Regulation of Working Regimes of Digging–Transportation Machines by Changing the Digging Depth

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It is by applying the methods of automatic control and regulation system theory that the present study endeavors at researching further the issue of regulation of operational regimes of digging-transportation machines by changing the excavation depth. A mathematical model of the regulation circle is presented here with a non-linear relay-type regulator. On the basis of such a model, it is analyzed the probability of appearance of self-induced oscillations in the regulation circle on the basis of algebraic and frequency procedures, depending on the initial conditions and system parameters. The study also demonstrates how to determine the amplitude and frequency of self-induced oscillations. Simulation of dynamic system behavior is used for examples with concrete numerical parameter values as well as analysis of errors due to linearization.

Keywords: *Digging-transportation machines. Regulation (Control), Working (Opperating) regimes, Self vibrations.*

1. INTRODUCTION

Digging and transportation machines (bulldozers, scrapers, graders) perform their operating process of digging and earth transportation under the traction regime and primary machine movement. It is accompanied by considerable variations of the driving system working resistances and loads. Common (characteristic) working regimes of these machines are the regime of a maximum traction power of the working device and regime of a maximum efficiency coefficient i.e. power efficiency. The maximum traction strength regime is a primary regime that characterizes traction possibilities of a machine and provides for a maximum machine performance. When operating under this regime, machines with mechanical transmission have efficiency that is by 10÷12% lower than a maximum obtainable one, while in machines with hydro-mechanical transmission it is lower by 4%. The maximum efficiency regime characterizes power efficiency of utilization of land development machines.

Under this regime, developed traction power of the working device is by 11÷12% lower than a maximum obtainable one in mechanical transmission machines, and by 5÷6% in hydro-mechanical transmission machines [4].

Thus, it is under the above described regimes that traction as well as power possibilities of machines are not used as effectively as possible.

There is a regime proposed by [3] under which the working device traction force is between the values that correspond to the maximum efficiency and maximum power. This is known as the regime of a maximum effective power of the working device.

Traction and power characteristics of a machine shall depend on the engine and transmission characteristics, as well as on the distribution of load over the movers i.e. on tractor's tractions [6]. To this end, operational regime regulation in these machines may be accomplished by regulation of operational regimes of engines or transmissions i.e. by regulation of the tractor's traction. The most commonly applicable one is the regulation of engine operational regimes.

Regulation of a selected engine operational regime at variable external engine operational loads may be conducted by:

- changing the transmission ratio,
- changing the technological parameters i.e resistances.

Regulation that is achieved by changing the transmission ratio is particularly suitable for the regulation of engine operational regimes at a maximum efficiency coefficient and given power. This regulation is conducted by means of automatic transmissions. By application of automatic transmissions it may be achieved that an engine operates under almost all exploitation conditions at the characteristic of minimum specific fuel consumption [11, 15, 21]. A universal diagram of specific fuel consumption of a diesel engine is exhibited in Fig. 1, where A-B curve represents a characteristic of minimum specific fuel consumption [11].

Varied types of automatic transmissions are applied nowadays in the automobile industry: hydro-mechanical, CVT/Continuously Variable Transmission, AMT/ Automatic Manual Transmission, DCT/Dual Clutch Transmission [13]. Transmissions designated as CVT offer the best convenience and fuel saving up to 10% in comparison to the automatic transmissions with four gears [13]. Multitronic CVT solution instead of former solutions with a rubber V-belt and later a steel belt, uses a link tape and has an incorporated torque sensor.

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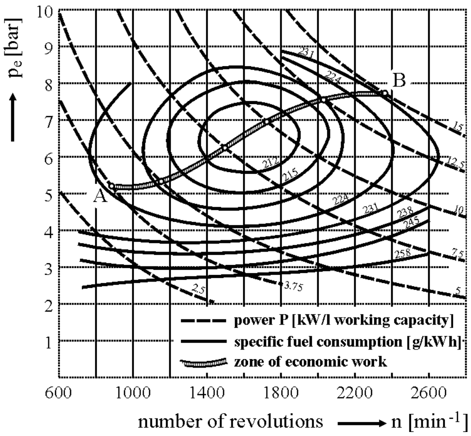

Figure 1. Universal diagram of specific fuel consumption of a diesel engine [11]

Automatic transmissions in tractors i.e. working machines are based on the implementation of hydro-mechanical or hydrostatic–mechanical power transmissions. Automatic hydrostatic transmissions are with continuously variable working volume of pumps and engines (CVT transmissions) [12]. Considerable effects are achieved by implementation of these transmissions. According to [19], should a mechanical transmission be replaced in tractors with a hydro-static transmitter with automatic control, performance of the tractor in corn cultivation shall be increased by 32.4%, while fuel consumption shall be decreased by 6.4% [19].

It should be emphasized that in hydro-mechanical transmissions and at certain parameter values, some cyclic variations in the transmission ratio are likely to occur [25]. Such a propensity to oscillations is also observable in the limit load regulation circle of a driving engine where regulation is achieved by means of a transmission ratio [17, 22].

Working regime regulation in digging-transportation machines by changing the working resistances is carried out by changes of excavation depth, whichis the subject matter of analytical researches of the present study.

Figure 2. Constructive schemes of digging-transportation machines (bulldozer, scraper, grader)

Taking into consideration the constructive conception of these machines, Fig. 2, it is realized by adjusting the working device position by means of hydraulic cylinders.

This represents an engine load regulation at given values of fuel supply. Should the fuel supply be a maximum one, it is then the engine limit load regulation.

