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Key words: *energy recuperation, self-driven crane, heavy machinery, running cycle, operating cycle, energy recovery, model stand*

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ENERGY RECOVERY FOR REDUCING TOXIC EXHAUST EMISSIONS IN SELECTED ENERGETIC STATES OF INDIVIDUAL OPERATING CYCLE IN SELF-DRIVEN HEAVY MACHINERY[1]

The Authors present the problems of theoretical analysis and experimental research related to the possibilities of energy recovery in selected phases of operating and running cycles of self-driven crane.

Heavy machinery powered by diesel engines is a source of solid toxic emissions. In order to limit these emissions, one install filters and filter regeneration systems. According to the concept presented here, the recovered energy might be utilised for regeneration of these filters by burning off accumulated solid particles (soot). Mechanical energy would be the power source to drive DC generators – the mechanical-into-electric energy converters. Filter's heating resistors, acting as the generators' load, would radiate a power of 3÷5 MJ to initiate burning of soot in the filter.

The calculations of energy consumed during sheave block lowering phase were made for three different lifting capacities taking into account the boom length and crane reach. Three running cycles of the crane: highroad, urban and off-road ones were also analysed. The time functions of variations of crane running speed and power of motion resistance at driving wheels were found. The results provided the background for determination of theoretical values of energy to be regained during braking phase of the analysed cycles.

The structure and operation of experimental stands was discussed. The stands contain units that, at proper size factor, represent the processes that occur in real cranes and that are related only to energy recovery. Computer software for system simulation, control and measurement was described. Measurement results and result analysis are presented. The value of energy found theoretically was compared with the energy recovered during experimental tests. The paper also contains simplified kinematic schemes of selected units of crane lifting and driving systems, including an additional DC generator. This concept, however, needs verification in future design solutions.

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1. Introduction

Heavy machinery propelled by diesel engines (self-driven jib cranes, excavators, loaders, etc.) is a source of emission of toxic solid pollutants. A working diesel engine emits to the atmosphere about 17 kg (on an average) of soot for each 1000 kg of burned fuel [1]. Globally, these engines produce thousands of tonnes of solid pollutants (soot). Data from experiments, as well as the statistical data published in literature, indicate that the problem aggravates. Such a great amount of solid exhaust ingredients creates a severe ecological hazard.

Filters of solid particle can restrain emission of solid substances contained in exhausted gasses produced by combustion engines, especially by the diesel engines. Thus, engines with filters represent ecology-friendly devices. The main ingredient of exhaust matter that, fortunately, is not dangerous to humans is soot. However, it adsorbs benzopyrene (3,4 benzopyrene is cancerigenous exhausts component) and converts itself into a cancerigenous substance. The filters should be regenerated periodically by burning out the soot.

Heat energy is needed for filter regeneration. Currently, the energy produced by burning gas and diesel fuel, or electric energy supplied from external electric-energetic systems, is utilised for this purpose. However, the use of additional electric energy, or additional fuel, significantly rises the running costs.

The concept of regeneration of filters of solid particles produced by diesel engines in heavy machinery, presented in this paper, is based on the assumption that it is possible to utilise the recuperation energy for this purpose. It can be recovered, for example in self-driven crane, during selected phases of operating and running cycles of the machine. The energy recovered during lowering of loaded sheave block (operation cycle) phase and during braking phases (running cycles) is the drive source for DC generators. These generators, treated as mechanical-into-electric energy converters, deliver power to heating resistors in filters of solid particles that are a supplemental source of heat. Filter regeneration, based on periodic burning of accumulated soot, requires self-ignition temperature of about 900K be obtained. The burning process (exhaust gas temperature) must be maintained until filter content burns out. According to the experiments carried out by the Authors [2], one must supply (electric) energy of 3 to 5MJ in order to obtain the soot self-ignition temperature. A foregoing theoretical analysis complemented by experimental tests is then needed to verify the possibility of recovering the required amount of energy during the operation of heavy machinery.

2. Operation cycle of self-driven crane

The operation cycle of self-driven crane is a distinct cycle, in which the motor load is an effect of either motion of load carrying mechanism, or motion of the travelling machine. In practice, these two kinds of load do not occur simultaneously. It is assumed that, in typical operating conditions of self-driven crane, transportation of the machine to different operation areas takes 20% of its working time. Transportation conditions can be characterised by the following parameters assumed for crane operation analysis [3]:

- Annual running distance approximately 14000 km, including
- Driving on asphalt surface roads – 70 % of annual running distance,
- Driving on unpaved roads – 10% of annual running distance,
- Average number of start-ups per 100 km of covered distance: at highroad running 36, in urban zones 100, in off-road running conditions 15.

The DUT-0300 all-terrain crane was chosen for the theoretical analysis and experimental studies. The machine is constructed to perform tasks of building, assembly reload and emergency works. The crane is equipped with a telescopic boom, and a turn-around table fixed on automobile undercarriage. The crane has a capacity of 30Mg and is powered by a diesel engine of 178.5kW.

2.1. Cycle of operating mechanisms

The description of typical cycle of self-driven crane mechanism operation, useful for the energy analysis, can hardly be found in literature. All the operational mechanisms of crane body are driven by hydraulic systems. The energy is delivered by a diesel engine that drives hydraulic pumps through a power transmission and a gearbox. For the exemplary calculations of energy recuperated during the lowering phase of loaded sheave block, one selected the following values based on crane lifting capacity characteristic representing the dependence of lifting load on boom length and crane radius. The values were consequently used in three cycles of crane operational mechanisms.

