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METHODS FOR DETERMINING MECHANICAL LOSSES OF MARINE DIESEL ENGINES

Leszek Wontka

Polish Naval Academy, Mechanical and Electrical Engineering Faculty, Śmidowicza 69 Str., 81-127 Gdynia, Poland; e-mail: l.wontka@amw.gdynia.pl

ABSTRACT

The paper presents based on literature critical evaluation of commonly known methods for determining the mechanical losses of a piston engine. Their advantages and disadvantages were pointed out also the possibility of their use in a marine propulsion system was assessed.

Key words:
mechanical losses, marine diesel engine.

Research article

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INTRODUCTION

Unquestionable disadvantage of the piston engine is its relatively large mechanical losses. Numerous polish and foreign researches focus on minimizing mechanical losses in the context of reducing fuel consumption by the engine. Also researches in the context of reducing mechanical losses during engine start-up are conducted. Almost each technical university in Poland conducting researches in this area, however, Poznan University of Technology is the polish leading center dealing with this problem. However, relatively little space is devoted in the literature for mechanical losses testing in the aspect of piston engine diagnostics. The exceptions are the studies carried out by P. Bielawski and A. Piętak. All of them, were limited to the diagnosis of car engines. Work [10] is a certain supplement to the gap in the study of mechanical losses of marine engines.

Regardless of the purpose of mechanical loss testing, verification of results is always carried out by determining mechanical losses on the real object. In considered case it is engine in the ship propulsion system. Therefore, it is very important to choose the appropriate method for assessing mechanical losses.

INTRODUCTORY KNOWLEDGE

Fig. 1 presents propulsion system with medium speed marine diesel engine (1) drives through a mechanical reduction gear (2) a fixed or variable pitch propeller (4). The bearing points of the shaft line are carrier bearings (3). It is a typical drive system with a medium speed engine used in Navy.

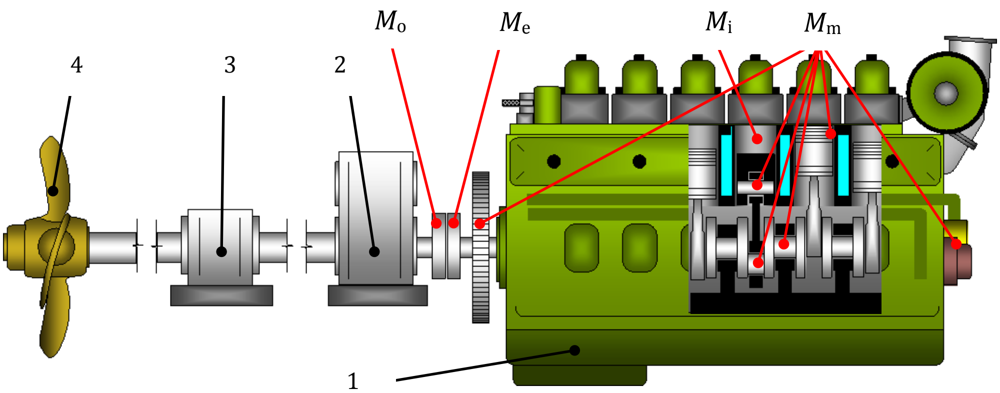

Fig. 1. Intermediate drive system with medium speed engine

According to the d'Alembert's rule:

$$J_\mathrm{o} \cdot \frac{\mathrm{d}\omega_o}{\mathrm{d}t} - M_\mathrm{e}(t) + M_\mathrm{o}(t) = 2 \cdot \pi \cdot J_\mathrm{o} \cdot \frac{\mathrm{d}n_\mathrm{o}}{\mathrm{d}t} - M_\mathrm{e}(t) + M_\mathrm{o}(t) = 0 \tag{1}$$

where:

J_o — inertia moment of the torque receiver reduced to the axis of the crankshaft;
ω_o, n_o — angular and rotational speed of propeller;
$M_\mathrm{e}(t)$ — engine torque as a function of time — t;
$M_\mathrm{o}(t)$ — propeller torque as a function of time.