In a similar way as with the engine load regulation by changing the transmission ratio, propensity to self induced oscillations also exists when the engine load regulation is performed by means of changing the excavation depth.

Appearance of self-induced oscillations within the observed regulation circle is followed by continuous lifting and lowering of the working device.

Examinations of conditions for the appearance of oscillations within the regulation circle as well as ascertainment of the value of their amplitudes and frequency represent primary objectives of the present study.

2. MATHEMATICAL MODEL OF REGULATION CIRCLES

Regulation of working regimes of digging-transportation machines by changing the excavation depth, which represents an operative and regulating effect, has already been analyzed in numerous literary sources, such as [3, 10, 14, 16, 18, 24]. These sources offer mainly description of the modes of regulation without elaborating on the relevant mathematical models of regulation circles.

In the research studies of this author [5, 7, 9] presented are mathematical models of working regime regulation circles in which, as a regulating value, the driving engine number of revolutions or transformer transmission ratio is applied. Regulation circles are linear, and control of working device cylinders is performed by means of proportional electro-hydraulic distributors. Such a regulation circle model provides for a very precise regulation. Taking into consideration a continuous variation of working resistances and driving engine loads that also implies a continuous variation of the working device position. However, in the majority of practical cases, it shall be sufficient to regulate just the operational regime range which is achieved by correcting the excavation depth, when the number of driving engine revolutions is replaced by Δn. Thus, it is indispensable that a nonlinear regulator with an insensitivity zone and limitation be incorporated into the regulation circle.

Figure 3 exhibits a diagram of a caterpillar-type bulldozer driving system, with a diagram of excavation depth regulation [8], while Fig 3.b depicts a regulation range of the selected diesel engine working regime.

It is on the basis of Fig. 3 that demonstrated in Fig. 4 in the form of a block diagram is a model of the operational regime regulation circle in digging-transportation machines by changing the excavation depth [8].

The reference value is voltage U_z , while the output value is voltage U_i. The material prism height h_1 represents a disturbance of stochastic nature, with h_2 that is a correction value for the working device position by height, and $\boldsymbol{h}$ by excavation depth.

The demonstrated nonlinear regulator represents a three-positional symmetric relay element with an insensitivity zone and limitation of the type $\{-c, 0, +c\}$.

The regulator is easy to realize with electrical components and in that case it can be described by the (1).

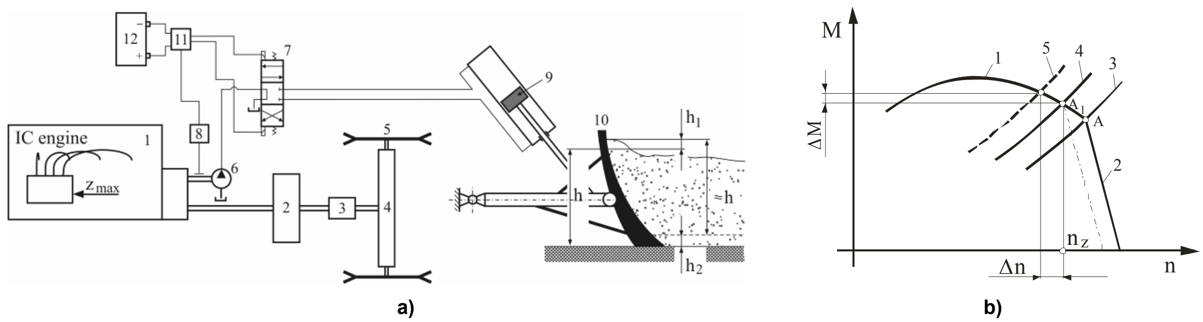

Figure 3. a) Scheme of a caterpillar-type bulldozer driving system with the excavation depth regulation (1 – driving engine, 2 – hydraulic transformer, 3 – mechanical gearbox, 4 – main transmission with lateral reducing gears, 5 – driving star, 6 – working device drive pump, 7 – trapezoidal electromagnetic valve, 8 – tachogenerator, 9 – hydrocylinder, 10 – dosing plate,. 11 – regulation electronics, 12 – power supply); b) Diesel engine regulation zone

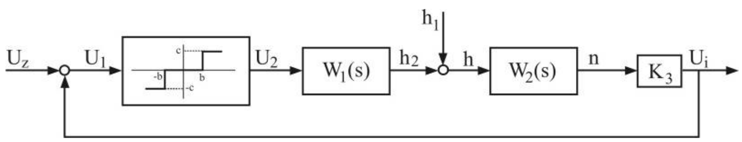

Figure 4. Block diagram of a model of the working regime regulation circle

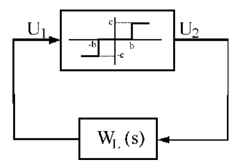

Figure 5. Regulation circle without external excitations

$$U_2 = \begin{cases} -c, & U_1 \le -b \\ 0, & -b \le U_1 \le b \\ +c, & U_1 \ge b \end{cases}. \tag{1}$$

It should be emphasized that this is a characteristic of the three-positional hydraulic distributor, as well.

Transmission function of the working device mechanism and drive with hydraulic cylinders driven by electromagnetic distributors, at earth intake by the working device, can be described by the following expression [8]:

$$W_1(s) = \frac{K_1}{s \cdot (T_1 \cdot s + 1)}. \tag{2}$$

Transmission function of the movement drive with reduced machine masses at the engine flywheel, for both transmission solutions (with hydrodynamic and hydrostatic transformers) assumes the following form [4, 9]:

$$W_2(s) = -\frac{K_2}{T_2 \cdot s + 1}. \tag{3}$$

In transmission functions (2) and (3): T_1 and T_2 are time constants, K_1 and K_2 amplifications; $s = \sigma + j\omega$ represents a complex variable where: σ is a real portion, ω an imaginary portion, and j an imaginary unit.

