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DEVICE FOR CONTROL THE VALVETRAIN AND CYLINDER PRESSURE OF A SPARK-IGNITION ENGINE

Jarosław Mamala

Opole University of Technology
Faculty of Mechanical Engineering
Mikołajczyka Street 5, 45-271 Opole, Poland
tel.: +48 77 4498437, fax: +48 77 4498446
e-mail: j.mamala@po.opole.pl
Science and Technology Park in Opole
Technologiczna Street 2, 45-839 Opole, Poland

Mariusz Graba, Andrzej Bieniek, Krystian Hennek

Opole University of Technology
Faculty of Mechanical Engineering
Mikołajczyka Street 5, 45-271 Opole, Poland
tel.: +48 77 4498439, +48 77 4498447, +48 77 4498449 fax: +48 77 4498446
e-mail: m.graba@po.opole.pl, a.bieniek@po.opole.pl, k.hennek@po.opole.pl

Abstract

This article describes the method of controlling an electric magnetic linear actuator that moves an inlet valve of an internal combustion engine. Thanks to the use of the electric control of the inlet valve of the internal combustion engine, it was possible to implement a variable effective compression ratio of the operating power unit, adapting it to the current needs and engine load. In this design, valvetrain was modified by introducing an autonomous intake valve operation with the use of a specially designed electromagnetic actuator. The introduction of this system necessitated an additional modification of the intake camshaft. The control was carried out with the use of a real-time controller with a built-in FPGA unit. The proposed design of a system with an electromagnetic actuator will allow obtaining an additional degree of freedom in the control unit. Particular attention should be paid to registered values or air pressure in the intake stroke for a closed or partially opened throttle, which generates significant pumping losses. The use of an electromagnetic actuator in the intake can help reduce said losses.

Keywords: *combustion engines, environmental protection, variable compression ratio, valve control*

1. Introduction

Nowadays, internal combustion engines are the most commonly used type of drive unit in passenger cars. Despite newest trends and legal regulations regarding emissions, IC engines are constantly improved. They will also continue to be used in all sorts of vehicles and machines, as is evidences by numerous publications [1, 3]. They owe their popularity to two characteristic parameters. The first one is related to very good energetics indicators, both in mass and volume aspects. The second one is related to a high calorific value of IC engine fuels. However, their main drawback is the emission of exhaust gasses to the environment. Increasingly strict regulations regarding emissions are constantly being developed. Therefore, engine manufacturers constantly strive to improve their designs, both in technical and ecological aspects. For the several past years, two main trends can be observed. The first one is a so-called engine Downsizing, which favours the design of engines with smaller capacity but highest possible power output. Down speed is the second trend, which aims to obtain possibly best IC engine operating indicators at lowest possible crankshaft speeds. Alternative hybrid power units and zero-emission „Tank to Wheel" (TTW) solutions are also in development.

In some newest IC engines, design solutions of variable compression ratio (VCR) (1) were used with the aim of adjusting momentary engine operation indicators to the momentary engine load resulting from current powertrain demand. However, this design is not commonly utilized due to complexity of VCR systems and their control units. Those systems often show increased mass and tendency for failures in comparison to traditional engine designs. Few designs of VCR engines are known, and those can be divided in two categories. The first one includes the designs where the variable compression ratio is achieved by introducing additional movement of moving engine parts (variable connecting rod length, pivots/eccentrics on crankshaft bearings). The second group includes designs, which incorporate the movement of traditionally stationary engine parts (moving engine head/block, additional combustion chamber of variable volume) [5, 6]. All those designs aim to improve the effective compression ratio (2) to adjust engine-operating parameters to its momentary load. However, the improvement in compression ratio does not result in an overall increase of IC engine efficiency, as it increases mechanical and pumping losses. Moreover, an increase in cylinder pressure due to an increased compression ratio is limited by the occurrence of engine knocking or its loud operation. Therefore, efficient solutions for adjusting the compression ratio in accordance with momentary engine operating conditions are sought.

Due to aforementioned reasons, most IC engines have a fixed value of compression ratio (1), whose value is most often 1:10 for SI and (1:18) for CI engines. The design compression ratio is fixed in the engines mentioned in the previous paragraph, however the effective compression ratio (2) is variable and achieved in various ways.

Design value of compression ratio (ε) is a geometric value given in equation below [2]:

$$\varepsilon = \frac{V_S + V_k}{V_k}, \tag{1}$$

where:
V_S – cylinder capacity,
V_k – combustion chamber capacity.

