EXPERIMENTAL STUDY OF THE MOVEMENT CONTROLLABILITY OF A MACHINE-AND-TRACTOR AGGREGATE OF THE MODULAR TYPE
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MODUĻA TIPA MAŠĪNAS – TRAKTORA AGREGĀTA KUSTĪBAS VADĪBAS EKSPERIMENTĀLIE PĒTĪJUMI

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ABSTRACT

The paper presents an analysis of the basic principles of formation, the properties and characteristics of a new modular energy tool, consisting of the energy and the technology modules. The purpose of this study is to assess the degree of impact of the throttle in the hydraulic line, connecting the cavity of the hydraulic cylinder, upon the controllability of the modular power tool with a mounted plough during the movement of the ploughing aggregate on the headland. As a result of the conducted tests, it was proved that increasing the controllability of the movement of the aggregate on the basis of a mobile power tool is possible by throttling one of the hydraulic cylinders that limit the mutual reciprocal rotation of the modules in a horizontal plane. Installation of the throttle modular power tool on the limiting hydraulic cylinder with a drag coefficient $1.03\times10^{6}\cdot N\cdot m\cdot s\cdot rad^{-1}$ *allows one to reduce two times the delay in the reaction of the relative bearing of the energy module to a change in the angle of rotation of its driven wheels.*

ABSTRAKTS

Darbā analizēti jauna moduļa tipa enerģētiska un tehnoloģiska līdzekļa vērtēšanas un raksturošanas pamatprincipi. Pētījumu mērķis – droseles ietekmes pakāpes novērtēšana hidrocilindru dobumus savienojošajā hidromaģistrālē aršanas agregāta ar uzkarināmu arklu kustības laikā pagrieziena joslā. Pētījumu rezultātā pierādījies, ka agregāta kustības vadības uzlabošanās uz mobilā enerģētiskā līdzekļa bāzes iespējama pie viena hidrocilindra droselēšanas, ierobežojot moduļu savstarpējo pagriešanos horizontālā plaknē. Ierobežojoša hidrocilindra uzstādīšana moduļa tipa enerģētiskajam līdzeklim ar droseles pretestības koeficientu $1.03\times10^{6}\cdot N\cdot m\cdot s\cdot rad^{-1}$ *ļauj divas reizes samazināt enerģētiskā moduļa virziena leņķa reakcijas nokavēšanos uz dzenošo riteņu pagriešanos.*

INTRODUCTION

Agriculture is the largest user of tractor equipment used to perform field work. One of the perspective directions is the modular construction of tractors *(Pădureanu et al., 2013; Klets, 2013; Bindi et al, 2013).* In this embodiment, the tractor consists of the energy and the technological modules. Their combination in a single design of a machine-and-tractor aggregate is a modular energy tool (Fig. 1).

The controllability of tractors was investigated by many scientists *(Wong, 2008; Taran and Bondarenko, 2017, Aoki et al., 2009; Bochtis et al., 2010; Popa and Buculei, 2013).* However, the controllability of energy modular units has a number of features and their further detailed study is required.

An energy module is a tractor the energy saturation of which should ideally be more than 14 $kW\cdot t^{-1}$. However, as practice shows, under real conditions, the efficiency of using a modular energy tool can also occur with a lower energy saturation of the energy module *(Bulgakov et al., 2015).*

The technological module of the modular energy tool is a bridge the wheels of which are driven from a synchronous power take-off shaft of the energy module *(Kutjkov, 2004; Gjachev, 1981).*

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In the frontal part of the technological module there is a hitch mechanism with which it is attached to the rear mounted mechanism of the energy module. Coordination of the peripheral linear speeds of the wheels of the technological module and the rear wheels of the energy module is carried out using a special gearbox, located on the frame of the technological module.