3. ANALYSIS OF SELF-INDUCED OSCILLATIONS IN THE REGULATION CIRCLE

Examination of oscillatory regimes within the regulation circle with nonlinear elements is of a special relevance due to the fact that self induced oscillations may be established at certain system parameter values. The method of harmonic linearization of nonlinearity is applied for such an analysis. The harmonic linearization method is an approximate method based on the assumption that the nonlinear portion of the system acts as a low-frequency filter which weakens higher harmonics to a considerable extent. It is on the basis of such an assumption that in harmonic linearization used is solely the first member of the Fourier's order. The nonlinear system is on that occasion divided into a linear and nonlinear portion [2, 20]. Impact of external excitations is excluded as oscillatory characteristics of the system depend solely on the system parameters. Accordingly, the regulation circle exhibited in Fig. 4 without the presence of any external excitations may be demonstrated by means of a block diagram, Fig, 5:

According to the block diagram, Fig. 4, transmission function of the linear portion of the system is:

$$W_L(s) = \frac{K_L}{s \cdot (T_1 \cdot s + 1) \cdot (T_2 \cdot s + 1)}, \tag{4}$$

where K_L is the coefficient of amplification of the linear portion of the system.

It is by implementation of the harmonic linearization method (descriptive function) that a transmission function of the linearized relay element is obtained, which in this specific case represents the coefficient of amplification rendered as the following expression:

$$W_N(a) = \frac{4 \cdot c}{\pi \cdot a} \cdot \sqrt{1 - \frac{b^2}{a^2}}, \quad a \ge b, \tag{5}$$

where a is the amplitude of a periodically variable voltage U_1 at the inlet of the nonlinear element.

Examination of probabilities for the appearance of self-induced oscillations and ascertainment of the amplitude value and frequency may be conducted by means of algebraic and frequency procedures [2, 20].

3.1 Algebraic Procedure

A characteristic equation of the linearized system is arrived at on the basis of a block diagram as presented in Fig. 5 and transmission functions (4) and (5):

$$T_1 \cdot T_2 \cdot s^3 + (T_1 + T_2) s^2 + s + \frac{4K_L \cdot c}{\pi \cdot a} \sqrt{1 - \frac{b^2}{a^2}} = 0 \qquad (6)$$

$$a \geq b \ .$$

Periodical processes occur in the system if the characteristic (6) has few purely imaginary roots, $s = \pm j\omega$.

In that case, a characteristic (6) may be written in the form as follows:

$$X(a,\omega) + jY(a,\omega) = 0 \ . \qquad (7)$$

It is on the basis of (7) that two algebraic equations are obtained:

$$X(a,\omega) = \frac{4 \cdot K_L \cdot c}{\pi \cdot a} \cdot \sqrt{1 - \frac{b^2}{a^2}} - (T_1 + T_2) \cdot \omega^2 = 0 \ , \qquad (8)$$

$$Y(a,\omega) = \omega \cdot (1 - T_1 \cdot T_2 \cdot \omega^2) \cdot \omega^2 = 0 \ , \qquad (9)$$

which help determine the frequency and amplitude of the required periodical solution, $\omega = \Omega$ and $a = A$.

Amplitude determined on the basis of (8) represents an approximate value due to the rejection of higher harmonics when linearizing the nonlinear element. However, frequency obtained from the (9) is of ample accuracy as sensitivity of the periodical solution frequency to higher harmonics is low [23].

Should the periodical solution be stable, an oscillatory process shall be established in the system.

A prerequisite for the stability of the periodical solution appears to be [2, 20]:

$$\left(\frac{\partial X}{\partial a}\right) \cdot \left(\frac{\partial Y}{\partial \omega}\right) - \left(\frac{\partial Y}{\partial a}\right) \cdot \left(\frac{\partial X}{\partial \omega}\right) > 0 \ , \qquad (10)$$

at the values $\omega = \Omega$ and $a = A$.

Pursuant to (8) and (9) and condition (10) it results that for the considered regulation circle the prerequisite of stability of the periodical solution has been satisfied for $a > b \cdot \sqrt{2}$.

Critical value of the coefficient of amplification for the nonlinear portion of the system is arrived according to (8) for $a = b \cdot \sqrt{2}$:

$$K_{L.\text{kr}} = \frac{\pi \cdot b}{2 \cdot c} \cdot \left(\frac{1}{T_1} + \frac{1}{T_2}\right) . \qquad (11)$$

The coefficient $K_{L.\text{kr}}$ represents a limit of stability as well as a limit of the self-induced oscillating range of the system. If $K_L < K_{L.\text{kr}}$ the state of equilibrium is stable at all values of initial conditions i.e. initial deflections from the equilibrium state. With $K_L > K_{L.\text{kr}}$ stability of the equilibrium state shall depend on the values of initial conditions.

3.2 Frequency Procedure

For the selection of regulation circle parameters, the frequency procedure is a more suitable one. According to the frequency procedure based on the Nyquist criteria, a periodical solution of the linearized system is obtained when the amplitude-phase frequency characteristic of an open circuit:

$$W(j\omega) = W_L(j\omega) \cdot W_N(a) \ , \qquad (12)$$

passes through the point (-1, j0) [2, 20].