- Cycle I, with crane radius of 3,0 m, lifted load 30 Mg, boom length 8,5 m,
- Cycle II, with crane radius of 4,5 m, lifted load 15 Mg, boom length 19,9 m,
- Cycle III, with crane radius of 10 m, lifted load 1,8 Mg, boom length 38,2 m.

Table 1 contains the values of power, energy and time at successive phases of crane operating mechanisms; i.e. lowering of loaded sheave block, for the cycles I, II and III.

There is also a theoretical possibility of energy recuperation after the completion of the phase of lowering of the loaded sheave block. If there was an inertial mass mounted on generator's shaft, the kinematic energy of still rotating mass could be the source of generator drive power even after the lowered load had been laid down. During this time, the generator would be still capable to transmit power to load resistors.

The boom rotation phase, in both loaded and unloaded states, consists of three stages, of accelerated, steady and decelerated motion, respectively. A theoretical possibility to recover energy exists in the stage of decelerated motion. Preliminary calculations made for the first cycle have shown that the stage of decelerated motion of rotation phase of the loaded boom lasts for 1.3s and that of unloaded boom is as short as 0.07s. Irrespective of the amount of energy that could be recovered, practically there is no technical possibility to usthis energy during such a short phase of boom rotation in decelerated motion. The energy is attainable, neither in the model stand, nor in actual conditions of crane operation.

Table 1.
Values of power, energy and time of duration of successive phases of loaded sheave block lowering in cycles I, II and III of crane operation mechanisms

No.	Cycle phase	Power [kW]	Energy [kJ]	Time [s]
1	Lowering of loaded sheave block in cycle I	48.4	1384	28.6
2	Lowering of loaded sheave block in cycle II	36.5	1697	46.5
3	Lowering of loaded sheave block in cycle III	5.3	454	85.7

2.2. Running cycles of crane

Three running cycles were assumed to represent the operation of travelling crane:

- Highroad running between operation areas (cycle A) with maximum travelling speed equal to 60 km/h,
- Urban zone running (cycle B) with maximum travelling speed equal to 30.6 km/h,
- Off-road running (cycle C) with maximum travelling speed equal to 27.5 km/h.

Example distributions of variations of crane running speed and power of motion resistance at driving wheels are shown in Figures 1, 2 and 3 for the cycles A, B and C respectively.

The fundamental assumption taken in defining the running cycle is that the start-up operation begins in the first gear, and ends in the maximum gear proper for that particular running cycle. As a rule, in start-up operation one usually applies maximum driving power on wheels in each gear. The calculations have shown that, in each running cycle, there appears the effect of negative energy associated with the braking phase.

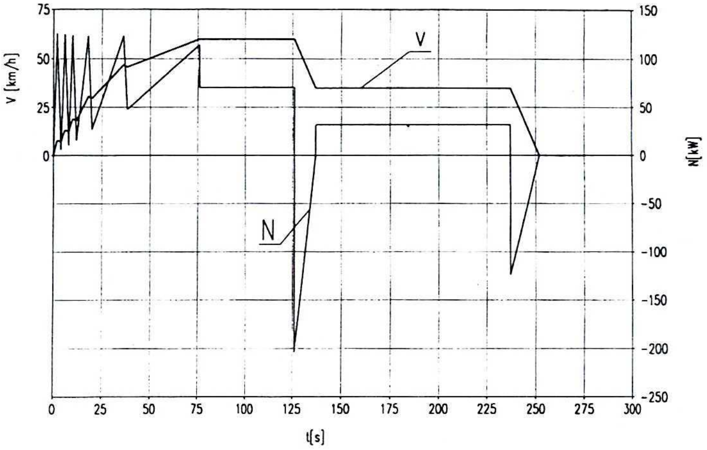

Fig. 1. Illustration of variations of running speed and motion resistance power (referred to driving wheels) in crane during highroad running cycle (cycle A)

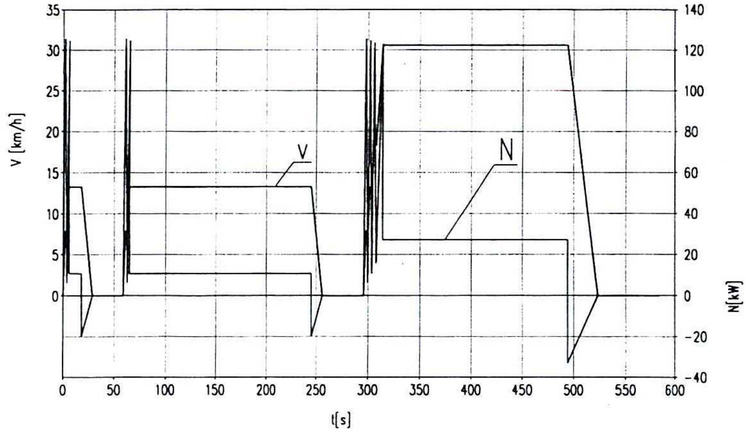

Fig. 2. Illustration of variations of running speed and motion resistance power (referred to driving wheels) in crane during urban zone running cycle (cycle B)

