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Change in power and fuel consumption when engine cylinders are partially disabled in a wheeled vehicle

The provided calculation methodology enables the evaluation of how disconnected cylinders affect engine power, overall efficiency, and fuel consumption. The study establishes that disconnecting cylinders leads to a proportional decrease in engine power. This means that an engine generating 154,5 kW power reduces to 113,4 kW with two disabled cylinders and goes down to 70,3 kW when four cylinders are disconnected. Reducing fuel consumption is especially notable at idle, showing a 27% drop after disabling half of the cylinders. However, fuel efficiency declines as the engine load increases until it reaches zero at the engine load factor. Discrepancies between the experimental and calculated data on fuel consumption and power are minimal, at around 7-8% during maximum load. Diesel engines have the potential to improve efficiency by shutting down certain cylinders, but the actual fuel savings depend on several factors, including the number of active cylinders, engine configuration, load, and mechanical losses incurred by the shutdown cylinders.

A method for analyzing additional energy losses in the engine caused by forced and natural vibrations of motor-transmission systems in wheeled vehicles has been improved. The analysis utilizes the Meander function in the context of harmonic moment and Fourier series. This text describes a method for determining the power of mechanical losses and energy for pumping strokes, while considering changes in the temperature regime in disconnected engine cylinders at increased torque irregularity. It also determines the permissible number of disconnected cylinders, taking into account their effect on power and reliability of wheeled machines. This paper presents a method for evaluating the dependability of fundamental engine components in the context of increased torque irregularity resulting from the disconnection of some cylinders.

effective engine power, power change, engine, wheeled vehicle, cylinder shutdown, fuel consumption

Formulation of the problem. In road transportation, 25-30% of the transportation work volume is carried out with wheeled vehicles. During transportation operations, the duration of work reaches 50%. Waiting for a loading vehicle causes a downtime of 25-30% [1].

While performing transportation work, the wheeled vehicle engine operates mostly at low loads and in idle mode, resulting in low fuel combustion efficiency and low engine efficiency.

One way to enhance engine efficiency during low loads and idling is to deactivate certain engine cylinders [2, 3].

Analysis of recent research and publications. Upon reviewing the literature, it was determined that the claim that an engine can develop effective power equal to half of its rated value by turning off half of its cylinders without overloading the remaining cylinders is inaccurate. The power function's nonlinearity with respect to the number of operating cylinders is due to mechanical losses distributed among them. Disabled cylinders' losses are compensated by increasing the fuel supply to the operating cylinders.

V.V. Berezny developed a method to calculate an engine's effective power while operating with cylinder shutdown. This method determines the engine's ability to perform

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without overloading the operating cylinders and the corresponding number of shutdown cylinders. The potential for increased efficiency by shutting down some cylinders is inherent in all diesel engines. [4] The actual fuel economy when operating based on the load characteristic relies on the number of operating cylinders, engine design and manufacturing features, load, and mechanical losses in the disabled cylinders [5].

Setting objectives. The purpose of this study is to enhance the performance of a motor-tractor engine by analyzing the power and fuel consumption when some cylinders are disconnected.

This entails completing the following objectives:

– developing the theoretical connections among the effective power, engine proficiency, and the number of disabled cylinders in a wheeled vehicle engine;

– determine the impact of disabled cylinders on the effective power of motor-tractor engines;

– identify the maximum reduction in fuel consumption resulting from disabled cylinders.

Presenting main material. When certain cylinders of the engine are deactivated during operation, the engine's indicator power decreases, leading to a reduction in both crankshaft speed and engine torque. To stabilize them at the same level, it is essential to boost the cyclic fuel supply to the active cylinders. With a higher fuel cycle supply in the active cylinders, the average indicator pressure increases and the combustion process is enhanced. It is crucial to determine the impact of cylinder shutdown on engine performance parameters without compromising crankshaft speed and load factor, specifically regarding:

1) engine power output;

2) fuel consumption at varying engine loads.

