Keywords: biodiesel; natural gas; vibrations; sound pressure; correlation analysis

Saulius STRAVINSKAS[1]*, Alfredas RIMKUS[2], Jonas MATIJOŠIUS[3]

EVALUATION OF VIBRATION AND NOISE CHARACTERISTICS OF A COMPRESSION-IGNITION ENGINE FUELLED WITH NATURAL GAS-BIODIESEL DUAL FUEL

Summary. As environmental requirements become more stringent and the planet becomes more polluted, the replacement of conventional diesel is attracting more interest. For alternative fuels, such as biodiesel and natural gas, to be used, their effects must be examined not only in terms of the engine's environmental indicators but also in terms of engine vibrations and sound pressure. This study examined the influence of dual fuel – biodiesel and natural gas – on vibrations and sound pressure of a compression-ignition (CI) engine. Conventional diesel or hydrotreated vegetable oil biodiesel was used as a pilot fuel for gas ignition. The gaseous fuel was natural gas, which was injected into the intake manifold with different energy shares of the gaseous fuel (40%, 60% and 80%). Tests were performed at a constant engine crankshaft speed and a fixed start of pilot fuel injection of 6° BTDC while the fuel composition and engine load were changed. This experiment revealed correlations between gas energy share (GES) in liquid fuel and ecological and energy indicators of a CI engine.

1. INTRODUCTION

Emissions from CI engines are extremely important, as they can cause global warming, which affects the entire ecosystem [1]. This problem is becoming increasingly relevant due to the growing number of vehicles that are major users of diesel [2]. Limited oil stocks, together with the noxious effects of fossil fuels on flora and fauna, are reasons for alternative fuel studies [3].

CI engines are very popular in the transportation sector due to their reliability, low fuel consumption and good dynamic characteristics. However, problems, such as high emissions of nitrogen oxides and other harmful gases and engine vibrations, cause significant pollution, as well as driver fatigue and discomfort [4, 5]. Vibration, which is often ignored, is a key element in an engine's overall performance and the comfort of passengers. Body vibrations that affect occupant health are closely related to engine vibrations [6].

Researchers have studied the vibrations and sound of CI engines. For example, Celebi et al. [7] conducted an experimental study with a CI engine operating at five different speeds using diesel-biodiesel blends with natural gas. They concluded that engine vibrations and sound pressure increase significantly with increasing crankshaft rotation speed. Moreover, compared to oil-based diesel, sound pressure and vibrations were reduced by using biodiesel blends, and vibrations and sound pressure values were reduced by the additional supply of natural gas together with the intake air. The results also revealed that biodiesel blends have a positive effect on CO emissions, while the use of natural gas

[1] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Saulėtekio al. 11, 10223 Vilnius, Lithuania; e-mail: saulius.stravinskas@vilniustech.lt; orcid.org/0000-0002-5429-4978
[2] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Saulėtekio al. 11, 10223 Vilnius, Lithuania; e-mail: alfredas.rimkus@vilniustech.lt; orcid.org/0000-0001-8995-7180
[3] Vilnius Gediminas Technical University, Faculty of Transport Engineering; Saulėtekio al. 11, 10223 Vilnius, Lithuania; e-mail: jonas.matijosius@vilniustech.lt; orcid.org/0000-0001-6006-9470
* Corresponding author. E-mail: saulius.stravinskas@vilniustech.lt

significantly increased CO emissions. Although the use of biodiesel increased CO_2 and NO_x emissions, the use of natural gas reduced them.

Calik also found that engine speed has a significant effect on vibrations. As the engine speed increases, vibrations also increase. The use of biodiesel made from used oil instead of conventional diesel reduced engine vibrations due to an improved combustion process. Also, higher oxygen content in biodiesel resulted in a shorter combustion delay period [8].

2. EQUIPMENT, METHODS AND MATERIALS

Experimental studies on the energy and environmental parameters of CI engines fuelled with liquid (diesel, biodiesel) and gaseous (natural gas) fuels were performed using a turbocharged direct injection engine (Table 1) with a load bench. The CI engine was equipped with a gaseous fuel supply system (Elpigaz-Degamix) to inject gas into the intake air (dual fuel). Natural gas was supplied before the turbocharger (Fig. 1).

