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DECOMPOSITION OF HARMONIC WAVELETS OF TORSIONAL VIBRATIONS AS BASIS FOR EVALUATION OF COMBUSTION IN COMPRESSION-IGNITION ENGINES

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Abstract

The aim of analysis presented in the article is results of measurements of torsional deflections of a crankshaft of three-cylinder internal combustion diesel engine. The wavelets of the run of torsional twists were processed by decomposition to harmonics using FFT. In order to exactly recognize all dynamic aspects of gas forces acting during working stroke, decomposition was done in two ways: first one relaying on records encompassing one working cycle (two revolutions), the second one based at separated periods encompassing angular an interval from TDC (Top Dead Centre) of one cylinder to TDC of subsequent in firing order. For three-cylinder engine, width of the interval is 240 degrees of crank angle. In order to obtain reliable results, torsional deflection signals acquisitions were recorded numerous times including changes of outer conditions (temperature, atmospheric pressure) and different values of the engine loads. The main goal of conducted experiments was looking for an answer of a question if exist any differences between frequency spectrums of harmonics of run of full cycle (two revolutions) and the same cycle divided by three separate intervals. Analysis was conducted in order to state any possibility of diagnostic signals acquisition caused by abnormalities of combustion process. Results were presented in form of comparison of frequency spectra taken from full cycle and divided intervals.

Keywords: *diagnostics, diesel engine, torsional vibrations, signal processing*

1. Introduction

Run of gas pressure in combustion chamber of compression ignition engine and its changes, are measure of engine's condition and performance. Superposition of gas force and mass forces creating torque strictly depends on quality of fuel injection, combustion process, and angular speed of a crankshaft. It let assume that Instantaneous Angular Speed (IAS) of a crankshaft can indirectly reflect effect of torques aggregate exciting shaft deflection and instantaneous acceleration [1, 7]. That can be basis for attempt of diagnose combustion related faults such as misfire, fuel leakage, fuel valve malfunctions in form of nozzle clogging leakage etc. Traditional method, relaying on cylinder pressure monitoring requires installation of indication cocks and in general, is not dedicated to permanent measurement due to constructional constrains, mostly due to high temperature of gases and contamination. In opposition, angular speed measurement can be realised at shaft ends, what let us call that method nonintrusive. Moreover, gas pressure indicators cannot give all information necessary for estimation of shaft torsion. In recent years, numerous researchers have been focused at IAS based diagnostics of combustion ignition engines. M. Geveci [3] carried out investigation of harmonic components of angular speed of the crankshaft of 6-cylinder diesel engine in domain of crank angle and discussed diagnostic algorithm based on harmonics amplitude variation during imbalance condition of work. F. Ostman [4] presented method of reducing of torsional vibrations of a crankshaft in way of balancing gas pressure deriving forces responsible for torque contribution depending on measurement if IAS. Xiang Yang et al. presented results of diagnostic analysis based on IAS harmonic components of 12-cylinder V type medium speed diesel engine. Also other researches [3, 7], were strongly focused on utilisation of IAS fluctuation signal for diagnosis. This article present novel in form of IAS recording at opposite ends of a crankshaft, what gives a picture of torsional displacement of shaft's ends forced by gas and inertia forces. Torsional vibration wavelets were processed using FFT decomposition in order to distinguish specific harmonics enabling detection of eventual failures. One of important limitation related to optical encodes based measurement system is angular discretion. Because of that, number of registered signals referring to single cylinder is going down with increase of total number. It strictly affect FFT accuracy (short window problem). Authors of the article tried find the answer whether diagnostic conclusion based on single cylinder and comparison cylinder – to – cylinder harmonics waveform is possible.

2. Description of experiment's assumptions and measurements plan

Experimental measurements were carried out at laboratory engine, equipped with 3 cylinder, medium speed (600 to 750 rpm) compression-ignition marine engine powering electro-generator. In Fig. 1 is presented model of masses being in reciprocating and rotating movement. It was assumed that parts of crankshaft between connecting rods and flywheel were elastic and undergoing torsional twist, but flywheel and rotor of the electro generator was reduced to one mass [1, 3]. That let consider that movement of the end of generator's shaft is equal to end of engine's crankshaft at point of flywheel. Thus measurement disc placed at end of the generator reflect movement of the flywheel end.