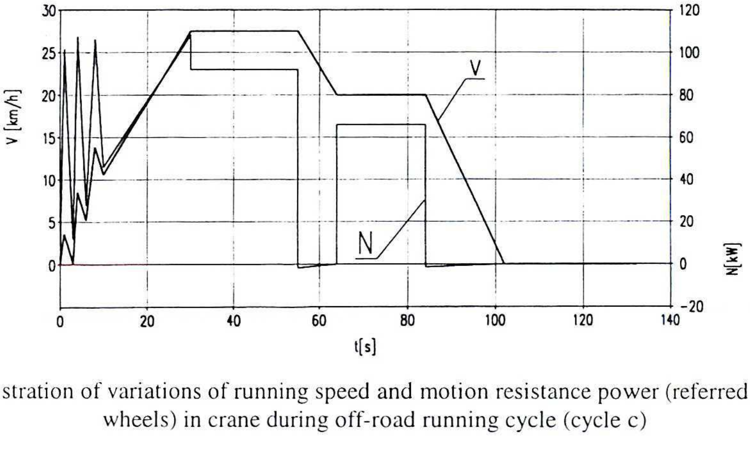

Fig. 3. Illustration of variations of running speed and motion resistance power (referred to driving wheels) in crane during off-road running cycle (cycle c)

3. Model test stand

3.1. Structure and operation of control and measurement systems of test stand

One can encounter many difficulties in performing, on an actual self-driven crane, the measurements of recoverable energy in the braking phases of mechanism operation cycle and in crane's running cycles. It requires that numerous specialised devices and measuring equipment be installed on the machine. For example, application of on-board computer significantly increases costs, and the tests carried out in both stationary and road conditions need a long time of experiment. Most frequently, the experiments are then carried out on model test stands. Devices installed in these stands represent, in a proper scale, the phenomena occurring in real objects [4], [5]. The block diagram of the test stand shown in Fig. 4 represents effects related to energy recovery during lowering of loaded sheave block and in the phases of crane braking.

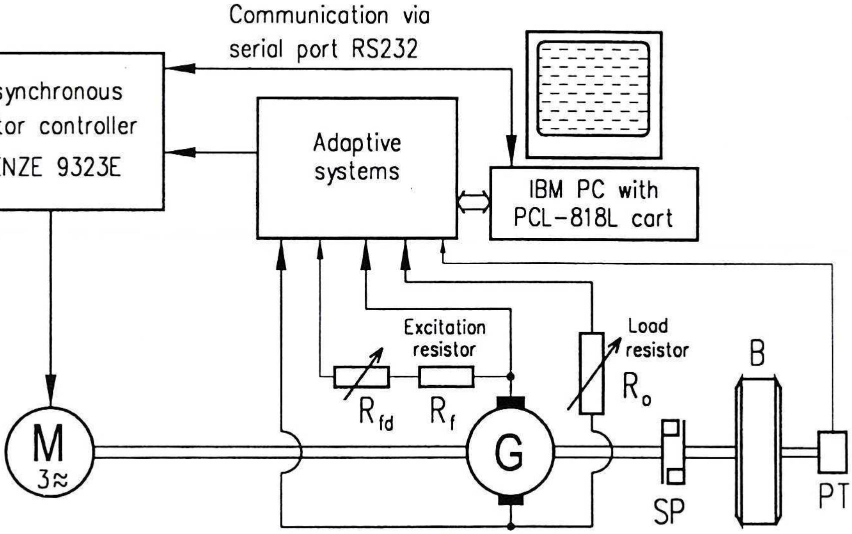

Fig. 4. Block diagram of test stand (M – three-phase inductive engine, G – DC generator, SP – clutch, B – inertia mass, PT – rate generator, R_o – generator load resistance, R_f – generator excitation resistance, R_{fd} – additional resistance of excitation coil)

In the stand, one installed the Fsg 100L three-phase induction motor of 3.0kW rated power and rotational speed of 2905rpm in order to represent energy parameters pertaining to specific phases of sheave block lowering in mechanism operation cycle of self-driven crane. This type of motor is dedicated for driving generators with wide range of rotational speed. The motor drives a DC shunt generator type ARBZc 132SZ with rated power of 2.5kW and rotational speed of 2850 rpm yielding rated load current of 10.9 A. Owing to the application of an internal fan, a suitable temperature is kept during operation. PTC-thermistor temperature sensors, installed for additional thermal protection, guarantee safe operation under various load and in a wide range of rotational speed. Such extra equipment allowed us to use the Vector Control EVF 9324 inverter with rated power of 3 kW for powering and rotational speed control of the motor. The LENZE inverter, equipped with some auxiliary electrical devices, has its own system for motor speed and torque measurements. The inverter co-operates with the PCL-818L data acquisition card on a PC computer.

The engine-generator drive unit is located on a heavy, self-supporting frame with four vibro-insulators provided with vibration damping elements. The vibro-insulators, by means of distancing bolts, ensure precise levelling of the frame. A rigid clutch type Bo Wex with double Cardan effect transmits the driving torque.

The IBM PC computer equipped with Celeron 300 MHz processor, DIMM 32 MB SDRAM, PCL-818L data acquisition card, and operating system Windows 95PL OSR2 was used to run simulation programs and to control measurement operations. Since the PCL-818L card had input voltage range of –5V/+5V, and digital signals must be TTL compatible, signal-forming circuits were used in the measuring set-up. The board of signal conditioning circuitry consisted of the following units: a power supply producing voltages of +24V and +15V, a LA55-P type converter for generator output current measurement, a LV-25-P type converter for generator output voltage measurement, Helipot type potentiometers for precise calibration of measurement parameters, a voltage follower and noise filter, built on a quadruple operation amplifier LM 324, used for amplifying signals from measurement circuits of generator output voltage and current, and the MCY 4050 signal conversion circuit transforming TLL signals into +24V level signals.