Table 1

The specifications of the tested CI turbocharged direct injection engine

Indicator	Value
Engine displacement V_H, cm^3	1986
Cylinders	4 cylinder in-line
Valve system	OHC
Compression ratio ε	19.5
Bore D, mm	79.5
Stroke S, mm	95.5
Power P, kW	66 (4000 rpm.)
Torque M, Nm	182 (2000–2500 rpm.)
Injector opening pressure p_i, bar	190–200
Fuel injection system	Distributor injection pump

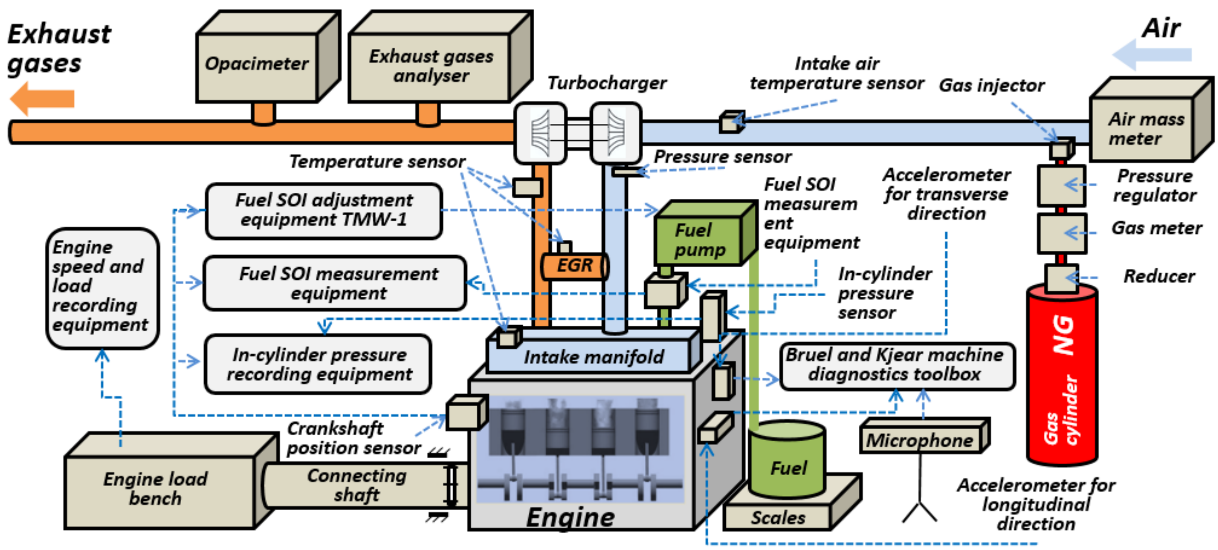

Fig. 1. Schematic diagram of experimental equipment

Engine load torque M_B (measurement error ± 1.23 Nm) and crankshaft speed n (rpm.) were regulated with a stand *KI-5543*. An electronic scale SK-5000 (measurement error: 0.5%) and a chronometer were used to measure the consumption of liquid fuel mass per hour B_f (kg/h). Natural gas consumption was measured with an RHM 015 type mass flow meter (measurement error: ± 0.1%). The mass of air intake into the engine was measured with a Bosch HFM 5 m (measurement error: 2%). The pressure in the engine cylinder was recorded using an AVL GH13P sensor mounted at the location of the glow plug (sensitivity of piezoelectric sensor: 15.84 ± 0.09 pC/bar). An A58M-F photoelectric encoder was used to determine the position of the crankshaft rotation angle (CA) (signal repeatability: 0.176° for the CA). In-cylinder pressure was fixed using LabView Real software and an AVL DiTEST DPM 800 oscilloscope (signal ratio: 1 mV/pC, input range: 6000 pC). Pressure in the engine intake manifold was measured with a Delta OHM HD 2304.0 device (measurement error: ± 0.0002 MPa). Temperature was measured using a K-type thermocouple (measurement error: ± 1.5 °C). The composition of pollutants in the exhaust gas was detected using an AVL DiCom 4000 exhaust gas analyser/opacimeter (Table 2).

