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THE PROGRAMMABLE STEERING MACHINE FOR THE ELECTRIC LIGHTWEIGHT VEHICLE

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Abstract – In this paper a programmable steering machine (PSM) and the lightweight electric powered vehicle, designed and made at the Kazimierz Pulaski University of Technology and Humanities in Radom (UTH Radom) have been presented. Both these technical objects are the result of the project carried out by the Student Research Group "Turbodoładowani". The steering machine has been developed with the programmable algorithms allowing to execute a controllable movement of the vehicle steering wheel. After execution, the system does not need an interaction with the driver. For this reason, a higher repetition of the vehicle traction measurements can be achieved. Such confirmation obtained in tests within which the time waveforms of rotation angle of the steering wheel by a set value of 45, 90, 180 and 360 degrees was recorded. In particular, the accuracy index for mentioned test conditions was calculated. Obtained results, expressed by the average value of the sensitivity index were lower than 2% within the tests carried out for ±45 degree maneuvers. In case of other tests i.e., for ±90, ±180 and ±360 degree maneuvers the accuracy index value was lower than 0.3%. In this way, it was confirmed that the tested PSM reached the appropriate operating parameters necessary for vehicle traction tests.
Key words – road safety, steering machine, electric vehicles, renewable energy, road transport

JEL Classification – 031, 032

INTRODUCTION

Development in the vehicles' technology depends on several factors. It seems that the most important are environmental regulations, safety in the road transport and political agreements. Environmental aspect requires that vehicles should be more and more "green". It means that such vehicles cannot impact negatively on surrounding environment by emitting an excessive noise, toxic gas components from the engines and particles from brakes and tires. Taking this into account the vehicles development is focused on several trends. The one of the most important seems to be environmentally friendly fuels. In this regard the researches on alternative and renewable fuels are still developed. These researches are focused mainly on biofuels [1-3] different blends containing selected alcohols and/or ethers [4, 5], hydrogen as well as CNG / LPG gas [6-8]. Another trend in the vehicles' development is focused on the safety and autonomous driving. This development is strongly related with the progress in the vehicle testing. It can be stated, that the design of safe and autonomous car needs series of advanced tests carried out with the use of programmable steering machines (PSM). The concept of such steering robots is described, for example, in the SAE paper [9]. In particular, these machines allow to describe the vehicle behavior in repeatable manner. As mentioned above, the future cars will become more independent and automated. According to the SAE classification the steering automation is classified in range L1 - L4 [10]. It should be pointed that this automation seems to be especially valuable for disabled persons. This is why, PSMs are helpful in the research of vehicles addressed for disabled persons [11]. All these tests must be carried out with the high-quality equipment, which will provide repeatable conditions for measurements. According to the state of the art., these conditions cannot be achieved with the human operator/driver. It should be pointed that even trained human driver do not allow to get a repeatable daily result [12, 13]. For this reason, the steering robots are more and more common also in the emission tests [14].

There are only a few PSM manufacturers on the global market. In Europe, the one of them is AB Dynamics founded in 1982 in England [15]. This producer offers the steering robots equipped with direct – drive motors. For this reason, the PSM made by AB Dynamics require no clutch or gears. Also, the rotational inertia of their steering robot is only 0.0074 kgm^2. Depending on the model of the PSM made by AB Dynamics, the torque available on the steering wheel varies in range 20 – 160 Nm. Another key feature of these robots is maximum rotational velocity reaching a top value of 2500 degree per second. AB Dynamics steering machines are commonly used by the vehicle manufacturers in the world. Also, these robots are helpful during scientific researches carried out also in Poland. For example, in 2012 the SR 60th steering robot made by AB Dynamics was used by The Military Institute of Armour and Automotive Technology in Sulejówek for military vehicle tests [16].

In Europe, the steering robots are also offered by German company the VEHICO [17]. This manufacturer produces the steering machines for different applications such as: ADAS, durability, ESC, AEB test and many more. Maximum torque available on the steering wheel varies in range 20 – 150 Nm, depending on the model. As mentioned, AB Dynamics and VEHICO steering robots are commonly used in the vehicle testing. However, other manufacturers offer similar steering robots. The most popular ones are Humanetics, Stähle GmbH and 4activeSystems [18-20]. In addition to robots for research purposes, there are steering machines designed for other applications such as agriculture [21]. For example, a company Sveaverken Agri AB offers autonomous steering system for tractors.

In this paper, the Authors would like to show the main features of the PSM built at the UTH Radom. In particular the accuracy and repeatability tests of this steering robot were carried out using the lightweight electric powered vehicle.

