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Simple model of a hybrid-electric propulsion system for an unmanned aerial vehicle

The paper presents an attempt of building a simple virtual model of a hybrid-electric propulsion system meant for driving an UAV (unmanned aerial vehicle). The model of the propulsion system was built in Matlab-SIMULINK environment. The model presented in this paper is only a preliminary one being a conception for further development. It was based on static mechanical characteristics of both propulsive units – electric motor and piston engine, where the latter one is treated as a main unit, while the former one (electric motor) is a supporting device.

The model is meant to enable estimating of energy demands of the propulsion system for a given stationary state of work.

The paper contains preliminary results of simulations carried on the elaborated model.

Key words: *hybrid-electric propulsion system, unmanned aerial vehicle*

Prosty model hybrydowego zespołu napędowego do bezzałogowego aparatu latającego

W artykule zaprezentowano próbę zbudowania prostego modelu symulacyjnego hybrydowego zespołu napędowego, przeznaczonego do napędu BAL (bezzałogowego aparatu latającego). Model zespołu napędowego został zbudowany w środowisku Matlab-SIMULINK. W artykule zaprezentowano wstępny model, jako bazę do dalszego rozbudowania. Model oparty został o statyczne charakterystyki mechaniczne obu silników – elektrycznego i tłokowego. Silnik tłokowy z założenia ma spełniać rolę głównej jednostki napędowej, silnik elektryczny jest urządzeniem wspomagającym.

Głownym przeznaczeniem modelu jest możliwość określania zapotrzebowania energetycznego całego układu, w przyjętym stacjonarnym stanie pracy.

Praca zawiera wstępne wyniki symulacji, prowadzonych przy użyciu opracowanego modelu.

Słowa kluczowe: *hybrydowy zespół napędowy, bezzałogowy aparat latający*

1. Introduction

Hybrid-electric propulsion systems are linked to an automotive industry. Every important motorcar manufacturer has at least one hybrid car in its offer. This is caused by the global tendencies to look for alternative energy sources and new propulsion systems based on them. These tendencies are intensified by some ecological aspects and issues related, like diminishing conventional hydrocarbon fuels or rationalization of energy management [4].

Designing, building and developing more efficient and economical propulsion systems may be perceived as a main domain of automotive industry companies because means of road transport are commonly available and present in almost every field of human life. However, there are many more areas of potential applications of these systems. For example, aviation is one of the branches that should not be omitted when implementing new solutions concerning a propulsion technology.

This paper contains a development of a conception of implementing the hybrid-electric propulsion system into an unmanned aerial vehicle (UAV). As a result of this development, a simple simulation model of the system is shown, along with energy management patterns appropriate for the UAV. This is a first attempt undertaken by the authors to build a simulation model of a hybrid propulsion system and it should be considered as preliminary results as the real physical system has not yet been assembled and there is no reference point for a virtual model.

2. Propulsion system configuration

As a basic arrangement of the hybrid-electric system, a parallel configuration has been chosen. A driving shaft is connected to a propeller (instead of wheels in automotive applications). The scheme of the considered propulsion system with its main components is presented in Fig. 1.

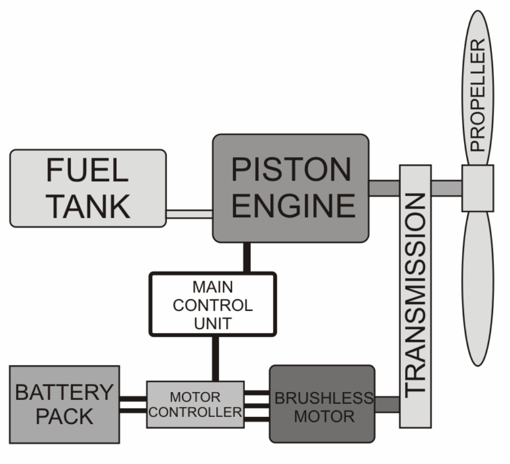

Fig. 1. A scheme of the aerial hybrid-electric propulsion system

The propeller is mounted on a piston engine shaft, optionally through a reduction gear. The piston engine is a main propulsion unit, while electric motor is an auxiliary unit [1]. Coupling between the engine and the motor is realized by a belt transmission. Also a common shaft coupling is taken into account as an alternative solution (mass reduction). The electric motor being a supporting unit, provides less power than the piston engine and is meant to work in various states (depending on the phase of a flight) due to its susceptibility to rapid changes of the operating point.

In general, a parallel configuration of the hybrid propulsion system has a great advantage over a serial one as it is more flexible and enables to obtain much more operating modes than the serial arrangement [1][2][3]. In the case described, this flexibility is limited due to fixed gear ratio, which extorts particular rotational speeds of the engine and motor. Yet, there is a possibility to switch between motor and generator working mode of the electric unit (in specified terms) allowing better matching to the actual state of flight. In particular stages of a flight (like cruise) the system may even be adjusted to work in electric current generating mode (e.g. to power aerial reconnaissance equipment) relieving the batteries. Another important issue is the fact, that in the parallel system a piston engine is coupled mechanically with wheels (or propeller – as in the paper) and thus there are fewer energy conversion nodes what reduces losses [3].