The described instrumentation, together with a dedicated software, allowed for real-time acquisition and visualisation of measured quantities, as well as data storing.

The DC electric machine used in the test stand was a generator with double-sided shaft output. This made it possible to connect to it, through a detachable clutch, an inertia mass as an element representing the crane's mass. ROTEX and Bo Wex clutches were used for this coupling.

The dimensions of the inertia mass were selected to make its kinetic energy equal to $104.5 \cdot 10^3$ kgm^2/s^2 (as a mechanical accumulator with moment of inertia 2.12 kgm^2) at rotational speed 3000rpm. That corresponded (with scale factor 1:32) to kinetic energy ($3{,}347 \cdot 10^6$ kgm^2/s^2) of 24 Mg crane moving at speed of 60 km/h.

As the inertia mass, one utilised two flywheels of tractor engine mounted on common multistage shaft supported by two (two-row) self-aligning ball bearings fixed in sectional housings by means of counter rings.

Since the Vector Control inverter had no facility to measure rotational speed during braking effected by the unit (inverter blocking); the opposite end of the shaft is connected to a tachometer generator.

3.2. Recovered energy investigation program, recording and visualisation of measured values

In order to represent braking phases of the cycles of operation mechanisms, the following assumption were accepted for the computer program.

- In each of the three cycles of operation mechanisms of self-driven crane, the energy is recovered during the phase of lowering of the loaded sheave block.
- The lowering time of the first cycle is equal to 28.6s; the recovered energy of 1384.2kJ corresponds to a power of 48.4 kW.
- The lowering time of the second cycle equals 46.5s, the recovered energy of 1697.2kJ, corresponds to a power of 36.5kW.
- The lowering time of the third cycle equals 85.7s; the recovered energy of 454.2kJ corresponds to a power of 5.3kW.

The remaining program tasks were: controlling the system electric motor – energy transformer (generator), and stabilising, first of all, its rotational speed (sheave block lowering at a constant speed). Additionally, the program controlled recording, data storing, and visualisation of the selected measured values. After completing the measurement experiment, the results were presented in tabular form or as time functions.

The inertia mass (whose moment of inertia defined the mechanical scale factor) was assumed as the test-stand equivalent of the actual crane mass. It accelerated to a maximum rotational speed, which might be recognised as the maximum running speed of the crane (for the analysed running cycle). The energy stored in the mass could be used as the driving energy for the mechanical-into-electrical energy converter.

The task of computer program was to represent, in terms of energy, selected braking phases of running cycle of the crane. It could be done in the following way:

The inertia mass and the coupled mass converter were brought up to the assumed rotational speed;

- The drive was switched off and, at the same time, electrical circuits of the converter were switched on to initiate measurements of selected quantities. The measurement continued until the rotational speed, or the power delivered to receiver resistance, approached zero.

In the described test stand, maximum rotational speed of the inertia mass equal of 3000rpm corresponded to the crane running speed of 60km/h.

In all the analysed cycles of the crane running, the energy was recovered in the following cycles:

- Highroad running cycle (cycle A), during the two braking phases. In the first braking phase, within 11s, the crane running speed decreased from 60km/h to 35km/h and the recovered energy could reach the value of 1770 kJ. In the second braking phase, within 15s, the crane running speed changed from 35 km/h to zero, and the recovered energy could be equal to 925kJ.

- Urban running cycle (cycle B), during the three braking phases. In the first and second braking phase, within 11s, the crane running speed decreased from 13.3km/h to zero, and the recovered energies could reach, in each phase, the value of 107.7kJ. In the third phase, during 30s, the crane running speed approached zero decreasing from the value of 30.6km/h and the recovered energy could reach 500kJ.
- Off-road running cycle (cycle C). Theoretically, the energy could be recovered during two braking phases. In the first phase, within 9s, the crane running speed decreased from 27,5 km/h to 20 km/h, and the recovered energy could be equal to 6.3kJ. In the second phase, within 18s, the crane running speed droped from 20 km/h to zero and the recovered energy could reach 7.1kJ. In practice, because of very high motion resistance, the off-road running cycle gave no possibility to recover energy during braking phases.

After the program starts, the opening window appears on the screen. It contains the main menu and boxes that display engine and generator parameters. The engine parameter box displays information on selected speed value and the current value of rotational speed of the engine (taken from inverter). The instantaneous values of current, voltage and torque (read from the inverter) are also presented there. It is possible to start up the driving system, to brake it, and to block inverter output what brings the system to the rest along a stop way. The generator parameter box contains information about rotational speed (that, during the measurements, reflect the phases of the running cycle; this value is measured by a rate generator), current and voltage values (read by means of Hall-effect converters), and about the power and energy values calculated by the program. The software makes it possible to switch on the excitation and load circuits of the DC generator.

The option "Drive System Configuration" gives the possibility to program the inverter in order to set-up the starting and braking times, as well as maximum rotational speed of the coupled machines.

The option “Measurement Parameters” allows the user to define the parameters representing crane’s operation during mechanism operating cycle, and the operation during crane running cycles. To initiate the experiment, one should activate menu “Start” starting the electric motor, and then, after reaching the assumed rotational speed, switched on the generator’s induction winding. The proper experiments (basic measurement) begin only after generator current and voltage have reached the steady state; the course of the experiment can be seen on the computer screen. Duration of the experiment is limited by the repetition time. The measured and calculated data obtained in the experiment are stored in a text file. The “Data” option facilitates file selection and activates the “Graph Presentation” option, showing a graph identical to that presented during the experiment.

