UNSTEADY ANGULAR SPEED OF DIESEL ENGINE CRANKSHAFT PRELIMINARY EXAMINATION

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Abstract

The paper discusses issues related to measurement of unsteady angular speed of diesel engine crankshaft. The focus is on the selection and optimization of the measuring method to obtain high accuracy, eliminating errors resulting from the unsteady angular speed of markers on diesel engine crankshaft. A method that uses a counter markers placed on the engine flywheel had been worked out. Markers location has been read out by two slit optical sensors. Number of markers and the distance between the sensors were chosen so as to counter tooth during the transition between the sensors count the more than 10,000 pulses at rated speed of the shaft. This provided a measurement method resolution at 0.01 %. Initial studies were performed on one-cylinder diesel engine with the greatest unsteady of angular speed. Additionally analysis which treated the measured unsteady angular speed of diesel engine crankshaft as a deforming pressure mapping as a function of the calculated piston movement was performed. This deformation is caused by the assumption that a constant rotation speed is proportional to time, and measurements are made at a constant rate. In the case of synchronized measurements of PLL circuits duplicating markers on the shaft against the expectations the deformations due to the activity of the follow-up mode of such systems are increased. The influence of these deformations on the designation of an average error of cylinder indicated pressure and other parameters obtained from the analysis of the pressure and vibration envelope has been examined.

Keywords: *cylinder pressure measurement, piston engine, indicating*

1. Introduction

Author of this paper has been working in the Polish Naval Academy about 20 years and during this time indicating main and auxiliary internal combustion engines on board civil and navy ships and gas engines and gas compressor type GMVH in gas stations in Poland. Previously conducted research in the Polish Naval Academy (PNA) was mainly focused on processing of indicator diagrams. Through the compression process approximation the model pressure curve was determined and on it basis: TDC, the initial pressure, the compression pressure, compression ratio, etc. was designated. The study confirmed that this method gives good results in the case of gas engines, diesel engines, diesel generator type 6AL20/24 engine in the laboratory and main engines A25/30 family on several types of ships. Satisfactory results were obtained even with a simple polytrophic model. However, on the same engine family A25/30 but on some others ships, and on the low-speed engines process model diverged significantly from the measured parameters and achieved results derived from the model in random way. Extension of the model which included a heat transfer during compression, the gas leakage trough gaps and the impact of the indicating channel had lengthen the calculations time, but had a negligible impact on the derived parameters. So it was decided to look after cause of the error during the measurement process itself.

During the indication measurements are usually expressed as a function of crank angle. In the laboratory measurements, for the timing measurements angular position detector integrated sensors are normally used with the required resolution, for example, 3600 pulses per revolution. This ensures a perfect reproduction of the pressure as a function of the way of the piston. In the operating conditions due to lack of access to the free end of the shaft assembly of such a sensor is difficult or even impossible. Therefore, to synchronize the measurements, less perfect other methods are used. In the past, duplicative methods dominated in which inductive sensors signals were responsive to the turning gears teeth, or specially-made marks on flywheels and shafts. The PNA developed a system for synchronization with two sets of PLL and a few counters. The system recognized the amount of markup and always generates 3600 pulses regardless of the number of tags. A novel method for measurements timing which was produced and used to diagnose marine diesel engine generator sets by PNA were ship electrical installation frequency multiplication method. The frequency multiplication of the power supply system 3600/*n* times, where *n* = number of generator pole pairs, obtained exactly 3600 pulses per revolution of the engine shaft. One should be aware that the PLL circuit is a follow up system and if there is a momentary angular speed change in one sector, then the answer in the form of changes in pulses density triggered measurements will be observed only in the 3 and 4 sectors. With a small amount of tags these leads to greater pressure curve deformation than in the present time course measurement method. So now, in all portable indicating devices measurements are made with a constant sampling rate obtaining the pressure curve in the time domain. Assuming that the angular velocity is constant, it is assumed that this is equivalent to mapping the pressure in angle domain.

The work of the piston engine is characterized by torque value fluctuations in time. At work stroke of the one cylinder engine gas pressure accelerates the crank system, while the remaining strokes decreases crank angular velocity. To minimize changes in the angular velocity multi-cylinder engines are used and fitted into relatively heavy flywheels. The measure of inequality is the engine angular velocity inequality ratio defined as:

$$\delta = \frac{\omega_{\max} - \omega_{\min}}{\omega_{śr}}. \tag{1}$$

In typical automotive engines the factor of inequality in the case of correct adjustment reaches values in the range from 1/250 to 1/150. With such a low value of engine angular velocity inequality ratio simplification that angular velocity is constant seems to be justified. Equally low values of these coefficients achieve auxiliary engines, where the load is balanced and the weight of the generator rotor also increases the moment of inertia of the flywheel. In the case of main marine diesel engines run effect of inequality is the result of interference between the engine torque variation and variability of the load torque. The load changes when the propeller blade passes directly in front of ruder fin, close to the hull surface, in particular by the action of sea waves.