Results of this paper are part of the project supported by the Ministry of Education and Science.[1]

1. MATERIALS AND METHODS

1.1. DETAILS OF THE TEST VEHICLE

In this research the lightweight vehicle, equipped with an electric powertrain, built at the UTH Radom has been used. The CAD model of this vehicle is shown in Figure 1. The vehicle is equipped with two seats, small trunk, pneumatic suspension and an electric powertrain system combined with the photovoltaic panels (PV) located on the vehicle roof.

Fig. 1. CAD Model of the lightweight electric vehicle designed by the Student Research Group „Turbodoładowani" at the UTH Radom

[1] The research described in this article was subsidized by the Minister of Education and Science with funds from the state budget within the framework of the "Student Scientific Circles Create Innovations" program. Project number SKN/5P/495820/2021

Fig. 2. Original view of the light electric vehicle made by the Student Research Group „Turbodoładowani" at the UTH Radom

Table 1. Fundamental technical parameters of tested vehicle

Parameter	**Value**
Power system	2 electric DC motors with top power of 1 kW
Top power	2 x 1 kW at 3000 rpm
Estimated top speed	25 km/h
Drivetrain ratio	1:12
Front/rear axis load	147/225 kg
Tyre size	115/70 R15
Wheelbase	197 cm
Photovoltaic panels (PV) top power	4 x 65 W made by SolarFam Co.
PV max. current	3.47 A
PV open circuit voltage	22.38 V
Solar charge controller	MPPT type

Meanwhile, a view of the vehicle after its development is presented in Figure 2. The vehicle has been equipped with all systems which are necessary for safe driving. In particular, it is equipped with lights, horn, mirrors, hydraulic braking system, and dashboard with speedometer.

Technically, this lightweight vehicle is expected to provide transportation for two people for up to about 25 kilometers or more depending on the solar radiation. The energy source for the vehicle's DC electric motors contains four traction batteries, which are connected in series. This resulted in a supply voltage for electric motors of about 48V. Meanwhile, the capacity of one battery used in the vehicle's power system is 26 Ah. A characteristic feature of the vehicle is the air suspension. It is an innovative solution in this type of lightweight vehicle. In addition, as designed, the vehicle is equipped with 4 photovoltaic panels connected in series. The panels used allow the batteries to be recharged, which increases vehicles range. More technical data of the test vehicle are listed in Table 1.

1.2. Programmable steering machine

1.2.1. Mechanical design

For this study, the programmable steering machine (PSM) has been designed in CAD system as shown in Figure 3.

It should be pointed that the PSM made at the UTH Radom can be applied in the research of different vehicles. In this case the PSM supported the research of the lightweight vehicle. However, the PSM features are enough for tests of commercial cars. The PSM is built with a servomotor (model: SMC60S-0040-30MBK-3DSH), the planetary gearbox with the aspect ratio 1:16 and a controller (model: FD124S-CB-000) made by KINCO Co. The torque – speed characteristic of this 400-Watt servomotor has been presented in Figure 4. This figure shows the servomotor torque characteristics as a function of speed for supply voltages: 24V, 32V, 36V and 48V. The solid lines show the torque values for continuous operation of the motor and the dashed lines for instantaneous operation. In the presented PSM, the motor does not run continuously, so it can be loaded according to the curves with the dash lines.

