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The Impact of Mechanical Losses on Engine Power of a Wheeled Vehicle under Cylinder Deactivation

A methodology for calculating mechanical losses in internal combustion engines has been proposed, enabling the assessment of the influence of the number of deactivated cylinders on the effective power output of a wheeled vehicle engine with an accuracy of approximately 10%. This method allows for the estimation of mechanical power losses and the mechanical efficiency (mechanical efficiency coefficient) under varying engine operating conditions.

It has been determined that when half of the engine cylinders are deactivated, the nominal power output decreases to approximately 35–40% of its full-capacity level. The discrepancy between the experimental and calculated values of the mechanical loss power change coefficient does not exceed 8%. At the same time, the deviation between the calculated and experimental values of the engine load coefficient based on power remains within 5%. Additionally, it has been established that mechanical efficiency increases by up to 7% when the engine is operated at a 48% load level, which indicates improved energy utilization under partial load conditions.

Furthermore, it was observed that as the number of deactivated cylinders increases, the magnitude of mechanical power losses correspondingly increases, while the mechanical efficiency of the engine decreases. This is primarily attributed to the redistribution of internal mechanical resistances within the engine and the non-linear behavior of frictional forces and parasitic losses under partial load regimes.

A clear correlation between the mechanical efficiency and the effective engine power has been identified. Specifically, an increase in the number of deactivated cylinders (as a factor variable) leads to a rise in mechanical losses (as a response variable) and a reduction in mechanical efficiency. These findings provide a theoretical and practical foundation for optimizing engine control strategies in variable load conditions and contribute to enhancing overall fuel efficiency and operational performance of wheeled vehicles.

variation, engine power, mechanical losses, wheeled vehicle, engine, cylinder deactivation

Formulation of the problem. The power of mechanical losses under all mechanical efficiency conditions changes in a similar manner [1], as it primarily depends on the crankshaft rotational speed and remains nearly constant. Therefore, mechanical efficiency is largely correlated with the mechanical loss power (mainly due to the reduction of pumping losses).

Automotive and tractor engines achieve maximum mechanical efficiency at approximately 75% of rated load, and this efficiency remains practically unchanged when the load is reduced to 50% of the rated value. When the load falls below 40% of the rated level, engine operating conditions deviate significantly from the optimal range, and mechanical efficiency declines rapidly. In high-performance engines, the threshold below which mechanical efficiency drops sharply is around 30% of the rated load.

Additionally, automotive and tractor engines often operate in idle mode, which, according to [2], accounts for more than 22% of total operating time.

Analysis of recent research and publications. A literature review has shown that there is a lack of data regarding the determination of mechanical losses during cylinder deactivation [3]. In many cases, the rated power of automotive and tractor engines exceeds the actual operational demand – these engines are rarely operated under full load conditions [3]. According to research conducted at enterprises in EU countries [3], engines typically operate at approximately 60% of their rated load. According to [4], electric motors achieve maximum mechanical efficiency at loads ranging from 60% to 100% of the rated value. However, according to data from [5] (USA), the relationship between efficiency and engine load is significantly different.

Setting objectives. The purpose of this study is to improve the performance characteristics of automotive and tractor engines by determining the mechanical loss power and substantiating the optimal number of deactivated cylinders.

Achieving the stated goal involves solving the following tasks:

 determine the impact of mechanical losses during the deactivation of some cylinders in automotive and tractor engines on their effective power output;

 determine the mechanical loss power and the mechanical efficiency under engine load conditions with partial cylinder deactivation;

 perform a correlation-regression analysis of the dependence of mechanical efficiency on the effective power output of the engine under various numbers of operating cylinders.

Presenting main material. If the fuel supply to a cylinder with a piston is interrupted, but the piston continues to move in idle mode, additional energy losses associated with the motion of the piston and the related mechanisms must be considered.