Table 2

Specifications of the exhaust gas analyser

Measured indicator	Measurement range	Accuracy
CO_2	0–20% (vol.)	0.1% (vol.)
HC	0–20000 ppm (vol.)	1 ppm (vol.)
NO_x	0–5000 ppm (vol.)	1 ppm (vol.)
O_2	0–25% (vol.)	0.01 % (vol.)
λ	0–1.0	0.001
Smoke absorption coefficient	0–99.99 m^{-1}	0.01 m^{-1}
Engine speed	250–9990 rpm	10 rpm

In all tests, the engine speed was n = 2000 rpm, and the engine load was changed: M_B = 45, 60 and 90 Nm (*BMEP*: 0.3, 0.4 and 0.6 MPa). The start of the injection of liquid fuel was fixed at 6° BTDC, as the standard engine control unit starts to delay it when gaseous fuel is added. This is due to the lower mass of liquid fuel required to maintain the specified torque. A fixed constant start of injection allows the combustion process of different fuels to be analysed and compared. Engine speed and load are selected to suit real driving conditions in the city and on the highway. Tests were performed with the EGR valve closed.

Experimental and theoretical studies were performed with a four-cylinder direct injection CI engine fuelled with dual fuel (liquid and gaseous). Conventional diesel or hydrotreated vegetable oil biodiesel (HVO) was used as a pilot fuel for gas ignition. The utilised gaseous fuel was natural gas. Table 4 shows their composition, marking and lower heating (energy) values (LHVs).

Table 3

Tested fuels and their labels

Fuel (% of energy)		Label	*LHV*,
Liquid fuel	Gaseous fuel		MJ/kg
Conventional diesel fuel and natural gas			
100%	0%	D100	42.82
60%	40%	D60+NG40	45.45
40%	60%	D40+NG60	46.92
20%	80%	D20+NG80	48.49
Hydrotreated vegetable oil and natural gas			
100%	0%	HVO100	43.63
60%	40%	HVO60+NG40	46.04
40%	60%	HVO40+NG60	47.25
20%	80%	HVO20+NG80	48.83

The compression of an ignition engine's sound pressure was evaluated with a Gras 46AE free-field microphone (range: 3.15–20,000 Hz; dynamic range: 17–138 dB; sensitivity: 50 mV/Pa). Bruel and

Kjaer 8341 CCLD accelerometers (frequency range: 0.3–10,000 Hz; sensitivity: 0.01 V/ms^{-2}) were used to measure engine block vibrations in longitudinal and transverse directions.

Collected vibration and sound pressure data were processed with Bruel and Kjaer software. For all tested fuels and engine loads, sound pressure and vibration data were gathered from the engine block at a frequency of 3.2 kHz (for vibration) and 25.2 kHz (for sound pressure).

Main combustion parameters, such as pressure rise, rate of heat release (ROHR), in-cylinder pressure and temperature, were set using AVL BOOST sub-software BURN. The parameters measured in experimental research (fuel consumption, air flow, cylinder pressure and boost pressure) were used to determine these parameters.

3. RESULTS AND DISCUSSION

During the tests, vibrations of the block in the longitudinal and transverse directions of the cylinders and sound pressure were measured. The engine was running on liquid fuel and in dual-fuel mode. Figs. 2, 3 and 5–8 show the correlations between engine vibrations, sound pressure, the combustion process and environmental indicators while changing gaseous fuel GES in liquid fuels (conventional diesel or biodiesel HVO). These relationships show the dependencies by which the influence of natural gas on energy and environmental indicators of a CI engine can be assessed.

Increasing GES in liquid fuels at an engine load of 45 Nm (*BMEP*: 0.3 MPa) decreases vibrations of the engine block in the transverse and longitudinal directions of the cylinders. A reduction in vibrations is observed when conventional diesel or biodiesel HVO is used as a pilot fuel. The reduction in sound pressure is more pronounced when using HVO biodiesel as a pilot fuel than when using conventional diesel (the higher cetane number of HVO probably has an influence). Increasing GES in liquid fuels positively correlates with exhaust gas temperature (T_{ex}) and combustion duration. This means that increasing GES in liquid fuel prolongs the combustion duration and increases the exhaust gas temperature at the beginning of the exhaust valve opening process. Negative GES correlations are observed with excess air ratio coefficient, maximum in-cylinder pressure (p_{max}), NO_x emissions, smoke, maximum ROHR, sound pressure and vibrations (Figs. 2 and 3).