The concept of using the engine angular velocity inequality in the diagnosis of the engine is almost as old as the engine itself. Measuring inequality of the engine speed is offered for example by the ENAMOR company as an additional option in torque meter. However, due to insufficient resolution and distortion caused by unequal loading, the usefulness of this type of equipment is insufficient to bring a clear diagnosis. You can clearly detect not-operating cylinder, but minor differences in engine balance lost in the interference from other sources.

In the current carried research works it was decided to separate from the course of the instantaneous acceleration velocity due to cyclic operation of the engine the accelerations caused by uneven load of the engine and the work of engine governor. The first step of the work is to develop a methodology for measuring of the instantaneous angular velocity of the engine being exploited to provide adequate resolution and to allow representation of the velocity in the crank angle domain.

2. Measurement of the instantaneous speed of the crankshaft

In a laboratory angular acceleration can be measured by using special design seismic sensors mounted on the shaft. These sensors are constructed on the basis of torsiograph Geiger detectors with a spring driven mass. Movement of this mass relative to the housing is measured. However, in operating conditions, due to lack of access to the free end of a shaft, other source of signal should be used. The simplest method is the counting method, in which the time that elapses between successive markers transition placed on the shaft in front of the sensor forehead is counted. Inductive or optical sensors are mostly used, and as markers turning gears teeth, specially fitted pegs or code discs mounted on flywheel or shaft. Tags are usually read-out by inductive or optical sensors.

Engine angular velocity inequality ratio in case of medium speed marine engine reaches a value of about 1/100. To perform mathematical analysis referred would be getting in this case at least 100 quantization levels, and therefore the resolution of the method must be greater than 1/10000. Since the accuracy of the counting systems is taken as ± 1 pulse it is known that to achieve assumed resolution of the counter between the markers at maximum engine speed has to count no less than 20000 pulses. To reduce the number of 16-bit counters, the counter should count no more than 2^{16} pulses at a minimum shaft speed. Thus, the angle between the marks must be written between:

$$\alpha_{\min}[°] = 360 \cdot \frac{T_{\min}}{f_{osc}} \cdot \frac{n_{\max}}{60} \text{ and } \alpha_{\max}[°] = 360 \cdot \frac{T_{\max}}{f_{osc}} \cdot \frac{n_{\min}}{60}, \tag{2}$$

where:

T_{min}, T_{max} – minimum and maximum number of pulses counted during the T period,
n_{min}, n_{max} – minimum and maximum engine shaft speed – RPM_{min}, RPM_{max},
f_{osc} – strobe pulse frequency

Assuming for the most popular in the Polish Navy A25/30 type Sulzer engine's family: $RPM_{max} = 750$; $RPM_{min} = 350$ and $f_{osc} = 12$ MHz frequency as a typical for 8-bit processors the smallest and largest angle between the markers were calculated:

$$\alpha_{\min} = 360 \cdot \frac{20000}{12000000} \cdot \frac{750}{60} = 7.5° \text{ and } \alpha_{\max} = 360 \cdot \frac{65536}{12000000} \cdot \frac{350}{60} = 11.5°. \tag{3}$$

Dividing the full angle by the angle between the markup and rounding the minimum result up and the maximum result downwards maximum and minimum number of tags has been obtained. In case of this engine it is a number from 32 to 47 marks. In studies conducted in other scientific centres far greater number of markers such as 134 or 120 were used. In this way can get more measuring points at the expense of resolution. Improvement in resolution was obtained by multiple results averaging, however, losing information about the unevenness of the load.

