

# Dynamic analysis of an internal combustion engine made in downsizing technology

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**Abstract.** Decisions made today in the automotive industry clearly indicate the inevitable end of the last resort for combustion engines, which were small-capacity engines made in line with the idea of downsizing. Certainly, one of the characteristic features of these engines will be maintaining the same power and torque with fewer cylinders, the best proof of which is the Twin Air technology engine proposed by Fiat. The consequence of this action was incomparably greater vibrations compared to classic, four-cylinder combustion engines. This article presents an analysis of various dynamic states of a small-capacity engine made using downsizing technology.

## 1 Introduction

Combustion engines designed in accordance with the idea of downsizing are currently the most popular internal combustion power units in passenger cars, especially in the case of hybrid vehicles. These engines include, among others:

- direct fuel injection (in the case of petrol engines) with a high compression ratio,
- turbocharging,
- variable phases and valve lifts,
- a number of electronic sensors that control the proper operation of the unit,
- more durable materials - necessary due to the much higher pressure above the piston (up to 130 bar, twice as much as in naturally aspirated units),
- reducing the weight of many moving engine components,
- timing drive chain instead of a belt,
- special shape of the engine block so that it heats up faster and reaches operating temperature,
- more effective engine mounts,
- dual-mass flywheels to protect the gearbox against vibrations transmitted from the engine.

The latest technological solutions used on a smaller scale were supposed to ensure not only similar characteristics to classic combustion engines, but also adequate durability and reliability, which unfortunately did not entirely succeed. The three-cylinder 1.2 TDI unit manufactured using downsizing technology is characterized by lower operating culture and, therefore, greater vibrations than the four-cylinder 1.6 TDI engine on which it was based. This article aims to compare the dynamic state of these two drive units and confirm the above hypothesis.

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## 2 Vibrations in the combustion engine

There are many components in an internal combustion engine whose motion repeats with each cycle or revolution. These elements may be the crankshaft, camshafts or balancer shafts, pistons, valves, etc. Constantly repeating motion is called periodic motion. It generates periodic vibrations with period  $T$ . The simplest periodic motion is sinusoidal motion described by the relationship [1,2]:

$$x = a \sin(\omega t) \quad (1)$$

where:

$a$  – maximum value of the function – amplitude,

$\omega$  – pulsation expressed in radians per second.

In a mechanical system, two periodic movements may occur, with the same amplitude and frequency, but the maximum values are obtained at different points in time. This means that they are shifted relative to each other by a phase angle  $\varphi$ .

$$x = a \sin(\omega t + \varphi) \quad (2)$$

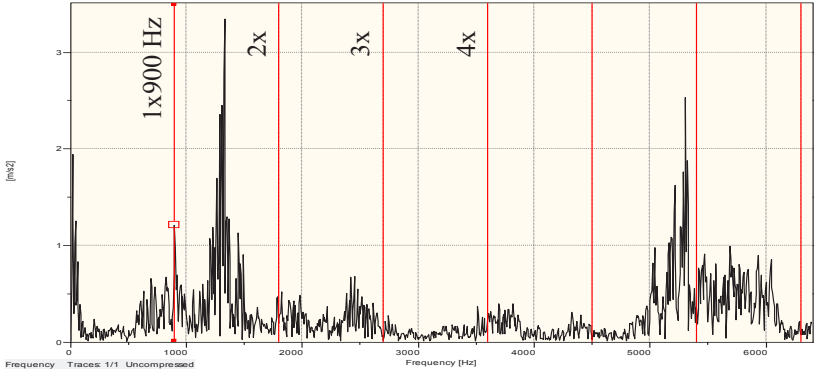
From the above formulas it can be concluded that knowledge is enough to describe periodic motion:

- angular velocity ( $\omega$ ), frequency( $f$ ) or period ( $T$ ) vibration,
- vibration amplitudes,
- phase displacement angle.