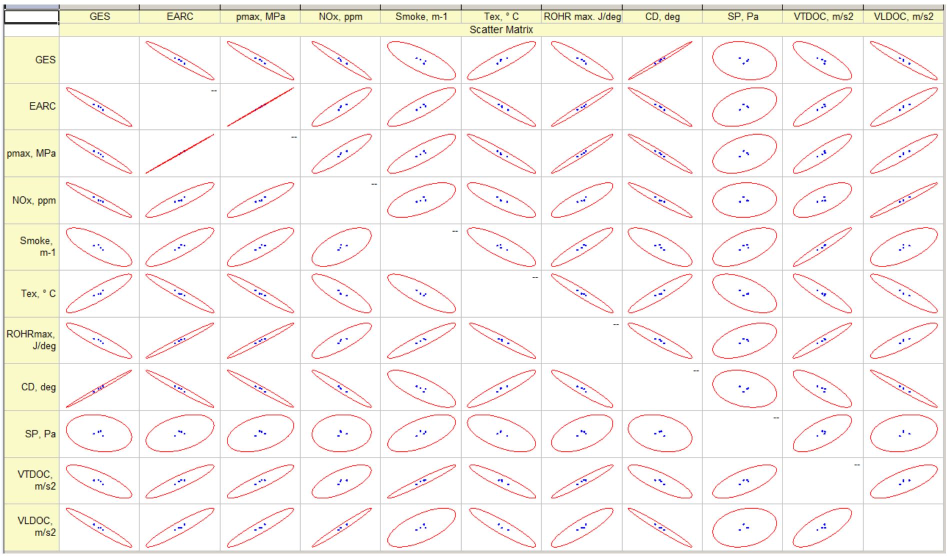

Fig. 2. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.3 MPa. Pilot fuel: diesel

Correlations, which are shown in Figs. 2 and 3 can be explained by the slow combustion of natural gas. Moreover, at *BMEP* = 0.3 MPa, the excess air ratio coefficient is too high (λ = 3–2.3) and exceeds the gas flammability limits (λ <~ 1.9) [9] for the spontaneous combustion of natural gas (Fig. 4). The results of this situation are a decreased ROHR, increased combustion duration and decreased combustion temperature. These trends are similar when conventional diesel or biodiesel HVO is used as a pilot fuel.

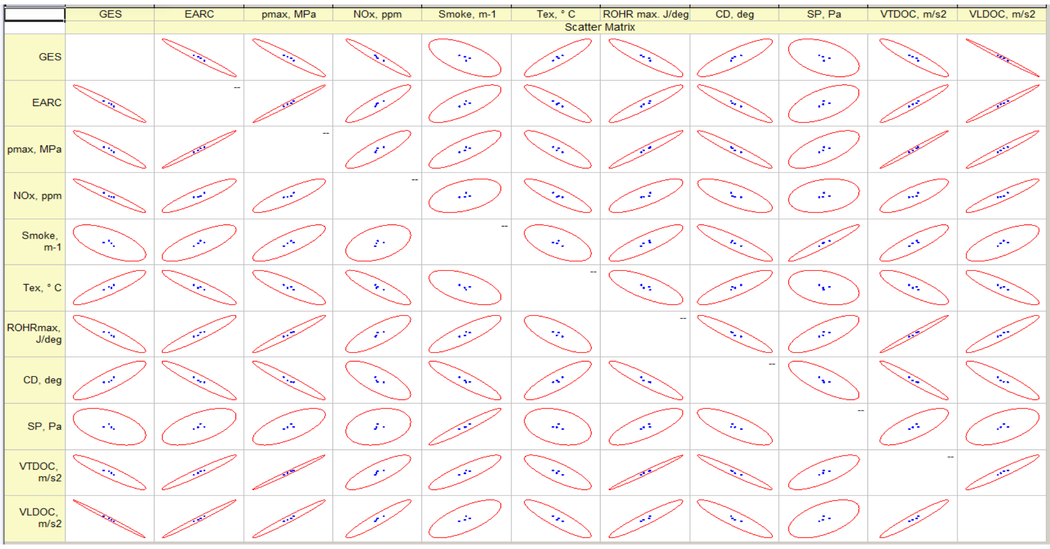

Fig. 3. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.3 MPa. Pilot fuel: HVO

