Journal of KONES Powertrain and Transport, Vol. 21, No. 3 2014

ISSN: 1231-4005
e-ISSN: 2354-0133
ICID: 1133166
DOI: 10.5604/12314005.1133166

VALIDATION OF REFERENCE SAMPLING FOR FAILURE DETECTION BY CRANKSHAFT ANGULAR SPEED ANALYSIS

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Abstract

The paper presents results of the experiment focused on evaluation of records of runs of the engine in good condition as a reference for subsequent detection of faults of fuel system of medium speed diesel engine. The aim of research was determination of limits of instantaneous angular speed's spread spotted between random starts of the engine, without any fault condition simulation. Due to fine variation of the load setup and different ambient condition, every record of angular speed of independent starting, despite of attempts to sustain the same load and rotational speed value, presents some deviations between runs. Having on mind utilization of such measurement as a template for further comparison, is crucial to find out how random changes of ambient conditions and accuracy of revolutionary speed setup affect the IAS magnitude course. The answer was got in way of registration of numerous runs of the test engine after independent starts and hand adjustment of required RPM's. The experiment was carried out at laboratory stand in Gdynia Maritime University, equipped with diesel engine Sulzer 3AL 25/30 driving electro-generator. Sulzer 3AL 25/30 is three cylinder, medium speed, four stroke marine diesel engine, with maximum output 400 kW at 750 rpm. Independent records were treated as random variable and were compared each other. Obtained results were compared with differences between healthy engine and with simulated malfunctions of fuel injection.

Keywords: *diagnostics, marine diesel engine, angular speed, reference comparison*

1. Introduction

Many malfunctions of diesel engines are related to the combustion process. The process can be disturbed because of wrong functioning of elements of injection system (high-pressure pumps and injectors).

Analysis of the crankshaft Instantaneous Angular Speed (IAS) irregularity as a source of diagnostic information has been already tested for malfunction detection of injection pumps and injection valves [3]. Advantage of this method is non-invasive measurement and relatively easy mounting of measurement elements of the system.

Detection of fuel system malfunction by analysis of IAS requires reference data representing runs of engine without any disturbances. Those data play the role of specimen for comparison with further diagnostic evaluation measurements of the engine condition. There are two ways of reference data base creating. First, one is mathematical model of dynamic behaviour of the engine. That method has three major disadvantages. As first, one has to notice that required high accuracy of reflection of the real object is hard to achieve by mathematical description. Other disadvantage is due to fact that even minor differences between engine versions or types strongly affect model's output data. Finally, obtained level of correlation between model and real object can be too low and error can overstep level of disturbances caused by defect [4]. The third one is impossibility to build up a universal model of the engine and every engine unit would require separate modelling. Taking above facts under consideration, one has to conclude that theoretical way of creation of reference template is not useful for practical implementation.

There is a another way to solve that problem, relaying on assumption that brand new engine or an engine after overhaul represents the proper level of performance and can be accepted as source of reference data. Every diversion from recorded healthy engine status can be considered as diagnostic symptom of deterioration of its condition.

IAS based diagnostic is focused on analysis of every single cylinder torque contribution to average torque distribution during one combustion cycle (one revolution for two-stroke and two revolutions for four-stroke engines). Detection of potential malfunction relay on comparison of healthy engine runs with the run disturbed by defect. Changes of magnitudes and peaks phases (see Fig. 3) shows deterioration of combustion process and subsequently allows to define affected cylinder and, in some cases even define fault element of injection system [1, 2].

Internal combustion engines, because of their principle of work are very sensitive at ambient condition changes. Variation of barometric pressure and outer temperature can result with significant changes of produced power level. That fact is a reason of necessary correction of power value in order to exclude ambient conditions influence. According to [5], drop of atmospheric pressure of 100 hPa can result with 7% decrease of output power; temperature rise of 5 K will cause power down of 2.5%. This fact leads us to the conclusion, that different ambient condition can affect uniformity of instantaneous angular speed of the crankshaft.

If implementation of diagnostic system based at IAS on board of a ship is expected, we cannot omit problems posed above. One has to assume that in sea practice measurements will be carried out under vary span of atmospheric pressure, humidity and temperature. We have also considered different quality of fuel, which coming from various bunkering points. It means that is necessary to know how broad deviation of runs of healthy engine caused by is:

a) changes of ambient condition,
b) accuracy of engine's load level,
c) periodical adjustment of injection system elements.