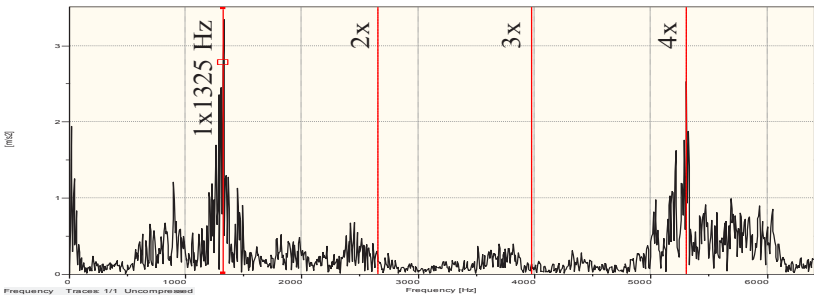
The vibrations described above are closely related to the functions describing them, and therefore their amplitude can be determined at any time in the future. These are determined signals. During the operation of the combustion engine, random vibrations also occur, resulting, for example, from differences in the combustion process in individual cylinders and continuous adjustment of the combustion process parameters by the engine control computer to the ambient conditions.

Mechanical vibrations, as a result of the action of forces, provide wide possibilities of using them in machine diagnostics. They make it possible to constantly monitor the machine's operation and, if any irregularities are noticed, to determine what is the cause of the malfunction. The key to effective work based on vibration analysis is the appropriate selection of parameters measured by the measurement method and sensors. Displacement measurements, either relative or absolute, demonstrate utility at low frequencies. Velocity measurement does not have the same frequency limitations as displacement measurement, according to standards is used to assess the intensity and intensity of vibrations. The displacement measurement shows a good picture of high-frequency loads. It is used, for example, to monitor rolling bearings. If the measured quantity has already been determined, appropriate measurement points and sensors should be used. The next challenge is to analyze and process the signal obtained in the research. Analysis of the time course by determining an estimate may be sufficient for ongoing monitoring of the machine's condition, but it will not be sufficient for diagnostic purposes. The method of processing the vibration signal is determined not only by the goal being achieved but also by the form of the vibrations themselves.

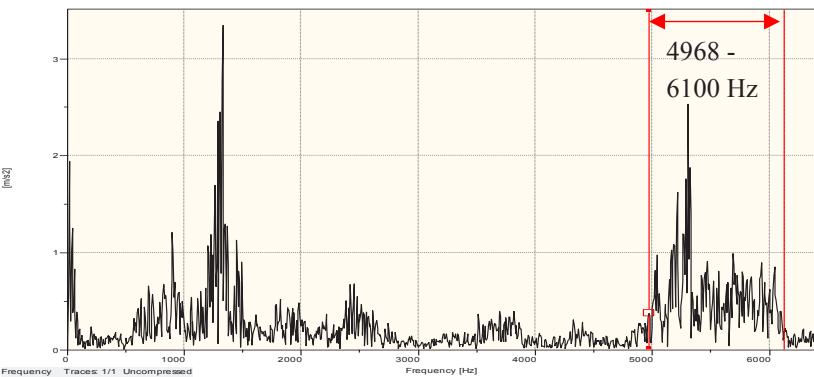
The frequency bands were determined on the basis of scientific articles devoted to this topic [3,4]. The charts below show the vibration frequency ranges of individual components of the tested engine.



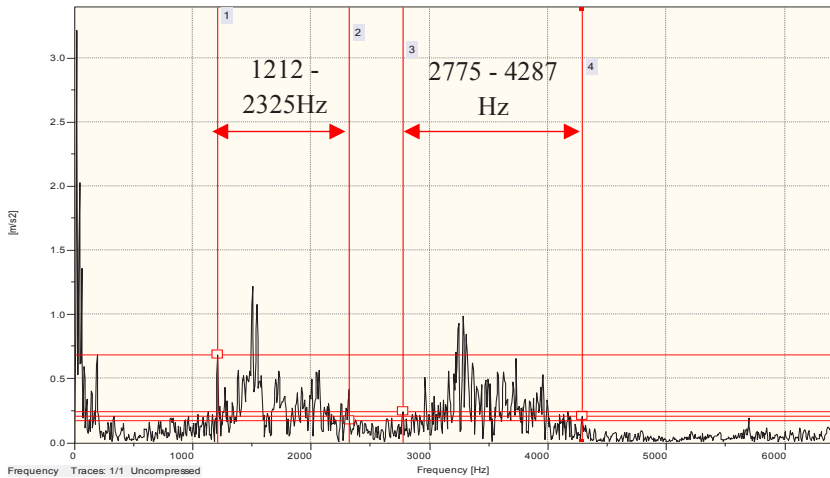
**Fig. 1.** The frequency of vibrations of the crankshaft at idle speed of the engine.