Propeller torque is the sum of the towing torque and the total friction loss torque of the shaft line (gears, bearings, shaft line glands and others):

$$M_\mathrm{o}(t) = M_\mathrm{h}(t) + M_\mathrm{lw} \tag{2}$$

where:

$M_\mathrm{o}(t)$ — propeller torque as a function of time;
$M_\mathrm{h}(t)$ — towing torque as a function of time;
M_lw — overall shaft line mechanical losses torque (gears, bearings, shaft line glands and others).

Based on [3, 5], the towing torque could be presented as:

$$M_\mathrm{h}(t) = \frac{P_\mathrm{h}(t)}{2\pi \cdot n_\mathrm{o}} = v(t) \cdot \frac{T_\mathrm{N}(t) - T_\mathrm{S}(t)}{2\pi \cdot n_\mathrm{o}} = v(t) \cdot \frac{R(v) + (m_\mathrm{K} + m_\mathrm{W}) \cdot \frac{\mathrm{d}v}{\mathrm{d}t}}{2\pi \cdot n_\mathrm{o}} \tag{3}$$

where:

$M_\mathrm{h}(t)$ — towing torque as a function of time;
$P_\mathrm{h}(t)$ — towing power as a function of time;
n_o — propeller rotational speed;
$v(t)$ — cruising speed as function of time;
$T_\mathrm{N}(t)$ — propeller thrust force as a function of time;
$T_\mathrm{S}(t)$ — propeller bank suction force as a function of time;
$R(v)$ — hull total resistance force as function of cruising speed;
m_K — hull mass;
m_W — escorting water mass.

By substituting (3) to dependence (2), it could obtained:

$$M_\mathrm{o}(t) = v(t) \cdot \frac{R(v) + (m_\mathrm{K} + m_\mathrm{W}) \cdot \frac{\mathrm{d}v}{\mathrm{d}t}}{2\pi \cdot n_\mathrm{o}} + M_\mathrm{lw} \tag{4}$$

On the other hand engine torque might be described as:

$$M_\mathrm{e}(t) = M_\mathrm{i} - M_\mathrm{m} - J \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = M_\mathrm{i} - M_\mathrm{m} - 2 \cdot \pi \cdot J \cdot \frac{\mathrm{d}n}{\mathrm{d}t} \tag{5}$$

where:

$M_\mathrm{e}(t)$ — engine torque as a function of time;
M_i — engine indicated torque;
M_m — engine mechanical losses torque;
J — engine inertia moment reduced to the axis of the crankshaft;
ω, n — angular and rotational speed of engine.

Transforming equation (5), the engine mechanical losses torque is obtained as:

$$M_\mathrm{m} = M_\mathrm{i} - M_\mathrm{e}(t) - 2 \cdot \pi \cdot J \cdot \frac{\mathrm{d}n}{\mathrm{d}t} \tag{6}$$

Analyzing formulas (1)–(6) it follows that the necessity of stabilization plays a very important role in determining mechanical losses obtained during ship measurements. In the general case the most important are stable:

- engine speed;
- speed of the power receiver (propeller);
- cruising speed.

During the ship's cruising, the external conditions have a decisive influence on it, mainly the wave of the sea and the correctness of the governors operation. In the case where $n = \mathrm{const}$, $n_\mathrm{o} = \mathrm{const}$ and $v = \mathrm{const}$, the dependence (6) takes the form:

$$M_\mathrm{m} = M_\mathrm{i} - M_\mathrm{e} \tag{7}$$

For idle, equation 1.6 takes form:

$$M_\mathrm{m} = M_\mathrm{i} - J \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = M_\mathrm{i} - 2 \cdot \pi \cdot J \cdot \frac{\mathrm{d}n}{\mathrm{d}t} \tag{8}$$

for $n = \mathrm{const}$, mechanical losses torque will be equal to indicated torque:

$$M_\mathrm{m} = M_\mathrm{i} \tag{9}$$

Therefore, the remaining measures of mechanical losses depending on the mechanical losses torque will be expressed by formulas:

- mechanical losses work:

$$L_\mathrm{m} = 2\pi \cdot \tau \cdot M_\mathrm{m} \tag{10}$$

- mechanical losses mean pressure:

$$p_\mathrm{m} = M_\mathrm{m} \cdot \frac{8\tau}{D^2 \cdot S \cdot z} \tag{11}$$

– mechanical losses power:

$$P_m = 2\pi \cdot n \cdot M_m \tag{12}$$

where:

D — cylinder diameter [mm];
S — piston stroke [mm];
z — cylinder number;
n — rotational speed;
τ — number of strokes discriminant: $\tau = 1$ for two stroke engine, $\tau = 2$ for four stroke engine.