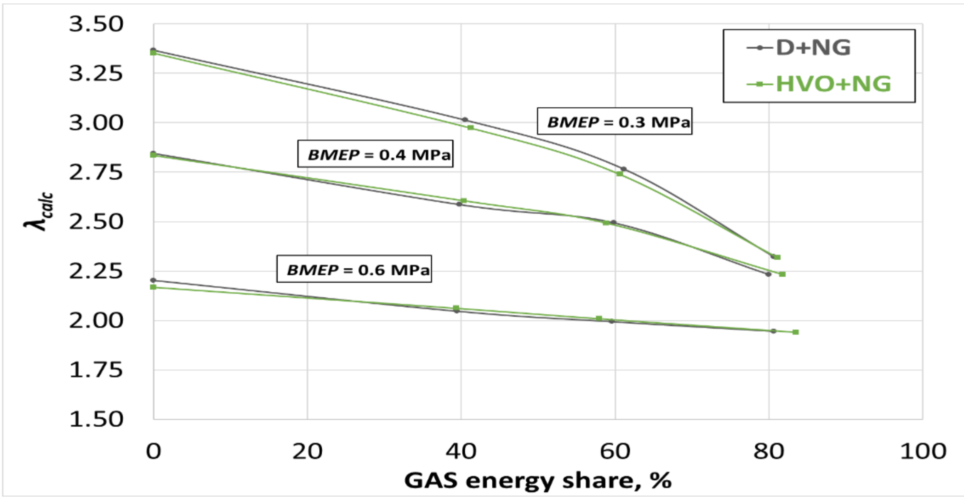

Fig. 4. Excess air ratio coefficient

By increasing the engine load to 60 Nm (*BMEP*: 0.4 MPa), the general trends in GES remain the same regarding reduced sound pressure, engine vibrations, smoke and NO_x emissions (Fig. 5, 6). The exhaust gas temperature rises, which indicates a longer combustion duration. In this case, the excess air ratio coefficient is still too high ($\lambda = 2.6–2.2$) for the gas to ignite spontaneously, resulting in a prolonged combustion process.

At 90 Nm (*BMEP*: 0.6 MPa), different correlations are observed. Increasing GES fuels in the liquid fuel (from 40 to 80%) increases the sound pressure and vibrations of the engine block in a transverse direction to the cylinders. Engine block vibrations in the longitudinal direction to the cylinders are difficult to estimate. These trends are similar for conventional diesel and biodiesel HVO pilot fuels. Increased GES in liquid fuels is positively correlated with exhaust gas temperature, maximum ROHR, sound pressure and vibrations in the transverse direction to the cylinders. Negative correlations are observed with excess air ratio coefficient, in-cylinder pressure, NO_x emissions, smoke and combustion duration (Figs. 7 and 8).

For such a correlation at *BMEP* = 0.6 MPa, load can be explained by the changed combustion process. It is possible that, at higher loads and at GESs of 60% and more, the coefficient of excess air ratio ($\lambda = 2–1.9$) decreased the flammability limits of natural gas ($\lambda <\sim 1.9$) (Fig. 4). Pilot fuel is needed to ignite the gas, but the flame front in the gas spreads spontaneously, and the sprayed liquid fuel burns together and faster. As a result, ROHR intensifies, but gaseous fuels still burn more slowly in the initial combustion phase than 100% diesel or biodiesel HVO, resulting in lower in-cylinder pressures, a shorter combustion duration and reduced NO_x emissions and smoke. These trends are similar when conventional diesel or biodiesel HVO pilot fuels are used.

