

# Fuel rail pressure pulsation analysis for detecting injection-related disturbances in internal combustion engines

Shevchenko O<sup>1</sup>, Linkov O<sup>1</sup>.

<sup>1</sup>National Technical University “Kharkiv Polytechnic Institute”, Ukraine

**Abstract. Problem.** Reliable diagnostics of internal combustion engine fuel systems is complicated by limited access to electronic control unit data and by the low informativeness of standard diagnostic parameters available through conventional onboard systems. In many cases, ECU-derived parameters are filtered, averaged, or partially inaccessible, which reduces their suitability for detecting local injection-related disturbances. Therefore, the use of direct physical signals, in particular fuel pressure pulsations, is a promising direction for improving the diagnostic informativeness of fuel system monitoring. **Goal.** The purpose of this study is to assess the possibility of using fuel pressure pulsations as a diagnostic indicator of injection-related disturbances in an internal combustion engine fuel system without relying on internal ECU diagnostic variables. **Methodology.** Experimental investigations were carried out on a gasoline internal combustion engine equipped with a port fuel injection system. Fuel pressure was measured directly in the fuel rail using a strain-gauge pressure sensor. Synchronous acquisition of fuel pressure, injector current, and crankshaft position signals was performed using a high-speed microcontroller-based data acquisition system. The recorded signals were transformed into the crank-angle domain over a complete 0–720° four-stroke engine cycle. A simulated disturbance was introduced by electrically disconnecting one injector, while the current signal of another active injector was used as a timing reference. **Results.** The obtained results showed that under normal operation, fuel pressure pulsations have a stable cyclic structure associated with injection events. Injector disconnection caused a systematic deformation of the pressure waveform, reduction of pulsation amplitude, increase in mean rail pressure, and disappearance or significant attenuation of one characteristic pressure minimum within the expected angular sector. **Originality.** The originality of the study lies in the use of cycle-synchronous fuel pressure pulsation analysis for detecting injection-related disturbances independently of ECU data. **Practical value.** The proposed approach can serve as a basis for non-intrusive diagnostic and condition monitoring systems for internal combustion engine fuel systems.

**Keywords:** fuel system diagnostics; fuel injection; fuel rail pressure pulsations; technical condition; combustion process; dynamic processes; reliability; mathematical model.

## Introduction

Reliable diagnostics of internal combustion engine fuel systems is an important factor in ensuring engine efficiency, environmental performance, and operational reliability. Modern fuel systems operate under high-pressure conditions and involve fast dynamic processes, which complicates the detection of early-stage deviations in their functioning. Conventional diagnostic methods are mainly based on data obtained from

the electronic control unit (ECU), access to which is often limited, while the signals themselves are subject to significant filtering and averaging [1-3].

Fuel pressure fluctuations in the fuel delivery system contain information about the dynamics of fuel supply processes, pump operation, and injection events. Pressure pulsations are formed as a result of periodic fuel delivery and cyclic operation of fuel system components, reflecting

both normal operating conditions and deviations caused by malfunctions. Despite this, fuel pressure signals are typically used for control purposes, whereas their diagnostic potential, especially in the high-frequency range, remains insufficiently explored [4-10].

Modern fuel systems exhibit pronounced hydraulic dynamics because fuel delivery, pressure regulation, and injection are cyclic processes with characteristic time scales comparable to a fraction of an engine cycle. In practice, diagnostic assessment is often restricted to ECU-reported values (rail pressure, injection correction factors, misfire counters, etc.), yet these signals are typically filtered, averaged, and in some cases partially inaccessible through standard diagnostic interfaces. As a result, early-stage deviations in the fuel supply and injection subsystems may remain undetected or be recognized only indirectly. This motivates diagnostic approaches based on direct physical measurements that do not rely on internal ECU variables and retain high-frequency information content independent of access to ECU data [4, 8, 11].

Fuel pressure pulsations represent a physically grounded diagnostic carrier. Similar diagnostic approaches based on pressure waveform analysis have been reported in previous studies [8, 12, 13]. Because they are formed by the balance between instantaneous fuel outflow during injection and pressure recovery caused by the pump and pressure regulation mechanism. From a hydraulic standpoint, each injection event produces a local pressure drop in the rail volume, while subsequent recovery reflects the capability of the supply system to restore pressure and damp pulsations. Therefore, pressure pulsations potentially contain information not only about the injection process itself, but also about the overall condition of the fuel system components (injectors, pump, pressure regulator) and the stability of supply-consumption equilibrium. Standard diagnostic practice generally treats pressure as a control variable, while the diagnostic use of its high-frequency pulsation structure has not been sufficiently exploited.

### Analysis of publications

Previous research has addressed pressure oscillations and injection-related dynamics mainly in the context of modeling, control, and component-level analysis, including pressure regulation mechanisms and common-rail system behavior, including pressure pulsation modeling and mitigation in gasoline injection systems [14, 15]. However, many published diagnostic

approaches still depend on ECU-derived parameters or on high-level statistical indicators, which may be insufficiently sensitive to local, cycle-resolved disturbances. The present work focuses on extracting cycle-synchronous diagnostic features directly from the pressure waveform, thereby enabling a condition assessment approach that is applicable even when ECU data are unavailable or strongly pre-processed.

The key methodological idea of this study is to transform high-frequency pressure measurements into the crank-angle domain ( $0-720^\circ$ ) and to analyze pressure minimum and recovery characteristics relative to injection events. This representation enables direct comparison across operating modes and facilitates the identification of missing or distorted injection signatures. The study concentrates on a practically relevant fault scenario-intentional disconnection of one injector-to verify the hydraulic origin of pulsations and to demonstrate that the pressure signal alone can reveal injection-related disturbances. Although experiments were carried out on a gasoline engine with port fuel injection, the proposed analysis concept is not tied to a specific engine type, since the physical mechanism (outflow-induced pressure drop followed by recovery) is common for fuel supply systems.