Thus, the periodical solution is ascertained by:

$$W_L(j\omega) = -\frac{1}{W_N(a)} \ . \qquad (13)$$

The solution is arrived at in such a manner that the amplitude-phase frequency characteristic of the linear portion of the system $W_L(j\omega)$ is drawn in a complex plane, based on the module $W_L(j\omega)$ and phase $\psi(\omega)$:

$$|W_L(j\omega)| = \frac{K_L}{\omega \cdot \sqrt{(1 + T_1^2 \cdot \omega^2) \cdot (1 + T_2^2 \cdot \omega^2)}} \ , \qquad (14)$$

$$\psi(\omega) = -90^{\circ} - \text{arctg}(\omega \cdot T_1) - \text{arctg}(\omega \cdot T_2) \ , \qquad (15)$$

as well as the hodograph of the nonlinear element harmonically linearized on the basis of:

$$-Z(a) = -\frac{1}{W_N(a)} = -\frac{\pi \cdot a^2}{4 \cdot c} \cdot \frac{1}{\sqrt{a^2 - b^2}} \ . \qquad (16)$$

Minimum value of the function *–Z(a)* module is:

$$|Z(a)|_{\min} = \frac{\pi \cdot b}{2 \cdot c} \qquad (17)$$

and it is obtained for $a = b \cdot \sqrt{2}$.

Intersection points of characteristics $W_L(j\omega)$ and $-Z(a)$ determine the values of amplitudes and frequency of periodical solutions.

Frequency value is determined on the basis of the curve $W_L(j\omega)$, and amplitude on the basis of the curve $-Z(a)$. It is indispensable for the stability of the periodical solution that the amplitude-phase frequency characteristic of the linear portion of the system $W_L(j\omega)$ embraces the part of the hodograph $-Z(a)$ that corresponds to smaller amplitudes [1].

4. ILLUSTRATION OF BEHAVIOR OF THE ECONOMIC OPERATION RANGE REGULATION CIRCLE

Behavior of the regulation circle, Fig. 4, is illustrated on the basis of an example with numerical parameter values of the system: $T_1 = 0.1$ s , $T_1 = 0.6$ s , $b = 0.150$ V , $c = 6$ V that may be regarded as real ones and very close to the parameter values of the derived solutions of machines. For the above system parameters, according to the expression (11), arrived at is the critical value of the coefficient of amplification of the linear portion of the system $K_{L.\mathrm{kr},A} = 0,4576$. Based on (8) and (9), dependence of amplitude a of the coefficient K_L, the curve 1 in Fig, 6, is obtained, as well. Applying both algebraic and frequency procedures and computer simulation, analyzed is the impact of amplification of the linear portion of the system K_L and width of the insensitivity zone b of the nonlinear element on the system behavior at varied initial conditions i.e. deflections from the equilibrium state.

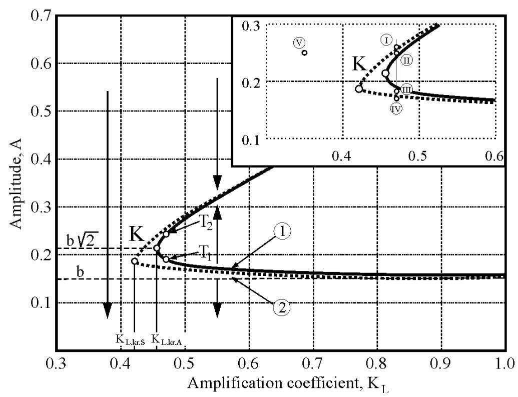

Figure 6. Dependence of amplitudes on the amplification coefficient of the nonlinear portion of the system (1 – curve obtained analytically, 2 – curve as a result of simulation)

Analyzed are the cases $K_L > K_{L.\mathrm{kr}}$ and $K_L < K_{L.\mathrm{kr}}$.

If taken that: $K_L = 0.47 > K_{L.\mathrm{kr}}$. For the given system parameters on the basis of (8) and (9), we arrive at the amplitudes of periodical solutions of the voltage U_1 at the nonlinear element input $A_1 = 0.191$ V and $A_2 = 0.241$ V, and frequency $\omega = \Omega = 4.08$ s. Corresponding to these values of periodical solutions are points T_1 and T_2 on the curve 1, Fig. 6, and points 1 and 2 of the intersection of curves $W_L(j\omega)$ and $-Z(a)$, Fig. 7.

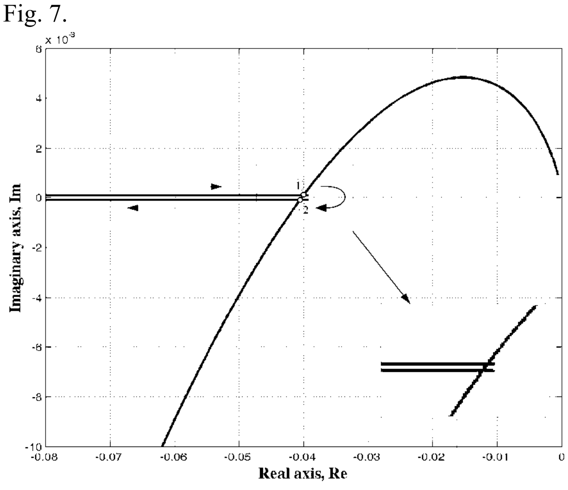

Figure 7. Frequency characteristics of the linear portion of the system with the amplification coefficient of K_L=0.47 and nonlinear element with parameters b = 0.150 V and c = 6 V

It is subject to the condition of stability of the periodical solution that oscillations with the amplitude A_1 are steadying, while with the amplitude A_2 self-induced oscillations $U_1 = A_2 \sin(\Omega t)$ are being established.