An effective compression ratio pressure described by the equation below:

$$\gamma = \frac{p_{e\max}}{p_{\min}}, \tag{2}$$

where:
$p_{e\,max}$ – maximum effective pressure,
p_{min} – intake air pressure.

The effective pressure ratio changes in a wide range, depending on engine type (naturally aspirated or turbocharged, spark ignition or compression ignition, fuel injected or carburetted) [3].

2. Variable effective compression ratio – vECR

This article describes a method and system for adjusting the effective compression ratio of an IC engine with indirect fuel injection with the aim of improving engine efficiency. In this design, modified in accordance with a reported patent [4], compression ratio was increased by means of modifying the engine head. The main goal of proposed modification is to introduce the possibility of modifying the amount of air accumulated in the cylinder at the beginning of the compression stroke. This can be achieved in two ways: by building a release valve into a separate canal in the engine head or by employing an additional valve train operation system with the aim of managing engine valve movement independently of camshaft motion.

The presented work is focused on an electrically actuated engine intake valve. In this design, valve train was modified by introducing an autonomous intake valve operation with the use of a specially designed electromagnetic actuator. The introduction of this system necessitated an additional modification of the intake camshaft. Mounting of the system and its connection to the intake valve are shown in Fig. 1.

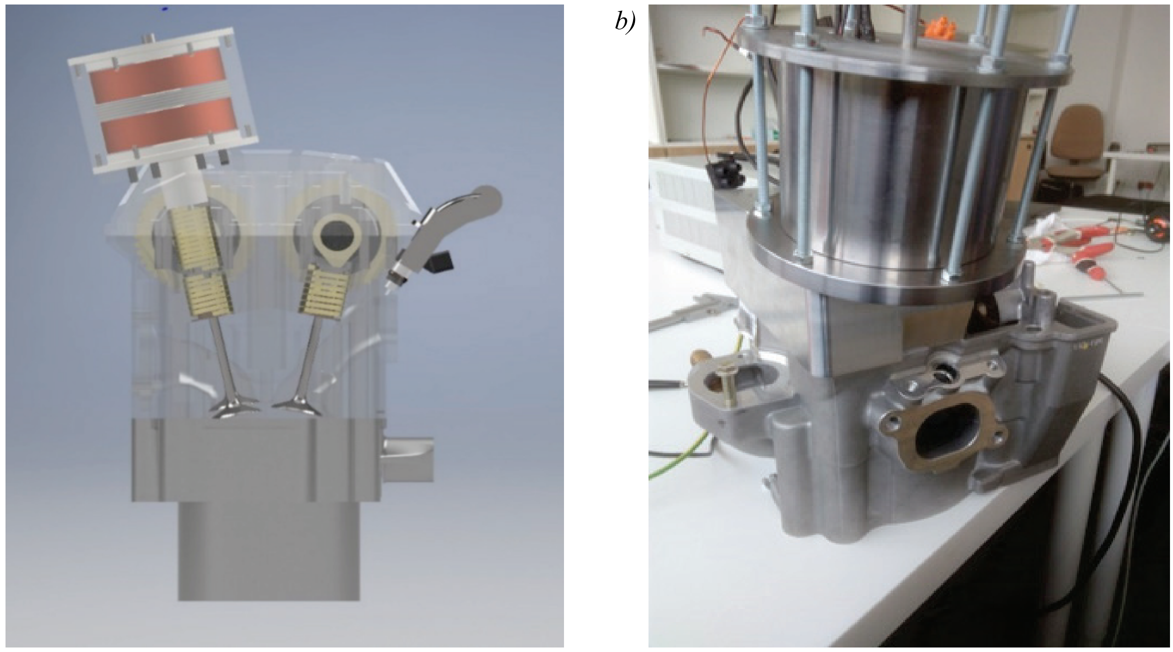

Fig. 1. vECR engine head with mounted actuator: a) designed electromagnetic actuator b) prototype electromagnetic actuator

Depending on engine operating point, the electromagnetically actuated intake valve will serve two functions – that of a traditional intake valve and of a release valve which regulates the compression ratio. Therefore, two control strategies have to be assumed:

a) in idling and partial load conditions, for traditionally controlled throttle and variable crankshaft speed the valve will operate in a normal working cycle, opening the valve per conditions shown in Fig. 2,
b) for variable load conditions the valve can execute a prolonged opening angle, which will be extended by a value necessary to obtain an effective compression ratio dependent on current engine operating conditions.