The hourly fuel consumption of an engine with partial cylinder shutdown $G_f^{i''_{cyl}}$ can be calculated by considering the efficiency of the indicator $\eta_i^{i''_{cyl}}$, effective power $N_e^{i''_{cyl}}$, and mechanical loss power $N_{mlp}^{i''_{cyl}}$.

$$G_f^{i''_{cyl}} = \frac{3,6}{H_u \cdot \eta_i^{i''_{cyl}}}\left(N_e^{i''_{cyl}} + N_{mlp}^{i''_{cyl}}\right), \text{ kg/h.} \qquad (1)$$

The engine operates without cylinder shutdown based on the following parameters.

$$i'_{cyl} = i''_{cyl} + \Delta i_{cyl}, \qquad (2)$$

where i'_{cyl} – number of engine cylinders,

i''_{cyl} – the number of operational engine cylinders when some of the others are inoperative;

Δi_{cyl} – number of disabled engine cylinders.

Indicator efficiency characterizes combustion in a cylinder. Changes in this efficiency can be determined by the engine's load characteristic without having to shut down the cylinders. This dependence $\eta_i = f\left(P_i\right)$ can be described accurately using a fourth-degree polynomial equation [6, 7].

$$\eta_i = a \cdot P_i^4 + b \cdot P_i^3 + c \cdot P_i^2 + d \cdot P_i + f, \qquad (3)$$

where P_i – average indicator pressure, MPa;

a, b, c, d, f – empirical coefficients for a diesel engine at rated speed are determined as follows: $a = 0;\ b = 1,44;\ c = -2,02;\ d = 1,34;\ f = 0$.

According to the Abel-Ruffini theorem, algebraic equations with a degree of five or higher cannot be solved by radicals, but they can be solved by other means.

The theorem does not claim that a general equation of degree five does not have solutions. If we include complex solutions, the fundamental theorem of algebra assures us of the existence of solutions. The Abel-Ruffini theorem states that it is impossible to find a closed formula for solutions to equations of degree greater than four, meaning that any formula containing only arithmetic operations and roots of arbitrary degree cannot exist. However, it is possible to obtain solutions using numerical methods, specifically utilizing Newton's method, which allows for an accurate solution to be obtained to any degree.

The Abel-Ruffini theorem doesn't claim that a general equation with n greater than $n \geq 5$ has no solution. If complex solutions are considered, the basic algebraic theorem ensures the existence of solutions. The theorem's crux is that there's no closed formula for solutions, involving only arithmetic operations and arbitrary roots, for equations of degree more than four. Numerical methods, such as Newton's method, can provide precise solutions to these equations with any desired level of accuracy.

Expression (3) can be written in the following form.

$$n_i = b \cdot (P_i - x_1)\left(P_i - x_2\right), \tag{4}$$

where

$$x_1 = -\frac{\sqrt{c^2 - 4 \cdot a \cdot e \cdot b} + c}{2 \cdot b}; \tag{5}$$

$$x_2 = \frac{\sqrt{c^2 - 4 \cdot e \cdot b} - c}{2 \cdot b}. \tag{6}$$

The average indicator pressure equals the total of the averaged mechanical loss pressure and the averaged effective engine pressure

$$P_i = P_{mlp} + P_e, \tag{7}$$

where P_{mlp} – conditional average pressure of mechanical losses of the engine,

P_e – conditional average effective engine pressure.

