

# The time-frequency method of signal analysis in internal combustion engine diagnostics

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**Abstract.** The paper presents the results of the study of applicability of time-frequency correlation functions to solving the problems of internal combustion engine fault diagnostics. The proposed methods are theoretically justified and experimentally tested. In particular, the method's applicability is illustrated by the example of specially generated signals that simulate the vibration of an engine both during the normal operation and in the case of a malfunction in the system supplying fuel to the cylinders. This method was confirmed during an experiment with an automobile internal combustion engine. The study offers the main findings of the simulation and the experiment and highlights certain characteristic features of time-frequency autocorrelation functions that allow one to identify malfunctions in an engine's cylinder. The possibility in principle of using time-frequency correlation functions in function testing of the internal combustion engine is demonstrated. The paper's conclusion proposes further research directions including the application of the method to diagnosing automobile gearboxes.

## 1. Introduction

The diagnostics of machines and assemblies that allows assessing their condition and predicting their performance is highly demanded in engineering [1]. Various methods of diagnosing mechanical assemblies have been devised, including those based on assessing the mechanical condition of the diagnosed device, such as, for example, thermal [2], acoustic [3], magnetic [4], and other conditions.

However, the most widespread diagnostic method is vibration monitoring based on study and assessment of the working mechanism's oscillations [2].

Oscillations appear in working mechanisms due to the movement of mechanical masses. Depending on the mechanism's design, the operating principle, and the purpose, the movement of the masses can have different nature, for example rotary, reciprocating, etc. A mechanism's vibration is generally determined by its moving masses' values and the nature of their motion, as well as the condition of its interface assemblies [5].

Increased clearances in the linkage of the mechanism's moving parts are accompanied by increased vibration, which indicates the diagnosed device's condition [5]. Vibration monitoring relies on the study and analysis of the vibration generated by a working mechanism.

Vibration signals from the working device under diagnosis are collected by vibration transducers that are installed on the device and transform mechanical oscillations into electrical signals. As a rule, vibration signals are high-frequency and can reach thousands of Hertz [6].

The practice of vibration monitoring may employ various methods based on the study of signals in frequency or time domains. They may also be combined, particularly in the form of time-frequency analysis, which is more complex but allows obtaining more information about the processes in the diagnosed device [7].

This paper addresses the application of a vibration study method that uses time-frequency



autocorrelation functions (TFACFs) [8] to solve the problem of vibration monitoring of automobile internal combustion engines (ICEs).

## **2. Vibration signal analysis methods**

The signals generated during the ICE operation are periodic and their main characteristic is the presence of an intense noise component. The sources of periodic signals in an ICE are the cylinder-and-piston assembly, the ignition system, the crankshaft, and some others [9]. This way, the main objective of vibration monitoring is to identify the mechanisms and their assemblies that are functioning incorrectly and are generating vibration signals.

From the point of view of signal processing, the aforementioned problem is reduced to detecting informative periodic signals, including pulses, against the background of intense noises and assessing their frequency and energy characteristics [7]. Different approaches based on correlation and spectral analysis are used to detect weak periodic signals in high-intensity noise.

Specifically, the form of a signal's autocorrelation function can be used to determine the presence of the periodic component in the studied signal and to identify its period [10]. However, the use of this approach becomes problematic when several periodic signals are present in the analyzed signal mixture.

In this case, there appears the additional necessity to obtain information about the signal's spectrum and, as a rule, to carry out signal filtering to identify the region of the spectrum that contains the only significant component. At the same time, this method has its shortcomings: the desired signal spectrum is most often initially unknown and can be partially overlapped by the noise component.

Taking into account the stated drawbacks and limitations of the traditional methods, the most promising method in terms of obtaining additional information about the studied signals during diagnostics is the approach based on using TFACFs, as it allows one to visually present the information about the analyzed signal in time-base and frequency sweep.