The aim of this work was to answer the question whether disturbances due to injection malfunction makes diagnostic signal strong enough to be clearly distinguished from deviations caused by ambient condition changes. To achieve this goal, experimental way with simulations of different malfunctions was undertaken.

2. The characteristics of the engine and test rig

Testing measurements were carried out at the test bed in Gdynia Maritime University Engines Laboratory.

The main engine was a turbocharged, medium speed diesel engine designed by Sulzer. This 3-cylinder in row engine develops 408-kWat average rotational speed of 750 rpm. The engine drives alternate current electro generator GD8-500-50, 500 kVA, connected to the main electric board. The load of the engine can be fluently adjusted by changing of the set up of adjustable resistor.

Simulation of malfunction can be done by installation of out of order injector; leakage of injection pump by unscrewing special drain bolt and leak from turbocharger air duct can be also simulated.

Angular speed measurement set consisting of perforated disc and optical sensor, (Fig. 1), data processing and storage block ETNP-10.

3. Plan of experiment

First stage of the experiment was to collect records of angular speed of healthy engine in different outer condition. Different outer conditions were defined as:

a) run of the engine in different ambient conditions i.e. temperature and atmospheric pressure,
b) separate starts of the engine and hand adjustment of the load (~ 250 kW).

The span of barometric pressures during experiments period was ~25 hPa and outer temperature was differ about 8 K. The second stage was repetition of above measurements after minor adjustment of one of the injectors (increase of valve opening pressure by setup of the injector spring). The adjustment aim was to diminish difference of exhaust gas temperature between cylinder number 2 and 3.

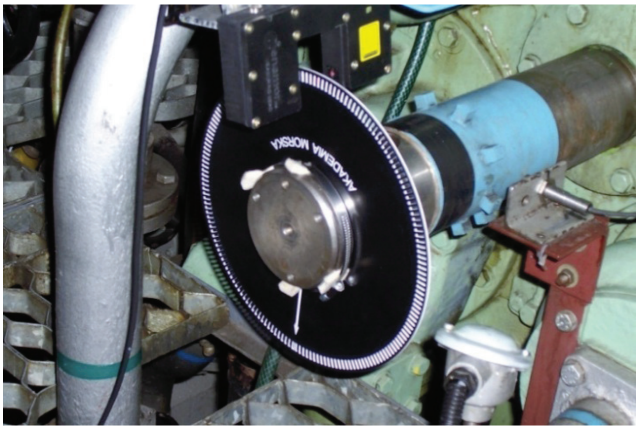

Fig. 1. Perforated disc and laser sensor mounted at crankshaft's free end

Third stage of experiment was measurement of IAS with simulations of different malfunction of the engine, related to the combustion process:

a) leak from injection pump,
b) partly clogged nozzle of injector,
c) higher pressure of injector opening.

Every measurement was done when engine was warmed up and cooling media temperatures were stabilised. Records were repeated three times, and every record consisted of 10 subsequent revolutions (5 cycles). After measurement, the engine was stopped for three hours and started again and measurement procedure was repeated. Number of recorded revolutions was limited by capacity of the memory of ETNP recording block

4. Results of experiment.

First conclusion coming out after analysis of recorded runs is that slight deviations of average rotational speed occurred under different outer conditions. In Fig. 1 are presented values of angular speed recorded twice during 3 separate starts of the healthy engines (number 1 – means first record of first start, number 1.1 – means 2nd record of first start etc.). The chart shows then differences of the speed values occur either between subsequent records of the same run or between runs after separate starts. Is also noticed that difference between angular speeds are higher for separate runs.