The average pressure attributable to mechanical losses of the engine under conditions where some of the cylinders are disconnected can be calculated using the following method

$$P_{mlp}^{i''_{cyl}} = k_{\text{м}} \cdot P_{\text{мп}}^{i'_{cyl}} \frac{i'_{cyl}}{i''_{cyl}}, \text{ MPa}, \tag{8}$$

where k_m – coefficient change in mechanical losses when some cylinders are shut down,

$$k_m = \frac{i''_{cyl}}{i'_{cyl}} \cdot M_1 + \frac{\Delta i_{cyl}}{i'_{cyl}} \cdot M_2 \cdot \Delta_{mlp}, \tag{9}$$

where M_1 – the coefficient which considers the alterations in mechanical losses within operating cylinders (when the load on them increases because of the shutdown of certain cylinders);

M_2 – the coefficient considers the alteration in mechanical losses during cranking without fuel supply and characterizes the change in friction losses;

Δ_{mlp} – the coefficient reflects the proportionate shift in mechanical losses of disabled cylinders versus the mechanical loss capacity of engine cylinders without shutdowns. Cylinders can be disabled through different methods: disconnecting the fuel supply alone or eliminating pumping losses in the cylinder-piston group (CPG) in addition to fuel supply shut-off. Fuel supply shutdowns alone can also disable cylinders.

$$\Delta_{mlp} = 1 - \Delta_{fp} - \Delta_t , \tag{10}$$

where Δ_{fp} – the percentage of mechanical losses that are used by the fuel pump drive;

Δ_t – losses from changes in temperature balance.

When fuel is disconnected and pumping losses are eliminated in the CPG through the introduction of a bypass valve into the combustion chamber

$$\Delta_{mlp} = 1 - \left(\Delta_{fp} + \Delta_t + \Delta_{ps}\right), \tag{11}$$

where Δ_{ps} – share of losses on pumping strokes in a diesel engine $\Delta_{fp} = 3\%$, $\Delta_{\text{НХ}}$ – up to 7% reduction in output per cylinder disabled, $\Delta_t = 10 - 15\%$.

When fuel is disconnected and pumping losses are eliminated by introducing a bypass valve into the combustion chamber and the engine design allows disconnecting the timing drive, the mechanical power losses of the disconnected cylinders will follow this distribution

$$\Delta_{mlp} = 1 - \left(\Delta_{fp} + \Delta_t + \Delta_{ps} + \Delta_{gdm}\right), \tag{12}$$

where Δ_{gdm} – the portion of losses attributed to the operation of the drive mechanism in gas distribution.

Let's introduce the name of the percentage of disabled cylinders

$$D_{cyl} = \frac{\Delta i_{cyl}}{i'_{cyl}} ; \tag{13}$$

$$\frac{i''_{cyl}}{i'_{cyl}} = 1 - D_{cyl} . \tag{14}$$

When determining the average pressure of mechanical losses, it is common to use only their dependence on speed [8, 9]

$$P_{mlp} = a + b \cdot n . \tag{15}$$

where a and b – empirical coefficients for each motor.

Let's make the following assumptions: $M_1 = 1$ і $M_2 = 1$, which is quite acceptable since we are studying engine operation at idle and light loads. The assumptions made mean that as the engine load increases, the power and average pressure of the mechanical losses are assumed to remain unchanged, so that when operating under load, the parameters of the mechanical losses are determined by the same relationships. Taking into account (13) and (14), we obtain

$$k_m = 1 - D_{cyl}\left(1 - \Delta_{mlp}\right). \tag{16}$$

Equation (16) shows that the coefficient of change of mechanical losses during cylinder shutdown is directly proportional to the fraction of cylinders shut down. The conditional mean pressure of mechanical losses during cylinder shutdown is obtained by substituting (14) into (8)

$$P_{mlp}^{i''_{cyl}} = \frac{P_{mlp}^{i'_{cyl}} \cdot k_m}{1 - D_{cyl}} . \tag{17}$$

The average effective pressure when a portion of the cylinders are shut down depends on the percentage of cylinders that are shut down

$$P_e^{i''_{cyl}} = \frac{P_e^{i'_{cyl}}}{1 - D_{cyl}}. \tag{18}$$

The average indication pressure of the motor, taking into account (17) and (18), is expressed as follows

$$P_e^{i''_{cyl}} = \frac{P_e^{i'_{cyl}} + P_{mlp}^{i'_{cyl}} \cdot k_m}{1 - D_{cyl}}, \text{ MPa.} \tag{19}$$

The effective power of the motor can be expressed by the motor load factor K_z, the degree of change in the speed of rotation K_n and rated power

$$N_e = K \cdot K \cdot N \text{ . kW:} \tag{20}$$

$$K_n = \frac{n}{n_{nom}}, \tag{21}$$

where n – the current value of the engine crankshaft speed,

n_{nom} – rated speed of engine crankshaft.

$$K_z = \frac{M}{M_{nom}}, \tag{22}$$

where M – current value of motor torque,

M_{nom} – motor torque value at rated operation.