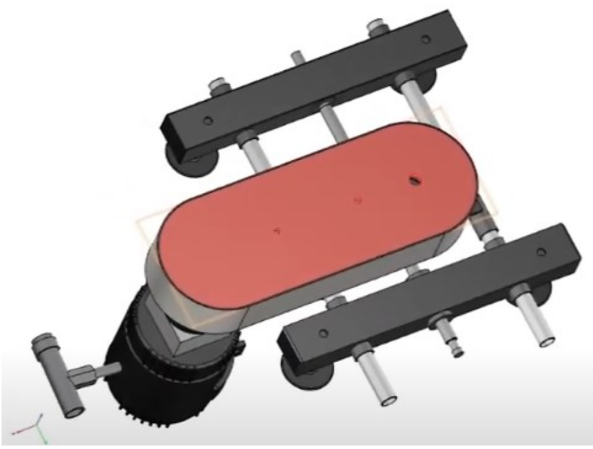

Fig. 3. CAD Model of the PSM designed for the vehicle steering wheel control

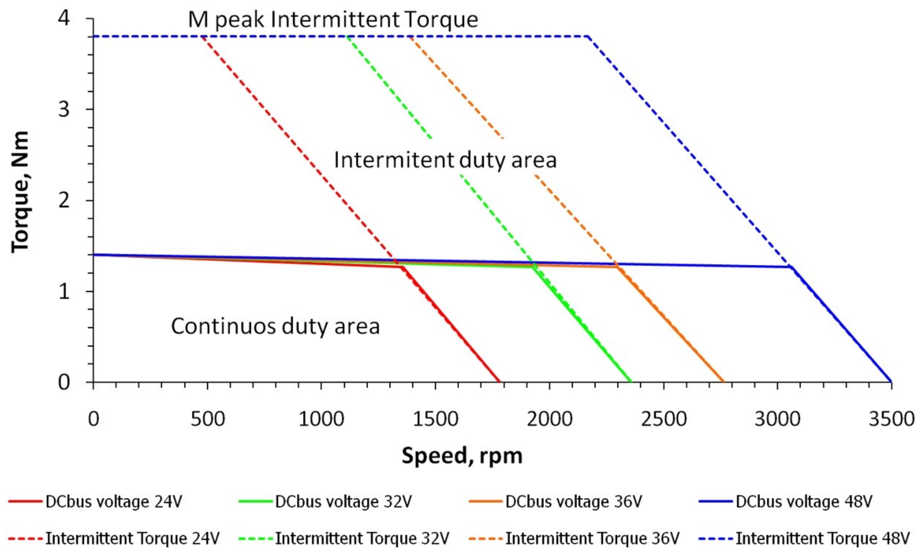

Fig. 4. Servo motor torque curve [adopted from ref. 22]

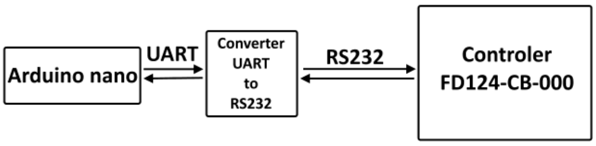

Fig. 5. Connection diagram of the Arduino to the PSM controller

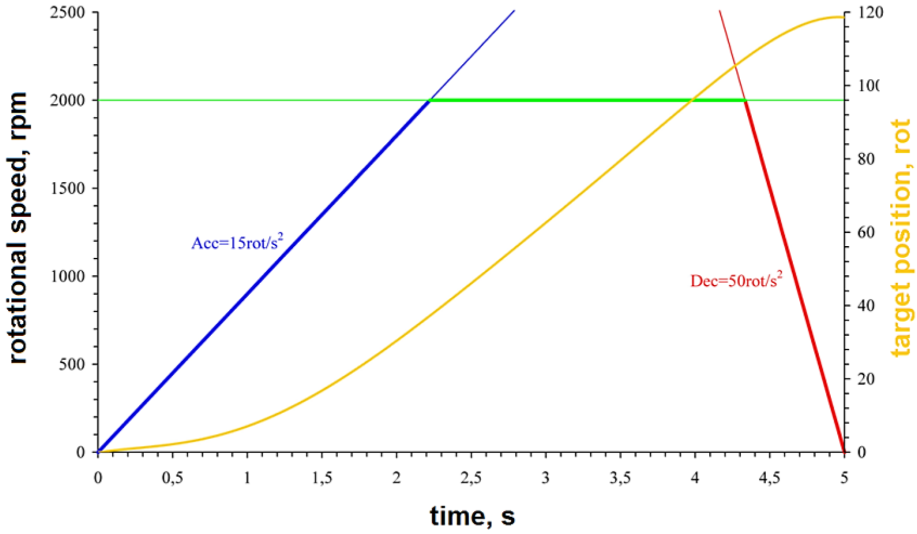

Fig. 6. Examples of servo motor motion parameters

The rotational movement of the servomotor shaft is transmitted by the chain to the vehicle steering wheel. The total gear ratio of this mechanical transmission is 1:32. However, other settings are also possible, for example gear ratio 1:16. For the base PSM configuration the electric motor rotational speed is reduced by 32. In practice, it means that the steering wheel will rotates with the top speed of 562 degrees per second under the nominal torque 40 Nm or even 120 Nm temporary. The servo motor is equipped with a magneto-electric 16-bit encoder with 10 thousand pulses per revolution. These parameters are good enough to control the vehicle steering wheel movement during the complex tests.

1.2.2. STEERING SOFTWARE

As mentioned above, the PSM works under the supervision of a low-voltage, DC-powered controller (model: FD124S-CB-000) made by Kinco Co., as shown in Figure 5.

It should be pointed, that all necessary commands for this controller can be send via the RS232 port or the CAN bus and the CANOpen protocol. In this way, specific movements of the servomotor can be achieved, as shown in the example Figure 6. This figure shows an example of how the rotational speed and position of the motor shaft change over time. The speed curve consists of three parts: acceleration with a given acceleration (blue), movement with a constant given speed (green) and deceleration with a given deceleration (red). Meanwhile, the yellow curve shows the motor shaft position due to changes in the set speed.