To count the pulses can be use any microprocessor having a fast 16-bit counter with the possibility of buffer the result. In the preliminary tests the ADuC841 type microprocessor consistent with 8052 standard was used, executes instructions in a single clock tact with possibility time measurement with a resolution of the CPU clock frequency. The T2 timer configured as a counter-timer counting pulses of 12 MHz frequency in mod 2^{16} was used. Falling edge of the pulse from sensor provided on input P1.1 (T2EX) will rewrite the counter result to the buffer register and interrupt request. In the interruption the difference between the buffer register state and its previous value can be transferred to a PC as two bytes and store the current state of the buffer register. For the measurement results sending serial port with clock rate of 115 000 Bps was used. The maximum frequency to sending 16 bits + 2 bits of the start and 2 bits of stop is potentially equal to 115200/20 = 5760 measurements/sec. Because the tags appear in the frequency $Z \cdot n_{max}/60 = = Z \cdot 48 \cdot 750/60 = 600$, so close to 10 times slower, it does not impede the transmission of measurement and do not need to buffer the results before sending. This measuring system is extremely simple requiring only the microprocessor with a quartz resonator and levels converter to RS232 transmission. However, such a system has one drawback. To maintain the assumed resolution requires the deployment of tags with an accuracy not worse than 1/20000 the distance between the marks. Such accuracy do not have turning gears teeth and manually mounted markers. For the detection of markers are not suitable popular inductive sensors that have too long and somewhat random response time, which depends mainly on the distance between the tag and the sensor. During the measurement due to shaft eccentricity and structure vibration this distance is changed so that the effect of unequal and changing the distance between the sensor and the marker brow dominated the registered signal. This was the main cause of failures of this type of research conducted in the past. Therefore, the solution in now built prototype, modelled on Enamour company torque meter uses optical sensors - common slot transoptors with an average response time 4μs. However, the uneven marks distribution error have remained. This error has been eliminated by expanding the measuring system with an additional sensor. The marker transit time between the two sensors has been measured. Both sensors detected the appearance of the same interval between markers. This required the development of counters control system according to the diagram in Fig. 1.

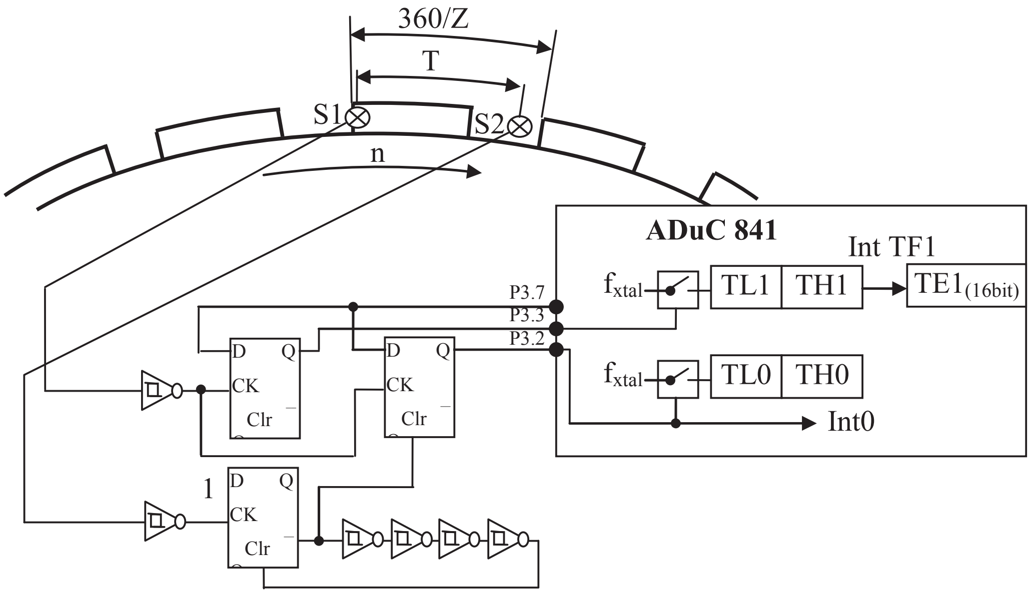

Fig. 1. Schematic of the measuring system

Falling edge of the sensor S1 initiates the time measurement and the falling edge of the sensor S2 stops counting and reports the interruption in which stores the state of the counter, resets the counter and sent remembered value to the PC. Even during the sending process system is ready for the next measurement. The angle between the sensors S1 and S2 must be less than the angle between the markers by the sum of the shaft rotation angle at the time necessary for transcription, and resets the counter and the distribution tolerance of markers. In a such situation wide differences in tags and their uneven distribution do not affect the timing error.

Timing at the relevant points of the measurement system are shown in Fig. 2.