These aspects lead to the conclusion, that the overall efficiency of the parallel system may be higher than the serial one. This seems to be especially important in aerial hybrid-electric propulsion where there is no possibility to recuperate energy from intervals of braking motion (contrarily to the road vehicles).

3. Characteristics of main components of the propulsion system

The entire propulsion system is a connection of three groups of devices: electro-mechanical components (motor, battery pack, motor controller, control and wiring system), thermo-mechanical components (engine, fuel supply system) and aerodynamo-mechanical component (propeller) – all subsystems coupled together mechanically (shafts, gears, clutches). Although each group of the devices bases on different type of energy, the common denominator is a mechanical part, thus, the essence of a problem is to put together the external mechanical characteristics of the components (simultaneously not neglecting the other types of relationships within particular subsystems). To obtain that goal, an acquaintance of these characteristics is necessary.

Electro-mechanical subsystem is based on brushless, three-phase, synchronous motor with permanent magnets. Controlling and supplying the motor with current is provided by a PWM controller, which is supplied with direct current and voltage (directly from battery pack) so the entire motor-controller system is frequently called a brushless DC motor. Because the BLDC motors do not have commutator and brushes, they are less susceptible to damage and they can operate in harsh environmental conditions. In comparison to other types of electric motors, the ratio of mass and dimensions to the output power is small, that is important in considered case. The main problem is a large cogging torque occurring in motors with permanent magnets. In some periods of hybrid-electric drive work the electric motor remains unpowered. For this reason, the cogging torque diminishes efficiency of the propulsion system. To reduce the loss of efficiency of propulsion system the BLDC motor has been specially designed for reducing the cogging torque and there is no equivalent in a typical series-produced motors. In the specially designed BLDC motor the amplitude of cogging torque does not exceed 0.003 Nm (which gives the power of about 2.5 W at the operating speed). The designed BLDC motor has the following basic parameters: 12 stator poles and 14 rotor poles (7 pairs of magnets on the rotor), working rotational speed 8000 rpm, power at operating speed 800 W, maximum voltage 29.6 V, maximum source current 63 A.

The piston engine characteristics were taken for the Saito FA-220A – a four-stroke, one-cylinder model engine with the displacement of 36 cc and maximum measured power of ca. 1.25 kW at 8500 rpm. As a basis for the elaborated model a set of static torque-speed characteristics has been taken. These characteristics were obtained experimentally for various values of a throttle position, during engine tests run on the test bench. The results allowed to acquire the engine operational map, presented in Fig. 2.

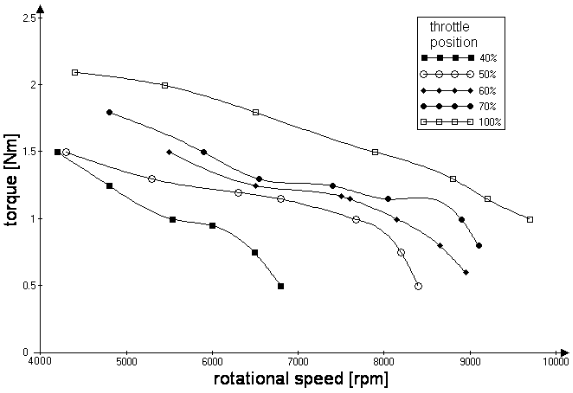

Fig. 2. The torque-speed map of the engine

The map allows to determine engine operational parameters for fixed working points and provides information about engine performances.

The tests were also conducted to determine fuel consumption for wide range of engine operational states. Except of the torque-speed curves, a set of specific fuel consumption characteristics were obtained. On the basis of these test results the engine economy map (shown in Fig. 3.) has been worked out.

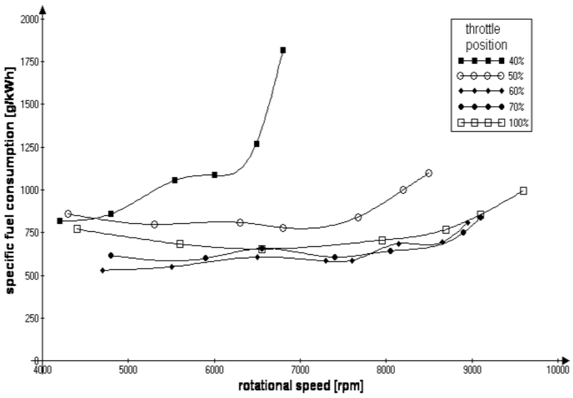

Fig. 3. The fuel economy map of the engine

In conjunction with the torque-speed map, the specific fuel consumption map allows to determine the most efficient regions of engine operating. This seems to be particularly useful in a system like parallel hybrid-electric drive, where the proper energy management is a substantial issue [1]. Due to the presence of supporting unit – the electric motor, the piston engine may operate at the point of maximum overall efficiency which gives the best fuel consumption-to-output power ratio and keeps the engine in a steady, stable state of work [1][3].