METHODS FOR DETERMINING MECHANICAL LOSSES

Method of external propulsion

In this method, the crankshaft of the engine being tested is driven by an external engine. The test consists in measuring the power or torque transmitted from the external engine to the tested one. Due to the easy determination of power without direct measurement of torque on the shaft, the most common external drive motor is an electric motor. The power of mechanical losses is described as:

$$P_m = P_1 + P_2 \tag{13}$$

where:

P_m — tested engine mechanical losses power;
P_1 — measured power of external engine working alone;
P_2 — measured power of external engine driven tested engine.

It is obvious that both measurements should be carried out at the same rotational speed. In order to obtain the results of tests that are as real as possible, the engine under test should be brought to the temperature corresponding to its normal operation. Theoretically, the only disadvantage of this method is the lack of the impact of tested engine load on the determination of its mechanical losses [1, 2, 4, 8]. In fact, even when the engine elements are brought to a temperature close to the engine's operating temperature, it is extremely difficult to maintain the temperature of the lubricating oil on the cylinder liner layer at a constant level above 200 °C while maintaining the temperature of this oil in the bearings at a constant level of 70–80 °C or below. This value corresponds to the temperatures of the lubricating oil during engine operation [6, 7]. In the case of marine engines, an additional drawback of this method is the practical impossibility of using it on board of ships. The crankshaft of an internal combustion engine in marine conditions can be rotated in a controlled manner by turning gears being electric motors, however with a rotational speed of n < 0,01 n_{nom} [7], which in fact disqualifies the determination of mechanical losses of naval engines.

Method of switching off successive cylinders

Method of switching off successive cylinders is reserved exclusively for multi-cylinder engines. This method is based on measurements of useable power of the engine. It is presented on fig. 2. First, the engine is measured in the normal statewith fuel supply and correct combustion in all engine cylinders (point A).

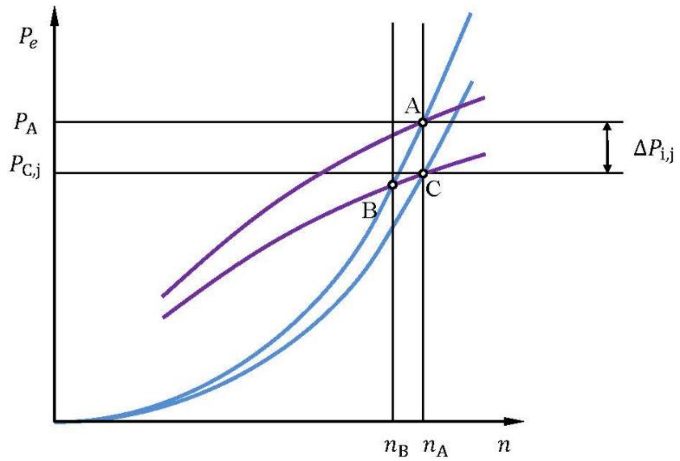

Fig. 2. The essence of determining mechanical losses by switching off successive cylinders

Subsequent measurements are made with the fuel supply switched off in one engine cylinder. This is manifested by the lack of combustion in this cylinder. It is important that during the measurement the engine have to work according to external characteristics or partial loads characteristic, then the lack of combustion on one cylinder will result (at the same fuel rail setting) with the change of the engine cooperation from point A to point B. Also the rotational speed will be reduced from n_{A} to n_{B}. Then engine load have to be reduced so that the speed again reaches the value of n_{A}, finally the engine operating point changes from point B to point C. Do not increase the speed by increasing the fuel dose, as suggested in [2], or omitting this stage [4, 8], due to the fact that the engine's operating point will again be set in point A (fig. 2).