Ascertainment of the system behavior is conducted with its simulation for the initial amplitude deflections a_0 at the inlet of the nonlinear element at points I ($a_0 = 0.26$ V), II ($a_0 = 0.25$ V), III ($a_0 = 0.184$ V) and IV ($a_0 = 0.18$ V) close to the points T_1 and T_2. Relevant diagrams of voltage oscillations U_1, excavation depth h and number of the engine revolutions n are exhibited in Figures 8, 9, 10 and 11, respectively.

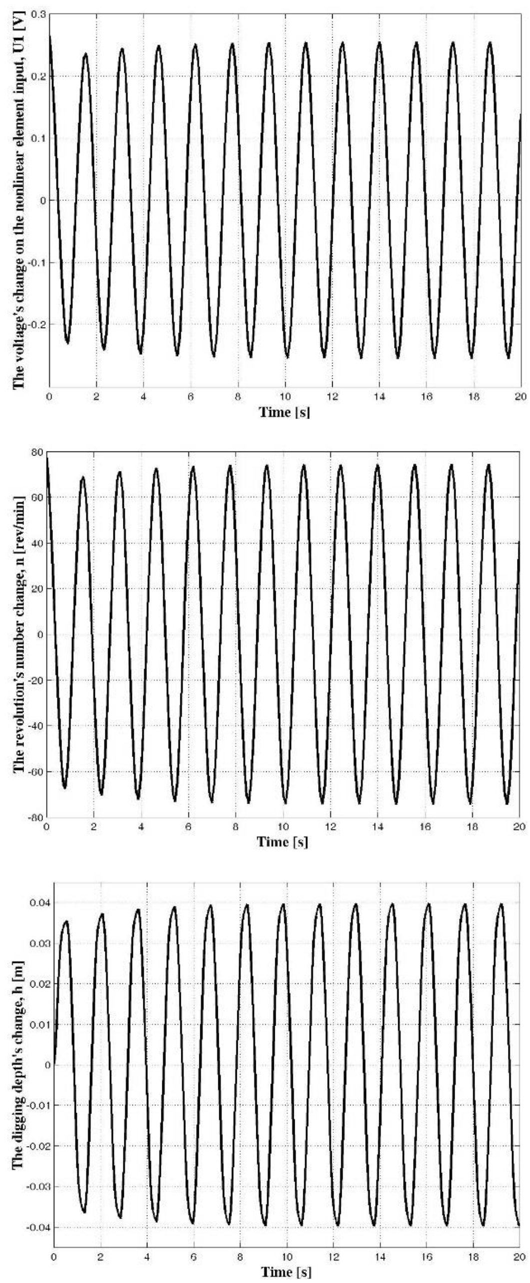

Figure 8. Oscillatory processes within the regulation circle with parameters K_L= 0.47, b = 0.150 V, c = 6 V and initial amplitude deflection a_0 = 0.26 V

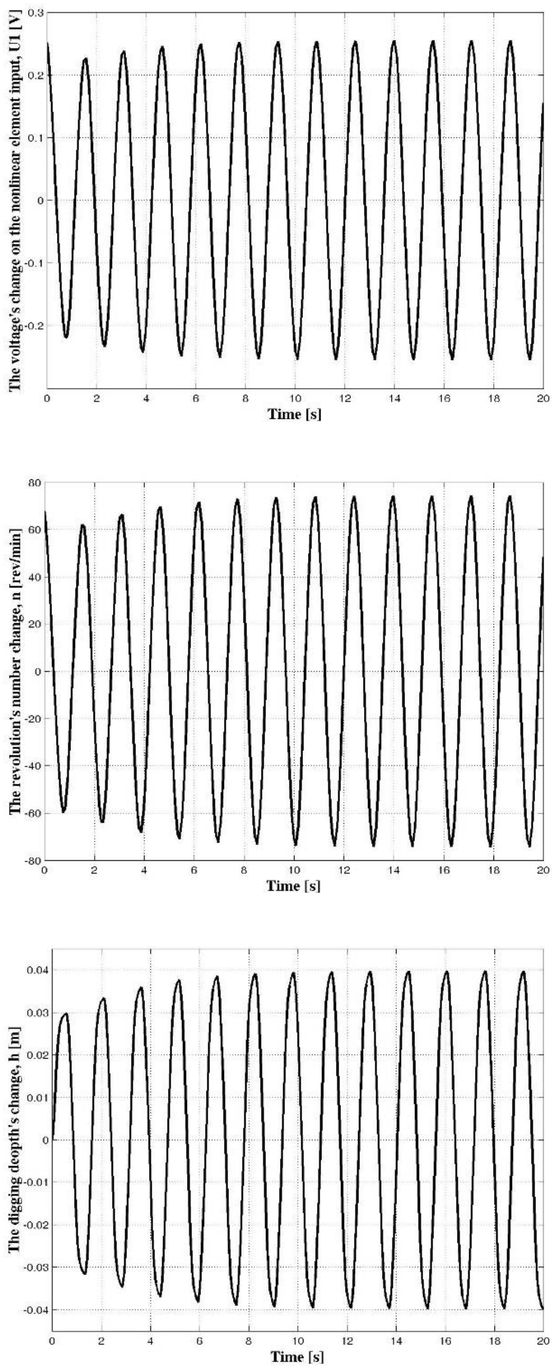

Figure 9. Oscillatory processes within the regulation circle with parameters K_L=0.47, *b* = 0.150 V, *c* = 6 V and initial amplitude deflection a_0=0.25 V