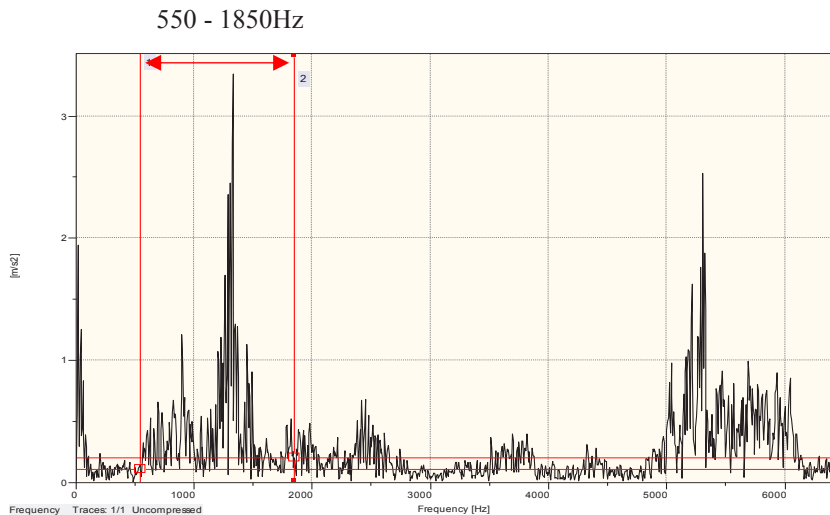
**Fig. 2.** The frequency of camshaft vibrations at engine idle.



**Fig. 3.** The frequency of vibrations of the intake and exhaust valves at idle speed of the engine.



**Fig. 4.** Turbocharger vibration frequency.



**Fig. 5.** The marked frequency range includes vibrations of such engine components as: camshaft pulley, timing belt tension pulley, crankshaft pulley, high pressure fuel pump, timing belt guide pulley, coolant pump, V-belt guide pulley, alternator pulley, compressor pulley air conditioning, oil pump.

Any unbalance of individual rotating elements, generating a sinusoidal signal, can be analyzed over time, which is sufficient to determine the amplitude and frequency of these vibrations [5]. In the case of complex rotating elements or a system of rotating elements, it is necessary to use a Fourier series and divide the signal into individual sinusoids included in it. If in a mechanical system, e.g. an internal combustion engine, in addition to a large number of rotating shafts and elements performing back-to-back movements (pistons), there is ignition of the air-fuel mixture, the amount of which varies in each cycle due to the operation of the engine controller and continuous adjustment of operating parameters, this means that random vibrations are added to the determined vibrations [6,7,8]. In such situations, the Fourier integral and the Fourier transform - the frequency function of vibrations - turn out to be helpful.

### 3 Object and measuring system

The tests were carried out on two engines: a three-cylinder 1.2 TDI diesel engine and a four-cylinder 1.6 TDI diesel engine. This unit was installed in cars such as VW Polo, Skoda Fabia, Roomster and Seat Ibiza. Table 1 shows the technical data of the engine in question.



