INSTANTANEOUS PISTON SPEED MEASUREMENT FOR MARINE DIESEL ENGINE COMBUSTION MONITORING

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Abstract

It is important that marine diesel engines run in their normal condition in order to maintain correct efficiency, low pollution and high reliability. The record of in-cylinder pressure pattern and its evaluation is one of the most powerful sources for experimental based analysis of internal combustion engines. In addition, collected data and calculated values expand the engine diagnostic system capabilities. From the other hand reliable calculation of mean indicated pressure and other performance data requires accurate measurement of cylinder pressures and detection of the crankshaft position. It is necessary to ensure correct synchronization of recorded pressure shape with crankshaft position. For this purpose magnetic pick-up to measure the rotational speed from flywheel is usually used as a source of sampling pulses. The instantaneous piston speed can be investigated using the linear movement sensor located inside the crankshaft box. For this purpose marine propulsion testing engine was equipped with optic fiber sensor to perform permanent piston position measurement. Test bed with examined engine is equipped additionally with: optoelectronic in-cylinder pressure transducer, magnetic pick-up to measure rotational speed from flywheel, optic fiber sensor to measure the rotational speed and angular increments from propeller shaft and strain gauge arrangement designed to provide effective torque measurement.

Keywords: marine diesel engine, sea transport, internal combustion engines, engine maintenance

1. Introduction

Marine engine cylinder diagnostics is performed through indicator valves and pipes. Unfortunately, the measurement of the cylinder pressure and TDC position inside of a running engine on board of a ship with easy to handle long lasting instruments is not a simple task. Combustion pressure is analyzed for specific quantitative values (indicated mean effective pressure, maximum pressure, firing pressure angle, cycle variation, etc.) during certain events (valve closures and opening, peak rate of pressure rise, etc.), as well as data variation between cylinders and within a specific cylinder over a certain number of cycles. The final aim is a calculation of indicated power for each cylinder as well as the total engine power derived from the measured cylinder pressures. Engine cylinder pressure analysis is also used to balance and tune the engine: valve and fuel injection timing as well as fuel rate and compression. Improving the reliability of the engine calls for development of engine diagnostics. One of the methods used to meet these requirements is a convenient and real-time cylinder pressure measuring system.

Such cylinder pressure sensors could be utilized in engine control systems. However, dynamic information on cylinder gas pressure in marine engines is restricted due to unreliable

synchronization of recorded pressure shape with crankshaft position [1]. Instantaneous engine crankshaft speed varies during the whole reciprocating engine operation cycle. Many possible ways of estimating the actual piston position through measured crankshaft signals are presented in literature [2], [3], [4]. Most of the methods do not require a specific sensor placed inside the engine crankcase, but are based on the engine speed – measured by the standard pick-up at flywheel. Computational modeling of each piston periodic crank shaft position and speed fluctuations could be used as a basis for engine diagnosis. Certain parameters were found, such as crank friction parameter or instantaneous engine speed that provide a better basis for fault engine diagnosis [5]. The methodology presented in this paper is based on instantaneous engine individual piston position and speed fluctuations, observed in crankshaft rotation inside the engine crankcase. There is an assumption that a correlation is present between the measured speed at engine flywheel and selected (one cylinder) piston position (and speed) inside the crankcase. This correlation has been tested using measured data.

2. Experimental setup

The experimental efforts described below were an attempt to observe crank shaft and piston dynamic position associated with measured engine cylinder pressure. Using test bed engine, having the specification listed in Table 1, examinations were made by means of acquisition setup with transducers listed as follows: magnetic pick-up on the flywheel - to measure average rotational speed, fiber optic sensor – to provide datum for actual piston position and optoelectronic pressure sensor. The cylinder pressure signal was delivered by means of optoelectronic, dynamic pressure transducer. The signal was measured at one of the cylinders of test engine. During measurement the engine was loaded by ship fixed pitch propeller – submerged in water tank at constant revolutions. Test engine propulsion unit and experimental setup is presented in figure 1.