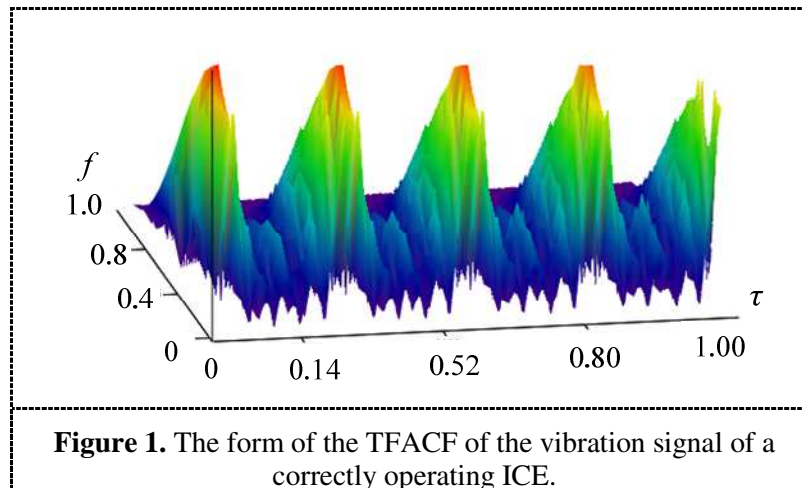
The essence of the method described in [8] can be reduced to calculating a series of autocorrelation functions for different disjoint frequency intervals of the studied signal. Graphically, the resulting TFACF represents a surface located above a plane formed by the axes of time and frequency. The shape of the TFACF surface can be used to identify the presence of weak periodic signals [8], including pulse signals.

## **3. Time-frequency analysis of ICE vibration signals**

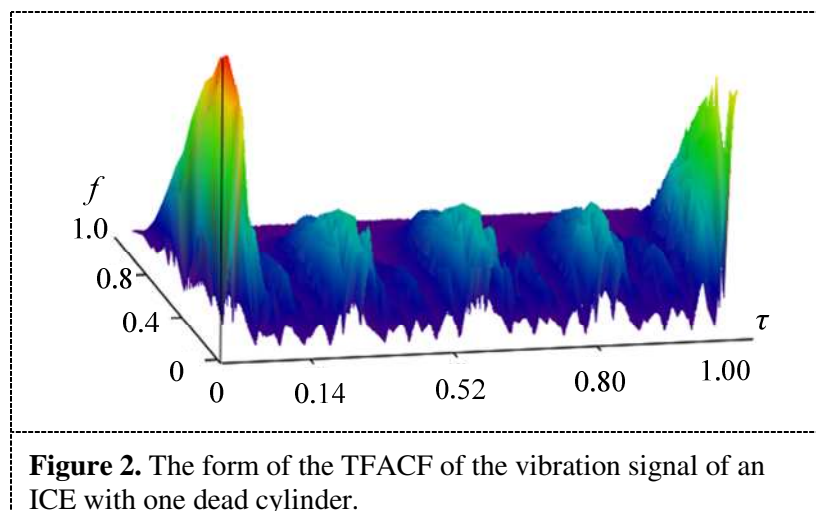
The applicability of TFACF to ICE vibration monitoring is theoretically justified by studying simulated pulse signals that model the ICE case vibration and is evaluated during an experiment with a Honda K20A automobile engine.

### *3.1. The form of the ICE vibration TFACFs*

The reciprocating motion associated with the operation of the cylinder-and-piston assembly is the source of ICE case vibration [3]. This being the case, when the engine is in order and operates normally, the vibration response to the cylinder operation is identical in the points in the casing that are equidistant from the cylinders. This way, all peaks of a correctly operating engine's TFACF are comparable in magnitude, as shown in Figure 1.

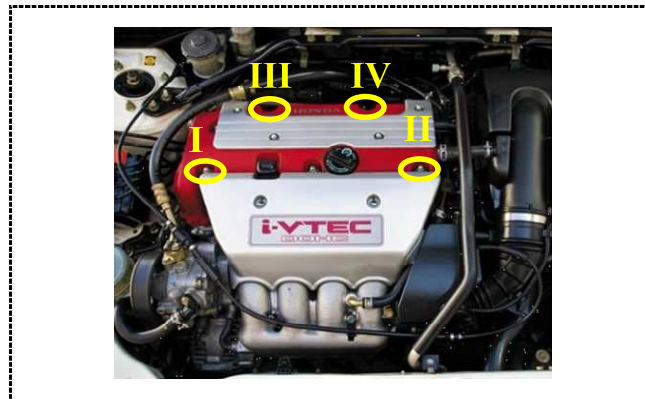


If the cylinder-and-piston assembly has a fault and the ICE is operating incorrectly, the TFACF's form will be significantly different. For example, in the case of fuel supply malfunction in one of the cylinders, each pronounced peak of the TFACF will be followed by three identical ones with lesser magnitude, as shown in Figure 2.