In the developed PSM, the steering system consists of specific successive maneuvers. In particular, the movements of the servo motor shaft, affects the movement of the steering wheel. Following commands are possible:

– movement with acceleration Acc [rot/s^2] with which the engine increases the rotational speed when starting the maneuver,
– movement with deceleration Dec [rot/s^2] with which the engine reduces the rotational speed at the end of the maneuver,
– motion with the constant rotational speed n [rpm],
– target position [rot] i.e., the number of revolutions the engine shaft rotates during the maneuver.
– waiting time for the next maneuver [ms].

Each of the above-mentioned commands was programmed by sending a 10-byte telegram, an example of which is shown in Figure 7 and in Table 2.

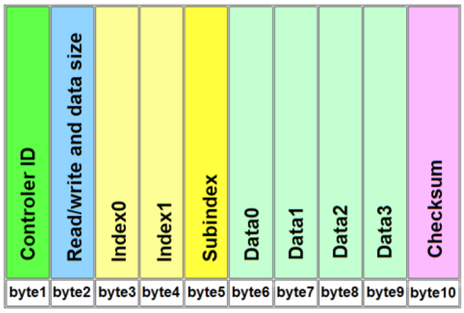

Fig. 7. An example telegram containing information for a servo motor controller

Table 2. Fundamental content of the telegram

Byte no.	Description
1	Controller ID. Controller with specified ID will receive the data frame.
2	The direction of data transfer (read/write) and the size of the data field. Data can be sent/ received to/from the controller. The data can be one, two, or four bytes.
3 and 4	INDEX (data address), i.e., a two-byte number (address) of the controller register to which the data is entered or from which it is read.
5	SUBINDEX (sub-data address)
6 - 9	Data. Single byte is contained in byte 6; double byte - in bytes 6 and 7
10	Checksum

Execution of each movement of the PSM requires earlier prepared data defining the functions assigned transmitted to the digital inputs. These data describes the acceleration, constant movement speed, deceleration and target position of the PSM. The last activity is the execution of the maneuver, which is performed at the time instant for the programmed maneuver start. Example of such execution is shown in Figure 8 and Table 3.

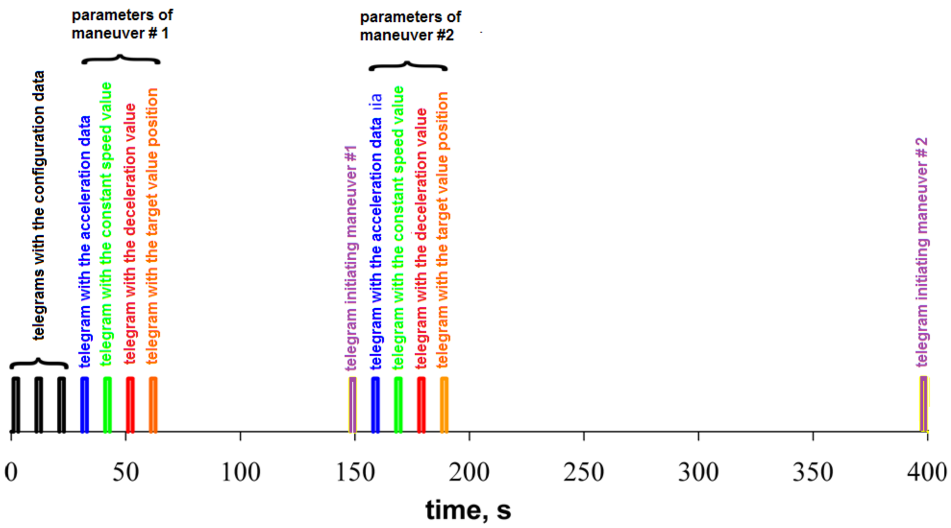

Fig. 8. Example view of the steering data sent to the PSM controller

Table 3. Example data necessary to execute sequence of 3 maneuvers carried out by the PSM

Maneuver no.	Acc, rot/s²	Speed, rpm	Dec, rot/s²	Target position, deg.	Maneuver time, ms	Delay, ms
1	50	800	30	90	956	544
2	100	-1500	50	-90	1015	485
3	40	500	100	0	1106	-

All programmable sequence maneuvers data are shown in example Table 3. After the PSM control procedure is started in the first maneuver, further data necessary to begin the next movement sequences are sent to the controller.

The variation of the engine speed and the steering wheel position presented in Table 3 are also shown in Figure 9.