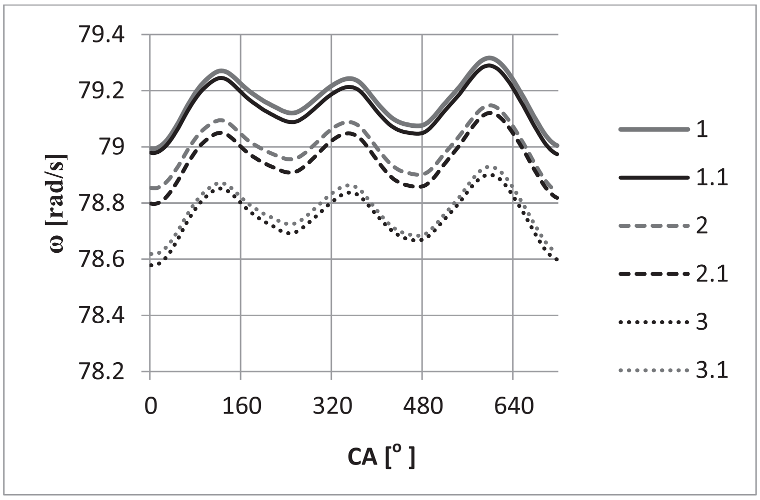

Fig. 1. Angular speed of healthy engine recorded in three different atmospheric conditions

Analysis of the angular speed leads us to the conclusion that this parameter cannot be taken as reference value because of high spread between measurements. The solution of the problem can be achieved by calculation of relative value of angular speed. It eliminates differences of speed level and leaves the shape of waves for evaluation. As presented in Fig. 2, for every of three separate starts, relative angular speed form are different but spread of average value was eliminated. The difference between speed values for decent subsequent positions of crankshaft angle are object of analysis and are detectors of potential malfunctions.

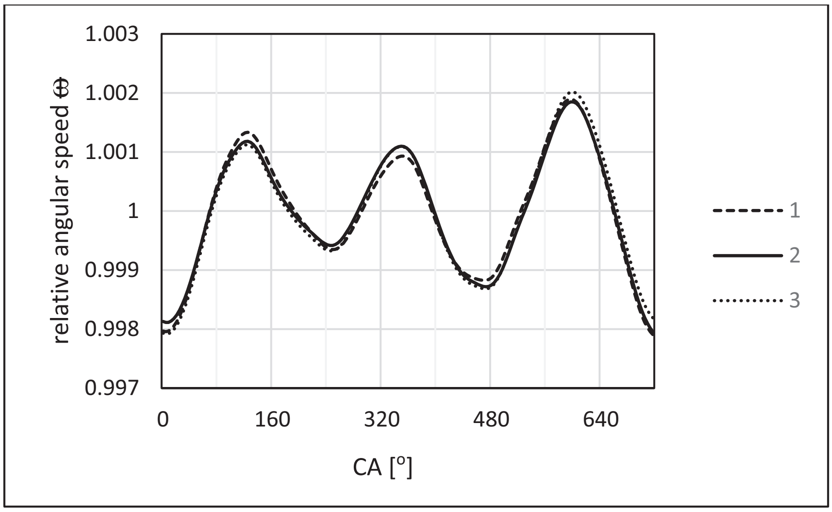

Fig. 2. Relative angular speed of three runs after separate starts of the engine

Measurement data of compared runs were treated as random variable and value of standard deviation was taken as a measure of strength of difference. Parameter σ was calculated as standard deviation of population consisting of equal number of values coming from reference state and comparable measurements, all recorded in the same position of crank angle given in CA degrees.

It was assumed that combustion disturbance should result with increasing of IAS curves difference between healthy and failure state, and as consequence, standard deviation shall rise.

According to assumptions undertaken as second stage of experiment, runs of engine before and after adjustment of injector were compared and analysed. Results of measurements show that regulation of the third cylinder injector affected the shape of relative angular speed. It is visible that contribution of 3. cylinder was increased after regulation (Fig. 3.)