Tab. 1. Test engine specification

Maker	Buckau-Wolf	
Type	four-stroke 8RDV136	
Nominal rate	P_e	220 kW
Nominal speed	n	380 rpm
Bore	D	240 mm
Piston stroke	S	360 mm
Connecting rod	l	720 mm
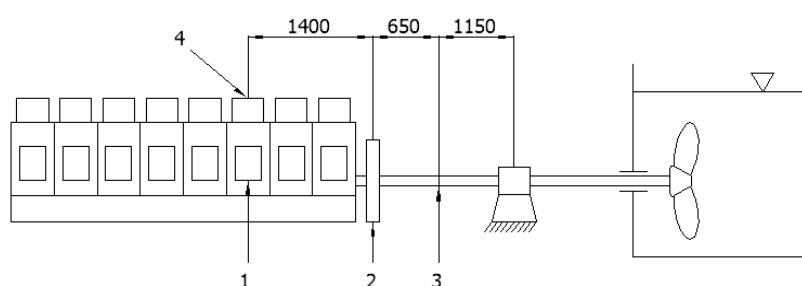
1- piston stroke measurement, 2- flywheel, 3 – propeller shaft, 4 – cylinder pressure measurement

Fig. 1. The test engine and experimental assembly

To avoid any errors when converting transducer's signal into pressure unit the analysis was conducted in voltage domain. Digitalization of the pressure signal was done with adequate sampling rate that should provide expected accuracy for crankshaft position approximation. The rated speed, for present experiment was kept constant by engine governor controller design. A basic acquisition equipment characteristic is presented in Table 2. The piston stroke measurement was done by means of detection arrangement, built in engine crankcase.

Tab. 2. Engine trial basic equipment details

Parameter	Transducer - part	Description
Cylinder pressure	Optoelectronic Optrand, F532A8-ACu	Range: 0 – 34 MPa, 0,85 mV/psi @ 200°C
Piston position	Fiber optic Keyence, typu FU-85Z	Oil and temperature resistance
Flywheel speed	Autronica, GF-1	1 pulse/360°
Data	Acqusition board	PCMCIA - AD126, 12 bit, sampling rate 175 kHz

The detection unit consists of a fiber optic sensor mounted under the cylinder liner and reflecting rod attached to the piston – figure 2. Equidistantly positioned teeth machined in the rim of the reflecting rod were a one way to measure linear piston speed in the engine crankcase environment. Developed acquisition software was used to measure time differences between the teeth as they pass the sensor. An array of time differences was extracted, where the first element of the toothed rod corresponds to the piston position before and after TDC of measured cylinder. From this time-stamp array, instantaneous piston speed as a function of piston position was calculated. Movable part of the measurement unit - reflecting rod was not able to cover the whole piston stroke, but gave a measuring range of 47.5 to 293.5 mm below TDC. That provided 38.35° to 122.84° of the crank shaft turn with 6 mm resolution and caused 42 pulses for one piston stroke. In the test bed, speed of the flywheel and the piston were measured. One thing that should be mentioned, if a position difference between two rotating engine parts exists this fact should be taken account of. In this work this occurrence was not defined. Software was created for extracting instantaneous piston speed data from fiber optic sensor assembly.
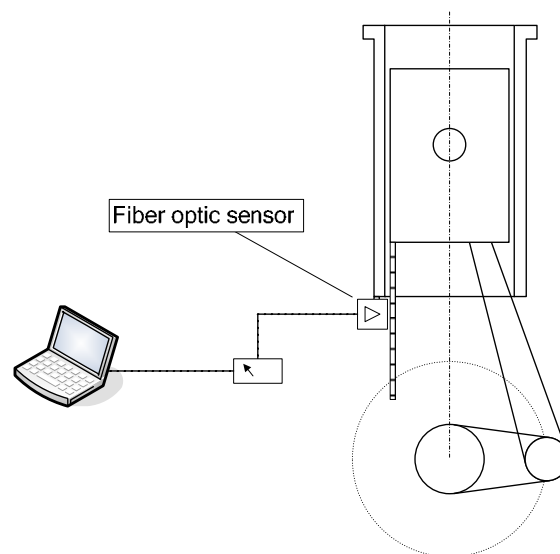

Fig. 2. The piston stroke measurement arrangement

Cylinder pressure measurement within the combustion chamber was almost exclusively made by means of pressure transducers and was associated with data processing system in time domain. Signals were collected to be able to synchronize pressure and speed signals. The pressure sensor (Optrand) mounted on the cylinder was precise, and its signal value was approximately linear to cylinder pressure. It was not feasible to recalibrate pressure sensor so it is assumed that the lowest pressure in the cylinder is close to the exhaust pressure. All signals were measured in the time domain and further analysis could be applied to transform the measured signals onto the angular domain.

