Досліджено підвищення незалежності роботи автотракторних двигунів від впливу зовнішнього навантаження на вал двигуна за рахунок покращення динамічних показників елементів системи автоматичного регулювання його кутової швидкості. Дослідження динамічних параметрів роботи дизельного двигуна виконані за допомогою імітаційного моделювання. Розроблена і досліджена інваріантна (комбінована) імітаційна модель системи автоматичного регулювання та контролю роботи дизельного двигуна та розроблено автоматизовану систему керування ківшом самохідної землерийної машини з використанням сучасного апаратного забезпечення. Знайшло продовження дослідження інваріантної системи САР кутової швидкості двигуна, яка забезпечує оптимальні показники його роботи, незалежно від зовнішніх збурень, шляхом включення в систему автоматичного керування коректувальної ланки. Час відновлення усталеного значення кутової швидкості двигуна при навантаженні зменшується приблизно в 7 разів, а величина падіння кутової швидкості – приблизно в 6 разів. Розроблена алгоритмічна структурна схема комбінованої інваріантної САР кутової швидкості двигуна із врахуванням впливу компенсаційного пристрою для випадку, коли дія збурення носить експоненціальний характер і яка враховує роботу пристрою обмеження перевищення максимально-допустимого значення дії збурення

Ключові слова: імітаційна модель, передавальна функція, коректувальна ланка, скрепер, дизельний двигун, кутова швидкість двигуна, землерийна машина

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DEVELOPMENT AND RESEARCH OF THE INVARIANT AUTOMATIC CONTROL SYSTEM OF ANGULAR SPEED OF DIESEL ENGINE

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1. Introduction

At present, construction is one of the most advanced and expensive branches in the industry. With increasing volumes of land works, volumes of machine production and variety of equipment for these works are increased too [1, 2].

One of the main directions of improvement of earthmoving machines is increasing of productivity, reduction of energy inputs for soil development, expansion of technological possibilities, increase of accuracy, reliability and durability, etc. In addition, much attention is paid to determining the saving operating modes of automobile and tractor engines and modernization of the mechanism of scraper knife control system [5, 6]. Increased productivity, reduced energy consumption for soil development are achieved, for example, due to improving the accuracy of excavation.

In the traditional scraper design, there are no mechanisms for controlling the level of cut chip, which reduces the accuracy of the work and increases energy costs. The use of diesel internal combustion engines on self-propelled earthmoving machines is due to their high efficiency (the highest among thermal motors) when operating both in the calculated mode and in the transition modes. Due to the exhaustion of oil reserves, further improvement of engine efficiency is undoubtedly an important task facing designers [3, 4].

2. Literature review and problem statement

One of the main trends of modern engine-building is the increase in the energy intensity of stationary and mobile power plants, and much attention is paid to the study of the working process of the scraper bucket [3, 4]. The process of digging and unloading the soil directly affects the loading and operation of the diesel engine, which in turn requires further study of its operation.

In [5, 6], the results of a study of diesel engines are presented, aimed at increasing their productivity, efficiency and reducing CO_2 emissions into the air. It is shown that the influence of design and operating parameters of the diesel cycle, such as stroke ratio (*d/L*), equivalence ratio *(ER)*, compression ratio *(CR)*, cycle temperature ratio *(CTR)*, cycle pressure ratio *(CPR)*, stroke length (*L*), friction coefficient *(FRC)*, engine speed *(N)*, average piston speed, inlet pressure and inlet temperature all influence engine performance. In addition, incomplete combustion *(IC)* energy losses, friction losses *(FRLs)*, heat transfer losses *(HTRLs)*, and exhaust gas output losses *(EOL)* have been described as fuel feed energy. But there are some unsolved issues related to automatic support of the nominal motor parameters (angular speed, torque, power), independence of automobile and tractor engines from the influence of external loading on the motor shaft. This may be due to the significant economic and time costs of conducting experiments in comparison with real-time analytical studies. An option to overcome such difficulties may be the development of a diesel engine speed control system using simulation modeling. This approach was used in [11], however, additional requirements imposed on the ACS are related to the need to improve individual engine performance, such as fuel consumption, exhaust gas toxicity (EG), metal consumption and engine mass and dimensions. This can be achieved by optimizing the engine operation programmatically and ensuring the optimal NO_2/NO_x ratio [7, 8]. In this case, it is desirable to ensure the invariance of the ACS with respect to disturbing actions – load and position of the accelerator pedal. These requirements can be met by increasing the efficiency of the engine cooling radiator and regulating the coolant temperature and by differently implementing the exhaust gas recirculation system using electronic ACS. This approach was used in [9, 10].