4. Experiments

4.1. Fundamental assumptions

The DC generator, acting as an energy converter built into the stand, can supply loading resistors with current of variable intensity during the experiment. These currents may be even higher than the rated load current (causing generator overload). Such a program can also be performed owing to three controllers installed in the test-stand power transmission line.

- There is a possibility to connect an additional shunt resistor R_{fd} to the induction circuit of the DC shunt generator inserted into the power transmission line; the resistor makes it possible to control the generator's induction current.
- The driving system applied in the transmission line allows for a continuous adjustment of rotational speed of the electric motor (including speed stabilisation at an arbitrary level) within the regulation range up to 3000rpm.
- The adjustable load resistance R_o offers the possibility to regulate the current in the load measurement line, which determines instantaneous value of the load power and the energy transmitted to the receiver [6].

4.2. Examination of energy recuperation in crane operation mechanisms cycles

The examples of experiment results are presented in Table 2. The calculated factor of recovered energy w_p defines the energy possible to recover within 1s of the loaded sheave block-lowering phase. The value of this factor depends on the value of power that was supplied to the stand generator at the moment of experiment start.

Table 2.

Experimental data from investigations on energetic properties of the model stand; quantities related to energy recuperation during lowering of loaded sheave block

Experiment No	Rotational speed	Load current	Voltage	Energy recovered	Experiment time	Energy recovery factor
–	rpm	A	V	kJ	s	kJ/s
1	2850	11.6	240	305	110	2.8
2	2850	10.8	232	275	110	2.5
3	2200	8.5	199	185	110	1.7
4	2200	11.4	178	220	110	2.0
5	3000	10.8	225	305	110	2.8
6	2775	13.0	277	396	110	3.6

The results experiment No. 2, shown in Table 2, pertain to the case when the generator reached the power level of 2.5 kW (the machine rated power). Time functions of quantities measured in the tests of this experiment are presented in Fig. 5.

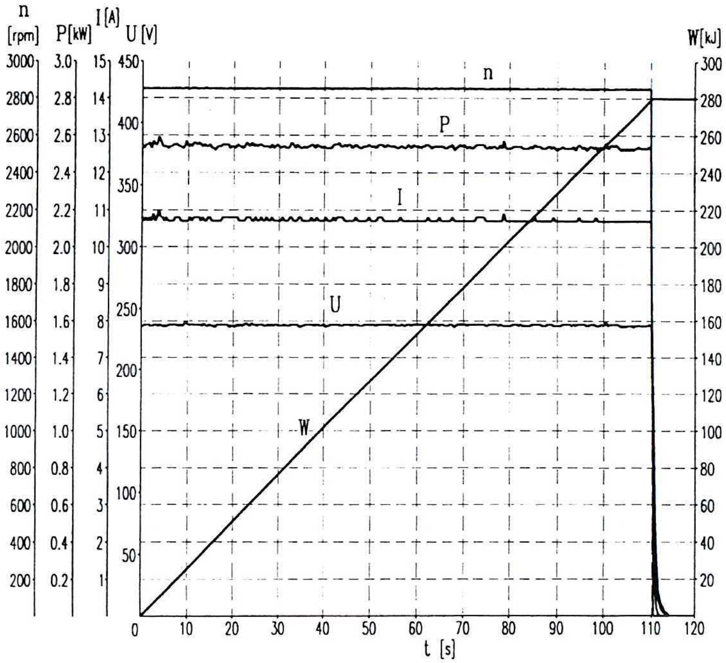

Fig. 5. Waveforms of current, voltage, power, rotational speed and recuperated energy in DC shunt generator during lowering of loaded sheave block (n= 2850 rpm, P= 2.5 kW)

The results of this experiment can be summarised as follows:

- generator power $P_2 = 25\text{kW}$ (rated power),
- energy recovered $W_2 = 275\text{kJ}$,
- experiment time $t_2 = 110\text{s}$,
- recovered energy factor $w_{p2} = \frac{W_2}{t_2} = 2{,}5\,\frac{\text{kJ}}{\text{s}}$.

In this case, the factor w'_{p2}, defined as the ratio of the recovered energy factor w_p to the power that the installed generator have reached at the beginning of the experiment, is a general factor (power P_2 equals to the rated power) whose value equals $w'_{p2} = 1$. In order to translate the results of experiment into an actual object, one assumed that the rated power of the generator installed in measurement line equals 48,4kW, and the energy of 1384kJ can produced by the load when lowered during 28.6 s in cycle I. Then, the following formula can be used to calculate the energy recovered in the real object.

$$\frac{w'_{p2} \cdot P_n}{P_2} \cdot t_n \cdot w_{p_2} = \frac{1 \cdot 48{,}4}{2{,}5} \cdot 28{,}6 \cdot 2{,}5 = 1384 \quad \text{kJ}\,,$$

where: P_n – rated power of generator installed in real object,

t_n – time of sheave block lowering in real object.

The energy recovered during braking phases of cycles II and III can be calculated in a similar way. However, one must take into account real times of lowering of the loaded sheave blocks, and assume in calculation the actual rated powers of generators installed in the crane. The analysis of results of experiment No 6 gives the following data:

- generator power $P_6 = 3.6\text{kW}$ (exceeding rated power),
- recovered energy $W_6 = 396\text{kJ}$,
- time of experiment $t_6 = 110\text{s}$,
- recovered energy factor $w_{p6} = 3.6\text{kJ/s}$.