3. Development of reference piston position model

For engine cylinder pressure supervision the engine speed measured at flywheel is compared with the measured piston position. The estimated engine piston position is constructed using approximations of the simple formula from which the speed may be calculated:

$$S_{(t)} = r \cdot \left[(1 - \cos \omega(t - t_0)) + \frac{\lambda}{4} \cdot (1 - \cos 2\omega(t - t_0)) \right], \tag{1}$$

where:

$S_{(t)}$ – piston stroke [m],

r – crank radial distance [m],
ω – rotational speed [rad/s],
λ – ratio of crank radial distance to connecting rod length – r/l,
t – time [s],
t_0 – relative phase lag coefficient [s].

Considering an arbitrary time stamp from the speed signal that is wedged in between two flywheel revolutions as angular speed, mean value of six subsequent engine cycles were calculated, and phase lag covered the time step of flywheel pulse for one crank shaft turn. The proposed, preliminary equation can be expressed:

$$\widehat{S}_{(t)} = r \cdot \left[(1 - \cos(\omega(t - a_1))) + \frac{\lambda}{4} \cdot (1 - \cos(2 \cdot \omega(t - a_1))) \right] \tag{2}$$

where:

$\widehat{S}_{(t)}$ – approximation function,

r, λ - test engine components,
t – experiment period,
$\omega = 29.425$ rad/s.
$a_1 = 0.1311665$ s,

The main reason for comparing the measured piston position with the signal from flywheel is to examine if any dynamical differences can be noted. If no major differences are seen, data from flywheel may be used as reference data for the model. However, this may be necessary to examine the flywheel signal with higher resolution. To assess the approximantion quality the corresponding error can be calculated as follows:

$$MSE = \frac{\sum_{i=1}^{i=n} \left(y_i - \widehat{S}_{(t_i)} \right)^2}{n} = 72.017 \tag{3}$$

where:

MSE – mean square error of approximation,

$\widehat{S}_{(t_i)}$ – approximation function for experiment period,

y_i – instantaneous position distance to TDC,

n – number of piston stroke measured samples ($n=545$),

t_i – instantaneous time.

Another approach to equation 2, where ω and a_1 value was established by means of least square technique, gives:

$$\widehat{G}_{(t)} = r \cdot \left[\left(1 - \cos(\omega(t - a_1))\right) + \frac{\lambda}{4} \cdot \left(1 - \cos(2 \cdot \omega(t - a_1))\right) \right],$$ (4)

where:

$\widehat{G}_{(t)}$ – approximation function,

$\omega=29.476$ rad/s,

$a_1=0.132367$ s.

Again, the approximantion quality with the corresponding error can be tested as follows:

$$MSE = \frac{\sum_{i=1}^{i=n}\left(y_i - \widehat{G}_{(t_i)}\right)^2}{n - 2} = 65.168,$$ (5)

Results from both comparison calculations show that the flywheel signals are not much different in their properties and significant error found. Therefore, it is proposed to exchange constant angular crank shaft speed with time - dependant expression:

$$\widehat{\omega}_{(t)} = a_2 + a_3 \cdot \sin(a_4 \cdot t + a_5)$$ (6)

where:

$\widehat{\omega}_{(t)}$ - approximation function of angular speed,

$a_{2..5}$, - determined coefficients (least square solution).

This approach should eliminate significant error observed in recorded data caused by small speed fluctuations. Updated approximation equation for piston position in time domain may be calculated as shown:

$$\widehat{H}_{(t)} = r \cdot \left[\left(1 - \cos(\widehat{\omega}_{(t)} \cdot (t - a_1))\right) + \frac{\lambda}{4} \cdot \left(1 - \cos(\widehat{\omega}_{(t)} \cdot (t - a_1))\right) \right],$$ (7)

where:

$a_{1..5}$ - determined coefficients (least square solution),

a_1=0.130781, a_2=29.380047, a_3=0.106109, a_4= -4.987484, a_5=7.710865.