The main contributions of this paper can be summarized as follows: (I) a measurement and synchronization approach for cycle-resolved, high-frequency acquisition of fuel rail pressure together with injection timing reference; (ii) a structured set of diagnostic features extracted from pressure pulsations in the crank-angle domain, including minimum positions and recovery dynamics; (iii) an experimental demonstration, under two operating modes, that disabling one injector produces a systematic deformation of the pressure waveform and a change in quantitative pulsation parameters, providing a basis for ECU-independent diagnostics. In the present study, the experimental validation is intentionally limited to one clearly interpretable fault scenario, namely complete injector disconnection. Therefore, the paper does not claim full-condition diagnosis of all fuel-system components, but rather demonstrates the diagnostic informativeness of pressure pulsations for detecting injection-related disturbances.

In existing scientific studies, the main focus is placed on diagnostics of individual fuel system components or on the analysis of parameters generated by the electronic engine control system. Such approaches may be insensitive to early-stage disturbances in fuel system operation

and do not always allow the detection of system-level changes in its dynamic characteristics. This necessitates the development of diagnostic methods based on the analysis of direct physical signals that are independent of access to ECU data [4, 8, 9, 11, 16].

### Purpose and Tasks

The purpose of this study is to assess the feasibility of using fuel pressure pulsations as a diagnostic indicator of injection-related disturbances in an internal combustion engine fuel system.

To achieve this purpose, the following tasks were formulated:

- to develop a measurement approach for high-frequency fuel rail pressure acquisition;
- to synchronize fuel pressure, injector current, and crankshaft position signals;
- to transform the recorded signals into the crank-angle domain over a complete 0–720° engine cycle;
- to compare fuel pressure pulsation features under normal operation and injector disconnection;
- to identify diagnostic features suitable for detecting injection-related disturbances independently of ECU-derived diagnostic variables.

The aim of this study is to assess the feasibility of using fuel pressure pulsations as a diagnostic indicator of the injection-related disturbances in an internal combustion engine fuel system. The paper proposes an approach for analyzing changes in the temporal characteristics of the fuel pressure signal and presents the results of experimental investigations carried out under various engine operating modes with simulated disturbances in fuel system operation.

### Experimental object and test conditions

Experimental investigations were carried out on a gasoline internal combustion engine Z18XE, equipped with an electronic control system and a port fuel injection system. The tests were performed under stationary conditions at various engine operating modes corresponding to typical load conditions. In order to evaluate the diagnostic informativeness of fuel pressure pulsations, a simulated disturbance of fuel system operation was introduced by disabling one injector.

### Measurement and data acquisition system

Fuel pressure was measured using a strain-gauge pressure sensor purchased via a commercial online platform. The sensor was installed directly in the fuel rail and provided continuous moni-

toring of fuel pressure variations during engine operation. The applied measurement approach did not require modifications to the standard engine control system and did not affect engine operating modes.

In addition to the fuel pressure signal, the following signals were simultaneously recorded during the experiment:

- injector control current signal, reflecting the timing and duration of injection events;
- crankshaft position sensor signal, used for measurement synchronization and for referencing the signals to the crankshaft angular position.

Synchronous acquisition of these signals made it possible to analyze the relationship between injection processes and the corresponding pressure response in the fuel system.

Experimental data acquisition was performed using an autonomous measurement system providing high-frequency sampling of analog signals. The sampling frequency was selected to ensure correct registration of fast dynamic processes in the fuel system and accurate reproduction of fuel pressure pulsations in the time domain.

The recorded signals were stored in digital form for further processing and analysis.

Signal acquisition was performed using an Arduino Portenta H7-based hardware-software module featuring three independent 16-bit ADCs and DMA support, enabling synchronous multi-channel sampling without data loss [7, 11].

A 16-bit ADC resolution was considered sufficient for the present study because the objective was to resolve cycle-to-cycle pressure pulsations in the low-pressure gasoline rail rather than to measure ultra-small pressure increments. In this application, the limiting factors are primarily sensor bandwidth, analog front-end noise, and synchronization accuracy rather than nominal ADC resolution beyond 16 bits.

Thus, increasing nominal ADC resolution beyond 16 bits would not necessarily improve the diagnostic informativeness of the measured signal under the given sensor and operating conditions.

Three analog channels were recorded simultaneously: fuel rail pressure (A0), Hall sensor signal for speed/angle reference (A1), and control current (A3).

The ADC operated at a raw sampling rate of 160 kHz, and every five consecutive samples were averaged to obtain an effective output rate of approximately 32 kHz per channel. This ap-

proach was selected to improve the signal-to-noise ratio and to preserve short transient features before decimation, which is preferable to direct low-rate sampling when pressure pulsations and injector-current edges are analyzed simultaneously. In other words, oversampling followed by averaging was used not to increase the final data rate, but to reduce measurement noise and improve the robustness of cycle-synchronous feature extraction.

Crank-angle synchronization was performed using the crankshaft position signal, where the missing-tooth event served as a cycle reference marker and the analysis was conducted strictly within 0–720° crank angle [3, 4].

For comparing operating modes and conditions (normal/injector disabled), the pressure and current signals were mapped onto a common crank-angle scale, allowing consistent alignment of pressure minimum with injection-related events.

For visualization and comparison, all recorded signals were transformed into the crank-angle domain and presented over one complete 720° crankshaft cycle, which corresponds to a full four-stroke engine cycle.