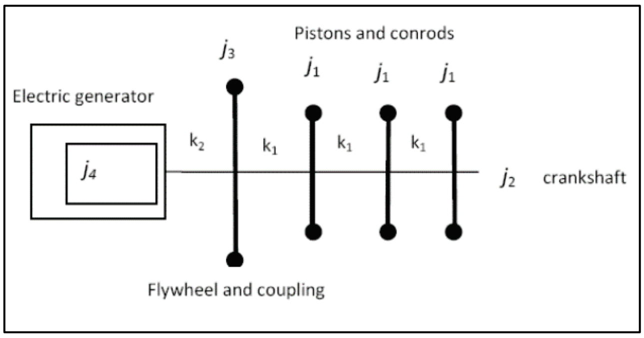

Fig. 1. Scheme of mass displacement for torsion calculation

Difference between angular positon of reference points A and B marked at both ends of the crankshaft gives the torsion magnitude Φ measure and lets to calculate torsion angle (see Fig 2).

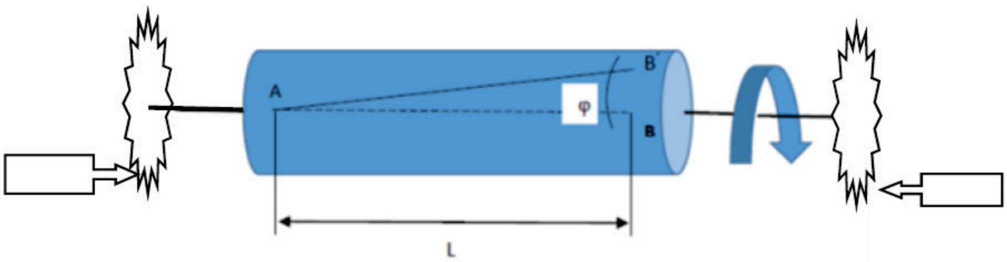

Fig. 2. Model of shaft's torsional displacement and its measurement

Mean Instantaneous Torsional Angle magnitude was calculated as a difference between distance done in the same time by points A and B. Differential angle value is due to different angular speed caused by torsional movement of the shaft. Angular shift between points A B was measured using two optical encoders installed at opposite ends of the shaft line, and triggered simultaneously after triggering signal from disc A.

3. Magnitudes of torsional deflection

The character of torsional deflection registered for speed of 750 rpm (78.53 rad/s) and low load (100 kW, 25% of Maximum Continuous Rating – MCR) is presented in fig 3. Analysis of 10 revolutions' runs shows that fluctuation of twist occurs within one cycle and has three peaks per cycle. Course of twist function repeated in every subsequent cycle, moreover, low frequency sinusoid component causing “waving” of envelop occurs as well. The form of phenomenon was also observed when load of the engine was increased to 260 kW what refer to 65% of MCR (see Fig. 4). These observations lead to a question about level of conformity between magnitude courses of subsequent cycles. It was also assumed that comparison of correlation between cylinders 1, 2, and 3, should bring interesting information. The aim of undertaken processing was looking for possibility of detection of deviations of combustion quality taking place in cylinders. The second interesting question was about forms of frequency spectra after decomposition of signals encompassing full cycle and single cylinder. It was assume that decomposition of a separated part of a record related to single cylinder can give information, which could be masked by other cylinders when all cycle is analysed.

In order to include impact of atmospheric condition, measurements were repeated in different days, characterised by different pressure and temperature. Two levels of engine load, 25% and 65% should show if value of combustion pressure has any impact at frequency of harmonic components.