**Fig. 6.** Object of research.

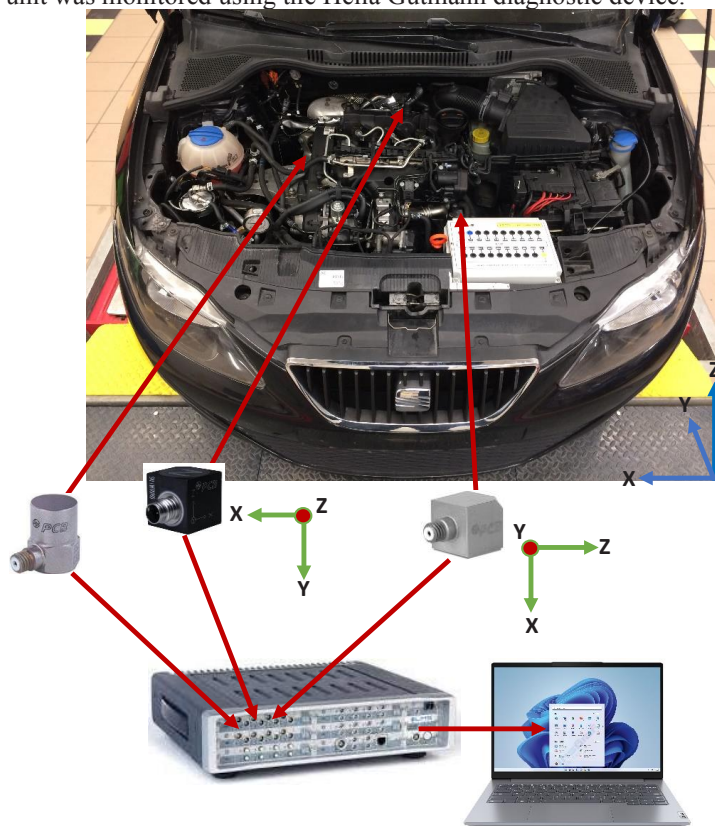
**Table 1.** Basic technical data of engines.

	<b>1.2 TDI CR (EA189)</b>	<b>1.6 TDI CR (EA189)</b>
<b>Parameters</b>	<b>Value</b>	<b>Value</b>
Number of cylinders	3	4
Displacement	1199	1598
Firing order	1-2-3	1-3-4-2
Engine type	Diesel	Diesel
Timing type	DOHC	DOHC
Timing drive	Belt	Belt
Number of valves per cylinder	4	4
Cylinder arrangement	Row	Row
Compression ratio	16,5:1	16,5:1
Maximum engine power	55 (75)	55(75)
Maximum torque	195	195
Injection type	Common Rail	Common Rail
Type of injectors	Electromagnetic	Electromagnetic
Dual-mass wheel	Yes	Yes
Turbocharger type	Turbochargers	Turbochargers

The tests were carried out according to the measurement scheme shown in Figure 7. Measurements were performed simultaneously at three measurement points. A single-axis sensor is installed on the right side of the engine compartment, on the left a three-axis sensor is used at the battery. The third measurement point was located near the turbocharger assembly, on the clamp securing the air supply line to the compressor. The measuring system of the station includes:

- a) computer with software LMS Test.Xpress,
- b) signal recorder Simcenter Scadas Recorder SCR05,
- c) analog-digital card V8-E,
- d) vibration acceleration sensor – PCB 356A16,
- e) vibration acceleration sensor – PCB 356A02,
- f) vibration acceleration sensor – PCB 352C33.

The idle speed is approximately 600 rpm, while the maximum speed achieved at standstill is 3000 rpm. The time of each measurement is 10 seconds. The experiment was divided into several stages. The first one was to measure vibrations of the drive unit at idle speed, and the second one was to measure the vibrations of the engine at idle speed, and the second one was to measure the vibrations of the engine at increased engine speeds, thereby activating other engine components, such as the turbocharger. Such measurements were carried out in accordance with the test conditions at idle speed of the engine, i.e. approximately 600 revolutions of the crankshaft per minute and the maximum rotational speed achieved by the engine at standstill, i.e. 3000 revolutions per minute with the engine not warmed up and warmed up. The recording of the vibration signal began after the engine operation stabilized after starting and reaching the rotational speeds set in the test conditions. The rotational speed of the drive unit was monitored using the Hella Gutmann diagnostic device.