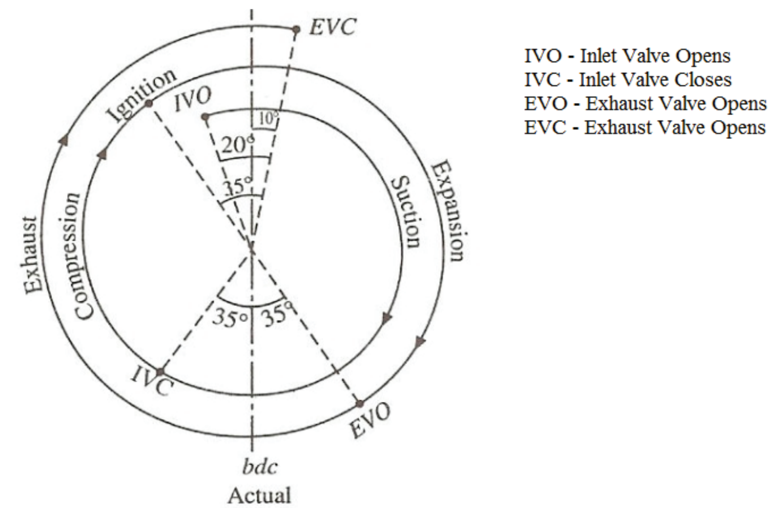

Fig. 2. Operating cycle of a four-stroke IC engine depending on crankshaft angle

In vECR engine, the operating cycle of an autonomously actuated valve is closely related to the crankshaft angle. Therefore, constant monitoring of crankshaft position with the use of a crankshaft angle sensor is necessary. The other signal that needs to be analysed is the throttle position, as the throttle is responsible for cylinder filling ratio in accordance with equation (2) and for effective compression ratio.

3. Research object, method and equipment

A single cylinder ProStar IC engine of 567 cm^3 capacity was used for research purposes. It is used to power ATVs (All-Terrain Vehicles). Engine technical data is given in Tab. 1.

Tab. 1. Engine technical data

Engine Type	ProStar 567cc, 4-Stroke DOHC Single Cylinder
Cylinders-Displacement (ccm)	567 ccm
Fuel System	Electronic Fuel Injection
Power	44 HP@ 6700 RPM
Maximum torque	49 Nm @ 5900 RPM
Cooling	Liquid
Compression ratio	9.2:1

The engine was subjected to experimental research on an engine dynamometer at the Department of Vehicles of Opole University of Technology. The electrodynamic brake allowed for propelling of the engine with its injection and ignition systems turned off and for investigation of engine operation under load. The dynamometer was equipped with a control system that allowed for measurement of crankshaft rotational speed, engine torque, torque loss, fuel consumption and other engine operating parameters [3].

Cylinder pressure values registered during compression stroke for a non-operating engine (ignition and injection systems turned off) are shown in Fig. 3. For the discussed example, crankshaft speed was set as constant at 3000 rpm, while throttle opening was set at 10% and 50%. In Fig. 3a), a lower overall compression pressure and lower compression stroke pressure can be seen. The compression stroke starts with an open intake valve. Therefore, it can be assumed that the same pressure value occurs in the intake manifold, which delivers air to the cylinder. With this assumption, an effective compression ratio for separate measurement points can be computed with the use of equation (2).