It is assumed that the lack of combustion in one of the cylinders is the same as the ‘loss’ of the indicated power of this cylinder. Indicated power of the whole engine is therefore the sum of all powers indicated from individual cylinders. However, the power of mechanical losses will of course be a difference between indicated power and usable power. Using the markings from fig. 2, the power of mechanical losses will be expressed by the formula:

$$P_{\mathrm{m}} = P_{\mathrm{A}} - P_{\mathrm{i}} = P_{\mathrm{A}} - \sum_{\mathrm{j}=1}^{z} \Delta P_{\mathrm{i,j}} = P_{\mathrm{A}} - \sum_{\mathrm{j}=1}^{z} (P_{\mathrm{A}} - P_{\mathrm{C,j}}) \tag{14}$$

where:

P_{m} — mechanical losses power;
P_{A} — measured useable power at the engine normal state;
P_{i} — whole engine indicated power;
$\Delta P_{\mathrm{i,j}}$ — j-cylinder indicated power;
$P_{\mathrm{C,j}}$ — measured useable power at the engine with j-cylinder switched off;
z — number of cylinders.

The disadvantage of this method is the impact of switching off a single cylinder from work on the process of charge exchange in the other cylinders in turbocharged engines. In the case of marine engines, the method could be applied only to motors cooperating with controllable pitch propellers, due to the possibility of reducing the engine load by reducing the propeller pitch resulting in increasing the speed from n_{B} to the original value of n_{A} (fig. 2). However, it would be possible only if the marine engines work according to external or partial loads characteristics, i.e. they were not equipped with multi-speed governors or after blocking their operation. This is theoretically possible, but under operating conditions very difficult. This is the reason why this method of determining mechanical losses is also not practical in the case of marine engines.

Run-down method

The run-down method is based on determination of mechanical losses based on angular acceleration — $\mathrm{d}\omega/\mathrm{d}t$ while stopping the engine from idle. In this method, the measure of mechanical losses is the torque of mechanical losses. It is based on the fact that when the fuel is suddenly cut off at idle, the engine crankshaft rotates for some time, but with lower and lower rotational speeds until it comes to a complete stop. During this process the sources of energy dissipation are only engine mechanical resistance. If the fuel supply is cut off, assuming that the indicated torque M_{i} = 0 and the torque M_{e} = 0 the dependence 1.6 will take the form:

$$M_{\mathrm{m}} = -J \cdot \frac{\mathrm{d}\omega}{\mathrm{d}t} = -2 \cdot \pi \cdot J \cdot \frac{\mathrm{d}n}{\mathrm{d}t} \tag{15}$$

where:

M_{m} — engine mechanical losses torque;

J — engine inertia moment reduced to the axis of the crankshaft;

ω — angular speed [rad/s];

n —rotational speed [min^{-1}];

t — time.

Determined value of the mechanical losses torque is true for idle and rotational speed at time of fuel dose cut off. The main problem of this method is the exact determination of $\mathrm{d}n/\mathrm{d}t$ values based on the measurement of rotational speeds after cutting off the fuel, i.e. on the basis of the $n(t)$ function and the lack of exact value of the moment of inertia of the engine [2]. In the case of marine engines, this method can be used in indirect drive systems, where engine decoupling is possible. Additionally due to the possible interruption of fuel cutting by existing multi-range governors and relatively short overrun time, it seems not very accurate and as such fraught with a big mistake.

Load characteristics extrapolation method

Load characteristics extrapolation method based on the fact that in diesel engines the load characteristics of the fuel consumption depending on the engine torque $G_{\mathrm{e}}(M_{\mathrm{e}})$ is practically linear for small engine loads [1, 2, 4, 8].

This is the reason why, it is possible to extrapolate with a straight line the load characteristic $G_{\mathrm{e}}(M_{\mathrm{e}})$ up to the intersection of this part of the characteristic with the abscissa axis (fig. 3). The value of fuel consumption for $M_{\mathrm{e}} = 0$ is a measure of engine mechanical losses for a given rotational speed. In the range of negative torque values, energy from fuel combustion with the consumption resulting from extrapolated load characteristics is no longer enough to keep the engine working, additional torque is required. The intersection of the extrapolated load characteristic with the abscissa axis, where $G_{\mathrm{e}} = 0$ determines the torque necessary to keep the engine working, so it is equal to the moment of mechanical loss of the engine at idle. In the case of marine engines, this method seems to be easy to perform due to the stabilization of the rotational speed thanks to the multi-range governors. However, its application is limited only to engines working with a controllable pitch propeller, due to the possibility of a smooth change of load, at constant engine speed.