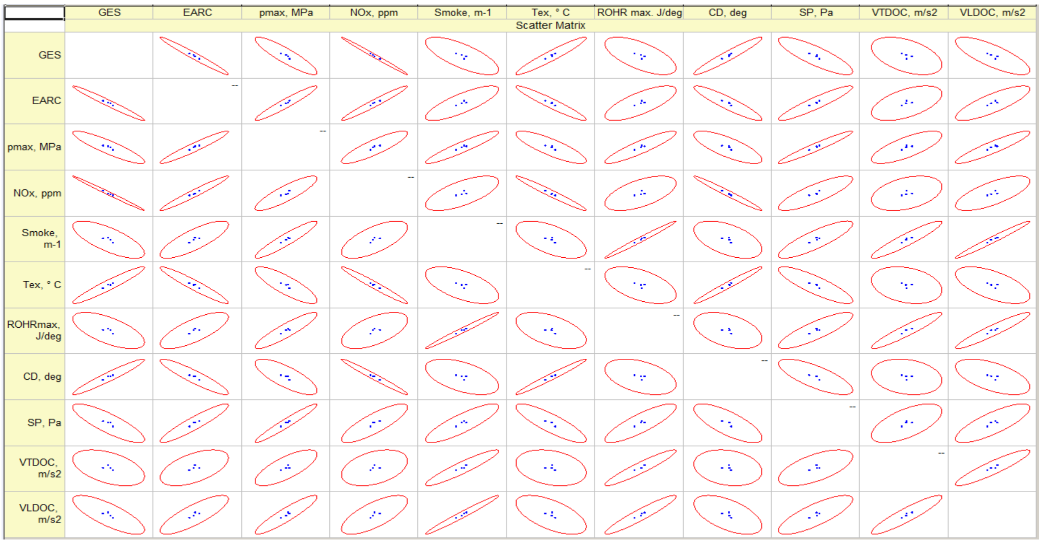

Fig. 5. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.4 MPa. Pilot fuel: diesel

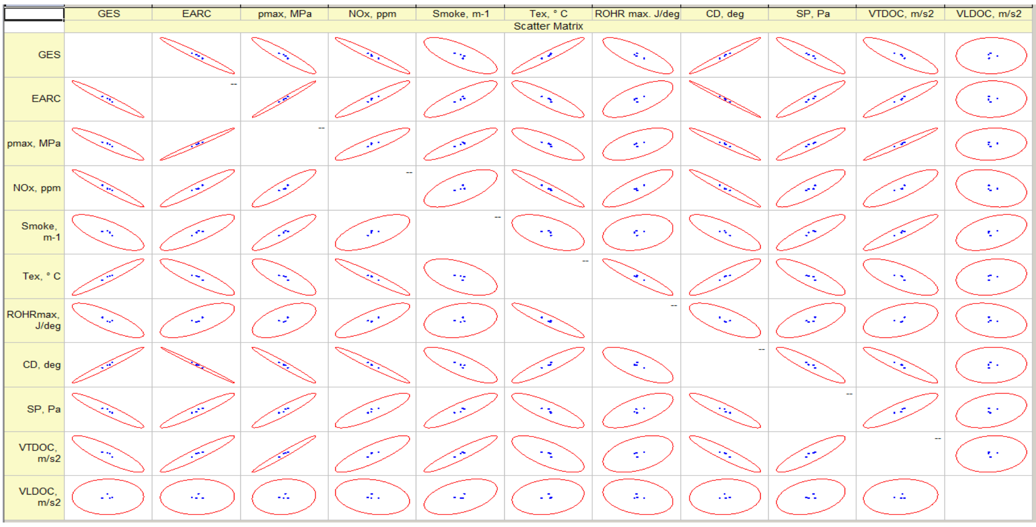

Fig. 6. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.4 MPa. Pilot fuel: HVO

4. CONCLUSIONS

The correlations between vibrations of the CI engine block in the longitudinal and transverse directions of the cylinders and the sound pressure with the engine running in liquid fuel and on dual-fuel mode and increasing GES fuels in the liquid fuel highlight the following relationships.

At low (*BMEP*: 0.3 MPa) and medium (*BMEP*: 0.4 MPa) engine loads, the increasing GES in liquid fuel positively correlates with exhaust gas temperature and combustion duration. Negative correlations are observed with the excess air ratio coefficient, in-cylinder pressure, NO_x emissions, smoke, ROHR, sound pressure and vibrations. These correlations can be explained by the slow combustion of natural gas due to the excess air ratio coefficient, which is too high for the spontaneous combustion of natural gas. As a result, ROHR and combustion temperature decrease while combustion duration increases.