The mechanical loss power of a multi-cylinder automotive and tractor engine under different numbers of operating cylinders (without supercharging), denoted as N_{mv}, consists of the following components – power losses due to friction, N_{ter}; power losses due to pump strokes, N_{nv}; power required to drive auxiliary mechanisms, N_{dm} (fuel pump, oil pump, water pump, fan, gas distribution mechanism); and power losses resulting from changes in the thermal balance between the operating and non-operating cylinders, N_t.

$$N_{mv} = \frac{N_{in}}{\eta_m}\left(1-\eta_m\right). \tag{1}$$

or

$$N_{mv} = N_{ter} + N_{nv} + N_{dm} + N_t, \tag{2}$$

where N_{in} – the indicated power of the engine,

$\eta_m = \dfrac{N_e}{N_{mv} + N_e}$ – mechanical efficiency of the engine;

N_e – effective power of the engine without cylinder deactivation.

The mechanical loss power of the engine at different numbers of operating cylinders $N_{mv}^{i''_{cyl}}$ can be represented in the following form [6]

$$N_{mv}^{i''_{cyl}} = N_{mv} \cdot \left(\frac{i''_{cyl} \cdot k_1}{i'_{cyl}} + \frac{\Delta i_{cyl} \cdot k_2}{i'_{cyl}} \right) \tag{3}$$

where i'_{cyl} – total number of cylinders;

i''_{cyl} – number of operating cylinders;

Δi_{cyl} – number of deactivated cylinders;

k_1 – coefficient accounting for the variation in mechanical losses in operating cylinders (for calculation purposes, it is assumed that mechanical losses do not change with load);

k_2 – coefficient accounting for the variation in mechanical losses in deactivated cylinders

$$k_2 = f_\Delta \cdot \Delta_{mv} \tag{4}$$

where f_Δ – coefficient characterizing the variation in friction losses during cylinder cranking (for calculation purposes, it is assumed that these losses remain unchanged);

Δ_{mv} – portion of the mechanical loss power in deactivated cylinders compared to the mechanical loss power of the engine cylinders without deactivation.

In case of fuel supply deactivation only

$$\Delta_{mv} = 1 - \Delta_{pn} - \Delta_t \tag{5}$$

where Δ_{pn} – portion of mechanical losses spent on driving the fuel pump;

Δ_t – portion of losses due to changes in the thermal balance.

In the case of fuel supply deactivation and elimination of pumping losses in the cylinder-piston group (CPG) due to the implementation of a bypass valve into the combustion chamber

$$\Delta_{mv} = 1 - \left(\Delta_{pn} + \Delta_t + \Delta_{nx}\right) \tag{6}$$

where Δ_{nx} – portion of losses due to pumping strokes.

If fuel supply is deactivated and pumping losses in the CPG are eliminated by introducing a bypass valve into the combustion chamber, and if the engine design also allows disabling the valve train drive, the portion of mechanical losses in deactivated cylinders will be as follows

$$\Delta_{mv} = 1 - \left(\Delta_{pn} + \Delta_t + \Delta_{nx} + \Delta_{gtm}\right) \tag{7}$$

where Δ_{gtm} – portion of losses spent on driving the valve timing mechanism (gas distribution mechanism).

As a result of substituting (4) into (3), we obtain the following expression for determining the mechanical losses of the engine when part of its cylinders is deactivated

$$N_{mv}^{i_{cyl}^{''}} = N_{mv}^{i_{cyl}^{'}} \cdot \left(\frac{i_{cyl}^{''}}{i_{cyl}^{'}} \cdot k_1 + \frac{\Delta i_{cyl}}{i_{cyl}^{'}} \cdot f_{\Delta} \cdot \Delta_{mv} \cdot \Delta_t \right) \tag{8}$$

where $N_{mv}^{i_{cyl}^{'}}$ – mechanical loss power of the engine without cylinder deactivation.