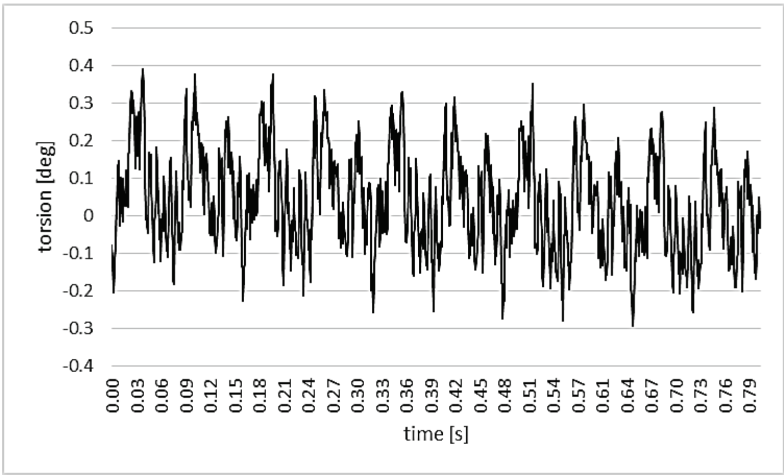

Fig. 3. Shaft’s torsion angle Φ registered for 10 subsequent revolutions in time domain; engine’s load 100 kW rotational speed 750 rpm

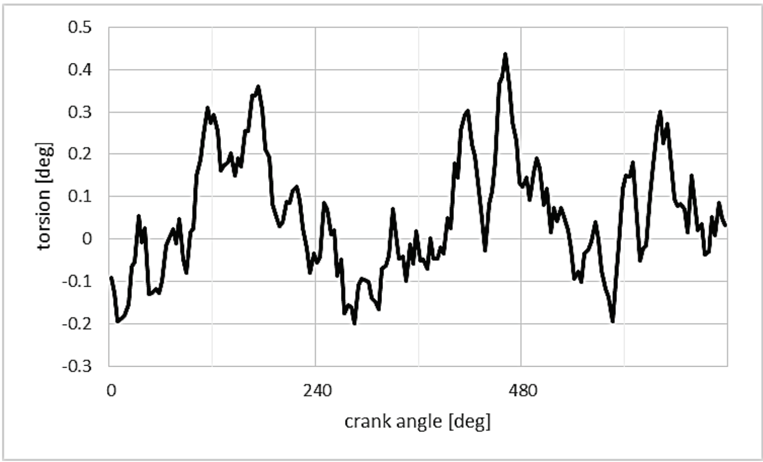

Fig. 4. Picture of torsional twist registered for 2 subsequent revolutions; engine load 260 kW, speed 750 rpm

Decomposition of basic signal was done in way of FFT. This kind of processing requires certain number of data, what means that length of record has significant impact at final result of given spectrum. It was certainly visible after decomposition of part of record encompassing one cylinder contribution and compared with spectrum of full cycle. Angular rotation distance between subsequent ignitions for 3 cylinder engines is 240º, and it covers 60 measured values of torsion (Fig. 4). In opposition, total record length is covering 10 revolutions and 900 measurement points. Due this inconvenience, number of discrete frequency peaks in range from 0 to 100 Hz is limited. Different picture is given by full cycle analysis; number of peaks in frequency range 0-100 Hz is bigger. Results are presented in Fig. 5 and 6. According to literature, analysis of four stroke engines shall be based on only first fourteen harmonics, what means that for considered engine parameters, frequency range should encompass 6.25×14 = 87.5 Hz. Short record of one cylinder zone, gives only 6 peaks within mentioned range (Fig. 5). In opposition to short signal, full record of 10 revolutions gives 40 peaks of discrete frequency (Fig. 6).

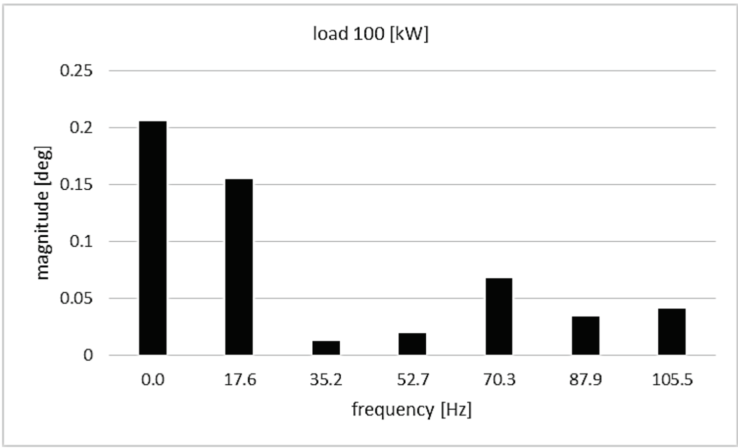

Fig. 5. Spectrum of decomposition of torsional deflection function in range of one cylinder contribution (240º)

