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PROCESSING OF LONG LASTING SIGNALS OF TORSIONAL VIBRATIONS MEASURED USING INCREMENTAL ENCODERS

Mirosław Dereszewski, Grzegorz Sikora

Gdynia Maritime University
Mechanical Faculty
Morska Street 83, 81-225 Gdynia, Poland
tel.: +48 58 6901398
e-mail: m.dereszewski@wm.am.gdynia.pl
g.sikora@wm.am.gdynia.pl

Abstract

The article describes processing method of a signal, coming from torsional deflections of an internal combustion piston engine's crankshaft, registered using two optical encoders ETNP-10. Standard measurement and recording set ETNP-10 enables recording of Instantaneous Angular Speed values encompassing 10 revolutions of the crankshaft, what is equal to 5 cycles of four-stroke engine. That time duration is sufficient for analysis of changes of angular speed caused by, for example, malfunction of fuel injection valve, but is insufficient in case of observation characterized by low frequency changes with period of fluctuations, lower than 0.8 sec. Short time for recording makes impossible following of instantaneous angular speed deviations caused by magnitude modulation of engine's load value. In the article is presented an algorithm written in MATLAB environment, which allows processing of the data recorded using the recorder DAS 1600 Sefram. The recorded this way signals have around 26 seconds' duration of engine work. Data acquired from two encoders mounted at opposite sides of the shaft, in form of square magnitude signals are transformed into instantaneous speed and subsequently to instantaneous angular shift, what is basis for torsions calculation. In the article is also presented method of elimination of systematic error due to assumed method of averaging. Finally, some examples of results of torsional deflection measurement and analysis are presented.

Keywords: *diagnostics, diesel engine, torsional vibrations, torque and angular speed*

1. Introduction

Diesel engines are one of the most critical mechanisms having impact on safety of shipping. Unpredicted failures of engines, installed on board as main propulsion or electro-generators units can result with serious consequences, jeopardizing human life and environment. One of the most common problems occurring during diesel engines operation are malfunctions of fuel injection systems and subsequently problems with main and journal bearings lifetime [1, 2]. Moreover, as far as electro-generators are concerned, irregularity of rotational speed can affect quality of delivered electric energy (frequency stabilization). Detection of the piston – sleeve set giving no proper contribution to the total engine's torque value is possible in way of measurement of in-cylinder pressure using electronic or mechanical indicators. That method, although very effective has some inconvenience. First one is related to an engine construction – one has to have indicator cocks at every cylinder, second one is due gauges vulnerability, high temperature and exhaust gases pollution do not let continuous monitoring. Above presented facts leads to the conclusion that any other way, free from presented inconveniences shall be accepted for practical implementation [5].

In internal combustion piston engines, reciprocating movement of pistons is converted to rotary movement of the crankshaft. The angular speed is strongly affected by tangential force coming from gas pressure and vertical imbalance inertial forces induced by reciprocating masses of piston and connecting rod. The character of acting forces let assume that IAS can be utilized for detecting engine faults related to combustion process. Because of sequential ignition in cylinders and differences of combustion quality (i.e. burning process speed and duration, heat emission, pressure expansion) occurring between cylinders, angular speed of a crankshaft is not uniform. Variations of instantaneous angular speed value are reflecting level of unsteady character of subsequent pistons contribution. Pressure of combustion gases is transformed to a crankshaft in form of variable force, which depends on pressure value and crankshaft position. That force creates torque necessary for attached driven mechanism movement. In our case that was electro-generator producing alternate current. Superposition of instantaneous values of torques coming from driving engine and driven generator, with opposite vector direction, is reason of torsional vibrations of the shaft. Due to origin of occurring forces, character of torsional vibrations shall reflect quality of combustion forces.

The main goal of carried out investigation was answer the question whether IAS based torsional signal coming out from both ends of the crankshaft can be a source of information about combustion irregularity and whether level of torsional vibration can be controlled using IAS measuring method.

