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COMBUSTION ANALYSIS AND DIAGNOSTICS OF DIESEL ENGINE BY MONITORING OF INSTANTANEOUS ANGULAR VELOCITY

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ABSTRACT: Instantaneous angular speed of diesel engine crankshaft contains a lot of information about gas pressure in cylinders and condition of other parts of crankshaft mechanism. This information can be used to diagnose combustion-related faults in engine and faults affecting the gas pressure, as well as faults resulted due crankshaft splits, insufficient oil quantity in engine and piston jamming, and many other irregularities.
In this paper, dynamic model of torsion-vibrating system of six-cylinder IC engine for heavy duty road vehicles is developed and presented, with its input parameters. For such approach it is important to have on disposal enough realistic model of the crankshaft torsion-vibrating system, with properly defined input parameters. Simulation of instantaneous angular velocity is made and simulated results based on such dynamic model are confirmed with results obtained by experimental measurements in laboratory conditions.
By analyzing different cases of irregular combustion in chamber of diesel engine, which are often occurred in practice, appropriate validities for combustion process monitoring and detecting the faults in engine's work are obtained successfully. Results of our investigation promise the development and application of such diagnose technique using instantaneous angular velocity signals. This technique is quite attractive because it utilizes crankshaft speed sensors that are widely available, relatively robust, and low in cost, and can improve combustion quality monitoring.

KEY WORDS: IC engine, angular velocity, torsional vibration, diagnostics

1. INTRODUCTION

Rapid development of the motors and motor vehicles, whose target is to keep motor vehicle in use, in electronic era, has for a consequence extensive use of mechatronic modules on vehicles. These are modules which control processes in engine (combustion process, injection process, ...) as well as processes on vehicle (synchronization of engine's and transmission's work, processes of vehicle stability during braking and steering, etc.).

Engine diagnostics and combustion quality monitoring have been areas of intense study in recent years because of the legislated need to infer vehicle emission compliance. Monitoring combustion quality is a necessary element of on-board diagnostics and critical for the integration of modern fuel, air, spark and EGR (exhaust gas recirculation) engine control strategies to meet stricter emission standards. Therefore, overcoming these difficulties is an important step in successful implementation of future engine control strategies for internal combustion engines (IC engines).

One real model of torsion-vibrating system with model parameters and crankshaft angular velocity signals is used, and results of our investigations in field of IC engine torsional-vibration phenomenon researching and possibilities of its application for engine operation diagnostics are presented in this paper.

2. EQUIVALENT DYNAMIC SYSTEM OF THE IC ENGINE AND SOLUTION OF EQUATION OF MOTION

By observation of any system in the scope of its analyze and mathematical interpretation of events evolving in it, as well as a limited knowledge and very often complicated mathematical apparatus which pursues its originally presentation, it is necessarily for practical application to develop equivalent systems that are simpler and at the same time with sufficient accurâcy represent circumstances in actual (real) system.

The IC engine is very complex system, with various phenomenon that are, essentially, interdisciplinary. Except basic construction of the IC engine, designed by engine gear (piston, connecting rod, crankshaft), head with valvetrain, engine block, oil house, etc.; for its applicable and proper work it is necessarily a group of auxiliary systems and aggregates which in a word can be described as engine equipment (fuel supply system, firing system, system for lubrication, belts, flywheel, gears, etc.). All prior mentioned systems affect on oscillatory condition of the engine gear. In the frame of IC engine torsional-vibration phenomenon researching, it is often-times shown that line equivalent system is an optimal solution, which besides of its simplicity in the same time gives very acceptable calculation results that are very close to events in real system. The equivalent dynamic system of in-line, six-cylinder, four-stroke, turbocharged, water-cooled diesel engine dedicated for heavy duty road vehicle is shown in the Figure 1.

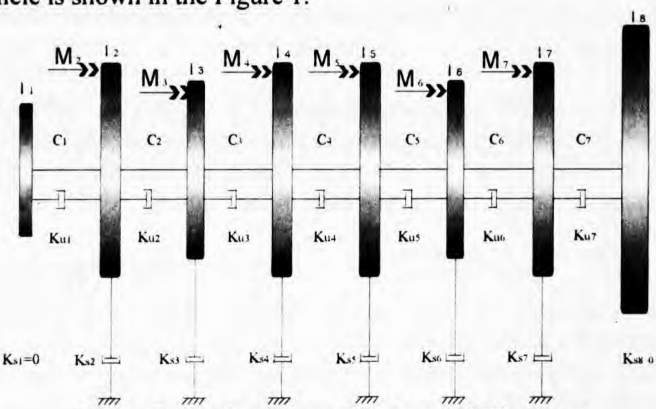

Fig. 1: Equivalent dynamic system of IC engine

It is visible from the Figure 1 that equivalent system consists of concentrated masses in the shape of discs with moments of inertia I, connected together with massless elastic shafts and stiffness c, internal damping K_u and external damping K_s. In this model discs represent following masses of the real system: disc 1- pulley and engine equipment which is driven by means of belt and reduced on pulley; disc 2-7 - first to sixth cylinder respectively; disc 8 - flywheel and engine equipment reduced on the flywheel (gear power of oil pump, valvetrain, etc.).