To determine the maximum effective power of the engine with the cylinders shut off, it is suggested to use the coefficient of variation of the maximum effective power k_{PN}

$$k_{PN} = \frac{N_{e\max}^{i''_{cyl}}}{N_e}, \tag{23}$$

where $N_{e\max}^{i''_{cyl}}$ – maximum engine power achieved through partial cylinder shutdown while maintaining a constant speed and maximum fuel supply;

N_e – rated motor power.

Maximum engine power is achieved at maximum hourly fuel consumption. In this case, it is assumed that the indicated power of one operating cylinder does not change when part of the other cylinders are shut off. The effective engine power when part of the cylinders are shut off is expressed as

$$N_e^{i''_{cyl}} = N_{in}^{i'_{cyl}} \frac{i''_{cyl}}{i'_{cyl}} - N_{mlp}^{i'_{cyl}} \cdot k_m. \tag{24}$$

The maximum effective power with partial shutdown depends on the rated horsepower of the engine

$$N_{e\max}^{i''_{cyl}} = N_e \left(\frac{1 - D_{cyl}}{\eta_{m\max}^{i'_{cyl}}} - k_{\text{м}} \left(\frac{1}{\eta_{m\max}^{i'_{cyl}}} - 1 \right) \right). \tag{25}$$

The coefficient in brackets reflects the change in maximum effective power when the cylinders are deactivated

$$k_{PN} = \frac{1 - D_{cyl}}{\eta_{m\max}^{i'_{cyl}}} - k_m \left(\frac{1}{\eta_{m\max}^{i'_{cyl}}} - 1 \right). \tag{26}$$

Substituting equation (16) into equation (26), we obtain

$$k_{PN} = 1 - D_{cyl}\left(1 + \Delta_{mlp}\left(\frac{1}{\eta_{m\,\max}^{i'_{cyl}}} - 1\right)\right). \qquad (27)$$

The maximum effective power of an engine can be determined by the proportion of excluded cylinders in relation to the coefficient of change in the maximum effective power k_{PN}, as shown in formula (24)

$$N_{e\,\max}^{i''_{cyl}} = k_{PN} \cdot N_e. \qquad (28)$$

The formula (1) determines the fuel consumption when some of the cylinders are shut down. The hourly fuel consumption can be estimated when the engine cylinders are turned off by using the coefficient of change in hourly fuel consumption k_{G_f}