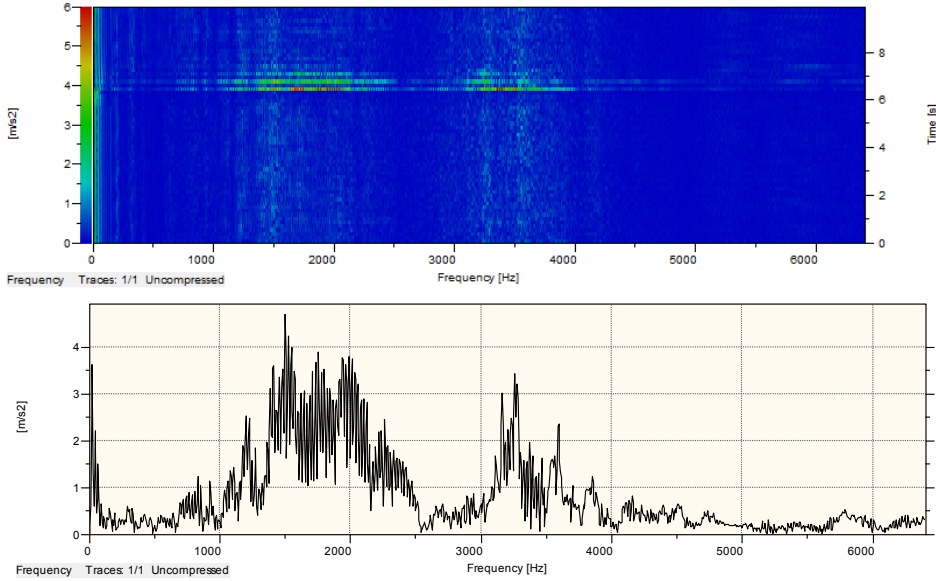
**Fig. 7.** Diagram of the measurement track with the spatial orientation of the sensors used.

The set settings of the measurement system and the method of recording the dynamic state of the tested object are presented below:

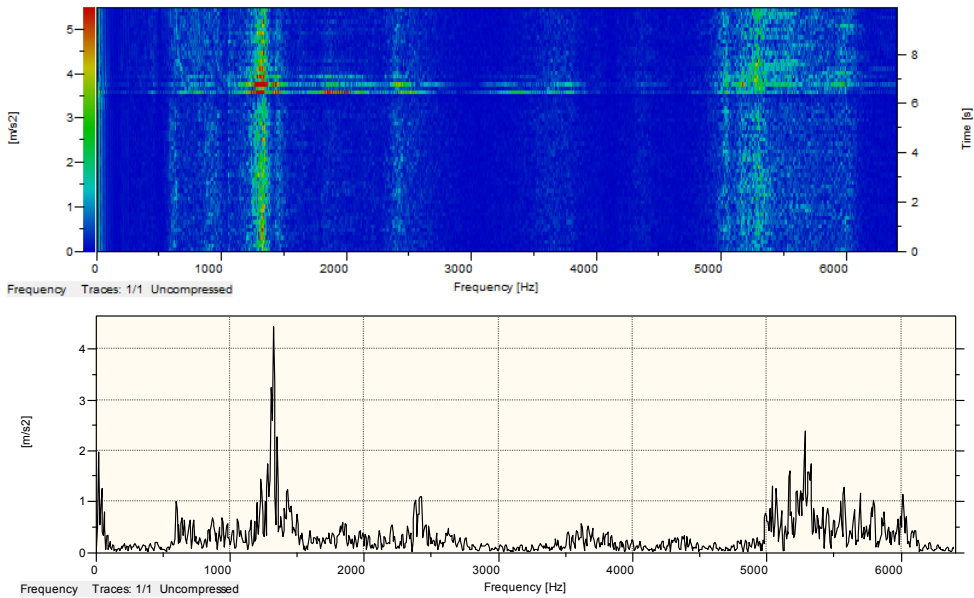
- 1) frequency range –  $0.7 \div 6400$  Hz,
- 2) signal sampling – 12800 Hz,
- 3) method of presenting results: amplitude-frequency waveform (FFT) and time-frequency waveform (STFT).