2. Description of IAS measurement system and characteristics of the test rig

One of advantages of every cylinder combustion quality evaluation based on IAS analysis is a possibility to utilise a flywheel teeth as a signal source [1, 5]. In that case however, one encounter of the problem of limited samples number, depending on a flywheel construction (number of teeth at flywheel), and necessity of marking a crankshaft position when 1st piston reaches TDC, in order to establish an angular domain for measurements function, and identify pistons' angular phases related to a combustion stroke. Other solution is mounting on a shaft f a toothed ring, with number of slots or teeth which multiplication gives 360 degrees. The slots number must not be less than 60; otherwise, accuracy of measurement is too low to evaluate dispersion of mean effective cylinder pressure [1].

All measurements were carried out using photo-optical torque meter ETNP-10, fabricated by the P&R Enterprise ENAMOR Ltd. The torque meter has two toothed rings, 90 teeth and slots each. Sampling is done by laser sensor with photodiode, on the way of counting impulses when slot is crossing a laser ray (value "1") and when a tooth is crossing a laser ray (value "0"). Number of counted impulses (emission is with constant frequency) represent width of the slot at instant angular velocity, and a number of "blind'' impulses represent width of a tooth. The torque meter possess two discs necessary for a measurement of shaft's torsion and subsequently torque calculation. For IAS analysis purposes one disc is enough, thus two discs mounted on shaft can be assumed as one disc with double slots number, or two independent measurements with a phase shift. One disc has an additional narrow slot, which role is to mark 1st cylinder TDC position. For torque measurement purposes, the distance between cylinders ends, clamped around the shaft is 4000 mm. Measurements data are recorded at a memory card of PLC (Programmable Logic Controller) SAIA PCD 3. Data, after conversion by dedicated computer program, can be transferred to MS Excel format, for further analysis. General constraint of SAIA recording programme is the limited number of registered revolutions. Originally, designed system was dedicated for control of power and torque but calculated as mean value of 3 revolutions. Setup of the system is adjusted for recording of 10 subsequent revolutions, what was establish for control of two stroke low revolutions marine engines. Two-stroke engines mode of work is different; than 10 revolutions refer to 10 cycles thus memory, setup was absolutely sufficient. During experiments based on measurement of torsional deflection, was observed phenomenon of "waving" of torsional wavelets (see Fig. 1). Available records covering 10 revolutions are too short to conclude about genesis of that behaviour. First analysis of FFT says that frequency of that additional component is less than 1 Hz what let assume that full cycle of considered waving covers more than 10 revolutions. Analysis of character and source of that phenomenon requires recording of many more revolutions, what cannot be done with standard system. Solution of that problem was possible by change of recorder. For that was selected multichannel signal recorder SEFRAM. It reads voltage type signal with sampling frequency of maximum 1MHz what is value 16 times lower than ENAMOR (16 MHz). Torsion calculation is based on differential value of instantaneous angular way, which is calculated from instantaneous angular speed. Instantaneous angular speed is calculated using formula (1):

$$\omega = \frac{\varphi \cdot f}{z}, \tag{1}$$

where:

ω – angular instantaneous speed [rad/sec],
φ – width of slot or tooth in disc [rad],
f – sampling frequency [Hz],
z – number of recorded impulses.

It means that with constant width of a tooth or slot, calculated angular speed is a mean speed, and its accuracy depends, from one hand, on number of slots around disc and frequency of signal receiving from the other. Number of slots is naturally limited by technology of discs manufacturing method.

It created a question about accuracy and resolution of measurement. Taking under consideration revolutionary speed of the engine and width of slot in the discs, one can get around 250 sampling signals for one slot.