Let us denote the expression in parentheses as k_{mt} – a coefficient that characterizes the variation in mechanical and thermal losses of the engine when part of the cylinders is deactivated

$$N_{mv}^{i_{cyl}^{''}} = N_{mv}^{i_{cyl}^{'}} \cdot k_{mt}, \tag{9}$$

Assuming that $k_1 = 1$ and $f_{\Delta} = 1$ [7]

$$k_{mt} = \frac{i_{cyl}^{''}}{i_{cyl}^{'}} + \frac{\Delta i_{cyl}}{i_{cyl}^{'}} \cdot \Delta_{mv} \cdot \Delta_t. \tag{10}$$

To verify the proposed method for calculating engine mechanical losses under partial cylinder deactivation, experimental studies were carried out on a multi-cylinder diesel engine of medium power class [8]. The test bench experiments were conducted under industrial conditions at a mechanical repair facility in Kharkiv, using appropriate measuring instruments and control equipment. Engine loading was performed using an electric dynamometer equipped with a balancing machine.

According to the calculations, deactivation of fuel supply and elimination of pumping losses in the cylinder-piston group (CPG) for four cylinders resulted in a reduction of mechanical losses by 10.7% (Fig. 1).

One of the key indicators of engine mechanical losses is mechanical efficiency η_m. Its maximum value is achieved at the rated engine power, which changes under cylinder deactivation. The new value of effective power $N_e^{i''_{cyl}}$ under cylinder deactivation can be determined using the following expression

$$N_e^{i''_{cyl}} = N_e \cdot k_{PN} \tag{11}$$

where k_{PN} – engine load coefficient by power, which characterizes the change in effective engine power during partial cylinder deactivation.

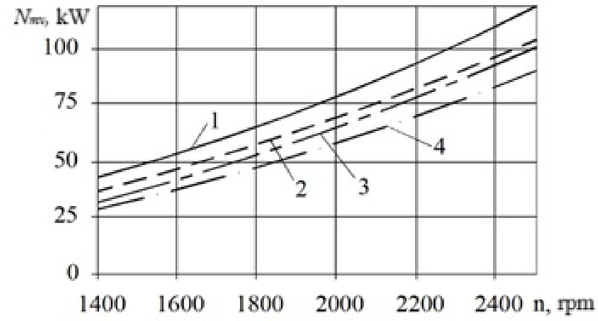

Figure 1 – Dependence of engine mechanical loss parameters on crankshaft rotational speed for the cases of all and half of the cylinders operating:
1 – N_{mv8} *exp.*; 2 – N_{mv4} *exp.*; 3 – N_{mv8} *calc.*; 4 – N_{mv4} *calc.*

Source: developed by the author

Let us define the coefficient k_{PN}, assuming that the theoretical indicated power of a single operating cylinder is

$$N_{in}^{1i''_{cyl}} = N_{in}^{i'_{ц}} / i'_{cyl} \tag{12}$$

where $N_{in}^{1i''_{cyl}}$ – theoretical indicated power of one operating cylinder;

$N_{in}^{i'_{cyl}}$ – indicated engine power.

The indicated power of the engine during cylinder deactivation at maximum fuel supply is equal to

$$N_{in}^{1i''_{cyl}} = N_{in}^{i'_{cyl}} / i'_{cyl} \cdot i''_{cyl} \tag{13}$$

Using the expression

$$N_e^{i''_{cyl}} = N_{in}^{i''_{cyl}} - N_{mv}^{i''_{cyl}} \tag{14}$$

and considering (8), (11), and (13), as well as several transformations, we can determine the coefficient k_{PN} that describes the change in engine power under cylinder deactivation

$$k_{PN} = \frac{i''_{cyl}}{i'_{cyl} \cdot \eta_m} \cdot \left(1 - k_1 + k_1 \cdot \eta_m\right) - \frac{\Delta i_{cyl}}{i'_{cyl}} \cdot f_\Delta \cdot \Delta_{mv} \cdot \left(\frac{1}{\eta_m} - 1\right) \tag{15}$$

Under the assumptions $k_1 = 1$ and $f_\Delta = 1$ [7], we obtain

$$k_{PN} = \frac{i''_{cyl}}{i'_{cyl}} - \frac{\Delta i_{cyl}}{i'_{cyl}} \cdot \Delta_{mv} \cdot \left(\frac{1}{\eta_m} - 1\right) \tag{16}$$