$$k_{G_f} = \frac{G_f^{i''_{cyl}}}{G_f^{i'_{cyl}}}. \qquad (29)$$

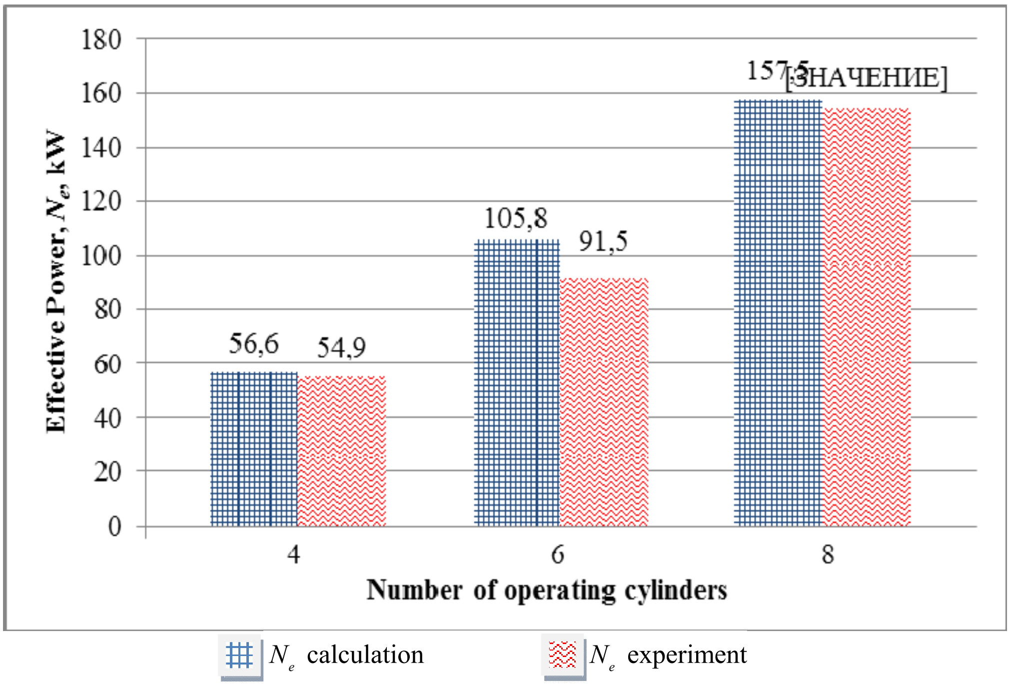

Figure 1 – Shows the comparison between calculated and experimental values for the maximum power of a diesel engine based on the number of operating cylinders

Source: developed by the author

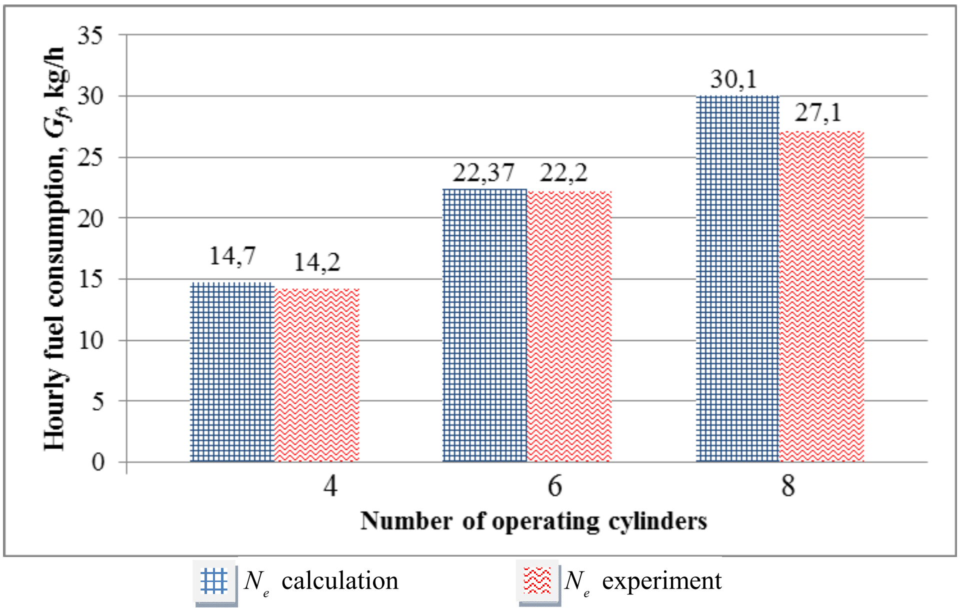

Figure 2 – Shows a comparison between the calculated and experimental data
for hourly engine fuel consumption at maximum power with partial cylinder shutdown