All this suggests that it is advisable to carry out a study on the effects of dynamic loading on a diesel engine, which will increase its energy intensity, efficiency, reliability, stable operation and reduce the amount of harmful emissions into the air.

3. The aim and objectives of the study

The aim of the study is to increase the independence of automobile and tractor engines from the influence of external load on the motor shaft by improving the dynamic performance of the elements of the automatic control system of its angular speed.

To achieve this goal, the following objectives were set:

– to develop and investigate an invariant simulation model of the automatic control system of the angular speed of the diesel engine to increase its independence from the effects of external loading;

– to determine the transfer function of the compensating device and its rational dynamic parameters.

4. Materials and methods of research of the combined control system of the angular speed of the diesel engine

The automatic control theory (ACT) mainly considers the independence of two quantities – the original value and the error signal from the input disturbance. In stabilization systems, it is necessary to seek the independence of the original value from the disturbance, and in the tracking systems – the independence of the error signal from the setting signal. Such a control principle can be applied if the nature of disturbance and its mathematical description are known. As a rule, the principle of disturbance control is applied in combination with the principle of deflection control (combined system).

The authors of [11] proposed a structural diagram of the invariant ACS of engine angular speed using a proportional controller (P-regulator).

Improvement of results is possible by the inclusion of not the proportional regulator, but the compensating element in the ACS.

The use of the combined control system of the angular speed of the diesel engine makes it possible to improve its performance. However, to confirm this prediction, it is necessary to determine the type of compensating element, its rational dynamic parameters, quantitative and qualitative indicators of the ACS operation, which requires analytical and experimental studies.

Such research, without significant economic cost, is possible through the use of simulation modeling.

Fig. 1 shows the proposed algorithmic structure of the combined disturbance stabilization system of the engine with compensating coupling.

The following elements are indicated by the symbols:

– *BZ*1 – engine nominal angular speed unit;
– *PP*1 – conversion device;
– *VM* – actuator;
– *RO* – regulator (engine fuel throttle);
– *OR* – engine (control object);
– *D*1 – feedback sensor (engine angular speed sensor);
– *D*2 – sensor of external disturbance of the object, disrupting the ACS operation;
– *BZ*2 – disturbing force unit;
– *KL* – compensating element;
– *NP* – normalizing amplifier;
– $X0(t)$ – setting signal;
– $X(t)$ – mismatch signal;
– $Y(t)$ – output signal (engine angular speed);
– $Yzz(t)$ – main feedback signal;
– $Z(p)$ – output signal of the compensating element;
– $F(t)$ – output of the disturbance sensor.

In Fig. 1, the disturbance is conditionally represented in the union of the disturbance force unit *BZ*2 and the object external disturbance force sensor *D*2.

The compensating coupling in the ACS acts on the initial value with the sign, which is always opposite to the sign of direct influence of disturbance. Given the rapid development of electronic information devices and the improvement of their technical characteristics, namely the ability to measure the effect of disturbance, it seems rational to use them to improve the operation of combined ACS.

The mathematical expression of the compensating device can be found if the transmitting disturbance ACS is known.