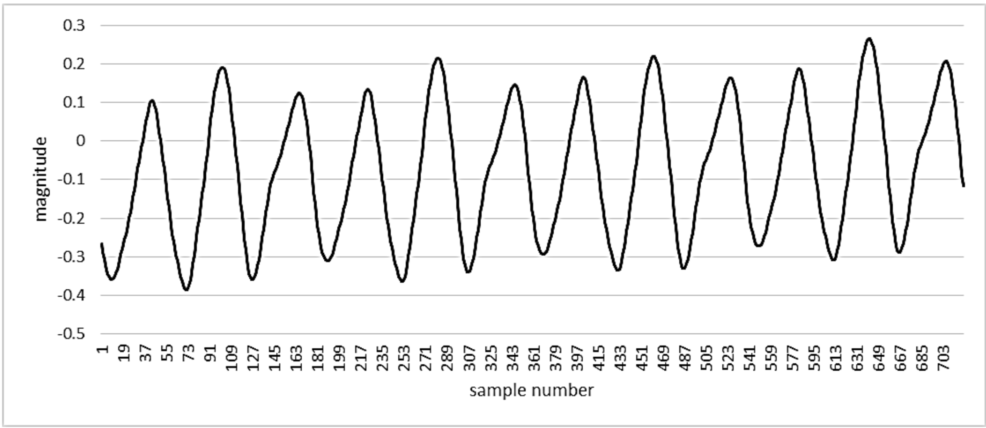

Fig. 1. Smooth signal waveform of torsional deflection encompassing four cycles (8 revolutions of the crankshaft)

For example, number of samples of ENAMOR measurement head is around 4000, what is the reason of memory limitation and data transfer constraints, but from other hand gives much bigger protection against errors due to signal rising and falling edge.

3. Description of experiment assumptions and measurements plan

For experiment purposes, ENAMOR measurement heads were connected to SEFRAM DAS 1400 recorder simultaneously with ENAMOR recording system. Registration of crankshaft torsions were conducted under load of 280 kW, what is corresponding to 70% of maximum continuous rate of test engine. The aim of test was to register signal as long as possible, with maximum sampling rate, for further processing. Expected result was to detect major harmonic components of the torsional wavelet, coming from reciprocating forces and mentioned before, “waving” source. It was possible to register 273 subsequent revolutions during 21.8 sec. Analysis of shows, that envelope of two revolutions (one cycle) has proper shape, but probably due to permanent error; generally, linear descent of wavelet can be observed (Fig. 2). Elimination of the error was crucial for further analysis, because in obtained form, results were absolutely not useful.

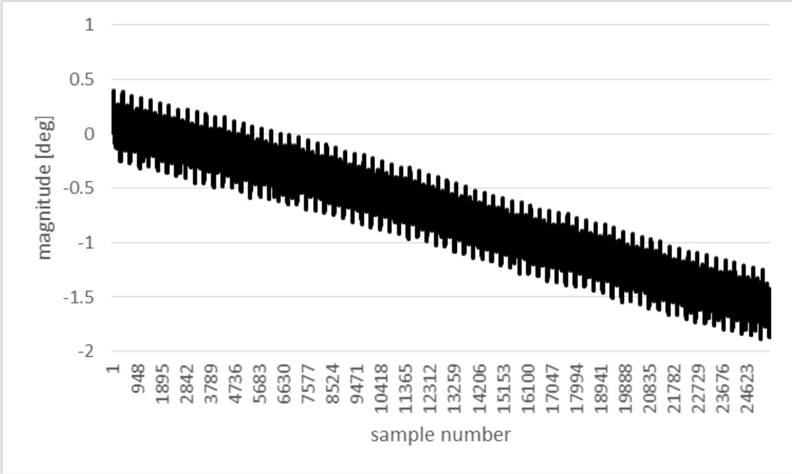

Fig. 2. Raw signal waveform of torsional deflection encompassing 273 revolutions of a crankshaft

4. Data processing

Recorder SEFRAM DAS 1400 is signal reading in voltage form from ENAMOR reading heads and writing it in the same form of voltage level. For optical head mounted in free end of the engine state of high signal level means voltage value 2.2 V, and low state is equal to -1.7 V. In opposite end of the crankshaft, mounted there optical head has high level signal of 2.25 and low level signal 0.85 V. Differences between optical heads were not intentional but because of development of measurement set. Original set was dedicated to IAS measurement only, the second disc and head were added later for torque control, thus the optical head is from later production, after modernisation.

High voltage state is given in case of a tooth detection; low state is related to detection of a slot. Examples of recorded levels of voltage and related Boolean state of signal are presented in Fig 3.