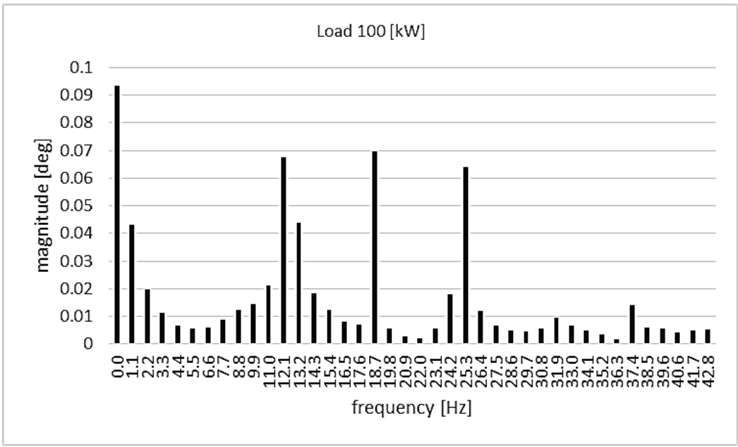

Fig.6. Spectrum of decomposition of the record covering 10 revolutions

This constraint forced and a solution based on creating of artificially extended signal constructed by sticking together 10 identical records covering one cylinder zone. Number of 10 record blocks for building was taken due to match requirements of FFT algorithm. An example of such course is shown in Fig. 7, and its spectrum, giving much more peaks is shown in Fig. 8. It means that decomposition of artificially created record reveals much more components, what can be probably a source of diagnostic information.

As can be observed, not only number of peaks but also frequency of high peaks is different. One cylinder peaks are for 17.6 Hz and its multiplications, full cycle spectrum shows peaks of multiplication of 12.5 Hz what is basic cycle frequency. Analysis of single cylinder spectrum shows major magnitude for frequency around 17 Hz what is close to frequency of fuel injection.

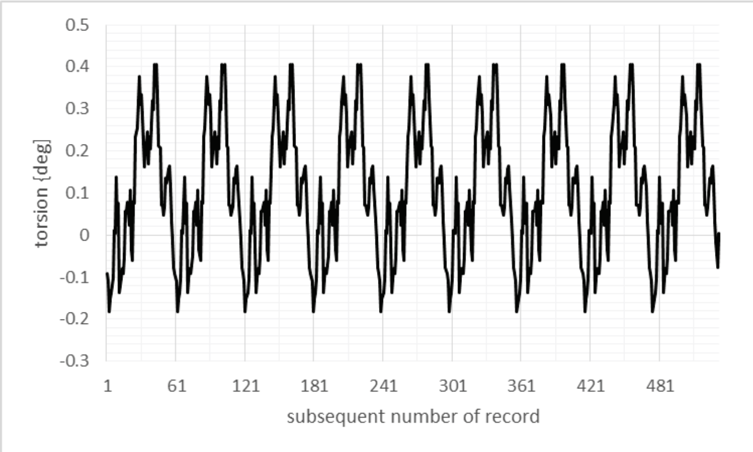

Fig.7. Example of artificial signal consisting of 9 duplicated blocks of 60 records