The transfer function of the disturbance engine angular speed ACS with regard to structural transformations is:

$$W_{YF}(s)=\frac{Y(s)}{F(s)}=$$
$$=\left(\frac{W_{OZ}(s)}{W_{BK}(s)W_{OR}^{1}(s)}-W_{KL}(s)\right)\frac{W_{BK}(s)W_{OR}^{1}(s)}{1+W_{BK}(s)W_{OR}^{1}(s)W_{D1}(s)}=$$
$$=\frac{W_{OZ}(s)-W_{KL}(s)W_{BK}(s)W_{OR}^{1}(s)}{1+W_{BK}(s)W_{OR}^{1}(s)W_{D1}(s)}, \quad (1)$$

where $W_{BK}(s)=W_{PP}(s)\cdot W_{VM}(s)\cdot W_{RO}(s)$ – transfer function of the control unit; $W_{PP}(s)$ – transfer function of the amplifier-conversion device; $W_{VM}(s)$ – transfer function of the actuator; $W_{RO}(s)$ – transfer function of the regulatory body; $W_{OR}^{1}(s)$ – transfer function of the control object; $W_{OZ}(s)$ – transfer function of the external disturbance sensor; $W_{D1}(s)$ – transfer function of the position sensor; $W_{KL}(s)$ – transfer function of the compensating device.

The control value $Y(t)$ in the ACS under consideration will not depend on the disturbance $F(t)$ if the transfer function (1) is zero.

$$W_{YF}(s)=0. \quad (2)$$

This condition is satisfied when the numerator of the transfer function (1) is zero. By equating the expression (1) to zero, we define the condition of invariance of the stabilized quantity with respect to disturbance:

$$W_{OZ}(s)-W_{KL}(s)\cdot W_{BK}(s)\cdot W_{OR}^{1}(s)=0. \quad (3)$$

It follows from (3) that in order to obtain the independence of $Y(t)$ from the disturbance $F(t)$, it is necessary that the dynamic properties of two parallel channels through which the disturbance $F(t)$ acts on $Y(t)$ be the same.

In accordance with (3), the transfer function of the compensating device is determined by the expression:

$$W_{kl}(s)=\frac{W_{OZ}(s)}{W_{BK}(s)\cdot W_{OR}^{1}(s)}. \quad (4)$$

In the block diagram, the transfer functions of the amplifier-converter device, the regulator, the position sensor, the normalizing amplifier, the object external disturbance sensor are taken as proportional elements [11]. Also, the transfer functions of the actuator, the control object, in accordance with [11], are adopted as first-order inertial elements. After substituting the accepted transfer functions of the ACS elements and transformations in (1)–(4), the transfer function of the compensating device is determined by the expression:

$$W_{KL}(s)=\frac{k_{OZ}\left(\left(T_{VM}\cdot T_{OR}\right)\cdot s^{2}+\left(T_{VM}+T_{OR}\right)\cdot s+1\right)\cdot s}{k_{PP}\cdot k_{VM}\cdot k_{RO}\cdot k_{OR}}, \quad (5)$$

where $T_{OR}=0.95c$ – control object time constant; $k_{OR}=0.662$ – control object gain; $T_{VM}=0.06c$ – actuator time constant; $k_{PP}=3$ – regulatory body gain; $k_{RO}=1$ – regulatory body gain; $k_{D1}=0.1$ – sensor gain; $k_{NP}=1$ – normalizing converter gain.

Using the dynamic parameters of the D240 bulldozer diesel engine, given in [11] and the dynamic parameters of the elements that can be used in ACS under consideration and neglecting the product $T_{vm}\cdot T_{or}$, since the sum $T_{vm}+T_{or}$ is by an order of magnitude greater than the product $T_{vm}\cdot T_{or}$, the final expression of the transmission function of the compensating element will look like:

$$W_{KL}(s)=\frac{k_{OZ}\left(\left(T_{VM}+T_{OR}\right)\cdot s+1\right)\cdot s}{k_{PP}\cdot k_{VM}\cdot k_{RO}\cdot k_{OR}}. \quad (6)$$

The obtained transfer function of the compensating device corresponds to the dynamic element whose properties are determined by the properties of the disturbance $W_{OZ}(s)$ and control $W_{BK}(s)\cdot W_{OR}(s)$ channels. If the inertia of the control channel greater than that of the disturbance channel, the compensating device must have the properties of differentiating element. The greater this difference, the greater the order of the differential element. The resulting expression of the compensating device confirms the conclusions made in [11]. It should be noted that a PID controller can be used as a compensating device in some cases.