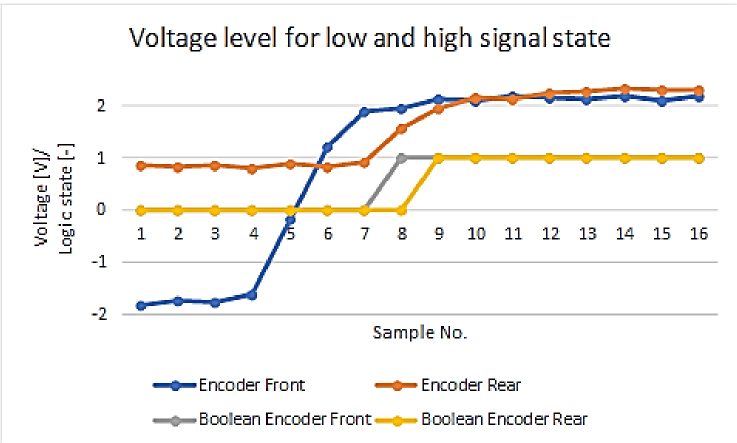

Fig. 3. Harmonic Spectrum of torsional deflection's raw signal, a – 650 rev/min.; b – 700 rev/min

In case of changes of state, problem of distinguishing between high state and low state does not occurs, and eventually error of measurement is limited to single impulses. Unfortunately, for some rising and falling edges, fluctuations of before stabilisation can reach 10% of signal value, and that is why detection threshold was set up at 1.984 V for master (engine's free end) and 1.7 V for slave (generator end) head. Mentioned fluctuations can be caused by numerous factors such as interference because of too low cable shield insulation, instability of power voltage, induction interference. Proper set up of threshold voltage is crucial factor for further analysis. Either too high or too low sensitiveness of the threshold can be reason of appearance of additional edges, and its number cannot oversteps 180 for one revolution of a crankshaft.

During analysis of falling edges of master disc, was spotted that in many cases, edge is falling for few microseconds, subsequently is rising to high state level, and after couple of microseconds is falling to decent level of low state. This phenomenon was observed in all registered records, regardless level of engine load and engine sate. It was preliminary assumed that mentioned phenomenon can be caused by vibrations of the engine or vibrations of the encoder head because of foundation vibrations, as second reason was considered high frequency torsional vibrations of the crankshaft. What is interesting from analysis point of view, that phenomenon does not occur at slave disc. Second (slave) disc is reflecting torsional vibrations of the generator rotor, thus obtained signal can be naturally smoother because of high mass of generator rotor and smaller impact of reciprocating forces. In Fig. 4 is presented an example of the edge affected by mentioned problem.

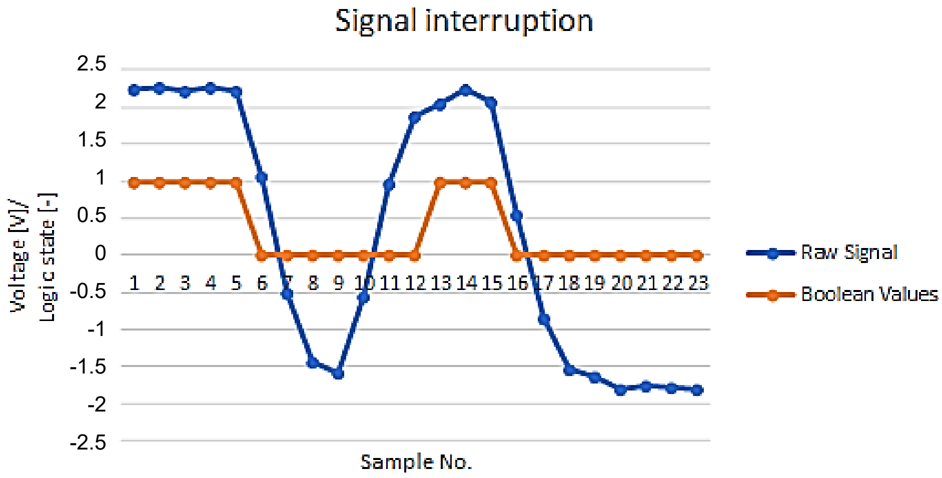

Fig. 4. Disturbance e of signal in form of short time falling of voltage during high state phase (jumping edge)