In the injector-disconnection experiments, the fault condition was introduced by electricaly disconnecting the injector of cylinder No. 2.

The injector current signal was measured on the injector of cylinder No. 1, which remained operational in all test conditions. Therefore, the measured current waveform represents a normal injection event and is used solely as a temporal reference for aligning pressure pulsations with injection timing.

Since the disconnected injector carries no current, its electrical behavior cannot be directly observed. Consequently, the current signal shown in the figures should not be interpreted as representing the faulty injector, but only as a reference marker indicating the expected timing of injection events.

### Signal analysis methodology

The experimental data analysis was based on comparing the temporal characteristics of the fuel pressure signal under normal engine operation and under conditions with simulated disturbances in fuel system functioning. Changes in signal waveform, amplitude characteristics, and pulsation repeatability within engine cycles were evaluated. Particular attention was paid to the temporal relationship between injector control current pulses and the resulting fuel pressure response [4, 9, 17].

### Crank-angle domain reconstruction and feature extraction

To ensure comparability between operating modes (idle vs. load) and between conditions (normal vs. injector disabled), the recorded time-domain signals were converted into a crank-angle representation. The analysis window was defined as one complete four-stroke cycle (0–720° crank angle). The cycle reference was derived from the crankshaft position signal: the missing-tooth event was used as a repeatable marker of a fixed crank-angle position, allowing segmentation of the continuous recordings into individual cycles.

After cycle segmentation, pressure and injector current signals were mapped onto a common crank-angle grid. This step is essential because raw sampling produces time-indexed signals, while diagnostic interpretation requires phase alignment with injection events. The mapping was performed by associating each time sample with an instantaneous crank angle obtained from the speed reference signal and resampling the pressure/current traces onto a uniform crank-angle axis. As a result, characteristic pressure minimum could be compared at the same crank angles across different engine speeds, and multiple cycles could be averaged if necessary for noise reduction.

Feature extraction was performed within each 0–720° cycle. The following parameters were considered informative:

- $P_{\min}$ : minimum pressure during an injection-related local drop;
- $P_{\max}$ : maximum pressure after recovery within the same sector;
- $\Delta P = P_{\max} - P_{\min}$ : pulsation amplitude, representing the intensity of the hydraulic response;
- $P_{\text{mean}}$ : mean cycle pressure, reflecting the supply-consumption balance;
- $N_{\min}$ : the number of local minimum within a full 0–720° cycle (under normal operation of a 4-cylinder engine, this corresponds to the number of injection events);
- $\varphi_i$ : angular coordinates of minimum ( $i = 1 \dots N_{\min}$ ), enabling localization of missing or distorted injection events in a specific cylinder sector;
- $t_{90}$ : pressure recovery indicator defined as the crank-angle interval (or time) from the local minimum to the point where pressure reaches  $0.9 \cdot P_{\max}$  during the recovery phase.

The parameter  $t_{90}$  was introduced to quantify the recovery dynamics of the fuel rail pressure after an injection event. An increased  $t_{90}$  indi-

cates slower pressure restoration and may reflect reduced ability of the supply and regulation system to maintain pressure, potentially being sensitive to pump- or pressure-regulator-related deviations. In contrast, injector-related disturbances are expected to primarily alter the presence, depth, and angular position of individual minimum ( $P_{\min}$ ,  $\Delta P$ ,  $\varphi_i$ , and  $N_{\min}$ ).

For injector disconnection experiments, the injector control current served as an independent timing reference to verify that local pressure minimum correspond to injection events. In the crank-angle domain, this alignment allows consistent localization of pressure drops with respect to current pulses and provides a physically interpretable basis for diagnostic classification.

### Fuel pressure and injection event signal registration

During the experimental investigations, synchronous acquisition of fuel rail pressure, injector control current, and the Hall sensor signal was performed in order to determine the crankshaft angular position. Measurements were carried out on a gasoline internal combustion engine Z18XE under two stationary operating conditions: idle speed (781 rpm) and elevated-speed operation ( $\approx 2,489$  rpm). Since the engine was not tested on a dynamometer, the term "medium load" is not used in a strict brake-torque sense.

Figure 1 presents the cycle-synchronous fuel pressure and injector current waveforms under normal engine operation. The signals are plotted over a full  $0\text{--}720^\circ$  crank-angle interval in order to visualize all injector-related events within one complete four-stroke cycle. The recorded time-domain waveforms demonstrate characteristic fuel pressure pulsations occurring during injection events and reflecting the dynamic response of the fuel system to injector opening and closing.

At idle speed, the mean fuel rail pressure was approximately 0.38 MPa. The pressure oscillations exhibited a nearly sinusoidal pattern with an amplitude of about 0.03 MPa. The injector current pulses lasted approximately  $15^\circ$  of crankshaft angle. A short-term pressure drop was observed at the onset of the current pulse, corresponding to injector opening and fuel discharge from the rail volume.

Under medium load conditions, the mean pressure increased to 0.43–0.44 MPa, while the injection pulse duration extended to approximately  $40^\circ$ . The amplitude of pressure

pulsations rose to 0.05–0.06 MPa, which is consistent with increased fuel demand and more intensive injection processes at higher engine load.

At higher engine speed, the pressure waveform after a local minimum exhibits a more pronounced recovery segment with secondary oscillatory behavior. As a result, the pressure-recovery pulsations may visually resemble an additional injection-related event, although physically they correspond to hydraulic pressure restoration in the rail rather than to a separate injector actuation.