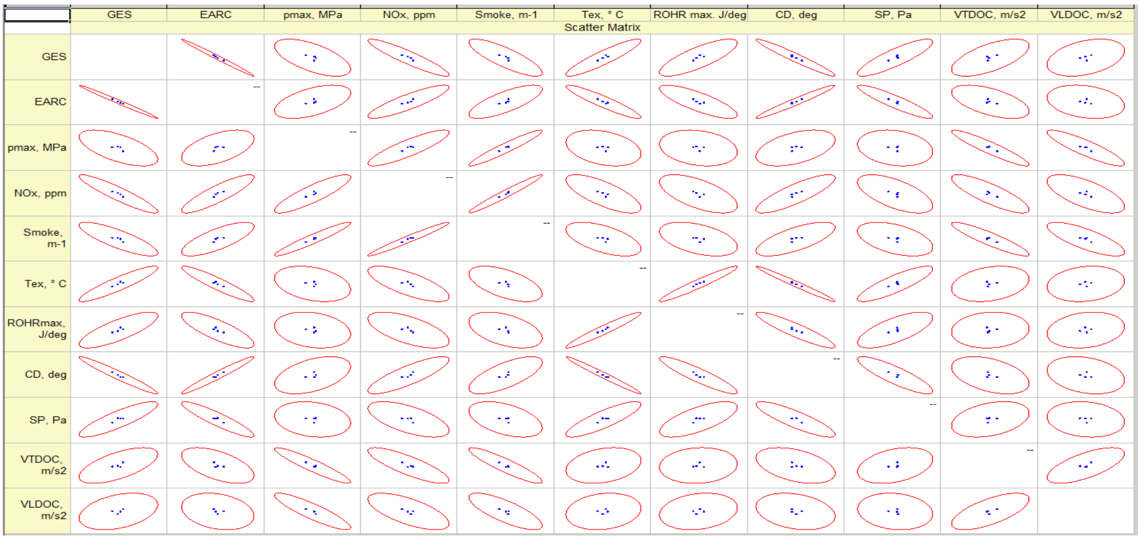

Fig. 7. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.6 MPa. Pilot fuel: diesel

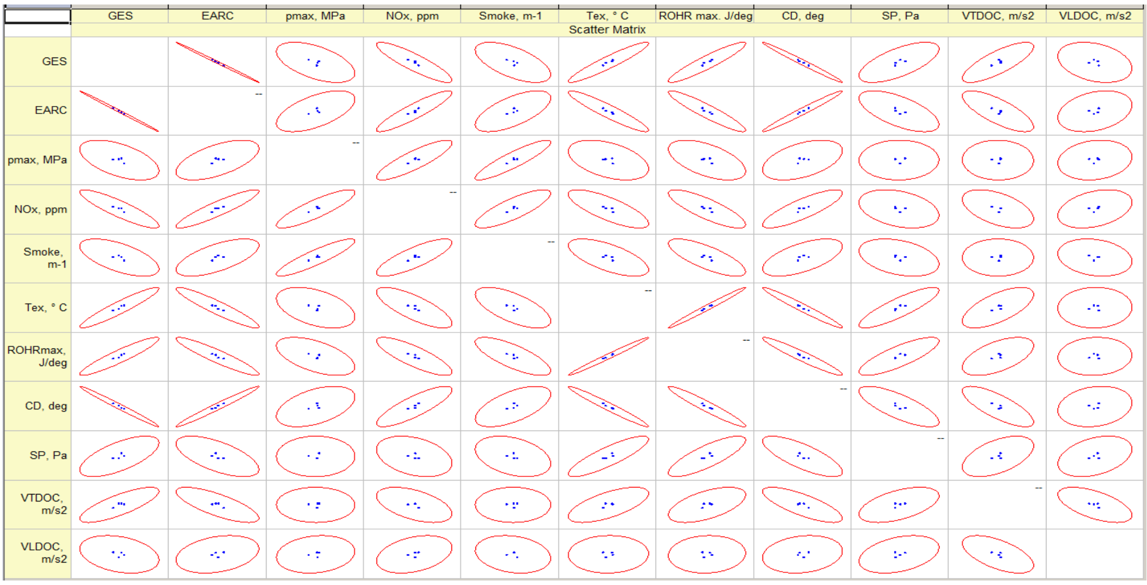

Fig. 8. Vibration and sound pressure correlations with engine parameters. *BMEP*: 0.6 MPa. Pilot fuel: HVO