To confirm the obtained calculation results and taking into account the adopted dynamic parameters of the ACS elements, a combined algorithmic structural simulation model of the ACS of the diesel engine was developed and implemented. The simulation was performed using MathLab, version 2018b, the functional diagram of the developed model is shown in Fig. 4.

The diagram reflects the ACS operation for the following cases:

1. The ACS operates without taking into account the effect of the compensating device *KL*. Load simulation is performed by signaling from the disturbance unit *BZ*2 and the force sensor *D*2, which provide a simulation of the reduction of the set angular speed depending on the load.

2. The ACS operates taking into account the compensating device *KL* (the aggregate chain of compensating elements – *KL*1, *KL*2, *KL*3) and the device limiting the maximum permissible value of disturbance (the device includes elements *BZ*3, *PP*2, *YR*, *YC*). The limiting device is required when the disturbance is exponential.

Load simulation is also performed by signaling from the disturbance unit *BZ*2 and the force sensor *D*2, which provide a simulation of the reduction of the set angular speed depending on the load.

The device for limiting the maximum permissible value of disturbance simulates, in the case of a decrease in engine angular speed when the load changes, a proportional increase in the magnitude of the disturbance force. After receiving the amplified misalignment signal from the amplifying and converting element *PP*2, the device provides for the activation of the hydraulic directional control valve *YR* to start up the hydraulic cylinder *YC* of the bulldozer bucket lifting mechanism. This reduces or increases the engine load to rated.

The design block diagram of the combined invariant ACS of engine angular speed allows: performing calculations and studies of the system with and without taking into account the influence of the compensating device. For cases where the disturbance is step and exponential, the model also takes into account the operation of the device limiting the maximum permissible value of disturbance. The block diagram of such combined invariant ACS of engine angular speed is shown in Fig. 3.

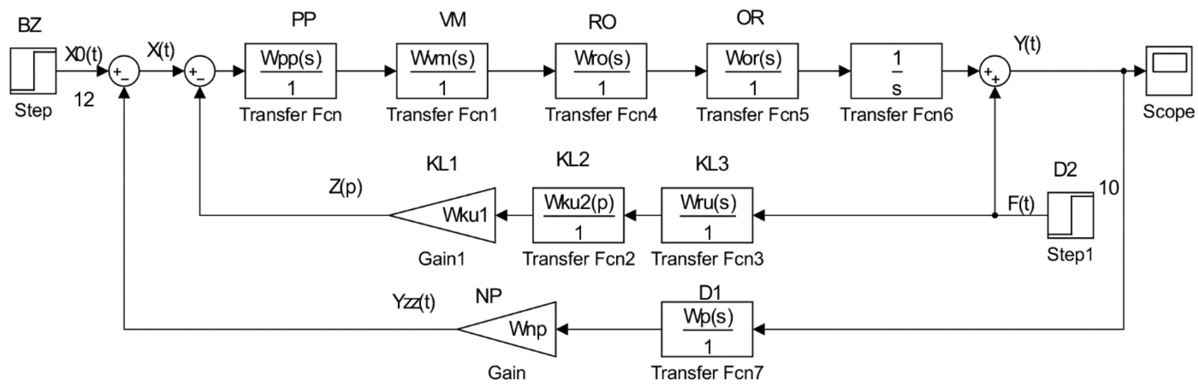


Fig. 1. Algorithmic structure of the combined disturbance stabilization system of the engine with compensating coupling