Therefore, in the high-speed operating condition, waveform interpretation must distinguish between a primary pressure drop caused by fuel outflow during injection and secondary oscillations associated with pressure recovery and hydraulic wave propagation.

This effect is especially important when the waveform is analyzed in the crank-angle domain over the full  $720^\circ$  cycle, because the recovery pulsations may appear as additional local extrema if not interpreted together with the timing-reference signal.

For this reason, the present study treats the injector current trace as a phase reference and interprets the pressure waveform on the basis of its dominant minimum and recovery structure, rather than assigning every local oscillation to a separate injection event.

### Comparison of normal operation and injector disconnection

To verify the diagnostic informativeness of the fuel pressure signal, an experiment with intentional disconnection of one injector was conducted. The objective was to confirm the hydraulic origin of fuel rail pressure pulsations and to evaluate the feasibility of detecting injection system malfunctions through changes in the pressure waveform.

Figure 2 shows the cycle-synchronous fuel pressure and injector current waveforms obtained with one injector disabled at 799 rpm and 2,315 rpm. The  $0\text{--}720^\circ$  crank-angle representation allows direct comparison of pressure minimum and pressure-recovery behavior associated with injector-related events within the complete engine cycle. When the injector was disconnected at idle speed, a reduction in pulsation amplitude and a loss of waveform symmetry were observed: one of the characteristic pressure drops within the engine cycle disappeared or was significantly reduced.

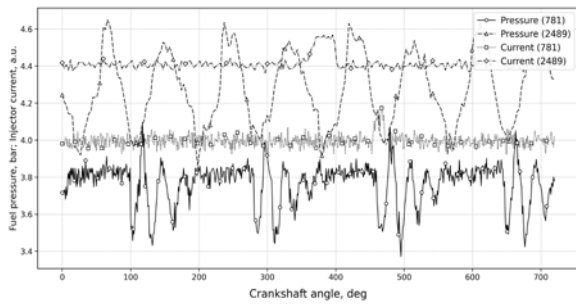


Fig. 1. Fuel rail pressure (left axis, bar) and injector current (left axis, a.u.) plotted versus crank angle over a full 0–720° engine cycle under normal operation at 781 rpm and 2,489 rpm.

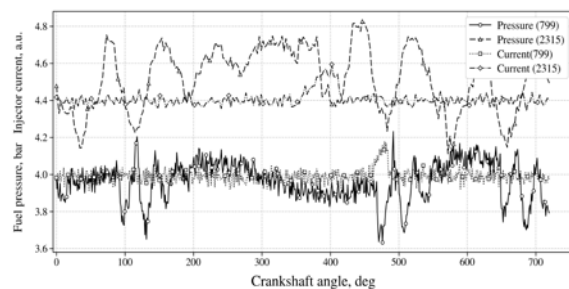


Fig. 2. Fuel rail pressure (left axis, bar) and injector current (left axis, a.u.) plotted versus crank angle over a full 0–720° engine cycle with one injector disconnected at 799 rpm and 2,315 rpm.

Simultaneously, the mean rail pressure increased, which can be explained by reduced fuel consumption from the rail while the pump and pressure regulation system continued to maintain supply. A similar effect was observed under load conditions: the pulsation amplitude  $\Delta P$  decreased and the waveform became asymmetric due to the absence of one injection event during the cycle.

Thus, injector disconnection leads to a systematic deformation of the fuel pressure signal, which can be used as a diagnostic indicator of disturbances in the injection system.

An additional quantitative feature is the number of local pressure minimum within a full 0–720° cycle: under normal operation of the 4-cylinder engine this number equals four, whereas disabling one injector reduces it to three, corresponding to the absence of one injection event.

All waveforms presented in this study are plotted in the crank-angle domain over a full 0–720° crankshaft interval corresponding to one complete four-stroke engine cycle. This representation makes it possible to visualize injector-related pressure events over the whole engine

cycle and to compare waveform structure under different operating conditions.

Fuel pressure is presented in physical units (bar), whereas the injector current trace is shown in arbitrary units (a.u.) and used primarily as a phase reference for injection timing.

### Quantitative evaluation of pressure pulsation parameters

For each operating mode, the minimum and maximum fuel pressure values within the engine cycle were determined, and the pulsation amplitude was calculated as

$$\Delta P = P_{max} - P_{min}. \quad (1)$$

The quantitative results are summarized in Table 1.

It was found that under normal engine operation the pulsation amplitude ranged from 0.072 to 0.079 MPa, whereas disabling one injector reduced  $\Delta P$  to 0.060–0.071 MPa. This reduction is attributed to the absence of one injection event within the cycle and the resulting decrease in total fuel outflow from the rail.

The obtained results confirm that fuel rail pressure contains informative cyclic features that can be used for assessing the injection-related disturbances in the fuel system and detecting malfunctions in injection-related components.

Thus, the experimentally demonstrated and quantitatively supported effects in the present study are: (i) deformation of the pressure waveform under injector disconnection, (ii) reduction of the dominant pulsation amplitude  $\Delta P$ , (iii) increase of mean rail pressure due to reduced outflow, and (iv) modification of the cycle structure of dominant pressure minimum. At elevated engine speed, secondary recovery oscillations may appear after the main pressure drop and should not be interpreted as separate injection events.

Table 1. Fuel rail pressure pulsation parameters under normal operation and with one injector disabled

Operating mode	n, rpm	$P_{min}$ , MPa	$P_{max}$ , MPa	$P_{mean}$ , MPa	$\Delta P$ , MPa
Normal operation	781	0.337	0.410	0.377	0.072
Normal operation	2,489	0.386	0.465	0.427	0.079
Injector disabled	799	0.363	0.423	0.396	0.060
Injector disabled	2,315	0.411	0.483	0.452	0.071

### Cycle-resolved evaluation of pressure pulsation features

In addition to amplitude-based parameters, cycle-resolved features of the pressure signal were evaluated in the crank-angle domain, including the number of dominant minimum ( $N_{\min}$ ) and their angular positions ( $\varphi_i$ ).