### 3.2. Symptoms of cylinder-and-piston assembly defects

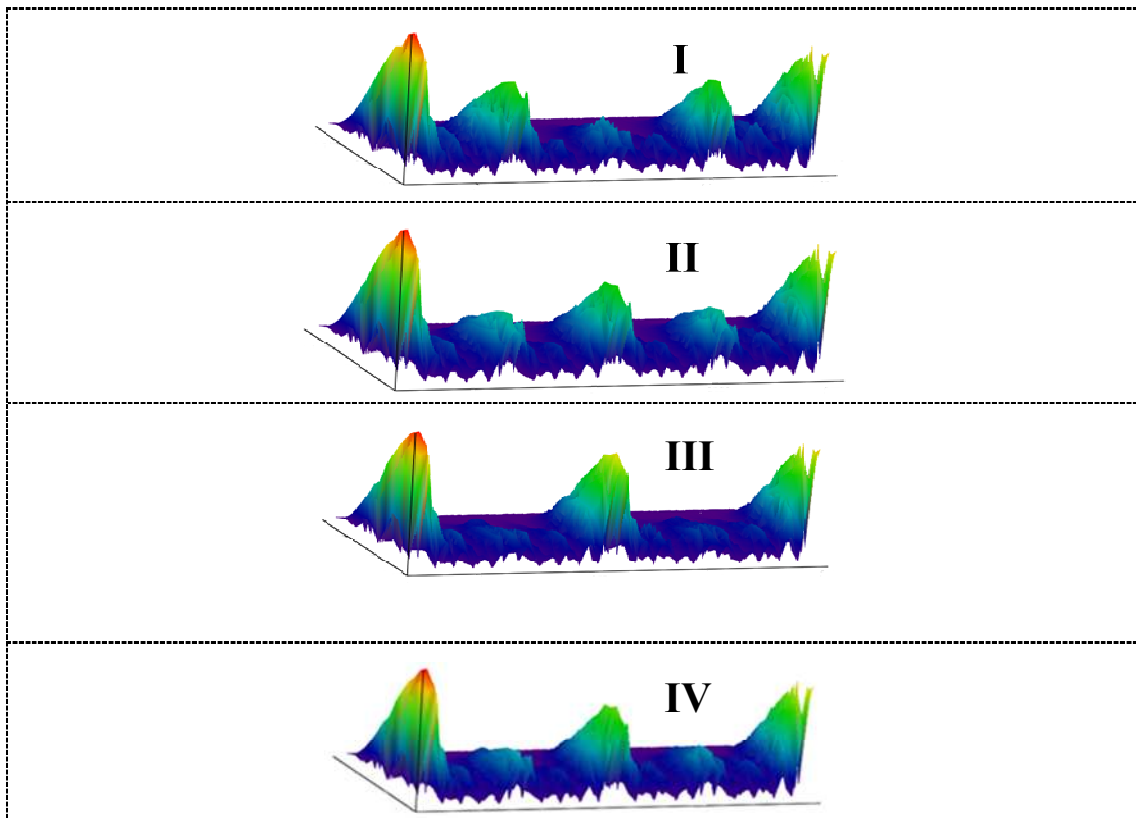
It is necessary to note that in the model used above, the distance to cylinders did not have any effect on the intensity of the vibration detected during gas combustion. However, such dependence actually exists in reality [11]. The closer the point in the ICE case is to the operating cylinder, the higher the vibration intensity is. For this reason, we will further consider the TFACFs of the vibration signals in the points in the ICE case that are located as shown in Figure 3.



**Figure 3.** Arrangement of sensors on the ICE case.

Thus, a sensor located in the vicinity of the first (I) cylinder will read a signal of the highest intensity during gas combustion in this cylinder. Then, with the cylinders' successive operation at an increasing distance from the sensor, the detected vibration intensity will decrease. The least intensive pulse will be detected during the fourth (IV) cylinder's operation.