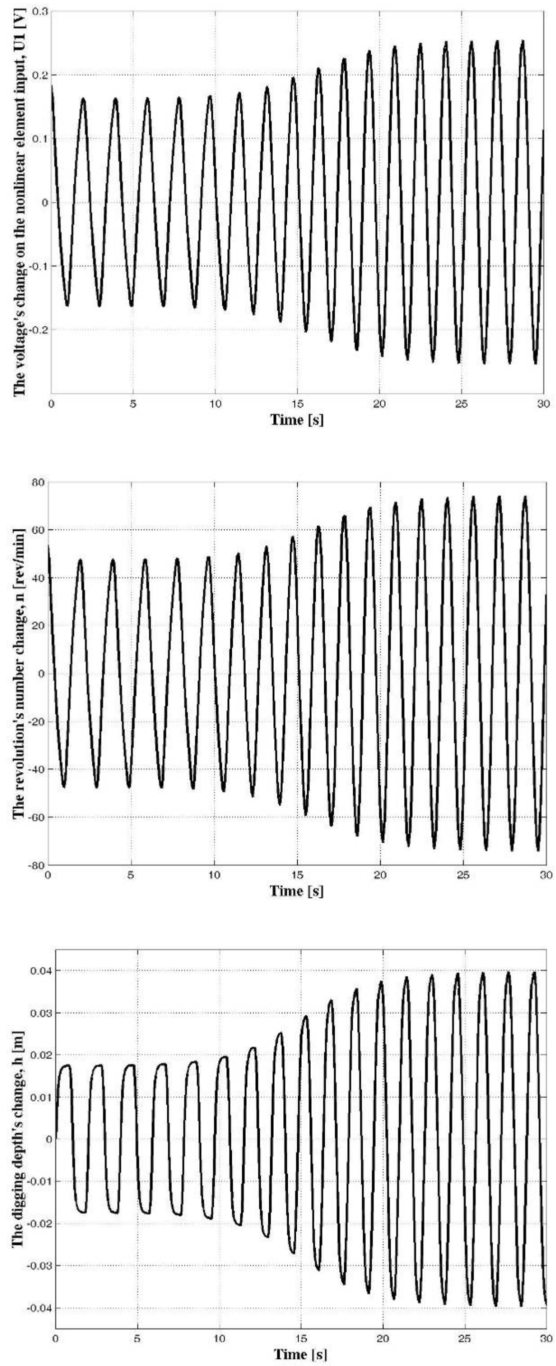

Figure 10. Oscillatory processes within the regulation circle with parameters K_L=0.47, *b* = 0.150 V, *c* = 6 V and initial amplitude deflection a_0=0.184 V

Diagrams in Figures 8, 9 and 10 demonstrate clearly that stable self induced oscillations of the voltage U_1 are established at initial deflections and at points I, II and III, with the amplitude 0.2548 V, which is $1.057\,A_2$, where $A_2 = 0.241$ V is the amplitude calculated value.

According to the diagram in Fig. 11, there is steadying of oscillations of the voltage U_1 with the initial deflection 0.18 V, which is $0{,}942\,A_1$, where $A_1 = 0.191$ V represents the amplitude calculation value.

Directions of changes of initial amplitude values at oscillatory processes are marked with arrows in Fig. 6.

It is on the basis of simulation of the system behavior for a larger number of values of the coefficient K_L and for a larger number of values of initial deflections of voltage amplitudes a_0 that the curve 2 is produced, Fig. 6, that renders accurate amplitude values. Deviation of the approximate curve 1 from the accurate curve 2, as exhibited in Fig. 6, appears to be largest

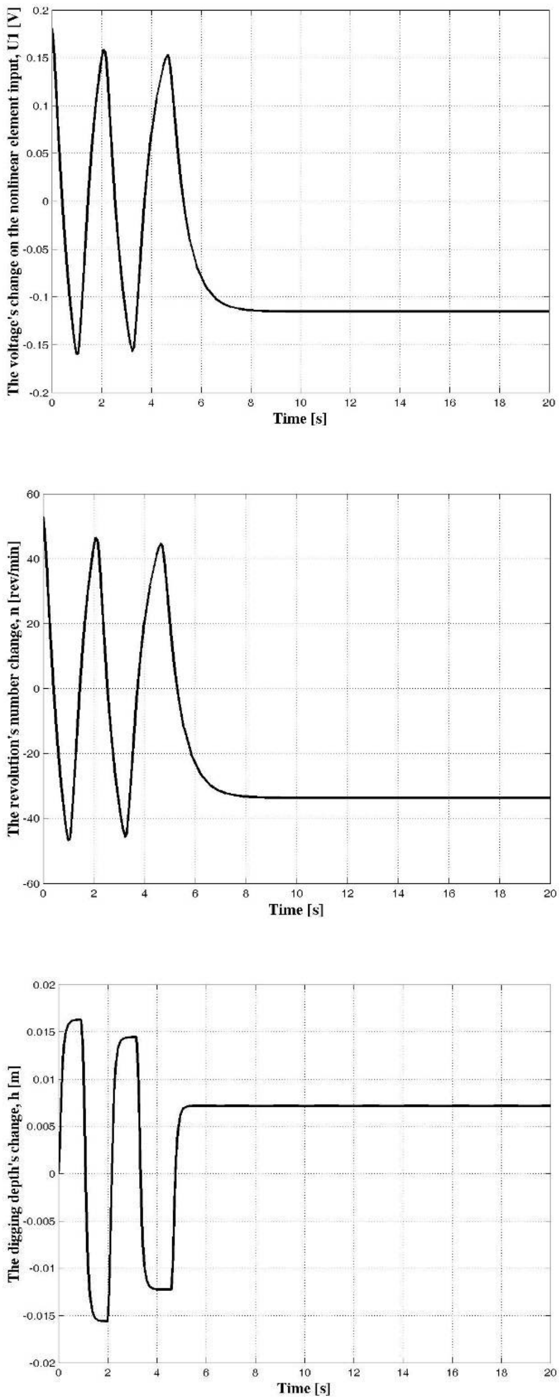

Figure 11. Oscillatory processes within the regulation circle with parameters K_L =0.47, b = 0.150 V, c = 6 V and initial amplitude deflection a_0 = 0.18 V