Under normal engine operation, the pressure waveform exhibited four dominant minimum within the 0–720° cycle, corresponding to four injection events in the 4-cylinder engine. These minima were approximately evenly distributed with a spacing close to 180° crank angle, confirming the cycle-synchronous nature of injection-related pressure disturbances.

When the injector of cylinder No. 2 was disconnected, a clear modification of the cycle structure was observed. At idle speed (799 rpm), the number of dominant minimum decreased from four to three, indicating the absence of one injection-related pressure drop. The missing minimum was localized within the angular sector corresponding to the disabled injector.

At elevated engine speed (2,315 rpm), the pressure waveform became more complex due to secondary oscillations occurring during pressure recovery. These oscillations may generate additional local extrema, which can visually resemble injection-related minimum. Therefore, in this regime, the identification of  $N_{\min}$  was performed with consideration of expected angular sectors spaced by approximately 180°, rather than by simple counting of all local extrema.

Using this phase-constrained interpretation, one angular sector exhibited a strongly attenuated or missing dominant minimum, consistent with the injector disconnection condition. This confirms that the parameter  $N_{\min}$ , when interpreted in a cycle-synchronous framework, remains a valid diagnostic indicator even in the presence of complex pressure dynamics.

The angular positions of dominant minimum  $\varphi_i$  provide additional diagnostic information by enabling localization of the disturbance within a specific cylinder-related sector of the cycle. Under normal operation,  $\varphi_i$  values are approximately equidistant, reflecting uniform injection sequencing.

In the fault condition, the absence or deformation of a minimum within one of the expected 180° sectors leads to a deviation from this regular pattern. This allows identification of the affected sector and confirms the relationship between pressure pulsations and individual injection events.

### Interpretation of cycle-resolved features in the crank-angle domain

Mapping the measured pressure and current signals onto the 0–720° crank-angle scale enables a direct interpretation of pressure pulsations as cycle-resolved hydraulic events. Under normal operating conditions, each injection current pulse is accompanied by a characteristic local pressure decrease, followed by a recovery segment. This structure remains stable across cycles and forms a repeatable pattern within the four-stroke cycle.

At idle conditions, the injection duration is relatively short, and the pressure response is characterized by local, distinct minimum and a comparatively fast recovery. Under medium load, injection duration increases, and the pressure response becomes more pronounced due to higher fuel demand and larger instantaneous outflow from the rail volume. The increase of mean pressure and the growth of pulsation amplitude between the two operating modes are consistent with the expected hydraulic behavior of the fuel system and confirm that the measured pulsations carry information on the intensity of injection processes.

The injector disconnection experiment provides a clear illustration of the diagnostic informativeness of cycle-resolved features. When one injector is disabled, one injection event is missing within the cycle. Consequently, one characteristic local pressure minimum disappears (or is significantly reduced), and the waveform becomes asymmetric. This behavior is captured quantitatively by the feature  $N_{\min}$ , which decreases from four minimum per 720° cycle to three minimum in the 4-cylinder engine case.

In addition, the disappearance of one injection-related minimum leads to a systematic change in the global pulsation structure: the overall amplitude  $\Delta P$  decreases and the mean pressure may increase due to reduced rail outflow while the supply system continues maintaining pressure. These changes support the feasibility of using pressure pulsation features as ECU-independent indicators of injection-related disturbances.

### Discussion

The obtained experimental results confirm that fuel rail pressure pulsations are a direct consequence of hydraulic processes associated with the cyclic operation of the injection system. Each injector opening event is accompanied by a short-term pressure decrease, corresponding to

fuel outflow from the rail volume, followed by pressure recovery due to the operation of the pump and pressure regulator. This mechanism is consistent with previously reported studies on fuel rail dynamics and pressure pulsation behavior in gasoline injection systems [7, 14, 15, 18].

With increasing engine speed and load, an increase in the mean fuel rail pressure and a growth in the pulsation amplitude are observed. This behavior is consistent with the physical nature of the process: higher fuel delivery demand and longer injection duration lead to more pronounced hydraulic oscillations in the rail. Therefore, pressure pulsation parameters can be considered informative indicators of the dynamic condition of the fuel system [8, 9, 19, 20].

The injector disconnection experiment demonstrated a systematic change in the pressure waveform. The absence of one injection event within the engine cycle results in the disappearance or significant reduction of one characteristic pressure drop, leading to waveform asymmetry. At the same time, the pulsation amplitude  $\Delta P$  decreases because the total injected fuel volume per cycle is reduced. The increase in mean rail pressure can be explained by the fact that the pump and pressure regulation system continue maintaining fuel supply, while fuel consumption from the rail becomes lower.

These findings confirm the feasibility of using fuel pressure signals as an independent diagnostic source for assessing the injection-related disturbances in the fuel system. Unlike conventional approaches based on electronic control unit (ECU) parameters, the analysis of physical pressure pulsations allows the detection of injection-related disturbances without requiring access to internal ECU data [1, 3, 12].

### Diagnostic parameters extracted from pressure pulsations

The performed investigations indicate that fuel pressure pulsations may be used not only to detect the presence of injection system disturbances, but also to form a set of diagnostic features suitable for condition assessment of major fuel system components [4, 8, 9, 17, 21, 22].