The PSM operation is controlled by the ATMEGA328P microcontroller installed on the ARDUINO NANO v.3 board. This microcontroller has a built-in hardware UART serial port. The voltages on its RX and TX lines vary in the range of 0 - 5V. The voltages on the RS232 serial port lines vary between (−3 V) - (−15 V) and 3 - 15 V. Taking this into account, a logic state converter was required in the PSM control system. The MAX3232 integrated circuit was used for this purpose. It has a built-in voltage multiplier operating in two directions of data transmission. It allows the voltage level of the UART port to be converted to the levels required for the RS232 port.

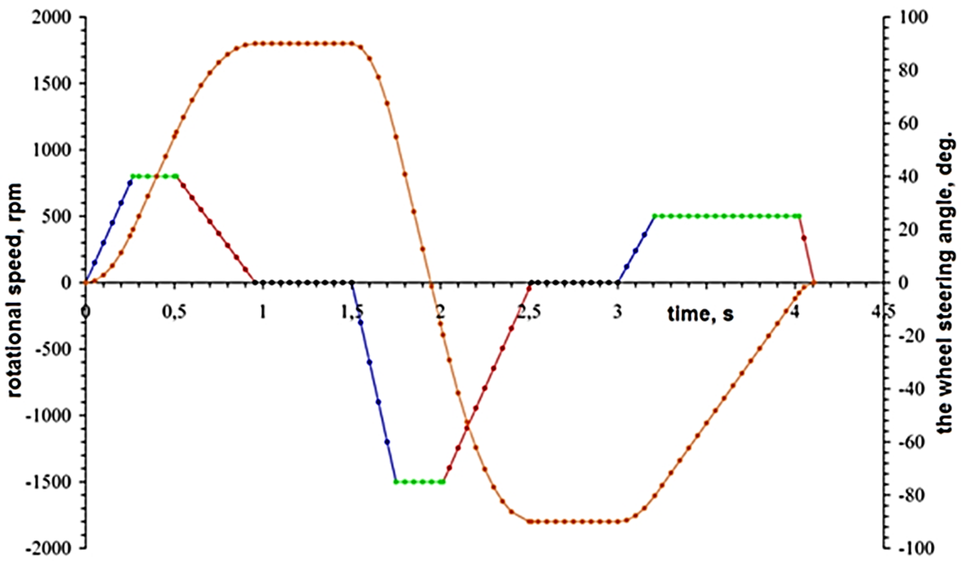

Fig. 9. Time series of the engine speed and the steering wheel position realized according to the sequence shown in Table 3

2. Research Methodology

The main aim of this study was to evaluate the precision of steering wheel control of a vehicle by the PSM made by the UTH Radom. For this purpose, a test stand was used, which is shown in the Figure 10. The test stand is equipped with the lightweight electric vehicle and the PSM operated under the control of the laptop equipped with necessary software. Angular position of the vehicle steering wheel was measured with the Kubler draw – wire encoder connected to the digital oscilloscope.

It was assumed to perform tests consisting in the implementation of a programmed sequence of turns of the steering wheel to the left and then to the right for the following angular values δH: 45, 90, 180 and 360 degrees with respect to the neutral position (Fig. 11).

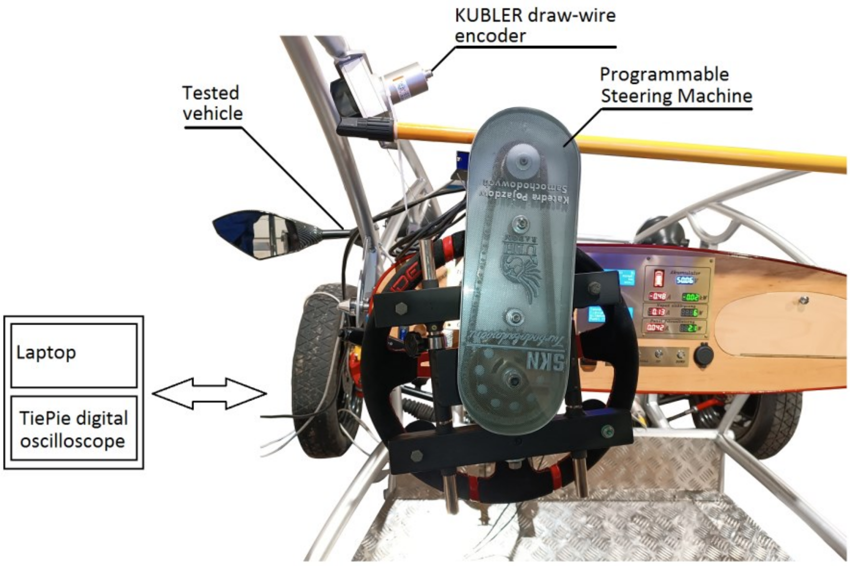

Fig. 10. The test stand view equipped with the lightweight electric vehicle and the PSM