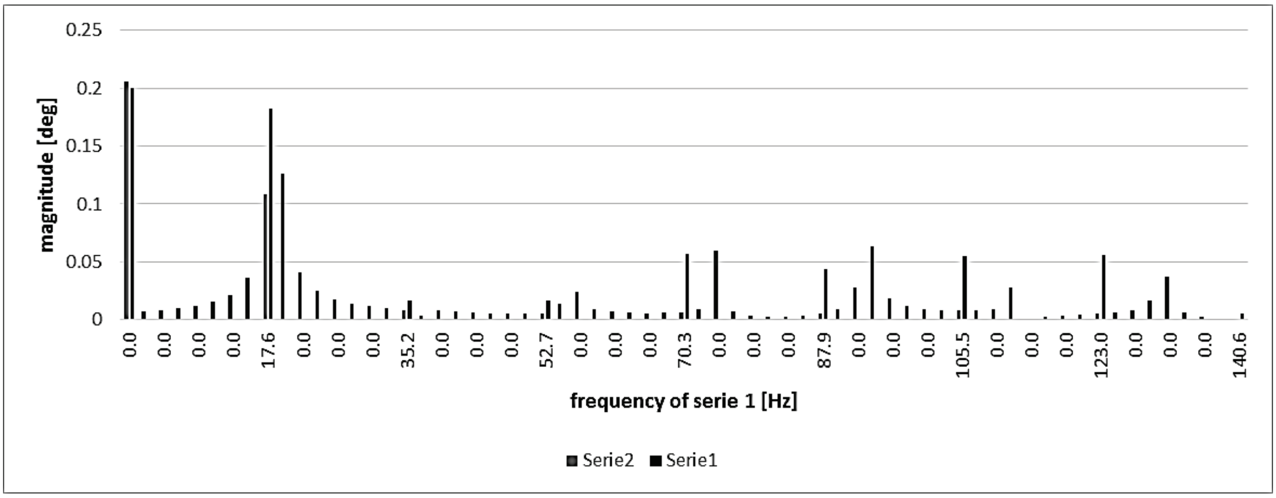

Fig. 8. Spectrum of artificially extended course by sticking together 10 short modules based on 240° records (series 2) in comparison to single module of one cylinder spectrum (series 1)

Figure 9 shows difference between discussed above spectra. Full records are giving three significant peaks in frequency range 0-40 Hz, one cylinder record (dashed line) is hesitating due to lack of clear peaks, but artificially extended record gives three significant peaks in range of 0-80 Hz. (dotted line).

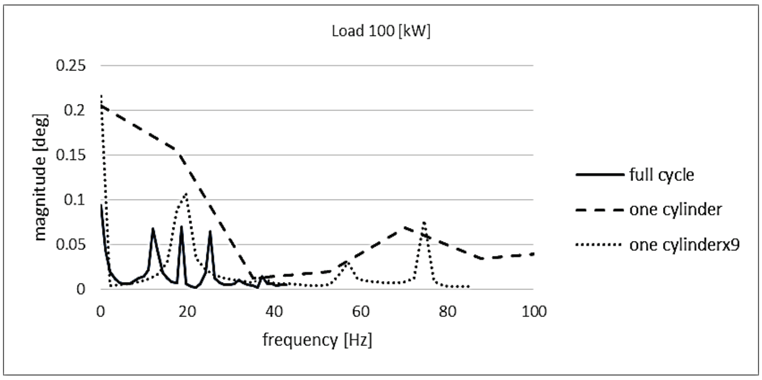

Fig. 9. Comparison of peaks of full record, short one cylinder section record and artificially extended record

It was a basis of further interest about single cylinder's related part of torsional deflection and its diagnostic value. Multiplication of data number can be done by repetition of short record segments and sticking them at end of previous one. Due to presented composition, "new" signal length, nine times longer, enable better FFT decomposition, and gives more clear spectral picture. Subsequent steps of analysis were based on comparison of cylinders number 1, 2 and 3 and looking for potential deviations, which can bearing any diagnostic worth. It was assumed that differences of combustion caused by for example fuel valve malfunction or wrong fuel pressure shall be reflected by appearance or vanishing of component peaks. Such kind of verification should enable distinguishing cylinders giving smaller contribution, and of course creating additional vibrations.

Verification of presented theory was carried out in way of several measurements including two levels of engine load i.e. 25% and 65% of maximum continuous rating. The aim of experiment was only verification of efficiency of the method, thus any simulations of fuel system malfunction were not implemented. Results are presented in Fig. 10 and 11. For 100 kW, frequencies of significant peaks are the same, but different values of torsional magnitude occur. Cylinders number 1 and 2 are similar and gives four maximum peaks, first two around 19 Hz, subsequent at 57 Hz and 74 Hz. Cylinder number 3 is characterised by low value of 19 Hz but maximum is for frequency of 37 Hz (Fig. 9). This is very interesting because frequency of injection for revolutionary speed of 12.5 revolutions per second is 18.75 Hz. It means that component of order 1.5 has lower contribution then its multiplication. Cylinders 1 and 2 have much stronger position of injection related frequency.