The diagnostic parameters defined in Section 2.4 were further interpreted with respect to their sensitivity to injector-related waveform deformation. In the present study, the experimentally validated parameters are  $\Delta P$ ,  $P_{\text{mean}}$ , and  $N_{\text{min}}$ . Their behavior under normal operation and injector disconnection indicates that pressure pulsations can be transformed into a compact set of cycle-resolved diagnostic features.

The recovery-related parameter  $t_{90}$  was introduced to characterize the dynamics of pressure restoration after an injection-related pressure drop. However, in the present study, its quantitative evaluation was limited by the complexity of pressure waveforms, especially under elevated engine speed, where secondary oscillations affect the identification of recovery boundaries.

Therefore,  $t_{90}$  is considered as a promising diagnostic feature primarily for pump and pressure-regulator-related analysis, and its robust application requires further investigation using an extended experimental dataset.

### Generalized interpretation of potential malfunctions

Based on the hydraulic nature of the processes in the fuel system, different types of malfunctions may manifest as characteristic changes in the extracted pressure pulsation parameters. A generalized interpretation of potential diagnostic indicators is presented in Table 2 [4, 8, 9, 17].

Within this study, the sensitivity of pressure pulsation parameters to injector disconnection was experimentally confirmed, whereas the use of  $t_{90}$  and other pump/regulator-related indicators requires further experimental validation.

The proposed table reflects the general diagnostic logic that may be applied in the development of automated fuel system condition monitoring systems. In the present study, the sensitivity of pressure pulsation parameters to injector malfunction was experimentally confirmed, whereas further validation for other fault types requires additional investigations [4, 11, 23].

Table 2 Generalized diagnostic indicators of possible fuel system malfunctions

Indicator	Injector	Pump	Pressure regulator
Shift of a single $P_{\text{min}}$ minimum	Yes	No	No
Shift of all minimum ( $\phi$ offset)	No	Yes	Yes
Different $\Delta P$ amplitudes between cylinders	Yes	No	No
Parasitic minimum	Yes (leakage)	No	Yes
Unstable mean pressure $P_{\text{mean}}$	No	Yes	Yes
Excessively high pressure	No	No	Yes
Increased $t_{90}$ (slow pressure recovery after injection events)	No	Yes	Yes

### Limitations and future work

It should be noted that the presented results were obtained for a single type of disturbance, namely complete injector disconnection. Future studies should address partial injector faults (reduced flow capacity, delayed valve response) and expand the experimental database to different engine types and fuel system architectures [4, 11].

Nevertheless, at this stage it has been demonstrated that fuel pressure pulsations contain stable and repeatable features that are suitable for diagnostic and condition monitoring applications in internal combustion engine fuel systems.

### Practical considerations and robustness of the proposed features

From an implementation standpoint, the proposed approach can be integrated into an ECU-independent condition monitoring workflow using a limited set of external signals. The minimum required measurements are (i) fuel rail pressure with sufficient bandwidth to capture injection-related pulsations and (ii) a cycle reference signal enabling transformation to the 0–720° crank-angle domain. In the present study, injector current was additionally recorded as an independent timing reference, which is useful for validation and for building a reliable association between pressure minimum and injection events. However, once the crank-angle reference is available, the diagnostic features can be extracted primarily from the pressure waveform itself.

A key advantage of the crank-angle representation is that it normalizes the analysis with respect to engine speed and enables direct comparison between operating modes. In practice, this facilitates the use of consistent detection rules for local minimum and recovery segments across a wide rpm range. For example, features such as  $N_{min}$  and  $\varphi_i$  are inherently cycle-synchronous: they depend on the presence and angular location of pressure drops, which remain interpretable even when injection duration changes with load. Similarly, the amplitude-related feature  $\Delta P$  provides an intuitive measure of the hydraulic response intensity, while  $P_{mean}$  reflects the global supply–consumption balance in the rail.

The recovery-related parameter  $t_{90}$  offers an engineering-oriented way to quantify the pressure restoration dynamics after an injection event. In a diagnostic context, injector-related disturbances are expected to primarily affect the existence and depth of individual minimum (e.g., a missing minimum and reduced  $\Delta P$  in the corresponding sector), whereas pump and pres-

sure-regulator deviations may manifest through slower recovery and increased  $t_{90}$ , as well as greater instability of  $P_{mean}$ . At the same time, it should be emphasized that the present experimental validation focused on a single fault scenario (complete injector disconnection). Therefore, thresholds and decision rules for pump/regulator fault detection should be established in future studies using dedicated fault injection and a broader experimental database.

Overall, the results indicate that pressure pulsation analysis in the crank-angle domain provides a structured and physically interpretable feature set that is suitable for further development of automated fuel-system condition monitoring algorithms.

### Conclusions

This study assessed the feasibility of using fuel pressure pulsations as a diagnostic indicator of the technical condition of an internal combustion engine fuel system. Based on the conducted experimental investigations, the following main conclusions can be drawn:

1. Fuel rail pressure pulsations exhibit a stable cyclic behavior and are directly associated with injection events, confirming their hydraulic nature.
2. When operating conditions change from idle speed (781 rpm) to medium load ( $\approx 2,489$  rpm), the mean rail pressure increases from approximately 0.38 MPa to 0.43–0.44 MPa, and the pulsation amplitude rises accordingly, reflecting more intensive injection processes.
3. The experiment with one injector disabled demonstrated a systematic deformation of the pressure waveform: one characteristic pressure drop within the cycle disappears, the signal becomes asymmetric, and the pulsation amplitude  $\Delta P$  decreases.
4. Quantitatively, the pulsation amplitude under normal engine operation was found to be 0.072–0.079 MPa, whereas injector disconnection reduced it to 0.060–0.071 MPa.
5. A set of diagnostic parameters  $\{P_{min}, P_{max}, \Delta P, P_{mean}, N_{min}, \varphi_i\}$  is proposed as a basis for assessing the injection-related disturbances in the fuel system and detecting injection-related malfunctions.
6. The obtained results confirm the potential of fuel pressure pulsation analysis as an independent approach for fuel system diagnostics without requiring access to internal electronic control unit data.
7. In the elevated-speed operating condition, pressure recovery after the main injection-related drop may contain secondary oscillatory

components. Therefore, robust diagnostic interpretation should rely on dominant cycle-synchronous features rather than on every local extremum of the pressure trace.