In this case, the factor $w'_{p6} = 1.44$. It defines the degree of overload of the generator installed in the experiment stand. It can also be treated as an indicator of the increase of the energy recovered in a real object when the generator rated power is increased by this factor. Under such overloading conditions, the energy possible to recover in a real object can be found from the following formula

$$\frac{w'_{p6} \cdot P_n}{P_6} \cdot t_n \cdot w_{p_6} = \frac{1{,}44 \cdot 48{,}4}{3{,}6} \cdot 28{,}6 \cdot 3{,}6 = 1993 \text{ kJ}$$

In practice, current generator of nominal rated power of, for example, 25 kW would be installed in the real crane. In such a case, one can use the following formulae to calculate the energy recovered during the phases of lowering of loaded sheave block (in crane operation mechanism cycle) taking into account the results experiment No. 2 and assuming real times of loaded sheave blocks lowering.

- cycle I $\quad \dfrac{w'_{p_2} \cdot P_n}{P_2} \cdot t_n \cdot w_{p_2} = \dfrac{1 \cdot 25}{2{,}5} \cdot 28{,}6 \cdot 2{,}5 = 715\,\text{kJ},$
- cycle II $\quad \dfrac{w'_{p_2} \cdot P_n}{P_2} \cdot t_n \cdot w_{p2} = \dfrac{1 \cdot 25}{2{,}5} \cdot 46{,}5 \cdot 2{,}5 = 1162\,\text{kJ}\,,$
- cycle III $\quad \dfrac{w'_{p_2} \cdot P_n}{P_2} \cdot t_n \cdot w_{p2} = \dfrac{1 \cdot 25}{2{,}5} \cdot 85{,}7 \cdot 2{,}5 = 2142\,\text{kJ},$

In cycle III, the generator works in underrated load conditions, and then the actual recovered energy reaches the value of approximately 450kJ.

Schematic diagram illustrating the principle of coupling of the generator with the loaded sheave block hoist mechanism is presented in Fig. 6.

The concept of energy recovery after the completion of the phase of loaded sheave block lowering, presented in section 2.1, may be verified in model test-stand conditions. The time function of energy recovered during 60 second of running is presented in Fig. 7. The graph was calculated on the assumption that the inertia mass installed on generator shaft is equal to the mass in the test stand (Fig. 4). The phases of loaded sheave block lowering in operation mechanism cycle not always coincide with those resulting from crane hoisting capacity characteristics. Load lowering times may be shorter, and heights may be lower, depending on the kind of performed tasks. However, long-term observations of operation of similar machines working at Warsaw subway construction site indicate that the phases of loaded sheave block lowering are generally consistent

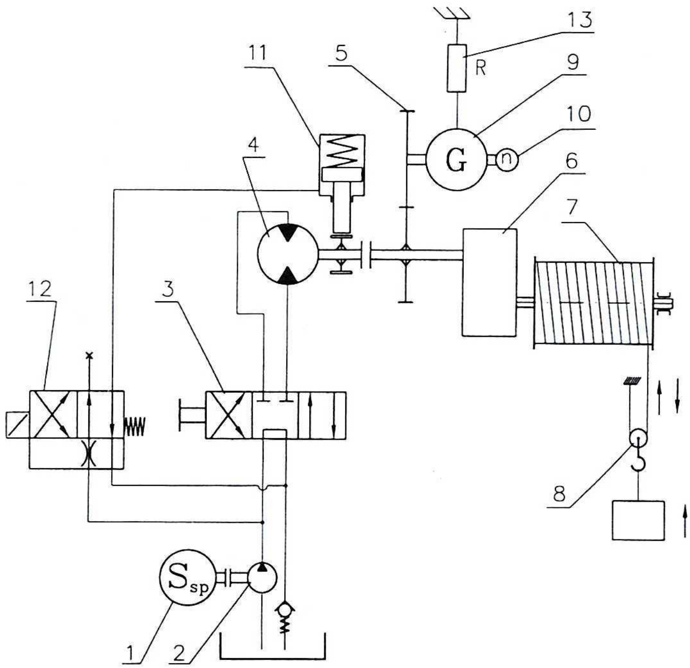

Fig. 6. Kinematic diagram of selected units of crane hoist mechanisms and energy recovery principle. (1 – combustion engine, 2 – hydraulic pump, 3 – distributor, 4 – hydraulic motor, 5 – winch gear, 6 – reduction gear, 7 – winch drum, 8 – pulley block, 9 – DC generator, 10 – rate generator, 11 – winch motor brake, 12 – brake control distributor, 13 – generator load – heating resistor)

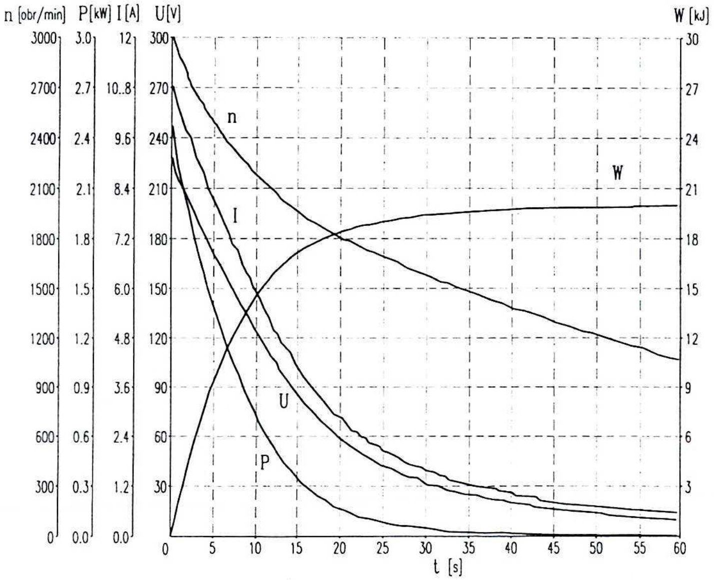

Fig. 7. Waveforms of current, voltage, power, rotational speed and recuperated energy in DC shunt generator during braking of inertia mass from rotational speed of 3000 rpm.