The instantaneous rotational speed can be calculated as:

$$n_i = \frac{f_{osc}}{T_i} \cdot \frac{\alpha_{(S1-S2)}}{360} \cdot 60\,. \tag{4}$$

The accuracy of such measurement is also determined by accuracy of measuring the angle between the sensors. Angle measurement using geometric methods in marine conditions is rather difficult. Counting transit time consecutive markers in the counter *T*0 and at the same time counting the entire measurement duration in the counter *T*1 instantaneous rotational speed was calculated from the formula:

$$n_i = \frac{\sum_{j=1}^{k} T0_j}{T1} \cdot \frac{T0_i \cdot 60}{f_{osc} \cdot Z}\,. \tag{5}$$

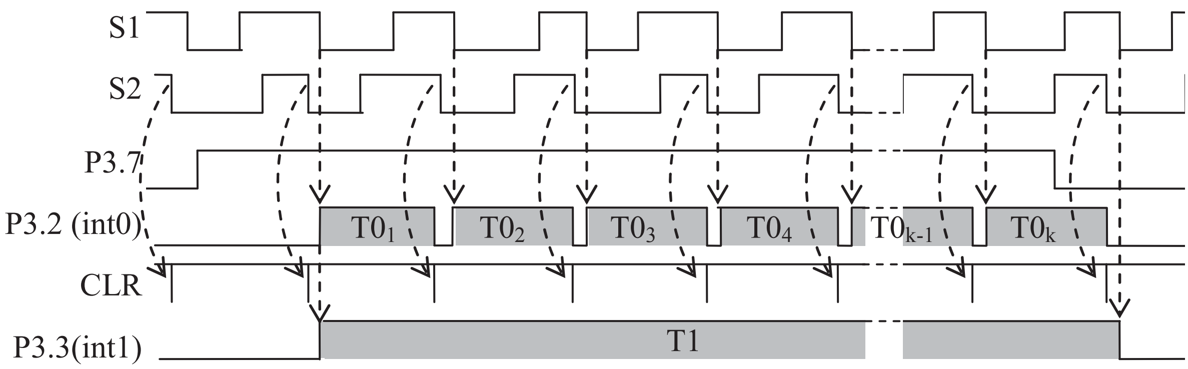

Fig. 2. Timing in the measuring system

3. Tests

Preliminary tests of measuring methods were conducted on KM-170 type engine. It's a small one-cylinder engine with displacement of 210 cm^3 and the power of 3.1 kW at 3600 rpm. Because of the higher rotational speed of the engine the number of tags was reduced to 18. Markers of aluminum plate with a thickness of 0.2 mm were glued to the flywheel. Mounting of markers and slot transoptors are shown in Fig. 3.

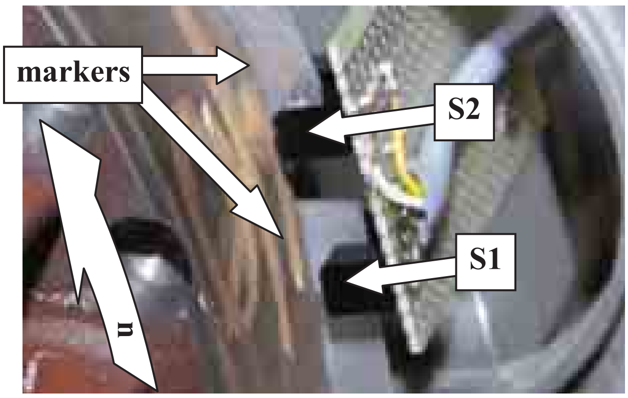

Fig. 3. Mounting of markers and slot transoptors

To facilitate results interpretation the tags were placed so that when the piston is at TDC the end of one marker was located exactly between the sensors. It is advisable so that in case of 4-stroke engine doubled number of tags is divisible by the number of cylinders. Sample results of the measurement times are shown in Fig. 4.

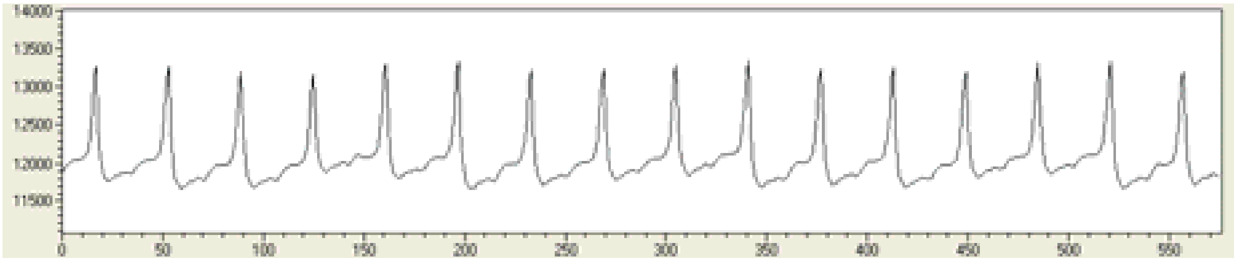

Fig. 4. Sample results of measurements of transit time consecutive markers between the sensors at 1,800 engine rpm with no load

On the basis of the measured times instantaneous angular velocity of the engine shaft was calculated. An example of instantaneous angular velocity calculations, expressed as a function of crank angle is shown in Fig. 5.