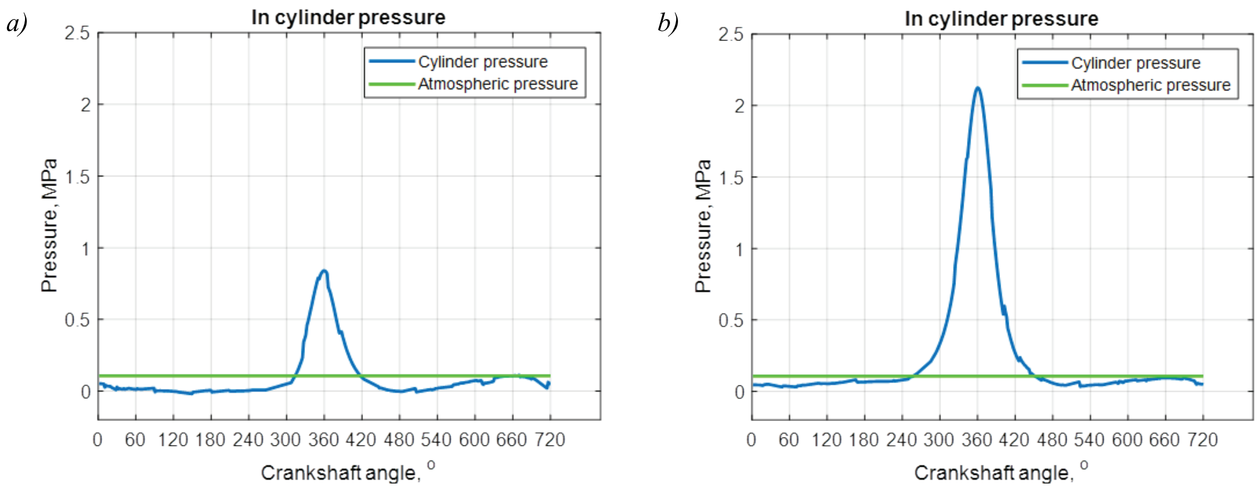

Fig. 3. Indicated cylinder pressure for 3000-rpm engine speed at: a) 10% throttle opening, b) 50% throttle opening

A maximum cylinder pressure at the end of the compression stroke was read from Tab. 2. Shown values are averaged from at least 30 cycles. Averaged values of pressure during the compression stroke at 90º crankshaft angle are shown in Tab. 3.

Tab. 2. Maximum indicated cylinder pressures [MPa]

		Throttle positon						
		5%	10%	15%	20%	30%	50%	100%
Rotation speed	1500 rpm	1.02	1.19	1.48	1.89	2.00	1.91	1.95
	2000 rpm	0.78	1.06	1.33	1.75	2.12	2.04	2.03
	3000 rpm	0.73	0.87	1.07	1.29	1.91	2.25	2.13
	4000 rpm	0.71	0.81	0.98	1.19	1.90	2.44	2.44

Tab. 3. Pressure at compression stroke for 90º crankshaft angle [MPa]

		Throttle positon						
		5%	10%	15%	20%	30%	50%	100%
Rotation speed	1500 rpm	0.09	0.107	0.108	0.108	0.108	0.108	0.107
	2000 rpm	0.014	0.017	0.040	0.050	0.107	0.108	0.108
	3000 rpm	0.012	0.014	0.015	0.035	0.059	0.084	0.050
	4000 rpm	0.013	0.011	0.013	0.022	0.055	0.069	0.108

For a constant engine speed, the maximum pressure is strictly dependent on throttle position (Fig. 4). In case of variable engine speed and fixed throttle position, differences are less significant. However, for partial throttle opening, the maximum pressure decreases with engine speed, and increases for full throttle opening.

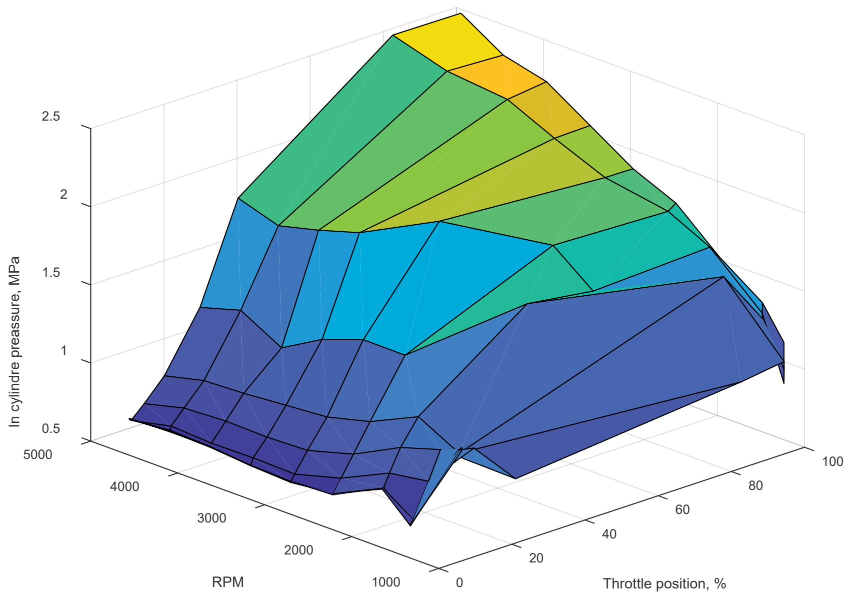

Fig. 4. Characteristic of averaged maximum cylinder pressure for a non-operating engine

A characteristic of an effective compression ratio for a single-cylinder IC engine with ε = 9.2 value of compression ratio looks similar. The effective compression ratio is dependent mostly on throttle position, as is shown in Fig. 5.