Thus, the power of a multi-cylinder automotive and tractor engine at different numbers of operating cylinders (without supercharging), taking into account (11), (14), and (16), is determined by the following expression

$$N_e^{i''_{cyl}} = N_e \cdot \left(\frac{i''_{\text{cyl}}}{i'_{\text{cyl}}} - \frac{\Delta i_{cyl}}{i'_{\text{cyl}}} \cdot \Delta_{mv} \cdot \left(\frac{1}{\eta_m} - 1 \right) \right) \quad (17)$$

The mechanical loss indicators were determined for the engine as fractions of the total mechanical loss power, which are known from [8, 9]: $\Delta_{pn} = 0,015 - 0,02$ %; $\Delta_{nx} = 0,13 - 0,15$ %.

During experimental studies with increasing engine crankshaft speed from 1400 rpm to 2400 rpm, at rated power output $N_{nom} = 154,5$ kW, the mechanical loss power of the output engine increased from 42.65 kW to 118.1 kW, i.e., $\Delta N_{mv} = 75,45$ kW. After eliminating pumping losses in four cylinders, the increase in mechanical loss power under growing engine speed from 8th cylinder activation was reduced to a range of 36.65 kW to 104.25 kW, i.e., $\Delta N_{mv} = 67,6$ kW.

The reduction in mechanical loss power with a decreasing number of operating engine cylinders occurs because, in deactivated cylinders, the gas exchange process ceases and the pumping losses become nearly zero. In this case, work is spent only on compressing and expanding the air, which practically equals the work of the air itself. When engine speed increases from 1400 to 2400 rpm, the coefficient of mechanical loss power change k_{mt} increases slightly and differs from the calculated value by no more than 8%.

The calculated engine load coefficient k_{PN} increases proportionally to the number of operating cylinders and characterizes the increase in the engine's maximum effective power [6, 10]. The difference between calculated and experimental values of k_{PN} does not exceed 5% (Fig. 2).

The nature of mechanical efficiency variation as a function of engine load coefficient under all-cylinder and partial-cylinder operation is practically the same (Fig. 3). The maximum mechanical efficiency at full-cylinder operation is $\eta_{mt} = 0,83$, and for seven, six, five, four, three, and two operating cylinders it is respectively: 0.79; 0.68; 0.5; 0.34; 0.14; and 0.04 – the last of which is practically unfeasible due to extremely low power output.

It is evident from Fig. 3 that mechanical loss power exceeds the effective engine power when mechanical efficiency is less than 1%.

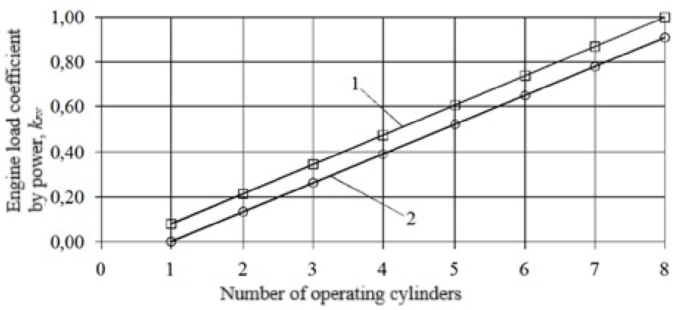

Figure 2 – Dependence of the calculated and experimental coefficients of nominal engine power variation on the number of operating cylinders ($n = 2400$ rpm): 1 – calculated; 2 – experimental
Source: developed by the author

Correlation analysis of the dependence of mechanical efficiency on the effective engine power at different numbers of operating cylinders solves two main tasks.

The first task is to determine the type of regression equation. This is of critical importance, as the correct choice directly affects the final result of studying the relationship between mechanical losses and the effective power of an automotive and tractor engine under various numbers of non-operating cylinders.

The second task is to select the polynomial form of the regression equation of mechanical losses with respect to the number of deactivated cylinders and the effective power of the engine, in order to determine the degree of influence of the number of non-operating cylinders on engine power depending on the engine load. This task is solved mathematically by determining the parameters of the correlation equation.