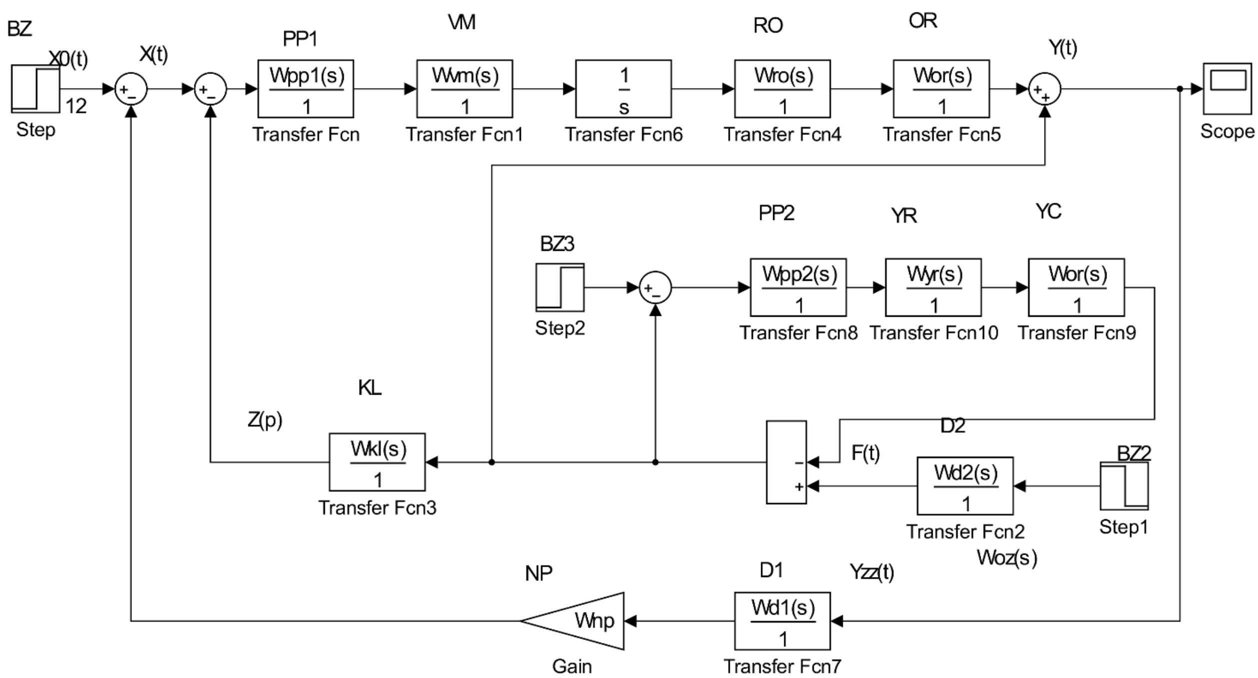


Fig. 2. Algorithmic block diagram of the combined invariant ACS of engine angular speed taking into account the influence of the compensating device for the case where disturbance is exponential and which takes into account the operation of the device limiting the maximum permissible value of disturbance