with the corresponding parameters resulting from crane hoisting capacity characteristics. According to the calculations done by the Authors and the performed tests, an efficient crane operator is able to make 45 hoisting cycles during 8-hour working day. It is assumed that crane mean operation mechanism cycle equals 400s. Under the assumption, based on calculation results, that energy recovered during a single cycle reaches 1000kJ, there is a theoretical possibility to recover 45MJ of energy during one working day of the crane.

Provided only 10% of crane operation in the phase of loaded sheave block lowering in the operation mechanism cycle is equivalent to that resulting from the parameters of crane hoisting capacity characteristic, regeneration of solid particles filter is still possible.

4.3. Examination of energy recuperation in crane running cycles

The applied software has the option "Running Cycle Work". The time functions of current, voltage, power, rotational speed and energy in the DC shunt generator installed in the experimental stand are presented in Fig. 7. These pertain to a generator with rated power of 25kW, and illustrate the phases of braking of the inertia mass starting from rotational speed of 3000rpm. The obtained results gave the ground for calculations of the available energy that can be recovered and delivered to the generator load resistor during the running cycles A, B and C. Only the braking phases of these cycles were analysed. In the calculations, one assumed linearity of time functions of both rotational speed and linear speed [2]. The maximum running speed of the crane in cycle A is equal to 60 km/h, while the maximum rotational speed of the installed generator equals to 3000 rpm. The analysis of characteristics presented in Fig. 7 lead to the conclusion that the generator rotational speed equal to 1500 rpm (corresponding to 30 km/h of the crane running speed) was the lower speed limit for the energy recuperation. As an example, the energy analysis of braking phases of cycle A (Fig. 1) was performed, and the results were compared to those found in experiments. In the analysis of cycle A of crane running, one assumed the factor values k = 1 through 2 and 3 through 4, and the corresponding co-ordinates of running cycle were equal to $V_{c(1)}$=60 km/h, $V_{c(2)}$=35 km/h, $V_{c(3)}$= 35 km/h and $V_{c(4)}$= 30 km/h. The co-ordinates found from measurement had the following values: $n_{p(1)}$= 3000rpm, $n_{p(2)}$= 1750rpm, $n_{p(3)}$= 1750rpm, and $n_{p(4)}$= 1500rpm. As the minimum running speed for energy recuperation was previously determined as of 30 km/h (1500 rpm), the other factors of braking phase were neglected, both in relation to the running cycle and to measurement points. The energy delivery time during measurements in the experimental stand equals

$$t_{p(1\text{-}2)} = 22.4\ \text{s},\quad t_{p(3\text{-}4)} = 11.6\ \text{s}.$$

Due to the previous assumptions, the test stand parameters were as follows: the stand generator power during experiments equal to 2.5kW (Fig. 7), and inertia mass selected to give the kinetic energy scale factor equal to 1:32 for the mass rotational speed 3000 rpm and the crane linear running speed of 60km/h. Then, the energy in real object would be:

- in cycle A, braking factors k = 1 through 2
  22,4 · 2,5· 32 = 1792kJ (the value determined theoretically equals 1770kJ),
- in cycle A for braking factors k= 3 through 4
  11,6 ·2,5 ·32 = 928 kJ (the value determined theoretically equals 925kJ).

Similar calculations for crane running cycle B and C confirm the closeness of the theoretically determined values of energy recuperated during braking phases of the real object, and those found from results of experiments on the model stand. The schematic diagram illustrating the principle of coupling of DC generator with combustion engine, torque converter (detached during braking phase) and transmission is presented in Fig. 8.