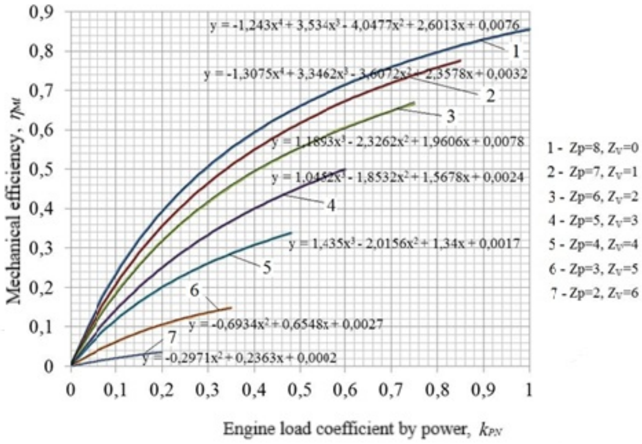

Figure 3 – Correlation between mechanical efficiency and engine power at different numbers of operating cylinders

Source: developed by the author

A decisive role in selecting the form of the relationship between these parameters belongs to theoretical analysis. As the number of deactivated cylinders (independent variable) increases, the mechanical loss power (dependent variable) increases and mechanical efficiency decreases. With the increase in the independent variable, the dependent variable generally increases proportionally. Therefore, the relationship between them can be described by a polynomial regression equation for each specific case of cylinder deactivation (Fig. 3).

Conclusions**. To improve the accuracy of the obtained results:**

1. A method for calculating mechanical losses is proposed, which allows determining the influence of the number of deactivated cylinders on the engine's effective power, mechanical loss power, and mechanical efficiency with an accuracy of approximately 10%.

2. It was established that, when half of the cylinders are deactivated, the rated power constitutes 35-40%; the discrepancy between experimental and calculated results of the mechanical loss power variation coefficient does not exceed 8%; the discrepancy between calculated and experimental values of the load coefficient based on power does not exceed 5%; mechanical efficiency increases by 7% at a load level of 48%.

3. A correlation relationship between mechanical efficiency and effective engine power has been established: as the number of deactivated cylinders (independent variable) increases, the mechanical loss power (dependent variable) increases, while mechanical efficiency decreases.

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Вплив механічних втрат на потужність двигуна колісного транспортного засобу за умов деактивації циліндрів

Запропоновано методику розрахунку механічних втрат у двигунах внутрішнього згоряння, яка дає змогу оцінити вплив кількості деактивованих циліндрів на ефективну потужність двигуна колісного транспортного засобу з точністю близько 10%. Ця методика дозволяє визначити втрати механічної потужності та коефіцієнт механічної ефективності за різних режимів роботи двигуна.

Встановлено, що при деактивації половини циліндрів двигуна номінальна потужність знижується до приблизно 35–40% від її повного значення. Розбіжність між експериментальними та розрахунковими значеннями коефіцієнта зміни потужності механічних втрат не перевищує 8%. Водночас відхилення між розрахунковими та експериментальними значеннями коефіцієнта навантаження двигуна за потужністю становить не більше 5%. Крім того, встановлено, що механічна ефективність збільшується до 7% при роботі двигуна на рівні навантаження 48%, що свідчить про підвищення ефективності використання енергії за умов часткового навантаження.

Також було зафіксовано, що зі збільшенням кількості деактивованих циліндрів зростає величина втрат механічної потужності, тоді як механічна ефективність двигуна знижується. Це зумовлено, передусім, перерозподілом внутрішніх механічних опорів у двигуні та нелінійним характером роботи сил тертя та паразитних втрат за умов часткового навантаження.

Виявлено чітку кореляцію між механічною ефективністю та ефективною потужністю двигуна. Зокрема, збільшення кількості деактивованих циліндрів (як факторної змінної) призводить до зростання механічних втрат (як результативної змінної) та зниження механічної ефективності. Отримані результати створюють теоретичну й практичну основу для оптимізації стратегій керування двигуном у змінних режимах навантаження та сприяють підвищенню загальної паливної ефективності й експлуатаційних характеристик колісних транспортних засобів.

зміна, потужність, механічні втрати, колісна машина, двигун, відключення циліндрів

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