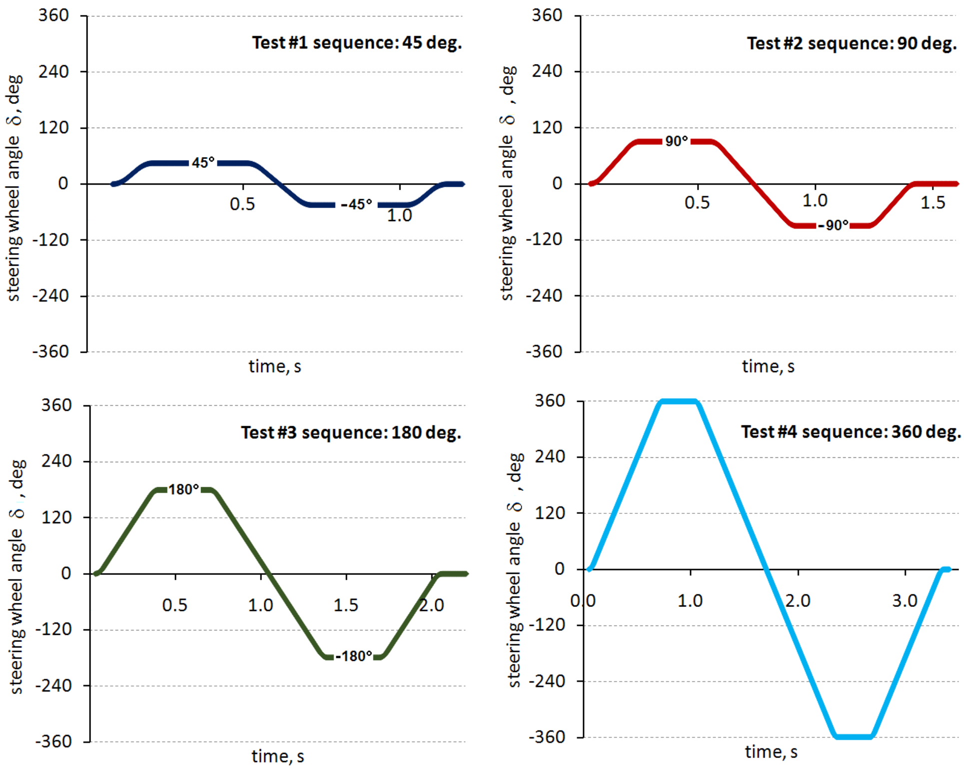

Fig. 11. Reference sequences of the programmed steering wheel motion used in the tests

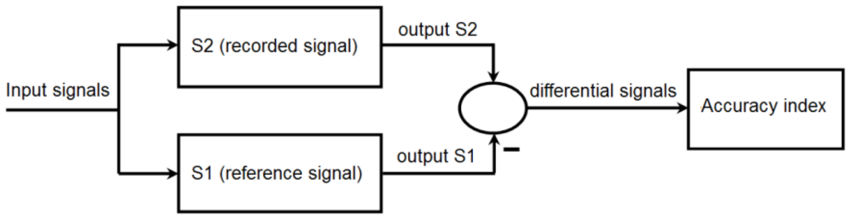

Fig. 12. The method of determining the PSM steering wheel accuracy index

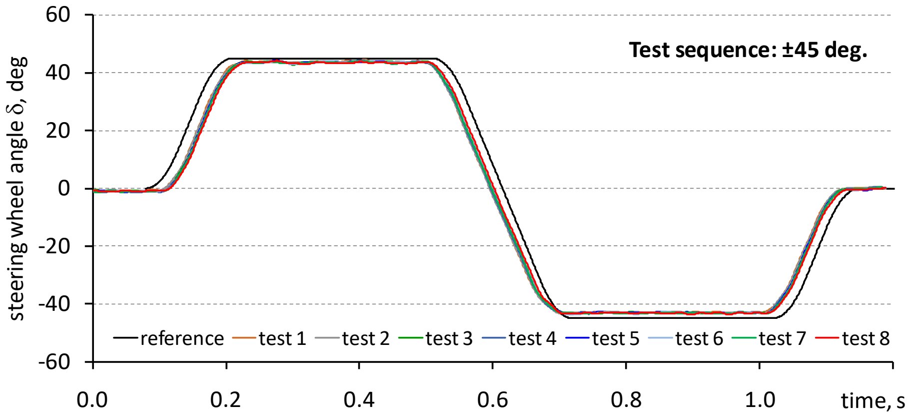

Fig. 13. Time waveforms of changes in the angular position of the steering wheel during the 45-degree turn maneuver