With use of $a_{1..5}$ in equation 6 and 7 mean square error test applies the comaprison with measured piston position data as follows:

$$MSE = \frac{\sum_{i=1}^{i=n}\left(y_i - \widehat{H}_{(t_i)}\right)^2}{n-5} = 28.515, \tag{8}$$

Equation 8 highlights the improvement of the reconstructed piston position if fluctuations are expressed as variable time - dependent. Piston position and speed fluctuations are present even in motoring condition. As it can be observed in equations 3, 5 and 8, where the comparison is carried out, the quality of approximation function is different. The best result achieved is still unsatisfactory. The consideration need to be modified when the motored and compression-expansion strokes occurred. Nevertheless, it has to be considered that since there are eight engine cylinders and eight combustions accordingly, all strokes are superimposed. This means there are 90 degrees shift between working strokes of the following cylinders (firing order) and all o them influence the speed variation at flywheel. It would be appropriate then to compute approximation function taking into account the measured piston position data over the whole cycle, leading to:

$$\widehat{I}_{(t)} = r \cdot \left[\left(1 - \cos(\widehat{\omega}_{(t)} \cdot (t - a_1))\right) + \frac{\lambda}{4} \cdot \left(1 - \cos(\widehat{\omega}_{(t)} \cdot (t - a_1))\right)\right] \tag{9}$$

where:

a_1=0.131235, a_2=29.376437, a_3=0.105726, a_4= -5.650138, a_5=8.196157.

With use of $a_{1..5}$ in equation 9, mean square error test applies the comaprison with measured piston position data as follows:

$$MSE = \frac{\sum_{i=1}^{i=n}\left(y_i - \widehat{I}_{(t_i)}\right)^2}{n-5} = 15.7615 \tag{10}$$

4. Experimental results

As it has been found, piston instantaneous position and speed is depended over an engine cycle on specific stroke and in-cylinder events. Its fluctuations are mainly due to in-cylinder pressure variations. The reliable calculation of mean indicated pressure and other performance data requires accurate measurement of cylinder pressures and detection of the crankshaft position. To meet this need, detailed piston position and speed on individual engine cylinder unit is expected. The essential idea for the piston position and speed reconstruction is that it can help establish individual cylinder angular coordinate. It could be utilized with flywheel speed measurement. The experimental validation of the piston position and speed reconstruction has been carried out using engine running test. The test under steady state conditions covers one arbitrarily chosen engine load. The effective propeller load – power to speed relation for experimental test-bed can be written:

$$P_e = 0,88993 \cdot n^{2,7759} \tag{11}$$

where:

> P_e – engine effective power [kW],
> n - engine running speed [rpm],

The piston position evaluation with corresponding motored cylinder pressure can be seen in figure 3. Usually, in normal engine service operation there is a necessity to relay on static TDC orientation. However, it does not correctly estimate cylinder dynamic TDC what can be seen as a difference with reconstructed piston position trace and static TDC point in figure 3.
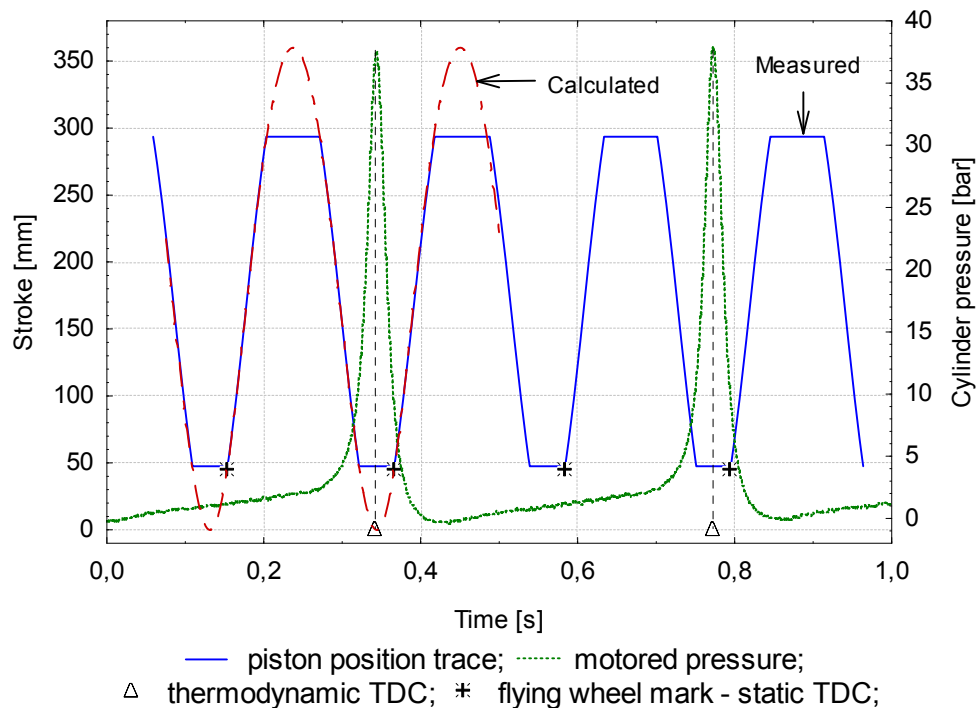