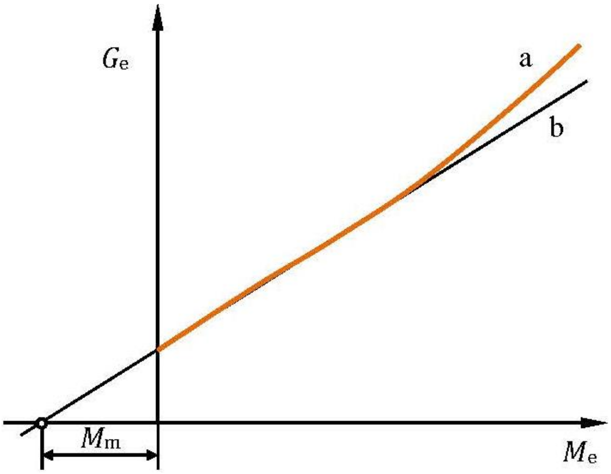

Fig. 3. The essence of determining mechanical losses
by load characteristics extrapolation method

Method of simultaneous indication and torque measurements

Method of simultaneous indication and torque measurements based on the indication and measurements of the selected mechanical loss measure torque which is a difference of the indicated and useful quantity for a constant engine rotational speed. Usually it is the power of mechanical losses or average mechanical loss pressure. It is not difficult to set any indicated measure at this time. For example, electronic indicators developed, constructed and used at the Institute of Shipbuilding and Exploitation of Ships of Polish Naval Academy, using primarily piezoelectric pressure sensors. It allows determining automatically any measure of engine load based on the next several cycles.

Therefore, determining the mechanical losses of marine engines equipped with indicator valves with this procedure looks to be simple. However, additional complications arise here. The use of two different methods for determining the components of the dependence (7) leads to an increase in errors in the determination of mechanical losses, and thus disqualifies the usefulness of this method for diagnostic purposes.

Idle indication method

This method is a special instance of the method for determining mechanical losses described in the previous point (Method of simultaneous indication and torque

measurements). It consists only of engine indication at idle. Obtained indicated measure (indicated work, average indicated pressure, indicated torque or indicated power) becomes for the constant engine speed the measure of engine mechanical losses. The main disadvantages of this method are:
– the effect of the engine load on its mechanical losses is not taken into account;
– restriction to engines equipped with indicator valves;
– limitation of use to ships in which main engine decoupling is possible.

On the other and, this method has a number of undeniable advantages, they are:
– minimization of measurement errors by using only one measurement method;
– determination of mechanical losses in real engine operation conditions;
– easiness of testing.

CONCLUSIONS

The adoption of an appropriate method for testing mechanical losses of a marine diesel engine is dictated mainly by the technical possibilities of testing, as well as their purpose. On an engine located in a laboratory bench equipped with a brake, it is possible to easily determine torque or effective power, which is the basis for the assessment of mechanical losses in most of the described methods. However, the measurement of the torque of the main propulsion engines in the engine room still presents many difficulties, despite the implementation of many new technical solutions. It is connected with temporary and time consuming assembly of shaft torque gauges. Independently of the design of the torque gauge, the measurement of the engine's torque in the ship's propulsion system is based on the shaft section twisting direct measurement [9]:

$$M_\mathrm{e} = J_\mathrm{w} \cdot \frac{G \cdot \varphi}{l_\mathrm{w}} \tag{16}$$

where:
M_e — engine torque;
J_w — moment of inertia of the shaft section on which the measurement is made;
G — Kirchoff module;
φ — twisting angle of the shaft section l_w;
l_w — length of the shaft section on which the measurement is made.

Then, to determine the engine torque it is necessary to know the value of the Kirchhoff module of shaft material on which measurements are made. Such information is not always available. An additional difficulty is often determination of the moment of inertia of the shaft, due to the fact that in the case of a drive system with controllable pitch propeller, the shaft is drilled, and the exact internal diameter of the shaft is rarely known. This is an additional disadvantage of the mechanical loss determination methods described in the previous section (points from method of switching off successive cylinders to method of simultaneous indication and torque measurements).