Fig. 1 - A modular energy tool

For aggregation with the agricultural implements the technological module is equipped with a hydraulic mounted system, its own power take-off shaft, a saddle device and a brake system. In a horizontal plane the energy module is connected to the technology module by means of a vertical hinge. Its presence ensures the rotation of the technological module relative to the energy module by ± 30° during the movement of the modular energy tool on the headland. In a longitudinal-vertical plane the energy module is connected to the technology module using a horizontal hinge. Due to it the modular energy tool can carry out quite satisfactory copying of the longitudinal profile of the field surface. The limited turning ability of the technological module relative to the energy module in a horizontal plane is provided by two hydraulic cylinders, connecting the frames of the energy and the technological modules. To ensure the flow of oil from the over-piston cavity of the hydraulic cylinder into the under-piston cavity, the cavities are interconnected by a hydraulic line. However, in the process of experimental research of the modular energy tool it was found that, when it moves as part of the aggregate on the headland, the technological module may have increased vibrations in a horizontal plane. As a result, a decrease in the movement speed of the modular energy tool on the field headland was required. And this, as it is known, leads to lower efficiency of this or that machine-and-tractor aggregate *(Bulgakov et al., 2018; Samorodov and Pelipenko,2016).* To eliminate this drawback, a throttle with a resistance coefficient $K_m = 1.03 \times 10^6 \cdot H \cdot m \cdot s \cdot rad^{-1}$ was mounted in the hydraulic hose of one of the hydraulic cylinders, connecting the energy and the technological modules (Fig. 2). The substantiation methodology of the value of this coefficient is described in detail *in (Bulgakov et al., 2019).*

The purpose of this study is to assess the impact degree of the use of the aforementioned inductor with a resistance coefficient K_m = 1.03×106 H m s rad^{-1} upon the controllability of a modular power tool with a mounted plough during the movement of this ploughing machine-and-tractor aggregate on the headland.

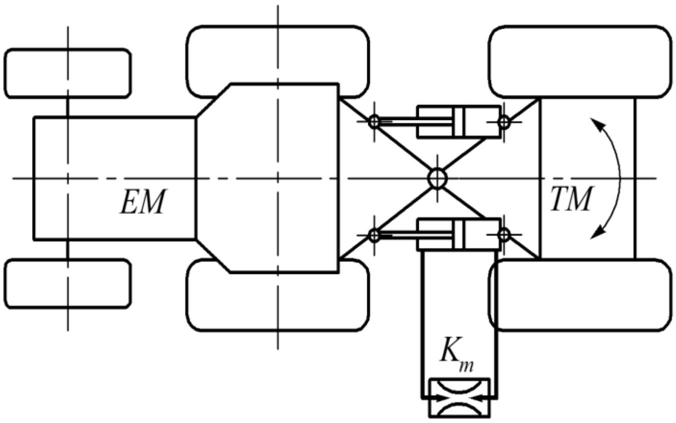

Fig. 2 - An installation scheme of a throttle in the hydraulic cylinder, connecting the energy and the technological modules of the modular energy tool

EM – the energy module; TM – the technology module; K_m – the inductor generating the resistance coefficient

MATERIALS AND METHODS

Experimental research of the ploughing aggregate based on a modular energy tool (table 1) were carried out on the field after peeling stubble of winter wheat (Fig. 3).

Table 1

Technical characteristics of a modular energy tool

Energy module	
Operating mass [kg]	3900
Engine power [kW]	77.2
Energy saturation rate [kW·t^{-1}]	19.8
Front wheels track [mm]	1500
Rear wheels track [mm]	1500
Front wheels tire size	13.6R20
Rear wheels tire size	15.5R38
Technological module	
Operating mass [kg]	2600
Wheel track [mm]	1500
Tire size	16.9R38

Fig. 3 - The ploughing aggregate, based on a modular energy tool

During experimental field research of the movement of this ploughing machine-and-tractor aggregate, based on a modular power tool on the headland, the average value of the soil moisture in the field in the 0 ... 10 cm layer was 15.3%. The soil density in the same layer did not exceed 1.24 g cm^3. The average value of the movement speed of this ploughing machine-and-tractor aggregate on the headland was 2.4 m s^{-1}. The longitudinal oscillations of the field irregularities were also recorded *(Dospehov, 2012).*

The movement of the investigated ploughing aggregate on the headland was effected in the same gear with a throttle installed (K_m = 1.03×10^6 H m s rad^{-1}) in the hydraulic cylinder and without it (K_m = 0). The path of the movement of the aggregate was equal to 50 m. Based on this, the speed of the aggregate (V_a) was determined by the formula:

$$V_a = 50 \cdot (t)^{-1} \tag{1}$$

where t – the passage time of the aggregate is 50 m long.