### 4 Results

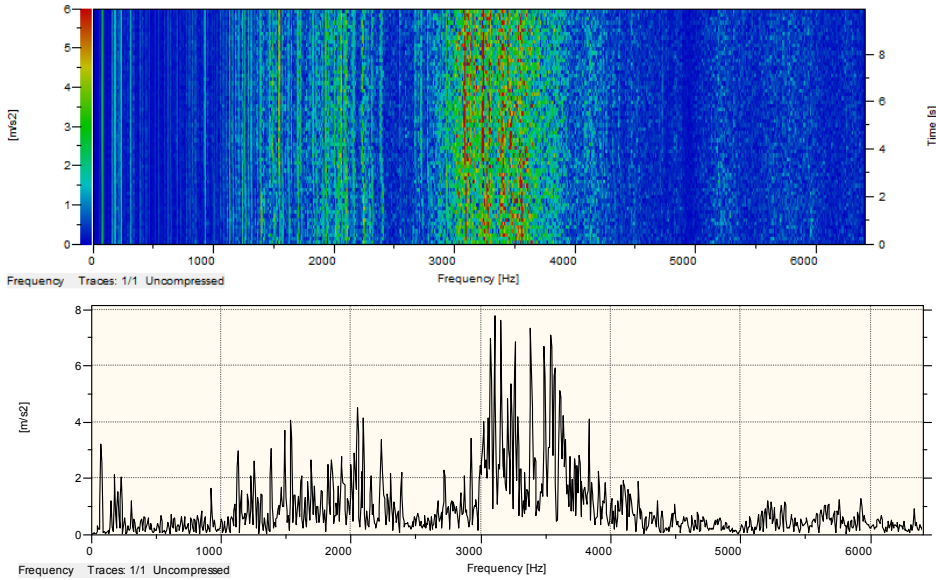
Time-frequency waveform analysis (STFT) was used to assess the dynamic state of the tested engines. The analysis mainly consisted in qualitative assessment at various engine speeds. A few selected figures 8 - 11 show changes in the vibration acceleration values only in the Z direction.



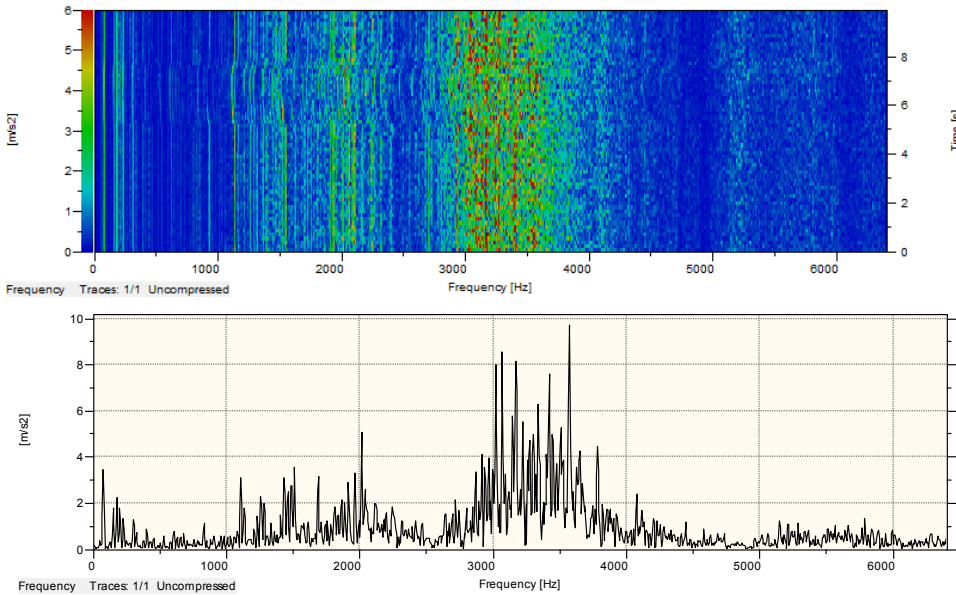
**Fig. 8.** FFT and STFT charts for the 1.6 TDI CR engine running at idle.



**Fig. 9.** FFT and STFT charts for the 1.2 TDI CR engine running at idle.



**Fig. 10.** FFT and STFT charts for the 1.6 TDI CR engine in the range of increased rotational speed, activating other engine components (e.g. turbocharger).



**Fig. 11.** FFT and STFT charts of the 1.2 TDI CR engine in the range of increased rotational speed, activating other engine components (e.g. turbocharger).

## 5 Conclusion

Based on the analyzes of the obtained experimental test results, a clear difference was noticed between the dynamic state of the 1.2 TDI CR engine and the 1.6 TDI CR engine. These differences are visible not only in the value of the vibration amplitude, but also in the case of changes in the frequency of vibration generation. This confirms numerous assumptions of

users of vehicles with 1.2 TDI CR engines that have a lower operating culture, which significantly translates into overall driving comfort.

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