within the range of low amplitudes. The critical value of the amplification coefficient of the linear element of the system obtained analytically ($K_{L.\mathrm{kr}.A}$ on the curve 1) deviates, as well, from the value that is obtained by means of simulation ($K_{L.\mathrm{kr}.S}$ on the curve 2).

The method of harmonic linearization produces a more accurate result due to the fact that each increase of amplitude causes decrease of sensitivity of the periodical solution amplitude to higher harmonics.

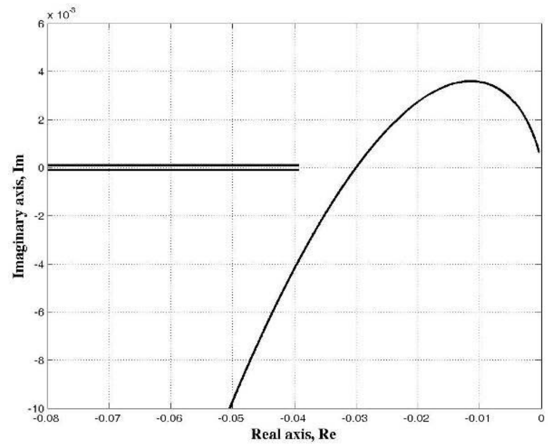

Figure 12. Frequency characteristics of the linear portion of the system with the amplification coefficient K_L= 0.35 and of the nonlinear element with parameters b = 0.150 V and c = 6 V

Side effects of self-induced oscillations within the regulation circle may be eliminated by decreasing the amplification coefficient of the linear element of the system K_L or by increasing the sensitivity zone width ***b*** of the nonlinear element.

Within the amplification range $K_L < K_{L.\mathrm{kr}.S}$ oscillatory processes are steady at all initial amplitude deflections of the voltage U_1. An illustration of the system behavior within this range is depicted in diagrams of frequency characteristics, Fig. 12, and diagrams of oscillatory processes, Fig, 13 for the initial deflection at the point V ($a_0 = 0.25$ V), Fig. 6.

Impact of the insensitivity zone width on the oscillatoriness of the regulation circle is demonstrated in Fig. 14 where dependence $a(K_L)$ is given for two values of parameter b. If the insensitivity zone width is increased from the value $b = 0.150$ V to the value $b = 0.155$ V self-induced oscillations at point III, Fig. 14 shall be eliminated as shown in diagrams of frequency characteristics, Fig. 15, and oscillatory processes, Fig. 16.

As indicated by the above analyses, parameters of the regulation circle in the presented system must be carefully selected by applying the methods of the automatic control and regulation system theory in order to prevent self induced oscillations to occur in the regulation circle i.e. continuous lifting and lowering of the working device. The present study, however, does not deal with the system behavior exposed to disturbances.

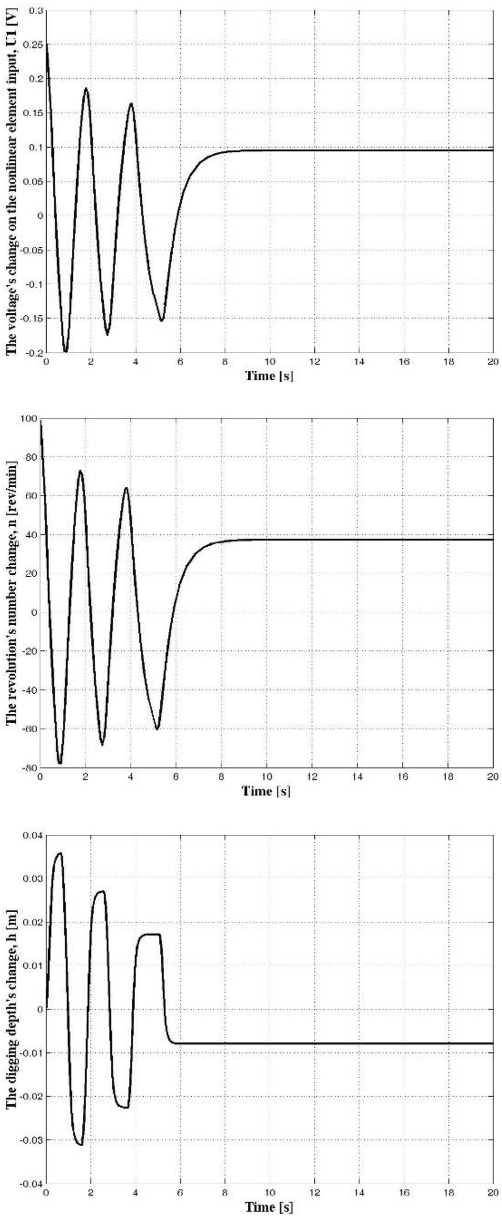

Figure 13. Oscillatory processes within the regulation circle with parameters K_L= 0.35, b = 0.150 V, c = 6 V and initial amplitude deflection a_0 = 0.25 V

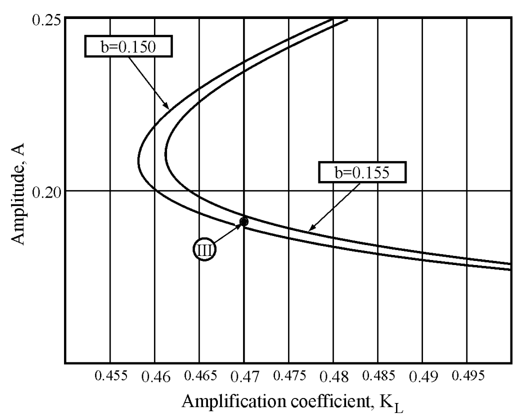

Figure 14. Dependence of amplitudes on the insensitivity zone width in a nonlinear element.