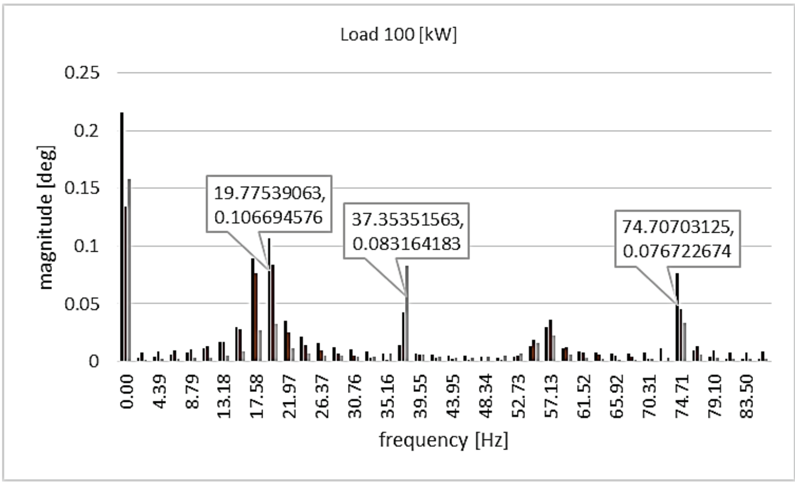

Fig. 10. Comparison of spectra of cylinder No. 1, 2 and 3. Load 25% of MCR

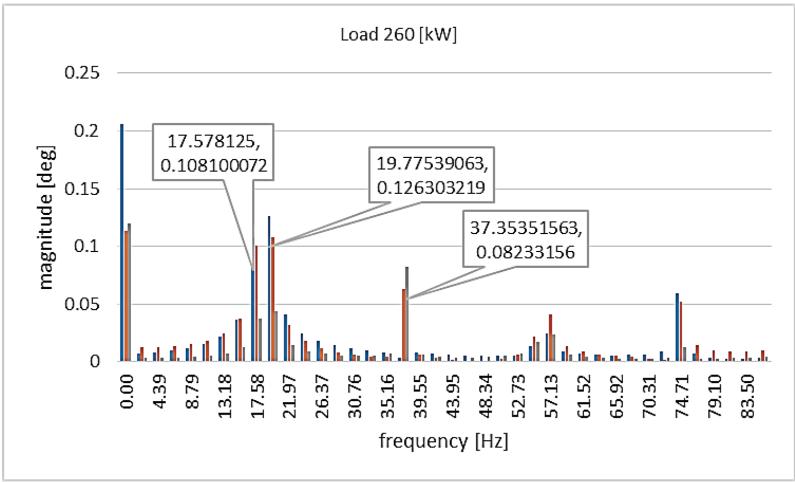

Fig. 11. Comparison of spectra of cylinder No. 1, 2 and 3. Load 65% of MCR

Comparison of spectra of different loads of engine shall give an answer about influence of rise of gas pressure. Increase of load causing higher value of mean effective pressure and maximal gas pressure in cylinder, what must be reflected by torsional deflection of the shaft. Results of comparison for higher load are presented in Fig. 11. General conclusion is, that frequencies of significant peaks are the same, and any new frequency strap did not appeared, only difference is because of bigger gas force and is reflected by increase of magnitude of basic frequency peaks of 20%. Increase of major magnitudes were observed for all three kinds of spectra, i.e. full cycle, single cylinder cycle and artificially extended one cylinder cycle.

4. Summary

Experimental measurements were conducted in order to collect necessary number of data for signal processing, and verification of undertaken way of extension of signal length. At presented stage of research, any simulations of malfunctions of fuel system elements were not implemented.

Analysis of obtained spectra shows differences between harmonic components of basic function of three-cylinder deriving torsion and function based at one cylinder record. In addition, comparison one to another, done for cylinders number 1, 2, and 3, gave interesting conclusions, what let assumed diagnostic potential of one cylinder analysis. Run of in – cylinder pressure depends of many factors related to fuel and air parameters. Changes of injection angle, fuel pressure, or compression pressure makes deviations from ideal combustion process. Any deviation of instantaneous value of gas pressure translates to tangent force and of course to torque value. In addition, variations of angular speed of generator, which creates torque of load, have impact at torsional vibrations of crankshaft. It is assumed that engine shaft bears all information about energy conveying, and detection of it can give information about engine condition. Further steps are foreseen and will be based on implementation of broad range of fuel valve malfunctions.

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