To record the movement time of the modular power tool with a plough on the headland, an electronic stopwatch with a measurement accuracy of ± 0.1 s was used.

In the process of the movement of the modular energy tool, the turning angle of the driven wheels of the energy module (α) and its relative bearing angle (φ) were recorded.

To measure the soil moisture (W), an MG-44 electronic device (Ukraine) was applied with an accuracy of ± 1%. The measurement of the soil density (ρ_g) was carried out by a device that we have developed according to the methodology *(Nadykto and Kotov, 2015).* The number of measurements of each of the parameters W and ρ_g was 50.

The turning angle of the energy module's driven wheels of the modular energy tool was recorded using a variable resistor SP-3A with a linear characteristic and a rating of 470 Ohm. The resistor was mounted on the rotation axis of the left frontal wheel of the energy module of the modular energy tool (Fig. 4).

Fig. 4 - Resistor SP-3A (440 Om)

Fig. 5 - The field profile meter

In order to measure the oscillations of the longitudinal field profile, a special instrument (Ukraine) was used, the recording element of which was a variable resistor SP-3A with a linear characteristic and a nominal value of 470 Ohm (Fig. 5).

The relative bearing angle (φ) of the energy module of the modular energy tool was recorded usin*g* a GY-521 gyroscope with an Arduino microcontroller (China).

The electrical signals from the gyroscope and resistors for recording the angle *α,* as well as the oscillations of the longitudinal profile of the field, were transmitted to an analogue-to-digital converter and then to a personal computer. The repeatability of the measurement of these parameters was 3.

Statistical characteristics, such as dispersion, as well as normalised correlation functions and spectral densities were calculated from the resulting data arrays *(Box et al., 2005).*

To analyse the movement controllability of the ploughing aggregate, based on the modular energy tool at different throttling values of the hydraulic cylinder, a normalised cross-correlation function *(Dospehov, 2012*) was applied that relates the oscillations of the turning angle of the energy module's driven wheels of the modular energy tool (*α*) with the oscillations of its relative bearing angle (*φ*).

RESULTS AND DISCUSSION

Analysis of the data, characterising the fluctuations in the irregularities of the longitudinal profile of the field surface, showed that the correlation length of the normalised correlation function of this process is 1 m (Fig. 6 a).

Knowing the movement speed of the machine-and-tractor aggregate, it's easy to determine the time of the correlation link. In this case, at the aggregate velocity of 2.4 m s^{-1}, it is equal to: 1 $(2.4)^{-1}$ = 0.42 s. In addition, it can be considered that the oscillations of the longitudinal profile of the field surface practically do not have a hidden periodic component. The information on the changes in the correlation function that take place in the graph, shown in Fig. 6a, is not enough to determine the source of their generation.

In addition, the dispersion of the oscillations of the discussed process is 0.91 cm^2. It is mainly concentrated in a rather narrow frequency range 0...2 m^{-1} (Fig. 7). Considering that the speed of the movement of this ploughing machine-and-tractor aggregate is 2.4 m s^{-1}, the range is 0...4.8 s^{-1} or 0...0.76 Hz.

The cut-off frequency of the spectral density, as can be seen from the graph, shown in Fig. 6 b, practically does not exceed 6 m^{-1} or 14.4 s^{-1}, which is equal to 2.3 Hz.

When this ploughing aggregate moved on the agrotechnical background with such characteristics of longitudinal profile oscillations, the control action in the form of the turning angle of the driven wheels of the modular energy tool changed in a very narrow range. Thus, the main part of the dispersion of this parameter's oscillations is concentrated in the frequency range 0...2.0 s^{-1} , or 0...0.32 Hz (Fig. 8).