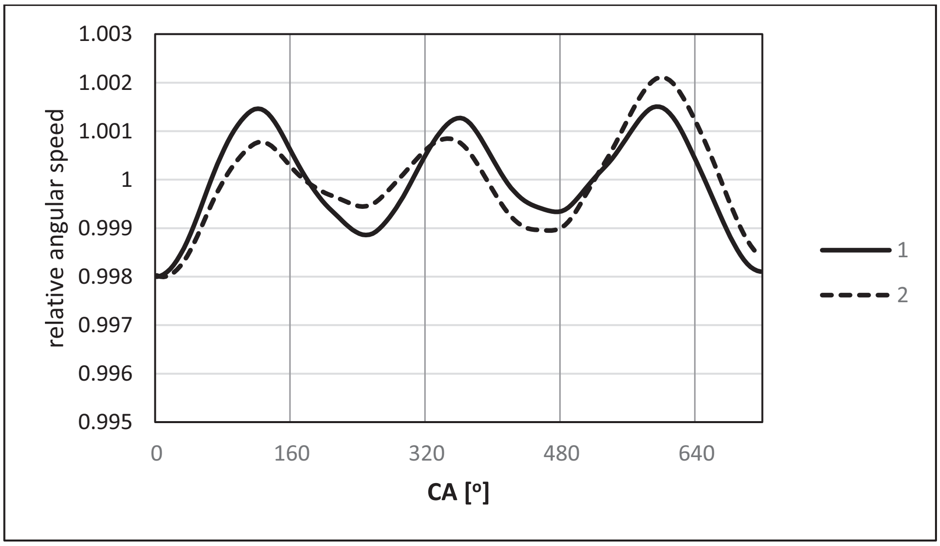

Fig. 3. Relative angular speed before – 1; and after adjustment of injector spring – 2

Comparison of standard deviations σ calculated for random starts of healthy engine and standard deviation between reference run and after injector adjustments, pointed at significant differences, what is presented at Fig. 4 and 5.