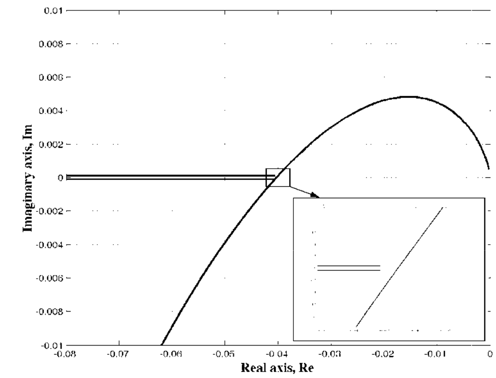

Figure 15. Frequency characteristics of the linear portion of the system with the amplification coefficient K_L= 0.47 and of the nonlinear element with parameters b = 0.155 V and c = 6 *V*

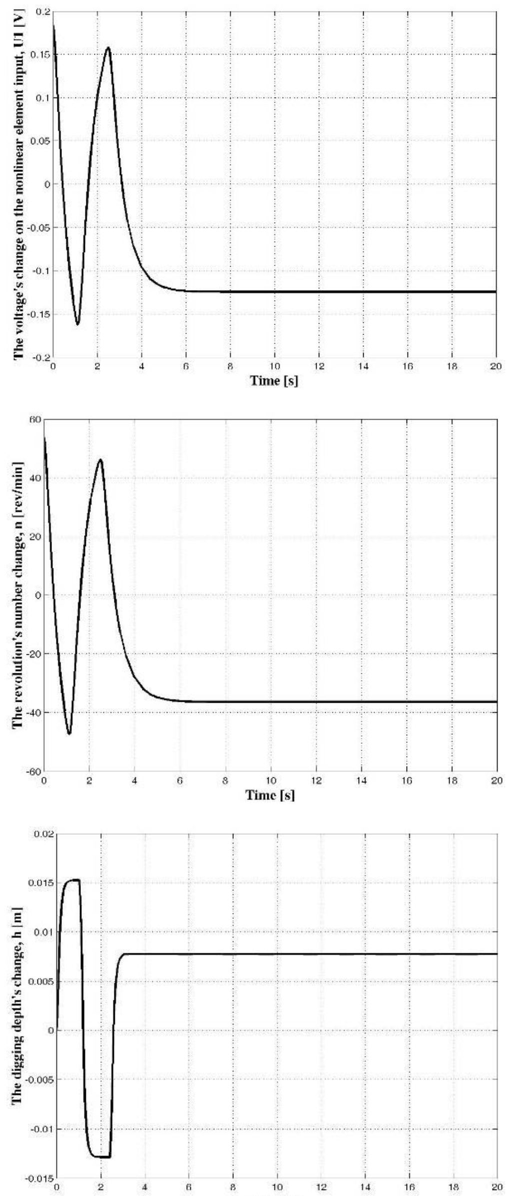

Figure 16. Oscillatory processes within the regulation circle with parameters K_L=0.47, b = 0.155 V, c = 6 V and initial amplitude deflection a_0 = 0. 84 V

5. CONCLUSION

It is on the basis of the analyses conducted and results obtained in the present study that the following conclusions are arrived at and may be formulated in the following manner:

- in digging-transportation machines, the work of machines at a selected regime may be achieved by means of changing the excavation depth, as an operating and regulating effect;
- dynamic behavior of the regulation circle for the working regime with a nonlinear relay-type regulator shall depend on parameter values within the regulation circle, as well as of the values of initial conditions;
- method of harmonic linearization of the nonlinear element with an insensitivity zone results in an error when determining a periodical solution amplitude, but also in a sufficient accuracy when determining frequency; each increase of amplitude entails decrease of amplitude sensitivity of a periodical solution to higher harmonics, resulting consequently in decrease of linearization error;
- regulation circle parameters (amplification of the linear portion of the system and insensitivity zone width of the nonlinear regulator), should be selected in such a manner so as to avoid, under dominant working conditions, any probability of appearance of unstable regimes or establishment of stable oscillations with continuous lifting and lowering of the working device.

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РЕГУЛАЦИЈА РЕЖИМА РАДА ЗЕМЉАНО-ТРАНСПОРТНИХ МАШИНА ПРОМЈЕНОМ ДУБИНЕ КОПАЊА

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У раду се, примјеном метода теорије система аутоматског управљања и регулације, разматра регулација режима рада земљано-транспортних машина промјеном дубине копања. Дат је математички модел круга регулације са нелинеарним регулатором релејног типа. На основу овог модела анализирана је могућност појаве самоосцилација у кругу регулације примјеном алгебарских и фреквенцијских поступака, у зависности од почетних услова и параметара система. Приказано је одређивање амплитуде и учестаности самоосцилација. За примјере са конкретним нумеричким вриједностима параметара дата је симулација динамичког понашања система и анализа грешке настале усљед линеаризације.