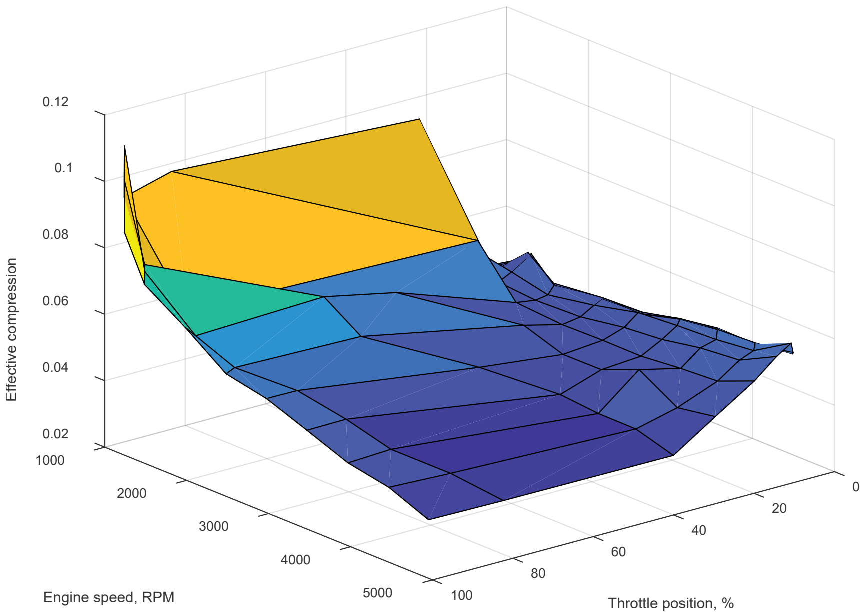

Fig. 5. Characteristic of effective compression ratio pressure for a non-operating engine

In relations to results shown in Fig. 5 for a non-operating engine, a load characteristic of an operating engine was also presented. An SI engine is controlled on the basis of the amount of air delivered to the cylinder, as is accordance with theoretical assumptions, the air-fuel mixture composition should equal $\lambda = 1$ and be homogenous. Fuel is not delivered to a non-operating engine; therefore effective compression ratio values for partial and full throttle openings will be lower.

This indicated a strict dependency of engine load on throttle position, which determined the cylinder filling with fresh air-fuel mixture. The effective compression ratio in cylinder (Fig. 5) shows a similar tendency.

4. Electromagnetic actuator

Basing on the analysis of tested engine parameters, it can be inferred that requirements towards both operating and control elements of the vECR system are very high. A sum of time needed for the control system to send the instruction and for the system to operate can range from few to over a dozen milliseconds. Control of the pressure-regulating valve must take place in the time of a single operating cycle. A duration of a single cycle decreases with a rise in engine speed.

Due to aforementioned reasons, a real-time NI CompactRio modular control unit, which allows for changes in input and output configurations, was chosen for preliminary tests of the actuator. A built-in FPGA unit allows executing a fast control of the external device, basing on information obtained from sensors connected to the control unit.

Two separate actuating units were used in the design of the electromagnetic actuator for controlling the intake valve. In traditional designs, the valve opening time and lift is controlled by an appropriate cam located on the camshaft. Therefore, the designed actuator must move the intake valve in a manner similar to the original cam to not disrupt engine operation. Performed calculations have shown that the valve should travel 8 mm in 2 ms, and that the total mass moved by the actuator is 200 g. Those parameters became the criteria in choice of materials and dimensions for the actuator design. Such a rapid movement of a significant mass necessitates activation of the actuator with the use of high electric currents. Therefore, an actuator activated by a 100 V voltage was designed, with momentary currents assuming values of up to 30 A. A control of an induction element, such as this actuator, with the use of high currents and a 100 V voltage forced the use of a special dedicate module designed for control of fuel injectors in compression ignition engines. This module is meant to be installed in a cRIO control unit casing, while control of the power output unit is realized with the use of FPGA unit. The test program panel is shown in Fig. 6. Graphs representing current values are refreshed for every program loop. By analysing them, one can see that observed values are in agreement with assumed ones.