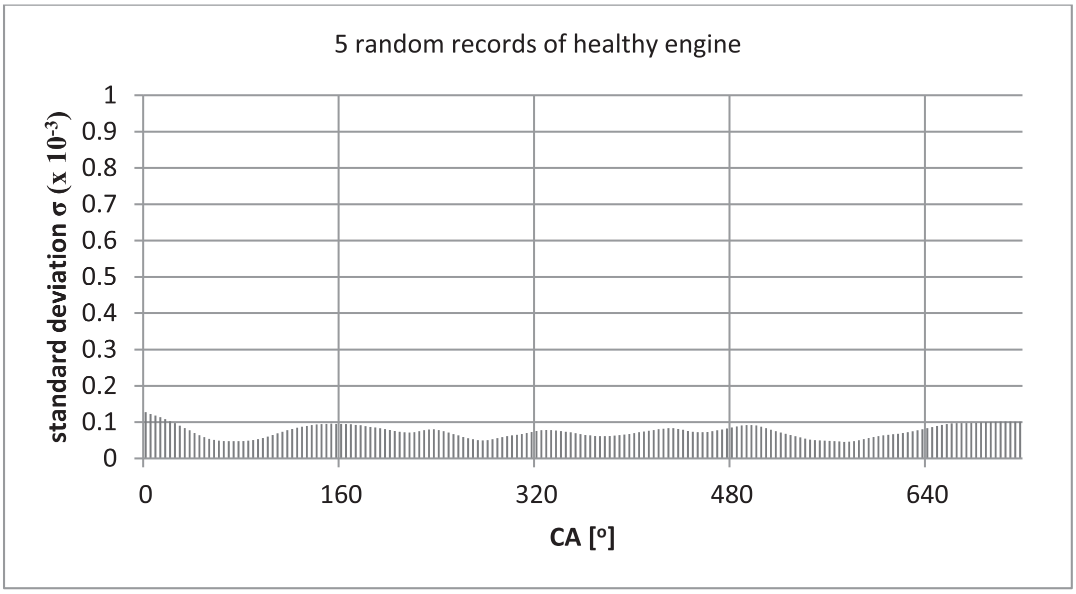

Fig. 4. Standard deviation of population of 5 separate starts of healthy engine

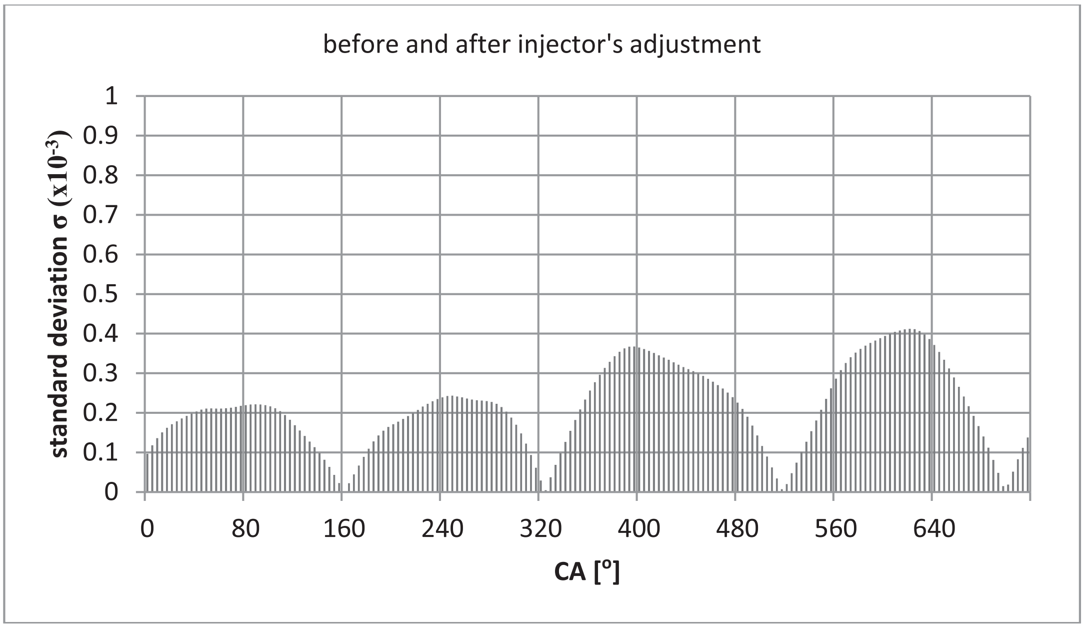

Fig. 5. Standard deviation of population consisting of measurements before and after adjustment of injector's spring

Adjustment of injector caused rise of magnitude almost 2.5 times and change of the chart shape for more sinusoidal form.

First implemented malfunction was leak from injection pump. The effect of that kind of failure is lower fuel dose delivered to the injector and expected symptom is lower contribution of affected cylinder [3]. Analysis of waveform of deviation σ between healthy runs and leakage case showed high level of disturbance. Maximum magnitude was three times higher (1.6×10^{-3} and 4.2×10^{-3}).

Partly clogged injector inducted much stronger diversion. Level of difference between waveform of relative angular speed recorded for healthy engine and waveform of run with clogged injector was represented by standard deviation's maximum and was almost five times higher than for healthy condition runs (see Fig. 7).

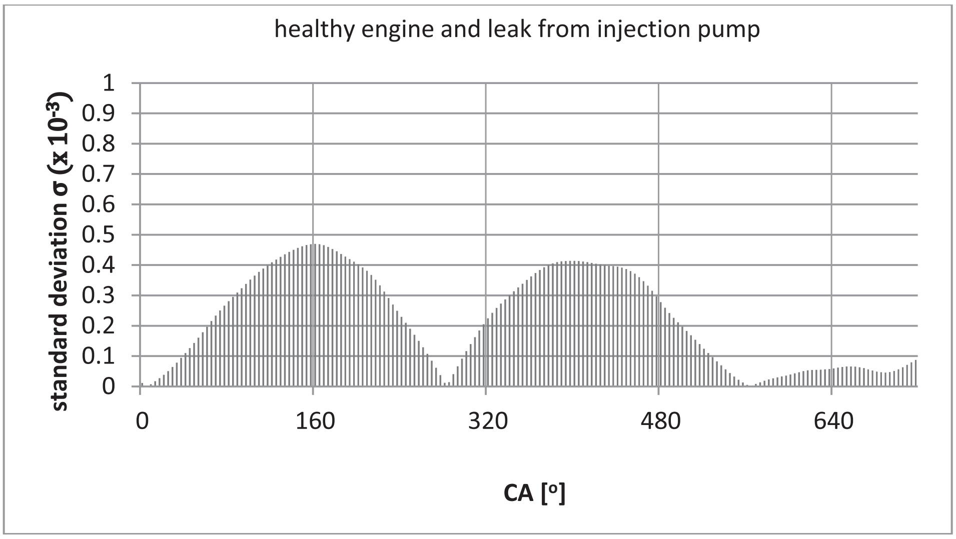

Fig. 6. Standard deviation of population consisting of measurements of healthy engine and with leak from injection pump