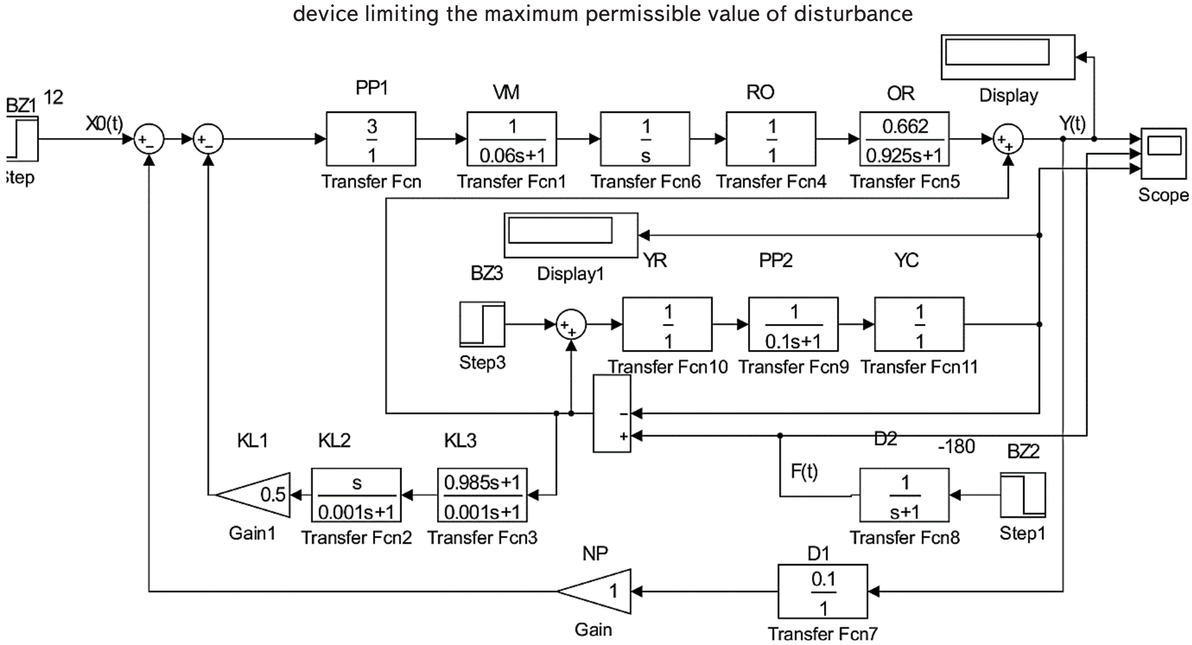


Fig. 3. Estimated block diagram of the combined invariant ACS of engine angular speed

Fig. 4 shows the waveform of the transient of engine angular speed ACS at the external load of the system in the form of step disturbance.

From the transient waveform shown in Fig. 6, it can be concluded that, with step disturbance, without taking into account the influence of the compensating device, there is a long and significant decrease in engine angular speed.

The ACS transient under exponential disturbance has the same appearance (there is only a slower decrease in angular speed).

The transient processes of the ACS at external load, which is exponential in nature, are shown in the waveforms (Fig. 5).

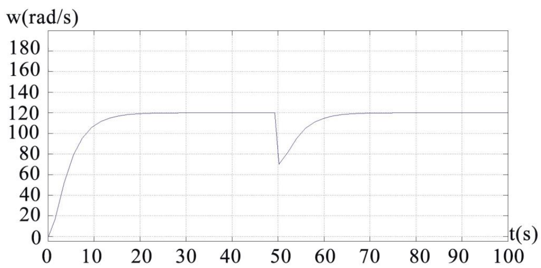
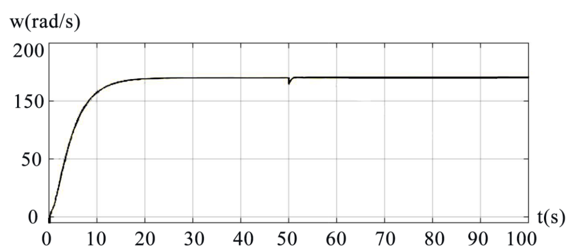
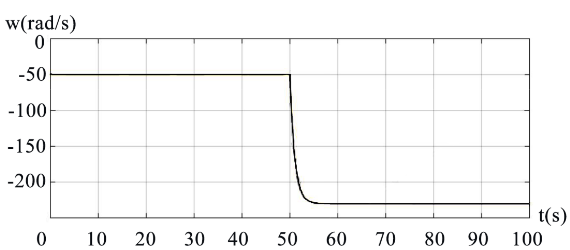


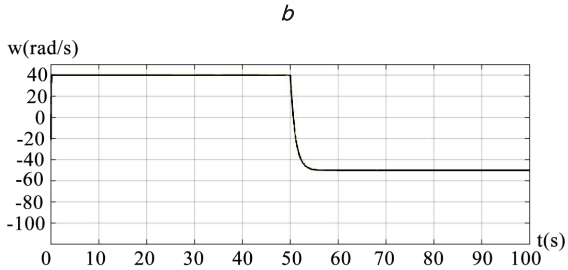
Fig. 4. Transient process of the combined invariant ACS of engine angular speed with step disturbance without taking into account the influence of the compensating device



a



b



c

Fig. 5. Transient process of the combined invariant ACS of engine angular speed taking into account the influence of the compensating device: *a* — output characteristic of the ACS; *b* — characteristic of the initial value of the disturbance; *c* — output signal characteristic of the device limiting the maximum permissible value of disturbance

The disturbing action that simulates exponential disturbance is represented in the scheme by an inertial element (D2) with the time constant, T=1.

The simulation model (Fig. 3) provides for the start of the disturbing action at the thirtieth second, that is, when the steady-state value of engine angular speed is reached. The magnitude of the disturbing force, at the same time, simulates the load, which causes a decrease in the nominal angular speed by one and a half times. The maximum permissible value of the disturbing action is accepted for conditions that correspond to the nominal operation mode of the engine and the nominal value of angular speed.