Phenomenon of short time jump of signal will be an aim of further investigation, and detection of its source requires additional experiments. For time, being, to enable measurement of torsional vibrations, was implemented filtering procedure, which eliminates this problem. Mode of operation of the filter bases on detection of teeth and slots having width lower than 20 impulses, and adding artificial number of impulses so as total number was equal to previously registered, it means creation of artificial tooth or slot as copy of previous. In Fig. 5 is presented result of filtering, run with sharp edge is the expected result of processing of signal presented in Fig. 4.

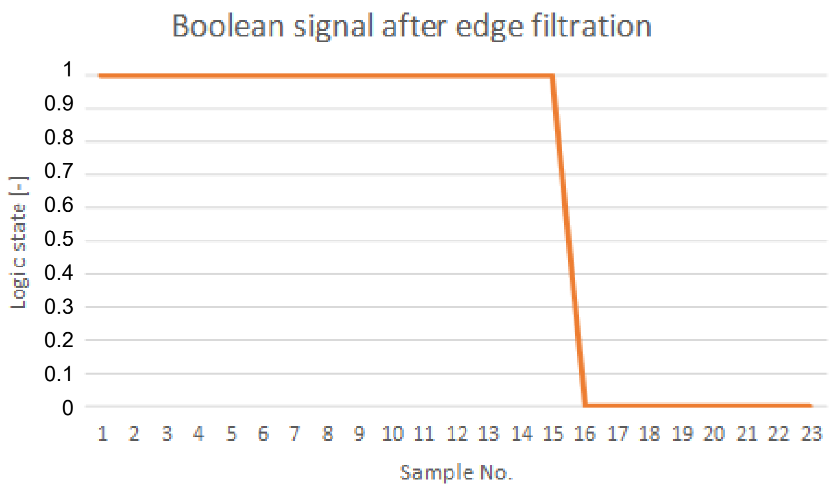

Fig. 5. Example of window's edge obtained by filter processing of the signal with jumping edge

Another observed disturbance giving finally different number of edges between slave and master disc within one revolution is trigger slot, additional narrow slot for identification of TDC (Top Dead Centre) position of 1st cylinder's piston. Such slot is only at master disc, what gives additional element for detection and finally creates errors. The problem is very serious, because makes linear descending of signal's envelope (see Fig. 2). Detection and elimination of this inconvenient is quite simple, because is symmetric and repeatable, occurs in every revolution and in the same angular position. Mode of processing is similar to that implemented for jumping edges, only difference is number of impulses for detection. Trigger slot is inside of standard width tooth what means that must be shorter than 60 impulses (for revolutionary speed of approximately 750 rev/min). Processing is based at addition of impulses. They coming from two short teeth and short slot what make one "standard" tooth. What is worthy to be mentioned, sequence of filtering is very important, first are detected, and eliminated jumping edge disturbances, and subsequently TDC trigger slot. Additionally, tooth with trigger slot is marked in additional colon of records, what gives opportunity of identification of eventual deviations and positioning in crank angle domain.

The final step is control of total number of edges for both discs, number must be equal, and total number of impulses must be equal. Such verification is simple and is based on comparison of matrix size. Example of signal from both ends of the shaft, after filtering, is presented in Fig. 6.