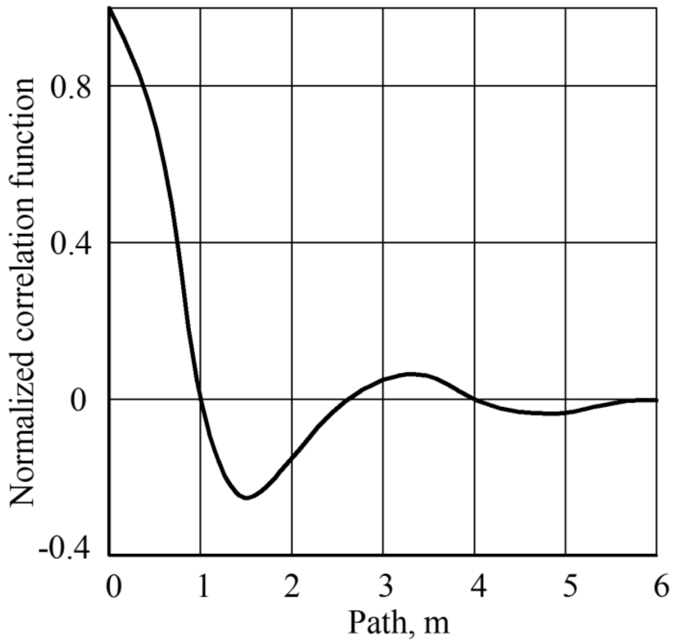

Fig. 6 - A normalised correlation function of oscillations of the field surface longitudinal profile

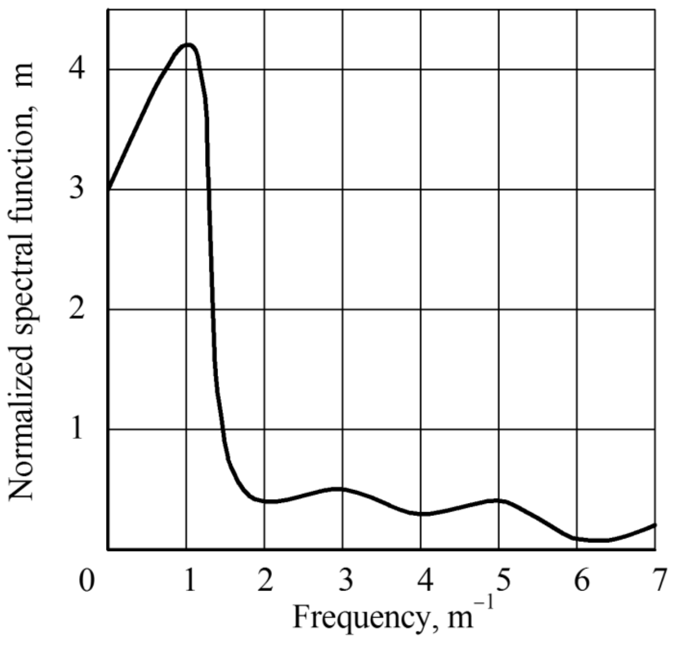

Fig. 7 - Spectral density of oscillations of the field surface longitudinal profile

The maximum value of the normalised spectral density of angle *α* oscillations falls on a rather narrow frequency range: 0.30 ... 0.35 s^{-1}.

As it turned out, the block-modular unit worked out the fluctuations in the input impact differently. In the absence of the hydraulic cylinder throttling of the technological module of the modular energy facility a positive correlation was found between the parameters *α* and *φ.* But, first, it is rather weak since the maximum value of the mutual correlation function does not exceed the mark (Curve 2 presented in Fig. 9).

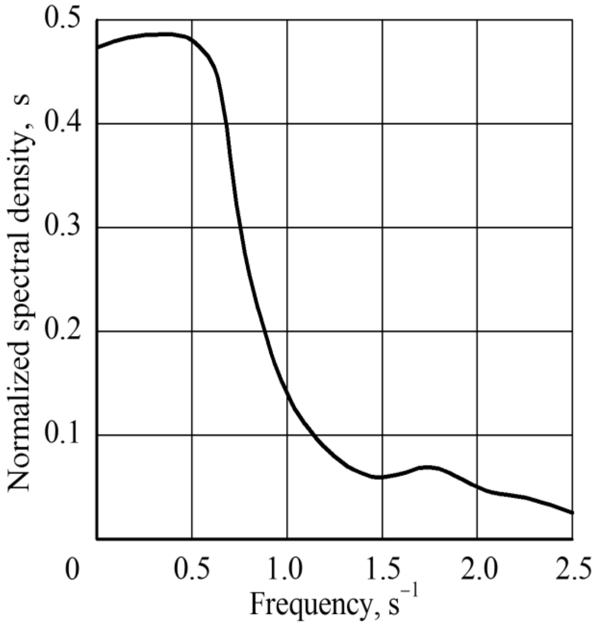

Fig. 8 - Normalised spectral density of the turning angle oscillations of the modular energy tool's driven wheels