5. Results of studies of the developed simulation model of the automatic control system of the diesel engine

From the transients obtained, we can conclude that using a compensating device, deviation of engine angular speed from the nominal value, even at low inertia of the disturbing action, is practically not observed. That is, with a rational choice of dynamic elements of the ACS, the compensating device with a transfer function satisfies the goal. The magnitude of deviation of engine angular speed from the nominal value, however, can be adjusted by changing the transmission ratio of the compensating device. Thus, in the actual operating conditions of earthmoving machines and similar mechanisms, it is advisable to use the obtained compensating devices in the diesel engine angular speed ACS.

With step disturbance and taking into account the effect of the compensating device, the duration of reduction and return of the engine angular speed to the setpoint of the shaft significantly decreases. But the amplitude of angular speed reduction remains practically unchanged and can reach significant magnitudes.

Frequent changes of load will significantly deteriorate the engine dynamics, uneven operation will be observed, which will reduce the wear resistance of not only the engine, but all the mechanisms of the bulldozer.

Since instantaneous disturbance virtually does not occur under real conditions, Fig. 3 shows the developed and investigated block diagram of the combined invariant ACS of engine angular speed. It works with regard to the effect of the compensating device for the case where the disturbing action is exponential. It also takes into account the operation of the device limiting the maximum permissible value of disturbance (the device includes elements *BZ*3, *PP*2, *YR*, *YC*).

6. Discussion of the results of the study of the automatic control system of the angular speed of the diesel engine

The results of the studies allowed obtaining the expression of the transfer function of the compensating device (6) and its dynamic parameters. Due to the developed structural simulation model of the system, it was possible to implement diesel engine control (Fig. 3) and confirm theoretical predictions of the possibility of improving the dynamic parameters of the control system. When using the proposed control system, these parameters are reduced accordingly – the recovery time of the steady-state nominal value of angular speed is reduced by about 7 times, and the magnitude of angular speed drop under load decreases by about 6 times.

A feature of the proposed method for improving the engine dynamics is the use of the invariant control system of engine angular speed. Typically, the control and stabilization of engine angular speed are carried out using closed-loop control systems. In such systems, microcontrollers that implement PID control laws are often used as a control device. In this case, the control parameters of the microcontrollers are adjusted to certain external disturbances (averaged) and require extensive experience of adjusters. The actual operating conditions of the mechanisms are quite varied, which makes it necessary to adjust the control parameters of microcontrollers. This disadvantage of such systems can be eliminated by the use of invariant control systems, including compensating devices whose cost is much lower than the cost of microcontrollers and which do not require adjustment.

The development and research of the proposed method require the use of computer equipment and special application modeling packages. However, with the development and improvement of modern advanced technologies, such a limitation of the proposed method can be considered insignificant.

Like most studies, the studies that have been performed require reliable information about the actual operating conditions of the working mechanisms driven by the diesel engine. That is, the results of the research should be based on real information both on operating conditions and dynamic properties of control system elements. In addition, the end result should be the introduction of research into production.

The continuation of the performed research is seen in the introduction of artificial intelligence in the diesel engine angular speed control system, namely neurocontroller control with the involvement of industry expert teams.

7. Conclusions

1. The invariant (combined) simulation model of the automatic control system of the diesel engine is developed and investigated, which increases the independence of automobile and tractor engines from the influence of external load on the engine shaft by improving the dynamic parameters of the elements of the angular speed automatic control system. The recovery time of the set steady-state value after the applied load without the proposed ACS is 22 seconds and the angular speed drop is approximately 50 rad/s. when the control system is not activated. These parameters are improved. In particular, when applying the proposed control system, these parameters are reduced accordingly – the recovery time of the steady-state value of angular speed decreases by about 7 times, and the magnitude of angular speed drop under load decreases by about 6 times.

2. The transfer function of the compensating device and its rational dynamic parameters (time constant and transmission ratio) are determined, the desired transient processes of the diesel engine are obtained, which allowed confirming the theoretical studies. In addition, research findings can be used in the development and design of similar ACS.

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