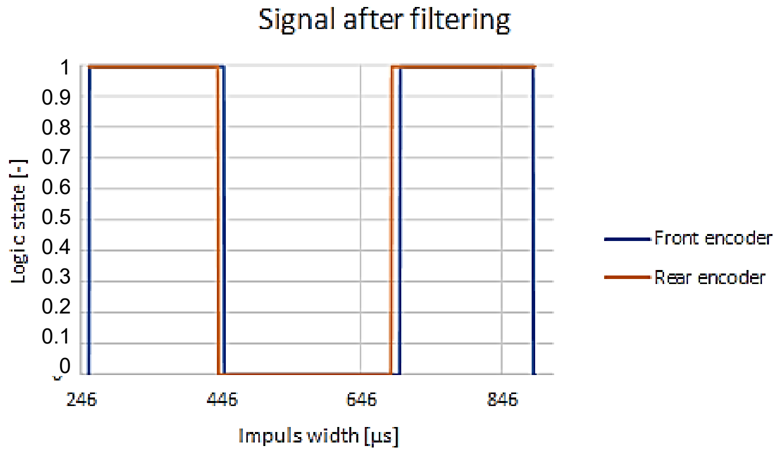

Fig. 6. Example of signal after filtering, run of logic state for master and slave discs with visible shift because of shaft torsion

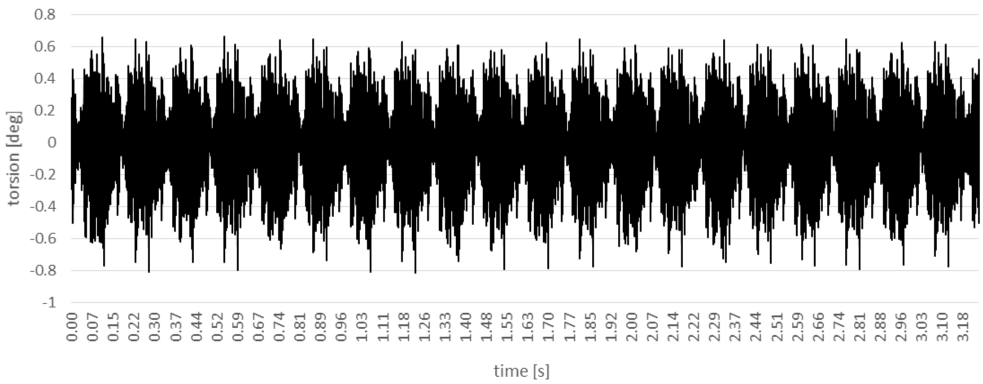

Fig. 7. Torsional vibrations raw signal record encompassing 40 subsequent revolutions of the crankshaft

5. Torsional vibrations picture

Implemented method of rejection of errors enables processing of long signals. Due to treatment by filters, all inconveniences such as jumping of signal and systematic descend of envelop were defeated and signal was ready for calculation of torsion. In Fig. 7 is presented run of torsional deflection registered during engine working at load of 280 kW what was corresponding to 70% of maximum continuous rating. As can be observed, signal is very proportional and symmetric. Records of healthy engine runs at gradually increased loads shall be basis for further detection of malfunctions in way of comparison. It is assumed that any deviations from reference state of combustion process shall result with difference of torsional vibration picture, what will be detected using simple mathematical formulas and enable diagnostic conclusions.

6. Summary

Proposed method of torsional deviations measurement is very convenient due to easy way of mounting of measurement system elements, simple and not expensive construction, high durability, and reliability. Data processing is not complicated and can be proceed with MS Excel program. High frequency of laser emitter gives high level of accuracy and ensures broad range of implementation, according to evaluation calculations; system is effective up to 25 seconds of recording. Longer signals are possible but data transfer takes much more time. What cover all ranges of diesel engines. Presented results seem to be very promising. Possibility of detection of fuel system malfunction and control of engine behaviour during time of half minute will be very important tool for diagnostic prediction. Further investigations will be directed to experiments with different injectors' nozzles, gives interesting information about accuracy of the method. Possibility to detect the difference between torsional vibrations caused by installation of two types of nozzles let assume that other deviations or disturbances related to combustion process can be detected.

Proposed method seems to be good tool for verification of various kind of theoretical models simulating malfunction of diesel engines.

Further steps of method's development shall be directed to proof obtained results by repetition of experiment under various outer condition. It is absolutely necessary to define impact of atmospheric pressure, humidity, and temperature at torsional deflection waveforms. Discovering straight relations between registered torsion variations and engine malfunctions, one is creating reliable basis for formulation of diagnostics conclusions.

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