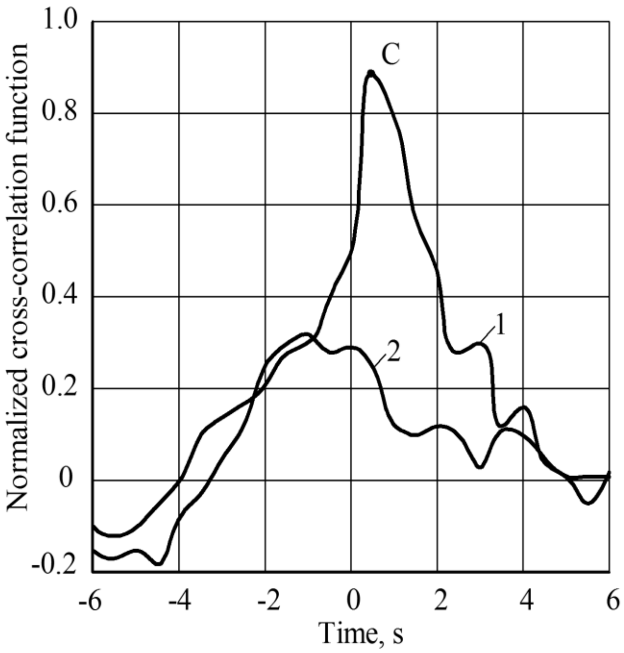

Fig. 9 - The normalised mutual correlation functions of the relative bearing angle *φ* oscillations, caused by angle *α* fluctuations at various throttling levels of the technological module's hydraulic cylinder
1) K_m = 1.03×10^6 N m s rad^{-1}; 2) K_m = 0

Second, the maximum value of this function is shifted to the left of the zero coordinate by about 1 s. This means that the input of this dynamic system is not the turning angle *α* of the driven wheels of the modular energy tool but its relative bearing angle *φ*. That is, the control impact is a reaction to the change in the relative bearing angle *φ* with a delay in time at the level of 1 s.

Besides, the cause of the change in the relative bearing angle *φ* of the modular energy tool may be the fluctuations in the expanding (turning out) moment, acting from the side of the technological module, or some other disturbance.

At the same time, the introduction of a hydraulic damper into the hydraulic cylinder of the technological module of the modular energy tool with a stiffness coefficient K_m = 1.03×10^6 N m s rad^{-1} essentially changes the behaviour of the mutual correlation function α–φ. The data obtained and processed by statistical methods of the experimental field investigations give reason to state the following:

First, the strength of the correlation link between the changes in the parameters *α* and *φ* sharply increases. Compared with the variant K_m = 0, the maximum of the mutual correlation function increases 2.6 times, reaching the level of 0.89.

Second, the maximum of the estimated function (Curve 1, Point C, shown in Fig. 9) is shifted to the right of the zero ordinate. And this indicates that the control impact (that is, angle *α*) is the input, and the relative bearing angle of the modular energy tool *φ* is the output of the dynamic system under consideration.

Third, the delay in the reaction of the relative bearing angle *φ* to a change in the control impact of the wheels of the modular energy tool is reduced almost two times. In this case it is approximately equal to 0.51 s. Such a result is desirable since the reaction of the consideration tracking dynamic system to a change in the control impact should, in the ideal, be instantaneous. That is, it proceeds with zero delay. But, since it is impossible to achieve this in practice, any structural and technological solution, aimed at reducing the response of a dynamic system to the useful input signal, is desirable. In our case, such a solution is to install a throttle in the hydraulic cylinder of the technological module of the modular energy facility

CONCLUSIONS

It is possible to increase the controllability of the aggregate movement on the basis of a modular energy tool, consisting of the energy and the technological modules, by throttling one of the hydraulic cylinders, which limit the mutual turning ability of these modules in a horizontal plane.