Registered courses are repeatable, which was verified with the use of an oscilloscope connected to the electromagnetic actuator shown in Fig. 6.

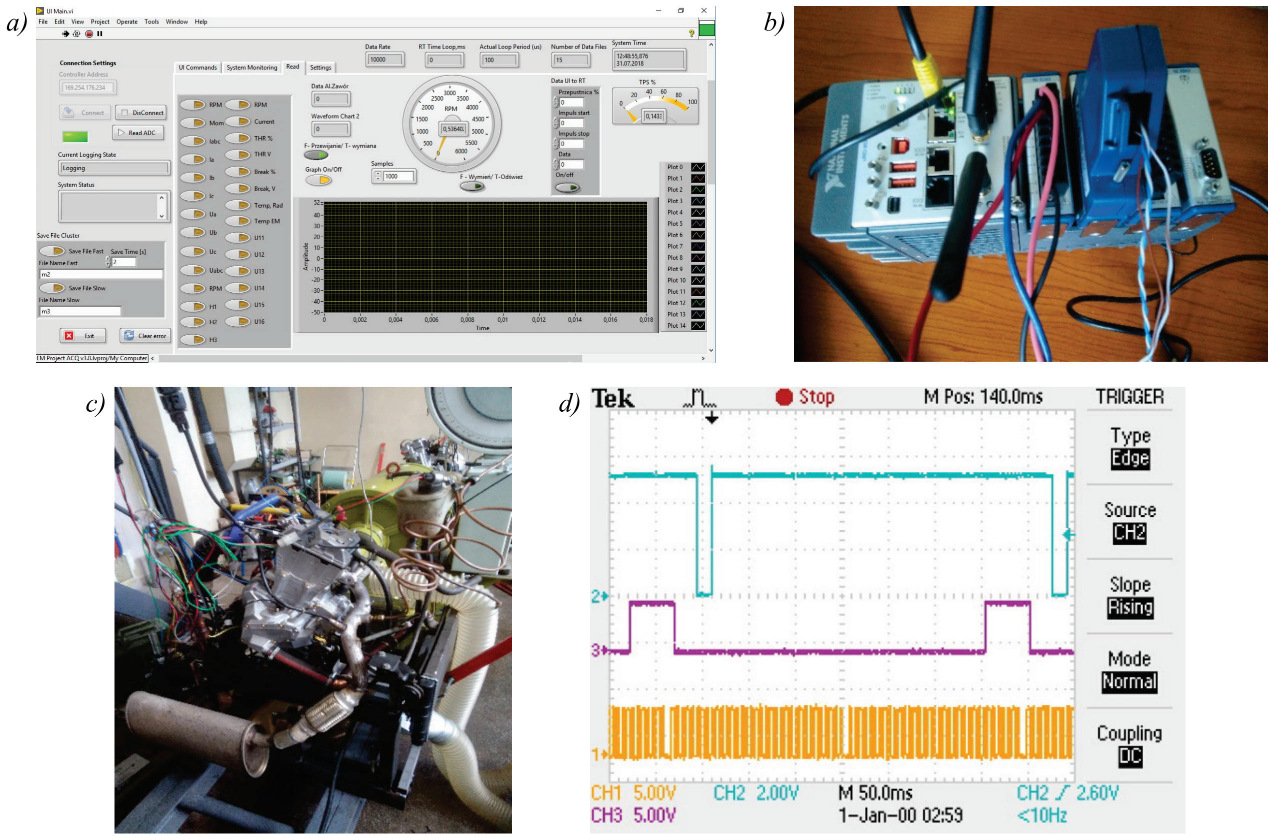

Fig. 6. vECR system components and control signals: a) application front panel, b) CompactRIO c) engine on the dynamometer, d) control signals

5. Summary

The analysis of changes in air pressure in the engine cylinder during intake and compression strokes shows that the engine load is not dependent exclusively on air pressure in the cylinder. Therefore, a proposed design of a system with an electromagnetic actuator will allow obtaining an additional degree of freedom in the control unit. Particular attention should be paid to registered values or air pressure in the intake stroke for a closed or partially opened throttle, which generates significant pumping losses. The use of an electromagnetic actuator in the intake can help reduce said losses.

Acknowledgments

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