8. Cycle-resolved analysis showed that under normal operation the pressure waveform contains four dominant minimum per 720° cycle, whereas injector disconnection leads to the disappearance of one minimum within the corresponding angular sector. This confirms that parameters  $N_{\min}$  and  $\varphi_i$  can be used for detecting and localizing injection-related disturbances.

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### Conflict of interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

### References

- Bosch, R. (2011). *Automotive handbook* (10th ed.). Robert Bosch GmbH. ISBN: 978-0-8376-1686-5.
- Guzzella, L., & Onder, C. (2010). *Introduction to modeling and control of internal combustion engine systems*. Springer. <https://doi.org/10.1007/978-3-642-10775-7>
- Merkisz, J., Pielecha, I., & Gis, W. (2017). Combustion engines in the context of sustainable transport development. *Combustion Engines*, 168(1), 1–8. <https://doi.org/10.19206/CE-2017-109>
- Hartl, F., Brueckner, J., Ament, C., & Provost, J. (2019). Rail pressure estimation for fault diagnosis in high pressure fuel supply and injection system. *IFAC-PapersOnLine*, 52(15), 193–198. <https://doi.org/10.1016/j.ifacol.2019.11.673>
- Jiang, H., Zheng, J., Jin, H., et al. (2025). Analysis of rail pressure stability in an electronically controlled high-pressure common rail fuel injection system based on GT-Suite simulation. *Energies*, 18(3), 550. <https://doi.org/10.3390/en18030550>
- Lan, Q., Bai, Y., Ma, X., Fan, L., Xu, J., et al. (2021). Stability analysis upon high-pressure common rail fuel injection system under multiple injection modes. *International Journal of Automotive Technology*, 22, 353–370. <https://doi.org/10.1007/s12239-021-0034-2>
- Linkov, O. U., & Shevchenko, O. S. (2024). Use of IIoT technologies in engine monitoring and control systems. *Internal Combustion Engines*, 2, 42–45. <https://doi.org/10.20998/0419-8719.2024.2.06>
- Neumann, S., Varbanets, R., Minchev, D., Malchevsky, V., & Zalozh, V. (2023). Vibrodiagnostics of marine diesel engines in IMES GmbH systems. *Ships and Offshore Structures*, 18(11), 1535–1546. <https://doi.org/10.1080/17445302.2022.2159985>
- Payri, F., Bermúdez, V., Payri, R., & Salvador, F. J. (2004). The influence of cavitation on the internal flow and the spray characteristics in diesel injection nozzles. *Fuel*, 83(4–5), 419–431. <https://doi.org/10.1016/j.fuel.2003.09.010>
- Wei, Y., Fan, L., Wu, Y., Gu, Y., Xu, J., & Fei, H. (2022). Research on transmission and coupling characteristics of multi-frequency pressure fluctuation of high pressure common rail fuel system. *Fuel*, 312, 122632. <https://doi.org/10.1016/j.fuel.2021.122632>
- Linkov, O. U., Shevchenko, O. S., & Savchenko, A. V. (2025). Analysis and calibration of fuel pressure sensor for diesel engine injector fault diagnostics. *Internal Combustion Engines*, 1, 74–79. <https://doi.org/10.20998/0419-8719.2025.1.09>
- Karczewski, M., & Koliński, K. (2018). Diagnostics of common rail components based on pressure curves in the fuel rail. *Combustion Engines*, 173(2), 3–8. <https://doi.org/10.19206/CE-2018-201>
- Varbanets, R., Minchev, D., Kucherenko, Y., Zalozh, V., Kyrylash, O., & Tarasenko, T. (2024). Methods of real-time parametric diagnostics for marine diesel engines. *Polish Maritime Research*, 31(3), 71–84. <https://doi.org/10.2478/pomr-2024-0037>
- Postriotti, L., Cavicchi, A., Paolino, D., Guido, C., Parotto, M., & Di Gioia, R. (2016). An experimental and numerical analysis of pressure pulsation effects of a gasoline direct injection system. *Fuel*, 173, 8–28. <https://doi.org/10.1016/j.fuel.2016.01.012>
- Spegar, T. D. (2011). Minimizing GDI fuel system pressure pulsations by robust fuel rail design. *SAE Technical Paper*, 2011-01-1225. <https://doi.org/10.4271/2011-01-1225>
- Lepeshkin, A. A., et al. (2021). Damping of pressure pulsations in fuel systems. *IOP Conference Series: Materials Science and Engineering*, 1086, 012011. <https://doi.org/10.1088/1757-899X/1086/1/012011>
- Wang, H. P., Zheng, D., & Tian, Y. (2016). High pressure common rail injection system modeling and control. *ISA Transactions*, 63, 265–273. <https://doi.org/10.1016/j.isatra.2016.03.002>
- Li, J. Z., Treusch, C., Honel, B., & Savaresi, S. M. (2005). Simulation of pressure pulsations in a gasoline injection system and development of an effective damping technology. *SAE Technical Paper*, 2005-01-1149. <https://doi.org/10.4271/2005-01-1149>