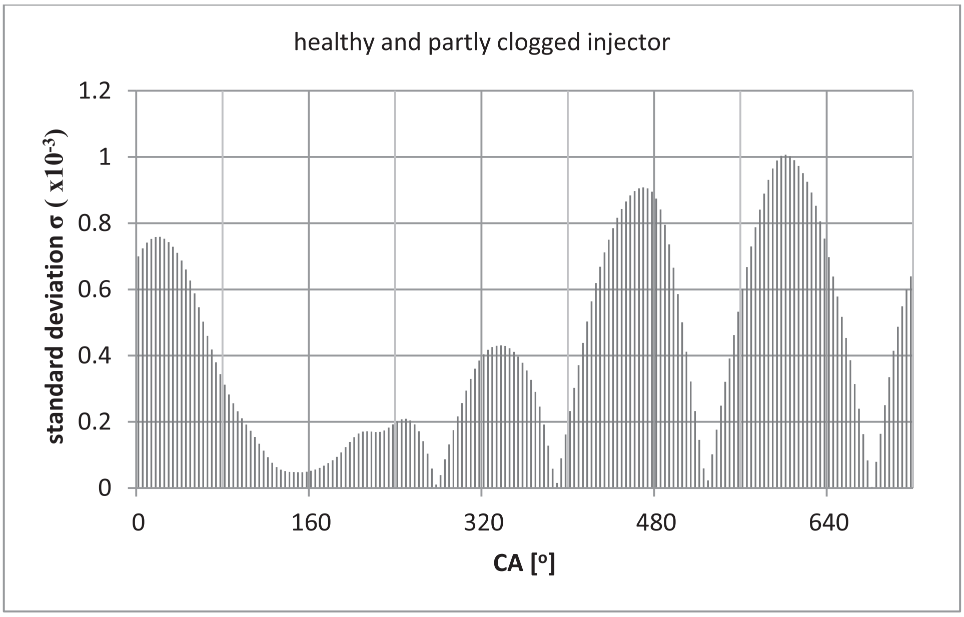

Fig. 7. Standard deviation of population consisting of measurements of healthy engine and with partly clogged injector

Lower pressure of injector's opening was simulated by installation of injector with lower tension of the spring. That kind of failure can occur during engines exploitation because of material aging. Low pressure of injectors' opening has impact at fuel dose and injection angle. It results with changes of cylinder's contribution to mean torque value and disturb IAS waveform. Figure 8 presents values of standard variations for "weak spring" simulation. Deviation's form shape is characterised by six peaks with maximum values between 0.8 x 10^{-3} and 1.0 x 10^{-3}.

The last simulated problem was leak from air duct after turbocharger. Obtained results showed that disturbance level is similar to that which was observed for measurement under changes of atmospheric pressure and temperature (see Fig. 9). It was obvious that the method based at analysis of instantaneous angular speed, in that case was useless. Charging air system of 3 Al25/30 engine consist of compensation tank after turbocharger, thus pressure variations affects all cylinders equally. Minor drop of air amount and pressure can be compared with changes of outer conditions, what was visible when results were compared with comparison of random runs.