The values of basic parameters of the considered system have taken from [1].

Differential equations of motion for respective discs can be described in form as for disc i (Lagrange's equations of the second order):

$$\frac{d}{dt}\left[\frac{\partial\left[\frac{1}{2}I_i(\alpha_i)\dot{\alpha}_i^2\right]}{\partial\dot{\alpha}_i}\right]-\frac{\partial\left[\frac{1}{2}I_i(\alpha_i)\dot{\alpha}_i^2\right]}{\partial\alpha_i}+\frac{\partial}{\partial\alpha_i}\left[\frac{1}{2}c_{i-1}(\alpha_i-\alpha_{i-1})^2+\frac{1}{2}(\alpha_i-\alpha_{i+1})^2\right]+$$
$$+\frac{\partial}{\partial\dot{\alpha}_i}\left[\frac{1}{2}K_{u,i-1}\left(\dot{\alpha}_i-\dot{\alpha}_{i-1}\right)+\frac{1}{2}K_{u,i}\left(\dot{\alpha}_i-\dot{\alpha}_{i+1}\right)+K_{s,i}\,\dot{\alpha}_i^2\right]=M_i^*(\alpha_i) \tag{1}$$

By introducing of the substitution for crankshaft angular motion in the form $\alpha_i = \omega_i t + \vartheta_i$, assuming constant angular velocity $\omega_i = const.$, deriving the function $I_i(\alpha_i), \frac{dI(\alpha_i)}{d(\alpha_i)}, M(\alpha_i)$ in surroundings of $\omega_i t$ point and rejecting high-order elements and constant values which do not affect on oscillating state of the system, equation (1) can be written in form:

$$I_i \ddot{\vartheta}_i + K_{s,i} \dot{\vartheta}_i + K_{u,i-1}\left(\dot{\vartheta}_i - \dot{\vartheta}_{i-1}\right) + K_{u,i}\left(\dot{\vartheta}_i - \dot{\vartheta}_{i+1}\right) + c_{i-1}(\vartheta_i - \vartheta_{i-1}) + c_i(\vartheta_i - \vartheta_{i+1}) = M_i \tag{2}$$

By proper identification of respective parameters of the analyzed system and determination of their sizes [3], it is possible to solve the system of differential equations, type of the equation (2) which describes its motion, using the matrix form:

$$[I]\{\ddot{\vartheta}\} + [K_S]\{\dot{\vartheta}\} + [K_u]\{\Delta\dot{\vartheta}\} + [c]\{\Delta\vartheta\} = \{M\}, \tag{3}$$

where ϑ is the torsional angle, $\dot{\vartheta}$ and $\ddot{\vartheta}$ are appropriate derivations of the torsional angle, $\Delta\dot{\vartheta}$ is the difference of torsional velocities between neighboring discs, while M is the excitation torque of the system.

Verification of the approach for real system reduction to equivalent system, system parameters identification, and confirmation of applied mathematical model for this engine, tested on test bench, is done on the basis of comparison of vibration amplitudes on the pulley (disc 1) obtained experimentally and computationally, that is presented in the Figure 2.

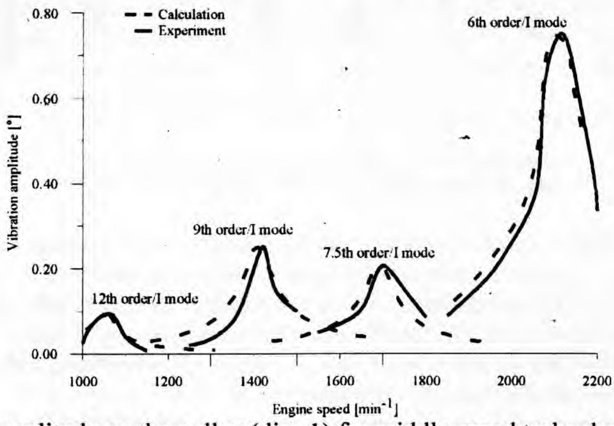

Fig. 2: Vibration amplitude on the pulley (disc 1) for middle speed turbocharged diesel engine

From the Figure 2 it is visible good accordance between experiment and calculation results, but in practical cases when very simple and quick analyze is needed, relatively diagnostics of IC engine work, such approach can not be used. The problem could be recognized in very complicated measurements which request, except specific measuring equipment, special prior-defined procedures of testing with possibility of doing testing of IC engine on test bench. Such approach is essential and valid during consideration of engine vibration phenomenon in phases of its developing, as well as at selection of additionally elements like torsional vibration damper, where is needed to test the IC engine on all working regimes.