Source: developed by the author

As a result of transforming expression (29) with consideration for principles (1, 4, 5, 6, 21), we achieve the following improved text

$$k_{G_f}=\frac{\left(P_i-x_1\right)\left(P_i-x_2\right)}{\left(P_i-\dfrac{x_1}{k_{pi}}\right)\left(P_i-\dfrac{x_2}{k_{pi}}\right)}\cdot\frac{1-D_{cyl}}{k_{pi}}, \tag{30}$$

where k_{pi} – an indicator pressure coefficient characterizes the change in pressure within operating cylinders while maintaining effective engine power.

$$k_{pi}=\frac{P_i^{i''_{cyl}}}{P_i}=\frac{1-D_{cyl}\left(1-\Delta_{mlp}\right)\left(1-\eta_m\right)}{1-D_{cyl}}. \tag{31}$$

The fuel consumption when deactivating some of the cylinders is determined by an expression

$$G_f^{i''_{cyl}}=G_f^{i'_{cyl}}\cdot k_{G_f}. \tag{32}$$

Figure 1 displays the results of the analysis and testing to determine the maximum effective power with four engine cylinders deactivated. The data reveals a proportional decrease in power as the number of operating cylinders decreases.

Figure 2 displays fuel consumption data obtained from both calculated and experimental determinations when some cylinders are deactivated.

Based on the results presented in Figure 1, the average difference between experimental and calculated data for determining power and fuel consumption is no more than 7-8%.

Conclusions.

1. The calculation methodology developed enables the evaluation of engine power and fuel economy following the disconnection of any number of cylinders.

2. It has been determined that engine power diminishes correspondingly with the number of inactive cylinders. For a diesel engine, the power output drops from 154,5 kW to 113,4 kW when two cylinders are deactivated, and to 70,3 kW when four cylinders are deactivated.

3. The idle state records the highest reduction in fuel consumption, wherein 27% reduction occurs by disabling half the cylinders.

4. Fuel efficiency declines with increasing engine load and reaches zero at the engine load factor. The disparity between the fuel consumption and power calculated values and the experimental values is no more than 7-8% at full load.

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Зміна потужності та витрати палива при частковому відключенні циліндрів двигуна в колісному транспортному засобі

Наведена методика розрахунку дозволяє оцінити вплив відключених циліндрів на потужність двигуна, загальну ефективність та витрату палива. Дослідження показало, що відключення циліндрів призводить до пропорційного зниження потужності двигуна. Це означає, що потужність двигуна потужністю 154,5 кВт знижується до 113,4 кВт з двома відключеними циліндрами і падає до 70,3 кВт при відключенні чотирьох циліндрів. Зменшення споживання палива особливо помітне на холостому ходу - на 27% після відключення половини циліндрів. Однак паливна ефективність знижується зі збільшенням навантаження на двигун, поки не досягає нуля при коефіцієнті завантаження двигуна. Розбіжності між експериментальними та розрахунковими даними по витраті палива та потужності мінімальні і становлять близько 7-8% при максимальному навантаженні. Дизельні двигуни мають потенціал для підвищення ефективності за рахунок відключення певних циліндрів, але фактична економія палива залежить від декількох факторів, включаючи кількість активних циліндрів, конфігурацію двигуна, навантаження і механічні втрати, що виникають у відключених циліндрах.

Розроблено вдосконалений метод аналізу додаткових енергетичних втрат у двигуні, спричинених впливом вимушених і власних коливань моторно-трансмісійних систем колісних транспортних засобів. Використано функцію Меандра в контексті гармонійного моменту та ряди Фур'є. Запроваджено метод визначення потужності механічних втрат та енергії на насосні ходи, що враховує зміни температурного режиму у відключених циліндрах двигуна за підвищеної нерівномірності крутного моменту. Визначено допустиму кількість відключених циліндрів, що враховує вплив на потужність і надійність роботи колісних машин. Представлено метод оцінювання надійності базових деталей двигуна в контексті збільшення нерівномірності крутного моменту при відключенні частини циліндрів.

ефективна потужність двигуна, зміна потужності, двигун, колісний транспортний засіб, відключення циліндрів, витрата палива

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