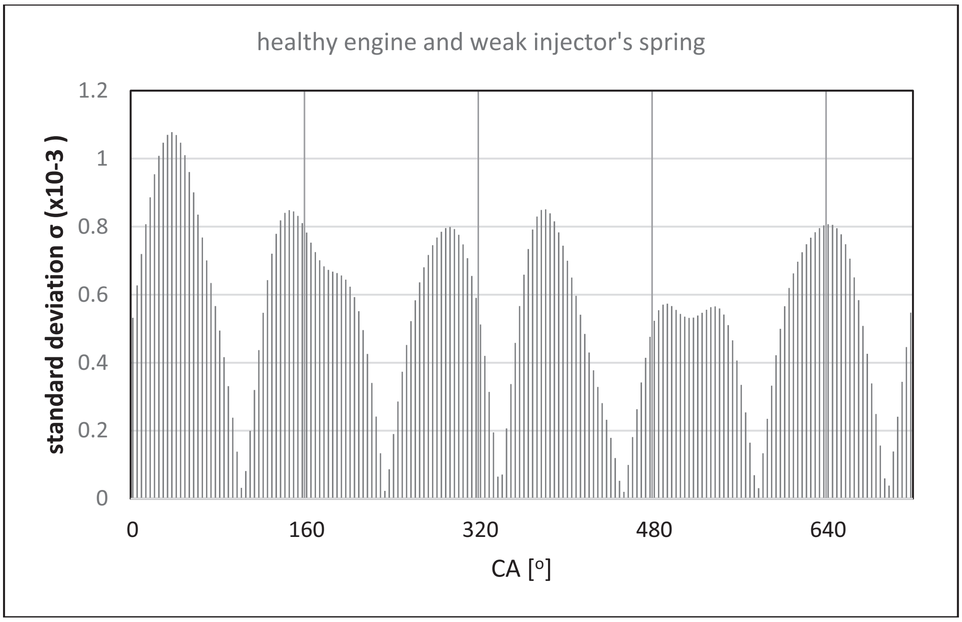

Fig. 8. Standard deviation of population consisting of measurements of healthy engine and with low pressure of injector opening

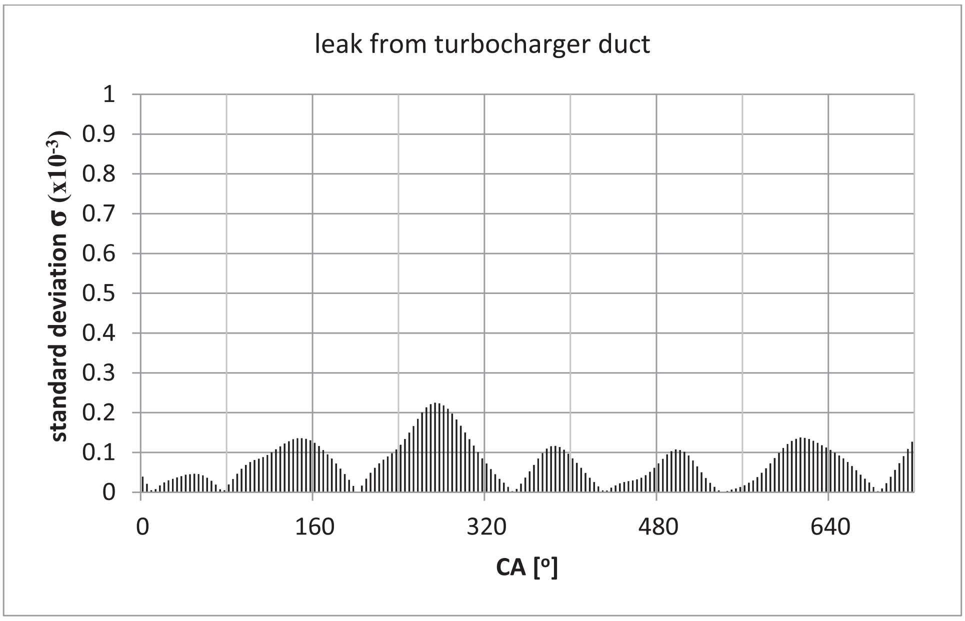

Fig. 9. Standard deviation of population consisting of measurements of healthy engine and with air leak from charging air duct

5. Conclusion

The results of conducted experiment show that malfunctions of injection valves were the source of angular speed deviations from normal condition. The level of deviations is strong enough to be detected by photo-optical measurement system. The signal obtained from the perforated disc after decomposing of noise, is a base for diagnostic analysis focused on identification and definition of reason of faulty condition. Implemented method is the comparative analysis, thus for detection and localisation of malfunction, necessary is having a template measurements of a healthy engine. From diagnostic practice is well known that collecting of healthy engine data can be done during commissioning of a new engine or during trials after overhauls. Results of conducted experiment lead to conclusion that:

- ambient condition during recording of data base for reference template has an impact at reference level,
- all simulated failures of high pressure injection elements caused much higher level of standard deviation than reference runs, what allows assume that reference template built on healthy engine records is good enough for malfunction detecting,
- level of diagnostic signal caused in case of compressor duct failure is the same like caused ambient conditions changes and is excluded for detecting by angular speed analyses,
- any adjustment of high-pressure fuel system strongly affects IAS waveform, what make necessary to refresh reference template waveform by new data collection.

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