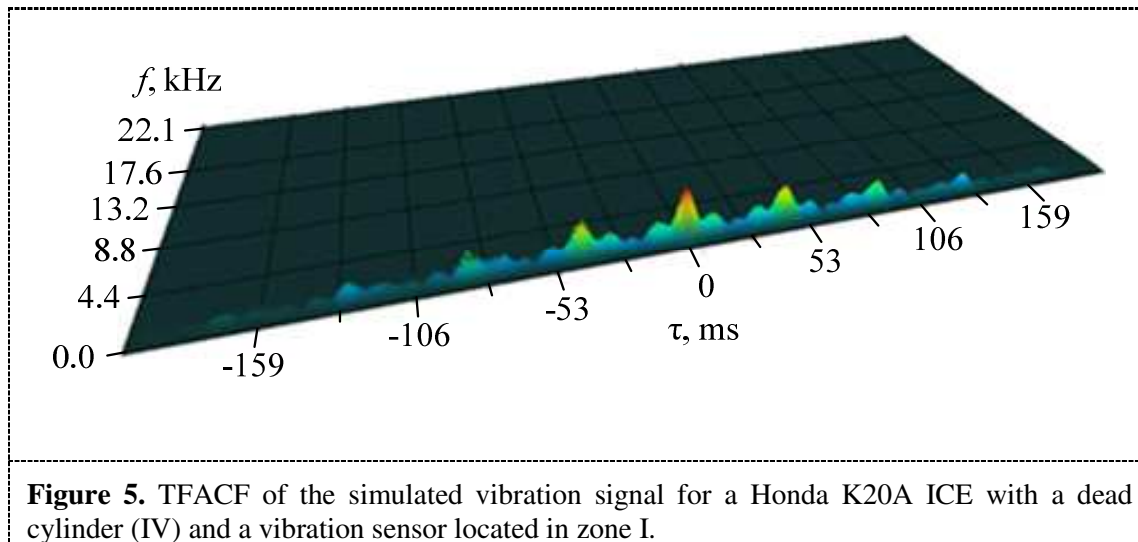
This way, due to the mismatch of the vibration impulses, the shape of a TFACF surface will be determined by both the functioning conditions of each of the four cylinders and the sensor position. The latter makes TFACF surfaces quite distinctive and allows using them in diagnosing the ICE cylinder-and-piston assembly defects. In particular, this method can identify the cylinder with a fuel supply system defect or malfunction. The shape of the TFACF surfaces for the different locations of the sensor is shown in Figure 4. It should be noted that the surfaces obtained this way can be used as defect symptoms.



**Figure 4.** The shape of the TFACFs of the vibration of an ICE with a dead cylinder (IV) when the sensors are located according to the demonstrated pattern.

### 3.3. Experimental verification of the method

With the purpose of validating the proposed method, experiments were carried out with a Honda K20A automobile engine. Vibration signals were read with a piezoelectric accelerometer installed at different points of the engine's case. The ICE fault was simulated by deactivating an injection nozzle in the fourth cylinder. As an example, Figure 5 shows the TFACF surface obtained using dedicated software [8]. In this case, the sensor was located in zone I.



**Figure 5.** TFACF of the simulated vibration signal for a Honda K20A ICE with a dead cylinder (IV) and a vibration sensor located in zone I.

The TFACF surface in Figure 5 is similar to the surface shown in Figure 4 (I), which corresponds to the defect replicated in the experiment. The correspondence between other experimentally designed defect symptoms and the actual malfunctions in the cylinder-and-piston assembly of an automobile ICE were identified in the same way.

## 4. Conclusion

This study proposes to use the mathematical method of time-frequency correlation analysis to solve the problems of ICE diagnostics, particularly to identify faults in the cylinder-and-piston assembly. The applicability in principle of the proposed diagnosis method is theoretically justified and experimentally validated during work with a Honda K20A ICE.

Cumulatively, the obtained results allow one to assert that the TFACF shape is specific and can be used as a symptom of ICE piston-and-cylinder assembly malfunctions. At the same time, it is necessary to bear in mind that each engine has different characteristics and operating conditions that have a significant effect on the diagnosis procedure and must be accounted for during analysis. In particular, mutual arrangement of the cylinders and the sequence of their operation are obviously a factor.

The advantage of time-frequency correlation analysis, represented by the possibility of determining the time and frequency characteristics of periodic pulse sequences, is potentially substantial in diagnosing other automobile systems, namely gearboxes.

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