However, for such approach of engine work diagnostics it is necessarily to observe, relatively to measure angular velocity or angular displacement for all discs of the equivalent system. This can be

performable using contact-free methods for angular velocity measuring on the basis of incremental sensors.
Knowing angular velocity changing character, relatively angular displacement of the observing discs of the equivalent system, excitation torque can be calculated, as well as pressure in cylinder. Fixing up of irregularities in work is just a thing of comparison of the well-known excitation torque changing character for properly working engine with signal assigned from measuring. Thus it can be exactly stipulated which one cylinder, or more cylinders, is problematic. Beforehand mentioned phenomena can be identified by means of appropriate software which as a base uses the system of equations (3). It means, by using of suitable equivalent model of dynamic system and by proper identification and definition of model parameters, as well as by suitable solution of the equation of motion (3), a very efficient tool for behavior prediction of dynamic systems could be set up.
Calculation results shown in this paper are based on using numerical method of central differences, while MatLab is used software.

3. SIMULATION OF IRREGULAR COMBUSTION IN CYLINDERS OF IC ENGINE

Gas pressure in a diesel engine includes a lot of information, which reflects the condition of the diesel engine and the combustion efficiency. Direct measurement of the gas pressure in the cylinder is impractical because installing pressure transducers inside the cylinder is generally difficult and uneconomical for the practical use. In contrast, instantaneous angular speed measurement of the diesel engine is very convenient, economic, reliable and non-invasive. The instantaneous angular speed is related to the exciting torque, relatively to the gas pressure in cylinder. Thus, the diagnostics of the combustion-related faults and other faults affecting the gas pressure by analysing the instantaneous angular speed can be achieved. Some characteristic cases at engine's operation which can appear in praxis are analyzed in this paper.

3.1 Aggravated combustion in some cylinder

Aggravated combustion in some cylinder of IC engine can occur because of inappropriate fuel-air mixture and reason can be injector failure, defect of fuel supply regulator, variation of injection start angle etc. By measuring of angular velocity on pulley it can be obtained signal shown in Figure 3, and from corresponding analyze it follows excitation torque shape shown below in Figure 4.

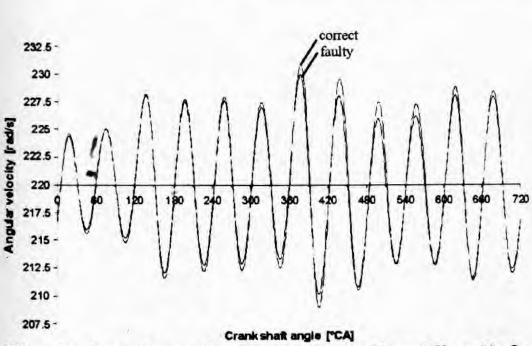

Fig. 3: Angular velocity on the pulley (disc 1) for the case of aggravated combustion in first cylinder at 2100 rpm

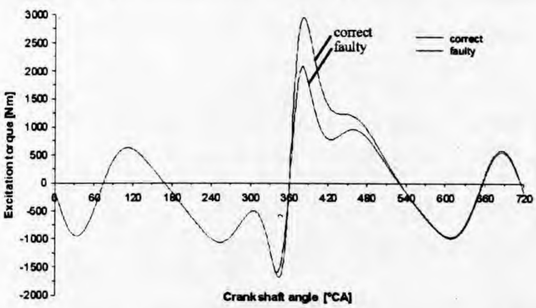

Fig. 4: Excitation torque for the case of aggravated combustion in first cylinder at 2100 rpm

3.2 Total absence of combustion in one cylinder

With absence of combustion in analyzed cylinder, it is not possible to set free bundled fuel chemical energy by way of combustion. By measuring of angular velocity on pulley it can be obtained signal shown in Figure 5, and from corresponding analyze for second cylinder it follows excitation torque shape shown below in Figure 6.