For each programmed (reference) sequence of steering wheel movement, eight measurements of its actual rotation were made. For this purpose, the KUBLER draw-wire encoder, type D8.3b1.0100.A223.0000 was used [23]. The encoder was connected to a digital oscilloscope enabling the recording of the necessary data with the frequency of 1 kHz. In the measurement system, a low-pass filter with a cut-off frequency of 40 Hz was used. In order to assess and compare the quality of the steering wheel rotation waveforms obtained during the tests, the accuracy index was applied, expressing the percentage discrepancy between the real (measurement) and the reference (calculated) waveforms, according to the concept shown in Figure 12.

The accuracy index $W\alpha$ is described by the formula [24]:

$$W\alpha = \frac{\int_0^{\tau} \left(S_1(t) - S_2(t)\right)^2 dt}{\int_0^{\tau} \left(S_1(t)\right)^2 dt} \cdot 100\% \qquad (1)$$

where: t = time, τ = 1.2, 1.5, 2.1 and 3.3 seconds for maneuvers shown in Figure 13-16, S_1 - reference signal data, S_2 - recorded signal data, α - target steering angle i.e.: 45, 90, 180 and 360°

3. Results

Results of the study performed are shown in the following Figures 13-16 and Table 4. In all these Figures the black line represents the reference waveform.

Figure 13 presents the time waveforms of the vehicle steering wheel angle recorded during the tests carried out for the ±45-degree turn maneuver. In this case the reaction of the steering wheel during the first turn was delayed by about 0.03 second in relation to the reference waveform. On the other side, all eight tests confirmed that the recorded waveforms were repeatable. The expected angles of turning the steering wheel were also obtained.

In the next research the ±90-degree turn maneuver was examined (Fig. 14). In this case, the reference and recorded waveforms were almost the same. However, it is visible that recorded maneuvers reached an angle -85 degree instead the reference -90 degree. The indicated discrepancy can be eliminated in the future by improving the control algorithm for the PSM operation.

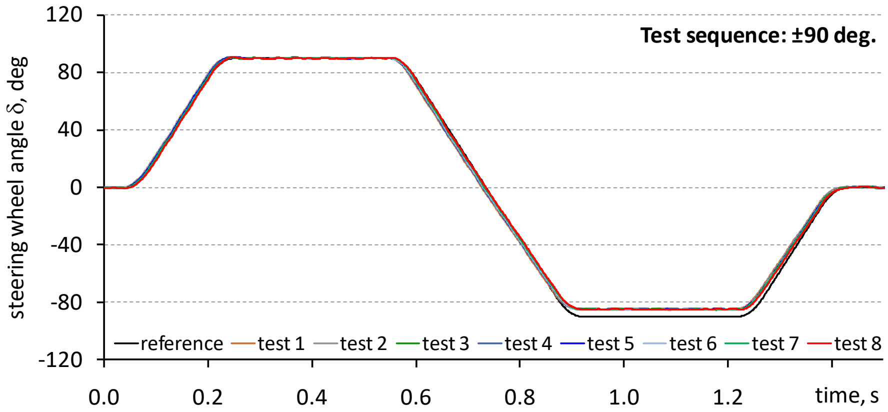

Fig. 14. Time waveforms of changes in the angular position of the steering wheel during the 90 degree turn maneuver

Fig. 15. Time waveforms of changes in the angular position of the steering wheel during the 180 degree turn maneuver

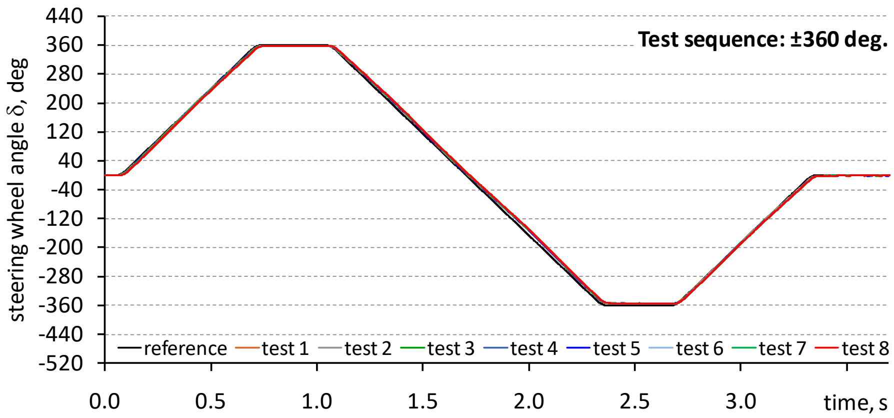

Fig. 16. Time waveforms of changes in the angular position of the steering wheel during the 360 degree turn maneuver

A minor discrepancy between the recorded maneuver angle and the reference signal were also visible in the next research carried out for ±180 and ±360 degree turns. According to the Figure 15 the steering wheel achieved +183 and -173 turn degree instead of expected +180 and -180 degree respectively. It can be pointed that all recoded waveforms were repeatable.