At 90 Nm (*BMEP*: 0.6 MPa), the increasing GES in liquid fuels is positively correlated with exhaust gas temperature, ROHR, sound pressure and vibrations in the longitudinal direction of the cylinders. Negative correlations are observed with the excess air ratio coefficient, in-cylinder pressure, NO_x emissions, smoke and combustion duration. These correlations can be explained by the changed combustion process. It is likely that, at higher loads and at the GES of 60% and more, the coefficient of excess air ratio (λ = 2–1.9) decreases to the flammability limits of spontaneous combustion of natural gas (λ <~ 1.9). Pilot fuel is needed to ignite the gas, but the flame front in the gas spreads spontaneously, and the sprayed liquid fuel burns together. As a result, ROHR intensifies, but gaseous fuels still burn more slowly in the initial combustion phase than when 100% diesel or biodiesel HVO is used, resulting in lower in-cylinder pressure, shorter combustion duration and reduced NO_x emissions and smoke.

Acknowledgments

The authors acknowledge the contributions of the AVL Company for supporting the use of the AVL BOOST engine simulation tool within the cooperation agreement between the Faculty of Transport Engineering of Vilnius Gediminas Technical University and AVL Advanced Simulation Technologies.

References

1. Ashok, B. & Thundil Karuppa Raj, R. & Nanthagopal, K. & Krishnan, R. & Subbarao, R. Lemon peel oil – A novel renewable alternative energy source for diesel engine. *Energy Conversion and Management.* 2017. Vol. 139. P. 110-121.
2. Owen, N.A. & Inderwildi, O.R. & King, D.A. The status of conventional world oil reserves – Hype or cause for concern? *Energy Policy*. 2010. Vol. 38(8). P. 4743-4749.
3. Ashok, B. & Jeevanantham, A.K. & Vignesh, R. & Bhat Hire, K.R. & Prabhu, K. & Raaj Kumar, R.A. & et al. Calibration of engine parameters and fuel blend for vibration and noise characteristics in CRDI engine fuelled with low viscous biofuel. *Fuel*. 2021. Vol. 288. No. 119659.
4. International Energy Agency. *World Energy Outlook 2014*. OECD. 2014. (World Energy Outlook). Available at: https://www.oecd-ilibrary.org/energy/world-energy-outlook-2014_weo-2014-en.
5. Satsangi, D.P. & Tiwari, N. Experimental investigation on combustion, noise, vibrations, performance and emissions characteristics of diesel/n-butanol blends driven genset engine. *Fuel*. 2018. Vol. 221. P. 44-60.
6. Omar, F.K. & Selim, M.Y.E. & Emam, S.A. Time and frequency analyses of dual-fuel engine block vibration. *Fuel*. 2017. Vol. 203. P. 884-893.
7. Çelebi, K. & Uludamar, E. & Tosun, E. & Yıldızhan, Ş. & Aydın, K. & Özcanlı, M. Experimental and artificial neural network approach of noise and vibration characteristic of an unmodified diesel engine fuelled with conventional diesel, and biodiesel blends with natural gas addition. *Fuel*. 2017. Vol. 197. P. 159-173.
8. Çalık, A. Determination of vibration characteristics of a compression ignition engine operated by hydrogen enriched diesel and biodiesel fuels. *Fuel*. 2018. Vol. 230. P. 355-358.
9. Kubica, G. & Flekiewicz, M. & Marzec, P. Selected aspects of the use of gaseous fuels blends to improve efficiency and emission of SI engine. *Transport Problems*. 2019. Vol. 14(1). P. 95-103.

Received 01.07.2021; accepted in revised form 06.03.2023