Fig. 3. Piston position reconstruction (cylinder No: 3, n = 282 rpm)

The effect of this error can be minimized if proposed approximation of piston position and speed is implemented. Figure 4 shows discussed piston position approximations error comparison against reference point. A more sophisticated algorithm is required for precise piston position acquisition, so far speed signal detection on flywheel shows improvement from 18 mm (maximum value – S(t) approximation) to 11 mm (maximum value – H(t) approximation).

A noticable differences are seen between reference line and *I(t)* approximate value even though maesurment data was used. That difference would be identified with compression and expansion strokes where the errors for all approximations are serious and confirmed [6].

The main reason of uncertainties in TDC and BDC position where all expected error curves were not made is lack of experimental data. This could be established when the additional measurement for piston position will be prepared in this range. Calculations and comparisons of MIP to other cylinder units are pointless without corrections of this inaccuracy.
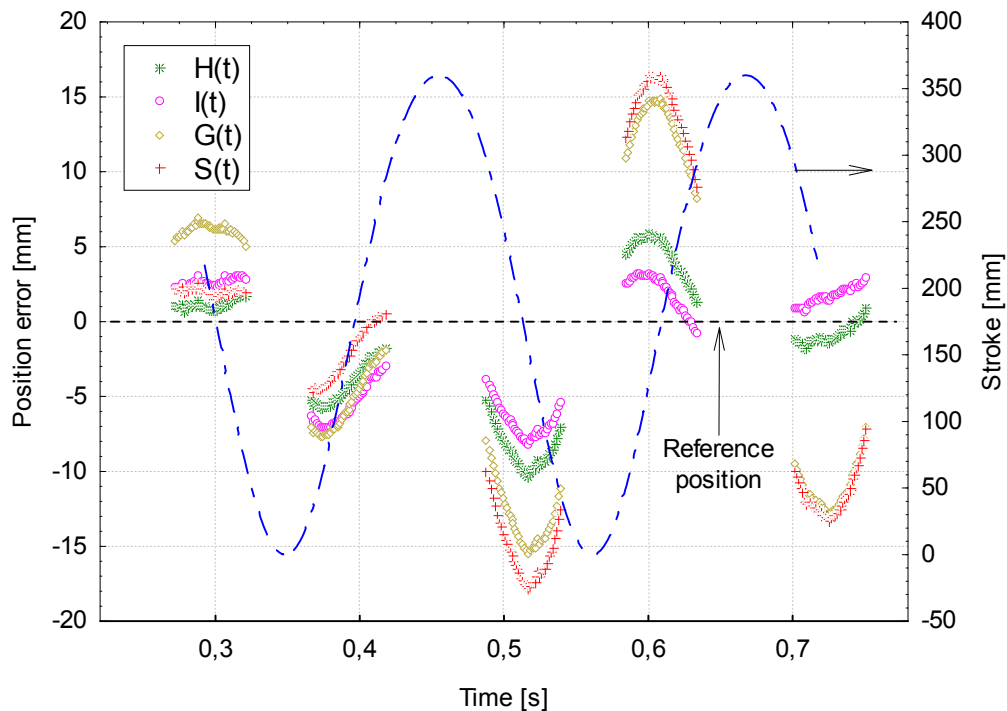
Fig. 4. The approximations error comparison over the full working cycle

5. Conclusions

The in-crankcase piston position and speed measurement system has been shown to be an effective technique for detection of specific speed fluctuations. The trial results from the diagnostic system showed that each piston stroke related to working cycle is different and can be distinctively recognized. As seen in figures in previous sections, each engine operational stroke creates different piston speed resonance. Obviously, this causes torsional vibrations in the crankshaft. The speeds from the piston measurement are significantly phase shifted comparing to the flywheel speed fluctuations. This may be due to engine - propeller configurations, but it is more likely due to dynamics between the flywheel and the specific piston unit in the test-bed environment.

Furthermore, the cylinder pressure estimation based on reconstructed piston position could be more reliable if the periodicity in the speed fluctuations with respect to crank angle will be modeled. Variations in this periodicity are strong indicators for individual cylinder and may be detected by comparison with the reference level.

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