Similar results were obtained during the research carried out for ±360 angle turns of the steering wheel. This time the recorded maximum turn angle was +358 and -354 degree instead of the reference value +360 and -360 degree respectively.

Results shown in Figures 13-16 confirm that the PSM operates with a minor discrepancy in regards to the maximum turn angle obtained. This problem can be solved in the future work on the PSM prototype. It should be highlighted that the PSM works repeatable. As it can be seen in Table 4, the sensitivity index W_α calculated for all tested angles were below 2% for α=45 degree, and below 0.3% for other measurement conditions. These results confirms that the PSM works in repeatable manner, in-line with the design assumption.

Table 4. Values of the accuracy index calculated for 45, 90, 180 and 360-degree maneuvers

Test no.	Accuracy index value [%]			
	W_{45}	W_{90}	W_{180}	W_{360}
1.	1.91	0.29	0.15	0.06
2.	1.92	0.25	0.16	0.06
3.	1.58	0.21	0.14	0.09
4.	1.79	0.22	0.15	0.08
5.	1.60	0.19	0.12	0.07
6.	1.60	0.18	0.14	0.09
7.	1.69	0.18	0.14	0.09
8.	1.44	0.17	0.14	0.12
Average	1.69	0.21	0.14	0.08

CONCLUSIONS

In this paper the design of the lightweight electric vehicle and the PSM made by the Student Research Group "Turbodoładowani" has been presented. In particular, the performance of the PSM was assessed within of the maneuver's tests carried out for selected turning angles i.e.: 45, 90, 180 and 360-degree. The results confirmed that the PSM meets the design assumptions. However, a minor improvement in the future works is still necessary. The research indicated that the steering wheel waveforms are repeatable with the accuracy index lower than 2% for the ±45-degree maneuvers. For higher turning angles the value of this index is even lower i.e., W<0.3%.

ABBREVIATIONS

1. **ADAS** - Advanced Driver Assistance System;
2. **AEB** - Automatic emergency braking;
3. **CAD** - Computer Aided Design;
4. **DC** - Direct Current;
5. **ESC** - Electronic Speed Control;
6. **PSM** – Programmable steering machine;
7. **PV** – Photovoltaic;
8. **SAE** - Society of Automotive Engineers.

PROGRAMOWALNA MASZYNA STERUJĄCA DLA LEKKIEGO POJAZDU Z NAPĘDEM ELEKTRYCZNYM

W artykule przedstawiono programowalną maszynę sterującą (PMS) oraz lekki pojazd o napędzie elektrycznym, zaprojektowane i wykonane na Uniwersytecie Technologiczno-Humanistycznym w Radomiu (UTH Radom). Oba te obiekty techniczne są efektem projektu realizowanego przez Studenckie Koło Naukowe „Turbo-doładowani". Maszynę sterującą opracowano z programowalnymi algorytmami pozwalającymi na wykonanie sterowanego ruchu kierownicą pojazdu. Po wykonaniu system nie wymaga interakcji z kierowcą. Z tego powodu można uzyskać większą powtarzalność pomiarów trakcji pojazdu. Potwierdzenie takie uzyskano w badaniach, w których rejestrowano przebiegi czasowe kąta obrotu kierownicy o zadaną wartość 45, 90, 180 i 360 stopni. W szczególności obliczono wskaźnik dokładności dla wspomnianych warunków testowych. Uzyskane wyniki wyrażone średnią wartością wskaźnika czułości były niższe niż 2% w badaniach przeprowadzonych dla manewrów ±45 stopni. W przypadku pozostałych badań tj. dla manewrów ±90, ±180 i ±360 stopni wartość wskaźnika celności była mniejsza niż 0,3%. Potwierdzono w ten sposób, że badany PSM osiągnął odpowiednie parametry eksploatacyjne niezbędne do badań trakcji pojazdu.

Słowa kluczowe: bezpieczeństwo ruchu, maszyna sterująca, pojazd elektryczny, energia odnawialna, transport drogowy

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