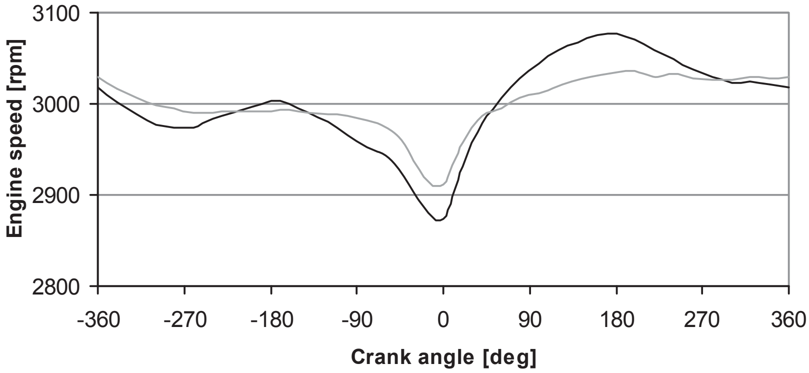

Fig. 5. Result of the conversion time to the instantaneous rotational recorded speed at a speed of 3000 rpm grey – no-load and black – load 1.2kW

Then a comparison was made of the shaft position at time T_i from the TDC calculated according to the simplified formula assuming constant rotational speed:

$$\alpha_{\tau i} = 360 \cdot \frac{T_i}{\tau}, \tag{6}$$

where:
T_i – time from start of measurement,
τ – time of one rotation.

From the shaft position calculated from measured instantaneous rotational velocity by the formula:

$$\alpha_{\omega i} = \sum_{k=1}^{i} \frac{n_k \cdot \dfrac{k}{f_s}}{60}, \tag{7}$$

where:
k – number of samples,
n_k – average speed between markers,
f_s – sample rate.

The comparison results are shown in Fig. 6.

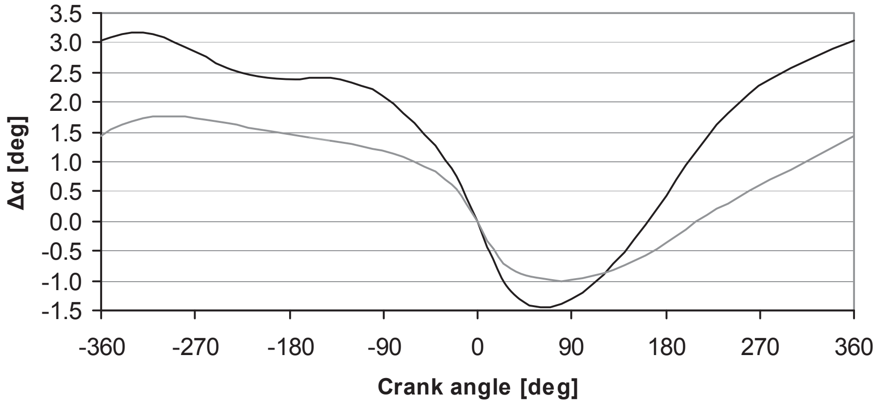

Fig. 6. Result of the instantaneous angular speed conversion on the angular samples error taken at a constant frequency rate at engine speed of 3000 rpm with no-load – grey, and load 1.2 kW – black

In case of tested engine differences in shaft position calculation by both methods depend on engine speed and engine load. At the nominal engine load the differences exceeded 4.5 deg. This error is also made when determining the characteristic points of the cylinder pressure curve from the graph. However, in a typical properly working multi-cylinder marine engine, these differences should be much smaller. Tuning errors or exemption from the work of one cylinder of a multi-cylinder engine can lead to a situation similar to the one-cylinder engine and the adoption in the calculation of the instantaneous angular velocity as a constant will be source of errors in the interpretation of indicator diagrams.

4. Conclusions

Studies conducted on the KM170 type engine confirmed high resolution of proposed instantaneous rotational velocity measuring method.

Error of the shaft calculated position by using method which not taking into account the uneven engine angular velocity in the worst case exceeded 4.5deg. It leads to deformation of the cylinder pressure curve that impedes the graph interpretation.

These studies were performed on a small one-cylinder engine, but the results are so alarming that this should be a check on the typical ship diesel engine.

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