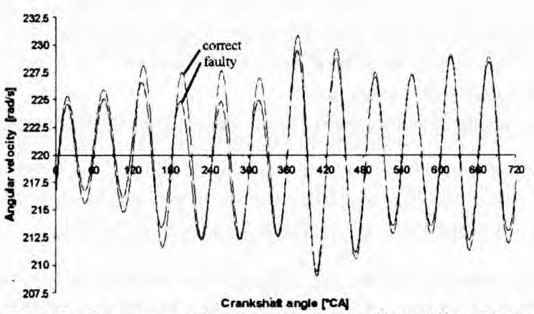

Fig. 5: Angular velocity on the pulley (disc 1) for the case of combustion absence in second cylinder at 2100 rpm

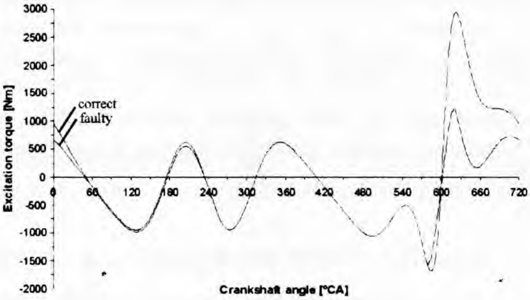

Fig. 6: Excitation torque for the case of combustion absence in second cylinder at 2100 rpm

Indicated pressure in engine now leads down to the pressure of pure compression and part of the excitation torque from gas pressure force has different values. It can be visible the same character as for former case, but with less value of torque in period of combustion and expansion process.

3.3 Total absence of combustion in two cylinders

In this segment absence of combustion in two arbitrary cylinders is analyzed. It is remarkable bigger disturbance of measured angular velocity, whose signal on Figure 7 is reciprocal for case when in the first and third cylinder combustion process does not exist. Analyzing such angular velocity signal, it can be obtained excitation torque changing character for these cylinders. Summarising values of excitation torques of all cylinders, in consideration of crankshaft position, as a result we have a diagram (Figure 8) from which one can easily identify problematic cylinders.

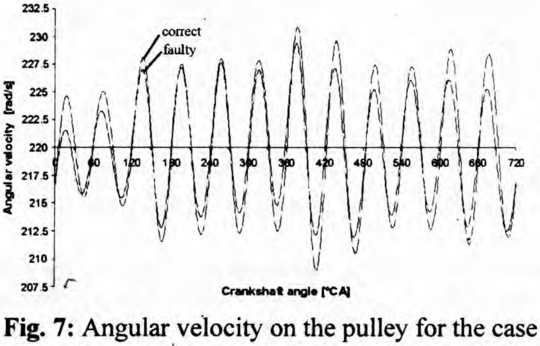

Fig. 7: Angular velocity on the pulley for the case of combustion absence in first and third cylinder at 2100 rpm

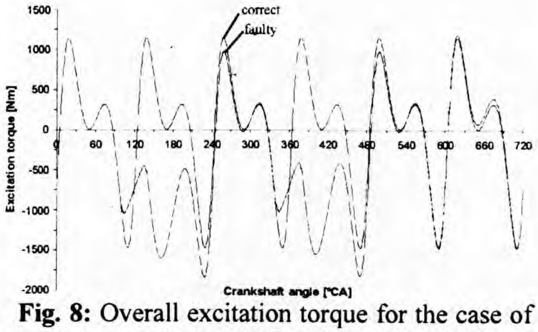

Fig. 8: Overall excitation torque for the case of combustion absence in first and third cylinder at 2100 rpm

Comparing results obtained for all observed cases it can be concluded that irregular combustion in one or two cylinders produced remarkable increasing of the angular torsion asymmetry, as well as decrease of excitation torque. For concrete case where in normal engine working conditions the sixth excitation order is the main order with expressive high torsional angle around uniform state of engine's crankshaft turning, by "falling out" of work one or more cylinders it is clearly visible disturbance and domination of excitation order. It is obvious dominant some lower excitation order here. Also, using such angular velocity or excitation torque signals and model described with system of equations (3), it can be identified engine cylinder in which combustion is aggravated or absented.

4. CONCLUSION

The simulation possibility of some combustion related anomalies in IC engine's work on the basis of equivalent torsional-vibration system and solution models for equations of motion of such system are shown in this paper. Contact-free sensors, used for angular velocity measuring, are relatively cheap and there is a possibility of their serial installation in modern IC engines. A small disadvantage is that sensors have to be mounted onto every disc in order to get an accurate enough matrix of angular velocity, which is a condition for calculating the excitation torque. Obtained calculating results indicate on great potential of this method for engine's work diagnostics, which can give, with appropriate database of analyzed singular cases, the statement about reasons of eventual irregularities in operation.

As it can be visible from presented calculation results, angular velocity curves are smooth curves obtained by way of mathematics, and by their using for comparison with curves obtained by measuring it needs to direct attention about processing way for source signal of sensor. Because of signal disturbances which can have different causes (for example sensor quality, transfer connections, chain of measurement, etc.) by its processing it needs to bear in mind that IC engine is cyclic machine that transforms bundled fuel chemical energy, by way of combustion process, into mechanical work. Stochastic character of the combustion process produces deviations between measured values per respective cycles. From that reason it needs, before comparison with simulated characteristics, to get an average measured value based on several observed successive cycles, and then their conditioning and processing.

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