The equipment of the hydraulic cylinder of the modular power tool with a throttle, having a resistance coefficient 1.03×10^6 N m s rad^{-1} , makes it possible:

– to bring the maximum value of the mutual correlation function between the control impact, i.e., the turning angle of the energy module’s driven wheels of the modular energy tool and its relative bearing angle to the level of 0.89;

– to shift the maximum value of this cross-correlation function to the right of the zero ordinate, thereby providing the turning angle of the energy module’s driven wheels of the modular energy tool with a role of input (rather than output) impact;

– to reduce practically two times the delay in the reaction of the relative bearing angle of the energy module of the modular energy tool to a change in the turning angle of its driven wheels.

REFERENCES

[1] Aoki, A., Marumo, Y., Kageyama, I. and Kuwahara, K., (2009), Controllability and Loading Conditions of Tractor and Semitrailer Combinations in Lane Change, *Transactions of the Japan Society of Mechanical Engineers, Series C*, Vol.75, No.749, pp. 66-73;

[2] Bindi, I., Blackwell, P., Riethmuller, G., Davies, S., Whitlock, A. Neale, T., (2013), This Controlled Traffic Farming Technical Manual. It Updates the Tramline Farming Systems: Technical Traffic Farming Technical Manual. It Updates the Tramline Farming Systems*: Technical Manual Bulletin 4607*, p. 78. Published by the Department of Agriculture and food, Western Australia;

[3] Box, G.E., Hunter, W.G.; Hunter, J.S. (2005), *Statistics for Experimenters: Design, Innovation, and Discovery* (2nd ed.). Wiley. 664 p;

[4] Bulgakov, V., Kyurchev, V., Nadykto, V., Olt, J., (2015), Structure Development and Results of

[5] Testing a Novel Modular Power Unit. *Agriculture and Agricultural Science Procedia*. Elsevier Srl, pp.40–44. https://doi.org/10.1016/j.aaspro.2015.12.028;

[6] Bulgakov, V., Ivanovs, S., Nadykto, V., Kuvachov, V., Masalabov, V., (2018). Research on the turning ability of a two-machine aggregate. *INMATEH - Agricultural Engineering,* 54, pp.139–146;

[7] Bulgakov, V., Parakhin, O., Mitkov, V., Chorna, T., (2019), The Coefficient Determination of a Damper Washer Hydraulic Resistance for Reducing a Technical Module Oscillation Amplitude. *Modern Development Paths of Agricultural Production*. Springer International Publishing, pp. 183–190. https://doi.org/10.1007/978-3-030-14918-5_20;

[8] Dospehov, B., (2012), *Methodology of field experiments.* Nauka, Moscow/Russia, 352 p. (In Russian: Metodika polevogo opyta);

[9] Gjachev L., (1981), *Stability of the movement of agricultural machines and aggregates.* Moscow/Russia, 206 p. (In Russian);

[10] Kutjkov G., (2004), Tractors and cars. *Theory and technological properties.* Moscow/Russia, 504 p. (In Russian);

[11] Nadykto, V., Kotov, O., (2015), *Method for determining soil bulk density* (in Ukrainian: Sposib viznachennya shchilnosti gruntu). Patent UA No 97828;

[12] Pădureanu, V., Lupu, M.I., Canja, C.M., (2013), Theoretical research to improve traction performance of wheeled tractors by using a supplementary driven axle. *Computational Mechanics and Virtual Engineering*. Braşov/ Romania, pp. 410–415;Klets, D.M. (2013), Modelling of mobile vehicle skid in traction movement mode. *Motrol Commission of Motorization and Energetics in Agriculture*, 15 (7), Lublin/Poland, pp. 157-162;

[14] Popa, G., Buculei, M. (2013), Experimental determination of u-650 tractor traction performances equipped with supplementary hydrostatic transmission. *INMATEH-Agricultural Engineering*, 41 (3), pp. 65-68, Bucharest / Romania;

[15] Samorodov, V., Pelipenko, E., (2016), Analysis of the development of modern transmission wheeled tractors. *International Collection of Scientific Proceedings «European Cooperation»*, 6 (13), pp.49-57;

[16] Taran, I., Bondarenko, A., (2017), Conceptual approach to select parameters of hydrostatic and mechanical transmissions for wheel tractors designed for agricultural operations. *Archives of Transport,* Volume 41, Issue 1, pp. 89-100;

[17] Wong, J.Y., (2008), *Theory of Ground Vehicles*. John Wiley & Sons, ISBN 978-0-470-17038-0.