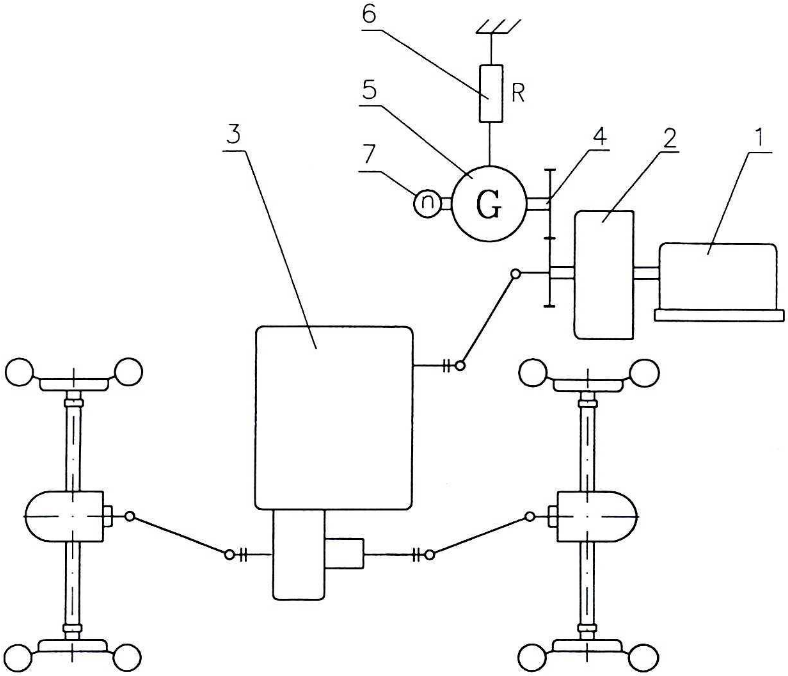

Fig. 8. Kinematic diagram of selected units of crane drive mechanisms illustrating energy recovery (1 – combustion engine, 2 – torque converter, 3 – transmission, 4 – multiplying gear, driving DC generator, 5 – DC generator, 6 – generator load – heating resistor, 7 – rate generator)

The experiments on energy recovery during the braking phases of crane running cycles and the phases of lowering of loaded sheave block in the operation cycle of crane mechanisms were carried out on model test-stand.

A method of determining of braking energy was described in [7], [8], but it referred to automobiles. Mathematical models of machines and control systems, appropriate for construction of a test stand, were presented there, and these were used in simulation tests. The results of these simulations were verified in experiments carried out on a model test stand. The Reader, who is familiar with electrical engineering and energy related problems in heavy machinery, who follows the development of research on energy recovery aimed at improving functioning of ecology-friendly machines, can accept the results of the presented investigations as optimistic, and recognise possibilities of their technological applications.

6. Concluding remarks

The presented idea of energy recovery during the phases of lowering of loaded sheave block in operation mechanism cycles, and during braking phases of crane running cycles, is practically applicable, provided an adequate DC generator is used as the mechanical-into-electric energy converter. The main objective of the research task, described in this paper, was then achieved. It enabled the Author to estimate the amount of energy possible to recover in the form of electrical energy. The analysis of investigation results, related to the DUT-0300 all-terrain crane, lead to the following conclusions:

- The possibility of recovering a significant amount of energy exists during the phases of lowering of loaded sheave block in operation mechanism cycle. There is a possibility to transmit the energy to load resistors of a DC generator additionally installed in the system. If a certain amount of energy is recovered in each operation mechanism cycle during its phase of loaded sheave block lowering, it is possible to recuperate a total energy of (3÷5 MJ) within 8-hour working day (the estimation takes into account filter's energy transformation efficiency, disruptions in energy supply cycle and reduction of the height of loaded sheave block lowering). On the other hand, energy recovery after complete lowering of the load (inertia mass rundown) seems to be purposeless.
- Energy can also be recovered during braking phases of highroad, urban and off-road running cycles, and it can be transmitted to load resistors. It was proven that energy could be recovered during braking phases of running cycles (what is considered as a real recovery) Therefore, it is quite evident that there is enough energy for regeneration of filters of solid particles.

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Pozyskiwanie energii do ograniczenia toksycznych składników spalin w wybranych stanach energetycznych rozdzielnego cyklu pracy samojezdnej maszyny roboczej

Streszczenie

W artykule przedstawiono problematykę dotyczącą obliczeń teoretycznych i badań doświadczalnych związanych z możliwością pozyskiwania energii w wybranych fazach cyklu mechanizmów roboczych i cykli jazdy żurawia samojezdnego. Maszyny robocze z silnikami o zapłonie samoczynnym (ZS) są źródłem emisji szkodliwych substancji stałych. W celu ograniczenia tej emisji są instalowane filtry i systemy ich regeneracji. Zgodnie z przyjęta koncepcją pozyskiwana energia będzie przeznaczona do regeneracji tych filtrów, która polega na wypalaniu nagromadzonych w filtrze cząstek stałych (sadzy). Energia mechaniczna będzie źródłem napędu prądnic elektrycznych prądu stałego stanowiących przetworniki energii mechanicznej w elektryczną. Rezystory grzejne filtra, stanowiące obciążenie tych prądnic powinny wypromieniować 3÷5 MJ energii w celu zapoczątkowania spalania sadzy w filtrze. Dla cyklu mechanizmów roboczych dokonano obliczeń energii w fazach opuszczania obciążonego zblocza, dla trzech różnych udźwigów żurawia, w zależności od długości wysięgnika i wysięgu. Przedstawiono również trzy cykle jazdy: szosowy, w obszarze zabudowanym i terenowy. Wyniki obliczeń pozwoliły na teoretyczne (uproszczone) określenie wartości energii możliwej do pozyskiwania w fazach hamowania tych cykli. Opisano budowę i działanie stanowisk badawczych, w których zainstalowane urządzenia odwzorowują w odpowiednich skalach wybrane zjawiska energetyczne zachodzące w rzeczywistym obiekcie, a dotyczące tylko pozyskiwania energii. Przedstawiono komputerowe programy badań i układy sterowniczo - pomiarowe. Zamieszczono wyniki pomiarów i ich analizę. Porównano teoretyczne wartości energii, z wartościami energii pozyskanej w procesie badań eksperymentalnych. W publikacji przedstawiono również uproszczone schematy kinematyczne wybranych zespołów mechanizmów podnoszenia i mechanizmów jazdy żurawia, z zainstalowaną dodatkowo prądnicą elektryczną prądu stałego jako koncepcje realizacji, które wymagają weryfikacji w przypadku przyszłych rozwiązań konstrukcyjnych.