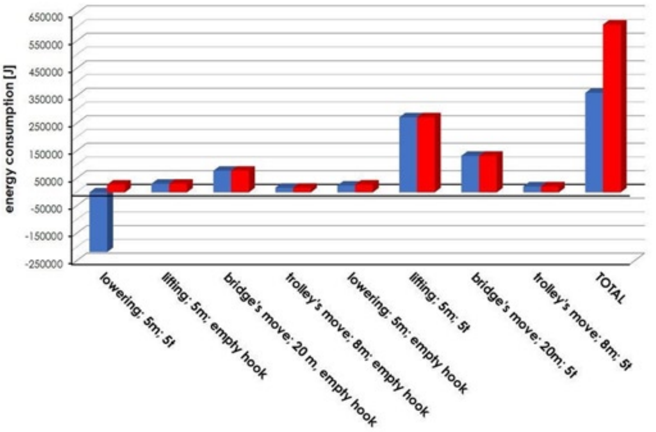

Fig. 5.7. Comparison of two types of duty cycle both with the energy saving system (blue) and without (red)

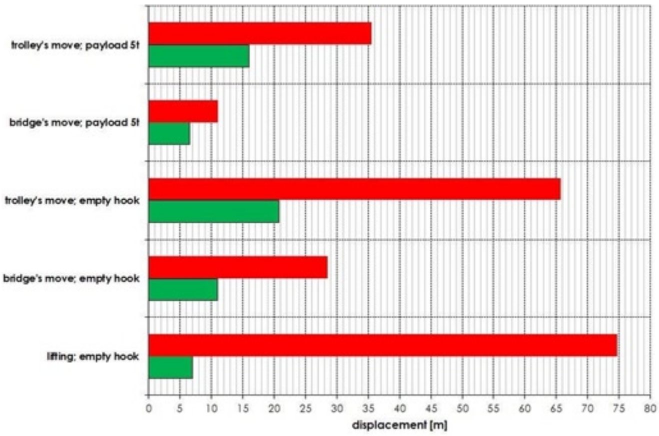

Fig. 5.8. Potential savings after lowering the 5 tons payload from the 5 meters height.

In order to illustrate the possibilities of using the energy of the hoisting mechanism, the possible travel lengths of individual mechanisms of an overhead crane using the same amount of energy from lowering 5 t on a road 1 m are presented in Figure 5.8.

Red bars shows movement possibilities of particular mechanisms according only to the numerical analysis. The green ones include also values of the energy consumed by the drives and brakes control systems.

6. Conclusion

This paper presents the analysis of overhead crane mechanisms operation for energy consumption. This analysis is based on the hybrid model developed using kinetic and dynamic relationships and also typical equations of dynamic elements and experimental data of the control system's energy consumption. The maximum range of crane travel was investigated in typical duty cycle for different loading conditions. It can be concluded that for the nominal payload 40% of the energy in overhead crane's duty cycle can be recovered.

This phenomenon can be observed mainly in the hoisting mechanism, but also during deceleration phases of traveling mechanisms. The analysis shows that this mechanism can provide significant energy savings during the lowering of the suspended payload even considering the energy consumed by control system and brakes. A significant share of the energy during the crane's operation is consumed to the release of electromagnetic brake based on the coils. In case of travelling or traversing mechanism energy consumption level of this system is several dozen percent of the energetic demand of the drive. Energetic demand of inverters and control system also cannot be neglected. It can be concluded that the investigation, which including also the energetic consumption of the control system and brakes, gives the full view of the crane's energy consumption.

Results of this investigation are important especially in the context of sustainable production. This seems to be important also from the economic and ecologic point of view. Increasing the energy efficiency of devices (including transport) is one of the directions of development of an environmentally friendly economy.

Results provided in this article can be considered in the context of implementing an energy storing or energy returning system to the grid. Magnitude of energy which is able to put to use again can be approximated as significant percentage of the energy needed in the whole duty cycle. In case of returning the energy back to the power grid can be consumed by other devices. On the other hand, engaging the energy storage, the energy can be consumed to finish the duty cycle during the loss of the electrical power network supply.

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Andrzej KOSUCKI
Łukasz STAWIŃSKI
Piotr MALENTA
Jakub ZACZYŃSKI
Justyna SKOWROŃSKA
Lodz University of Technology
Institute of Machine Tools and Production Engineering
ul. Stefanowskiego 1/15, 90-924 Łódź

E-mails: andrzej.kosucki@p.lodz.pl, lukasz.stawinski@p.lodz.pl, piotr.malenta@p.lodz.pl, jakub.zaczynski@dokt.p.lodz.pl, justyna.skowronska@dokt.p.lodz.pl