- 19 Gupta, V. K., Zhang, Z., & Sun, Z. (2011). Modeling and control of a novel pressure regulation mechanism for common rail fuel injection systems. *Applied Mathematical Modelling*, 35(7), 3473–3483.  
<https://doi.org/10.1016/j.apm.2011.01.008>
- 20 Stone, R. (1999). *Introduction to internal combustion engines* (4th ed.). Macmillan Education.  
<https://doi.org/10.1007/978-1-349-15079-3>
- 21 Song, E., Li, D., Fu, Y., Cai, Y., & Yu, X. (2019). A common rail injector fault diagnosis algorithm based on independent component analysis and adaptive symptom parameters. *Entropy*, 21(10), 923. <https://doi.org/10.3390/e21100923>
- 22 Wierzbicki, S., & Śmieja, M. (2018). Diagnostic methods for combustion engines. *Combustion Engines*, 172(1), 7–15  
<https://doi.org/10.19206/CE-2018-102>
- 23 Xu, L., Bai, X. S., Jia, M., Qian, Y., Qiao, X., & Lu, X. (2018). Experimental and modeling study of liquid fuel injection and combustion in diesel engines with a common rail injection system. *Applied Energy*, 230, 287–304  
<https://doi.org/10.1016/j.apenergy.2018.08.104>

**Shevchenko Oleksii<sup>1</sup>**, PhD student. – Engines and Hybrid Power Plants department,  
Phone.: +38 (099) 043-94-25,  
e-mail: shevchcross@gmail.com

ORCID: <https://orcid.org/0009-0007-3722-7873>

**Linkov Oleh<sup>1</sup>**, Associate Professor. Engines and Hybrid Power Plants department,  
Phone.: +38 (050) 910-35-28,  
e-mail: oleglinkov76@gmail.com  
ORCID: <https://orcid.org/0000-0002-2780-2412>

<sup>1</sup>National Technical University “Kharkiv Polytechnic Institute” Kyrpychova str., 2, Kharkiv, 61002, Ukraine

**Аналіз пульсацій тиску в паливній рампі для виявлення порушень, пов'язаних з упорскуванням, у двигунах внутрішнього згоряння**

**Анотація. Проблема.** Надійна діагностика паливних систем двигунів внутрішнього згоряння ускладнюється обмеженим доступом до даних електронного блока керування та недостатньою інформативністю стандартних діагностичних параметрів, доступних через штатні бортові системи. У багатьох випадках параметри, отримані з ECU, є відфільтрованими, усередненими або частково недоступними, що знижує їх придатність для виявлення локальних порушень, пов'язаних із процесом упорскування. Тому використання прямих фізичних сигналів, зокрема пульсацій тиску палива, є перспективним напрямом підвищення діагностичної інформативності моніторингу паливної системи. **Мета.** Метою дослідження є оцінювання можливості використання пульсацій тиску палива як діагностичного показника порушень,

пов'язаних із процесом упорскування, у паливній системі двигуна внутрішнього згоряння без використання внутрішніх діагностичних змінних ECU. **Методика.** Експериментальні дослідження виконано на бензиновому двигуні внутрішнього згоряння, оснащеному системою розподіленого впорскування палива. Тиск палива вимірювався безпосередньо в паливній рампі за допомогою тензорезистивного датчика тиску. Синхронне знімання сигналів тиску палива, струму форсунки та положення колінчастого вала здійснювалося з використанням високошвидкісної мікроконтролерної системи збору даних. Зареєстровані сигнали перетворювалися у кутову область колінчастого вала в межах повного чотиритактного циклу 0–720°. Імітоване порушення створювалося шляхом електричного відключення однієї форсунки, тоді як сигнал струму іншої активної форсунки використовувався як часовий опорний сигнал. **Результати.** Отримані результати показали, що за нормальної роботи пульсації тиску палива мають стійку циклічну структуру, пов'язану з подіями упорскування. Відключення форсунки спричинило систематичну деформацію форми сигналу тиску, зменшення амплітуди пульсації, збільшення середнього тиску в паливній рампі, а також зникнення або суттєве послаблення одного характерного мінімуму тиску у відповідному очікуваному кутовому секторі. **Наукова новизна.** Наукова новизна дослідження полягає у використанні цикло-синхронного аналізу пульсації тиску палива для виявлення порушень, пов'язаних із процесом упорскування, незалежно від даних ECU. **Практична значимість.** Запропонований підхід може бути використаний як основа для створення неінвазивних систем діагностування та моніторингу технічного стану паливних систем двигунів внутрішнього згоряння.

**Ключові слова:** діагностика паливної системи; упорскування палива; пульсації тиску в паливній рампі; технічний стан; робочий процес; динамічні процеси; надійність; математична модель.

**Шевченко Олексій Сергійович<sup>1</sup>** аспірант кафедри двигунів та гібридних енергетичних установок,  
тел.: +38 (099) 043-94-25,  
e-mail: shevchcross@gmail.com,  
ORCID <http://org/0009-0007-3722-7873>

**Ліньков Олег Юрійович<sup>1</sup>**, канд. техн. наук, доцент, доцент кафедри двигунів та гібридних енергетичних установок,  
тел.: +38 (050) 910-35-28,  
e-mail: Oleh.Linkov@khp.edu.ua,  
ORCID <http://orcid.org/0000-0002-2780-2412>

<sup>1</sup> Національний технічний університет “Харківський політехнічний інститут” вул. Кирпичова, 2, м. Харків, 61002, Україна