If the aim of the research would be to prepare an engine internal thermal balance, then it would be necessary to choose a method that allows determination of mechanical losses under different engine load conditions, the matter of their accuracy is secondary. If testing is conducted for diagnostic purposes, a method minimizing measuring errors and taking into account the actual engine operating conditions should be chosen. Due to the limited impact of the engine load on its mechanical losses, it is possible to impose the engine load selection that is convenient for a given method.

A comparison of methods determining mechanical losses was presented in tab. 1. Taking into account the advantages and disadvantages of particular methods and many years of experience of the Institute of Shipbuilding and Exploitation of Ships employees, the best method of assessing mechanical losses of a marine diesel engine from the point of view of diagnostics purposes seems to be method of idle indication. It easy to eliminate the impact of engine load, which in this method should be considered rather as advantage than disadvantage. Additionally significantly reduces errors in determining mechanical losses by limiting testing to one method.

As a measure of mechanical losses, the average pressure of mechanical losses was proposed. Compared to the work of mechanical losses, the power of mechanical losses and the mechanical losses torque, it has several advantages. First of all it is determined directly from the course of the indicated engine pressure at idle. Secondly, mechanical losses work, mechanical losses torque and mechanical losses power depend on the size of engine, or more strictly on the stroke volume of its cylinders. In addition, mechanical losses power is ‘loaded’ by the engine speed. The average pressure of mechanical losses is devoid of these errors and therefore makes it possible to compare the mechanical losses of different engines, regardless of their capacity and rotational speed.

Tab. 3. Comparison of advantages and disadvantages
of engines mechanical losses methods assessing in ship conditions

Method of determining mechanical losses	**External propulsion**	**Switching off successive cylinders**	**Run down**
Measured parameters	P_e or M_e, n	M_e, n	$\frac{dn}{dt}$
Determined measure of mechanical losses	P_m or M_m	P_m	M_m
Advantages		- easy to conduct	- real conditions - easy to conduct
Disadvantages	- unreal conditions - difficult to conduct	- the need to block governor - measuring errors possible	- short time of run down - possible big measuring errors
Limitation of use for marine engines	- almost impossible to conduct on ships	- only in propulsion system equipped with CPP - the need to block governor	- only in propulsion systems where engine uncoupling is possible - governor negative influence
Remarks		- torque meter have to be installed - influence of sea waves on measurements accuracy	

Method of determining mechanical losses	**Load characteristics extrapolation**	**Simultaneous indication and torque measurements**	**Idle indication**
Measured parameters	G_e, M_e, n	L_i, p_i, M_i, P_i, M_e or P_e, n	M_m or P_m
Determined measure of mechanical losses	M_m	L_i, p_i, M_i, P_i, n	L_m, p_m, M_m P_m
Advantages	- real conditions	- easy to conduct - real conditions	- real conditions - easy to conduct - smaller mistakes due to one method of measurements
Disadvantages	- possible big measuring errors	- bigger mistakes due to two methods of measurements	- connection between mechanical losses and engine load is impossible
Limitation of use for marine engines	- only in propulsion system equipped with CPP	- only on engine equipped with indication cocks	- only on engine equipped with indication cocks - only in propulsion systems where engine uncoupling is possible

Method of determining mechanical losses	**Load characteristics extrapolation**	**Simultaneous indication and torque measurements**	**Idle indication**
Remarks	- influence of sea waves on measurements accuracy	- torque meter have to be installed - influence of sea waves on measurements accuracy	

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METODY WYZNACZANIA STRAT MECHANICZNYCH OKRĘTOWEGO TŁOKOWEGO SILNIKA SPALINOWEGO

STRESZCZENIE

W artykule przedstawiono krytyczną ocenę powszechnie znanych metod wyznaczania strat mechanicznych silnika tłokowego na podstawie literatury. Wskazano na ich wady i zalety oraz oceniono możliwość ich zastosowania w okrętowym układzie napędowym.

Słowa kluczowe:
straty mechaniczne, okrętowy tłokowy silnik spalinowy.

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