Another important component is the final energy conversion node – the propeller. Its role is to convert mechanical power provided by the shaft from the rest of propulsion system to thrust force indispensable for the UAV to maintain its motion. The propeller may be considered as a specific steering element for the engine since it provides a load torque to the engine shaft. Assuming the fixed-pitch propeller (no changes in blades position) and neglecting a medium (air) density changes, the propeller torque varies with operational parameters: rotational speed and speed of flight [2]. The way the propeller load torque changes may be reflected on the cumulative propeller torque characteristics. The one for the fixed-pitch propeller used in UAV-class objects is shown in Fig. 4. The propeller load torque map presented in Fig. 4. allows to determine mating points between the propeller and driving units for required flight state.

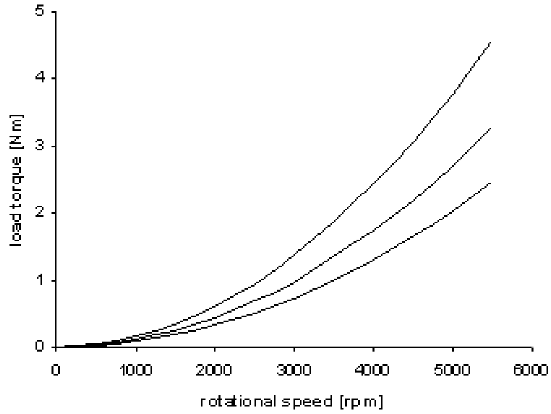

Fig. 4. The propeller torque-speed map

A transmission (seen in Fig. 1.) performs a role of a coupling device between both drive units (the engine and the motor). Its task is to sum the output torque of the devices while maintaining a constant ratio of their rotational speed (in particular case the ratio may be equal to unit so the engine and the motor operates at the same speed). In the model also a reduction of rotational speed has been simulated to meet the requirements of the propeller.

4. Major assumptions of the simulation model

The elaborated model of the aerial parallel hybrid-electric propulsion system is based on few assumptions and simplifications. They arise mostly from specification of the destination object (the UAV) as well as from some features of the hybrid drive itself. These are:

- Relatively simple (in comparison to road vehicles) profile of motion (or broadly speaking – the course of mission) which heavily reduces an amount of working states and their changes. In general, a simplified UAV mission consists of five main phases (as shown in Fig. 5.). Moreover, in many cases the two last phases: descending and landing (drawn with dashed line) may be neglected due to the fact that it is possible to perform these phases as a gliding flight [5] (with the propulsion system being shut down or uncoupled and working at idle state).

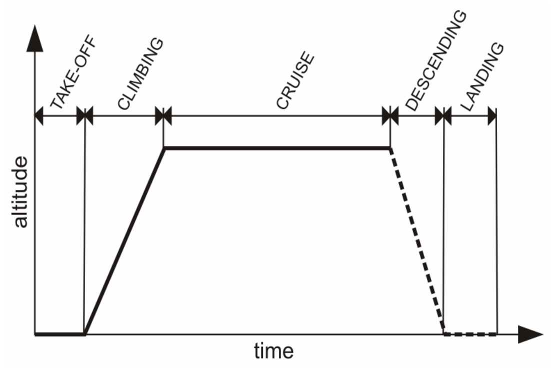

Fig. 5. The UAV mission profile

- A parallel hybrid-electric drive as a prime configuration. This type of arrangement has been chosen instead of a serial one due to its better flexibility to operating conditions and potentially greater overall efficiency of the system [3]. In a parallel drive, the piston engine is directly mechanically connected to a motive system that eliminates an energy conversion node (in series configuration, an engine drives an electric generator producing current to supply a second electric machine – a driving motor).
- Lack of energy recuperation. This comes directly from the UAV motion profile and from its construction (in road vehicles recuperated energy comes from the tractive system during breaking – the process is called a *regenerative breaking* [1]). In the UAV-class objects there are no breaking phases (in literal meaning). Theoretically, the breaking might be realized by adjusting the propeller to a windmill mode, but in objects of this size and purposes, such a solution is technically unrealizable and energetically inefficient [5].
- The substitute for the regenerative breaking is switching the brushless motor to electric energy generating mode. The motor-generator is driven by the engine through the transmission. In some phases of the flight (like cruise) required power may be lesser than engine output power at optimum working point (best efficiency point). The surplus of the engine power may be used to drive the electric motor (functioning like a generator) and thereby to charge the batteries. Energy accumulated in the batteries may be utilized to power some additional systems (e.g. aerial camera) or to provide additional power required during maneuvers or wind blasts.
- The model is built on the basis of static characteristics of particular components and in its present form it does not take the dynamics into account. Such a simplification is preliminary – in further work the model will be developed. However due to a specific motion profile of the UAV, the propulsion system operational pattern may be considered as periodically quasi-static and so using the static characteristics of the hybrid drive components seems to be justified. Relations between characteristics serve to determine the points of work and rules of adjusting individual devices (control algorithm) [4].
- The main assumption for the entire system is that it operates near the line of optimal work of the piston engine. This line is simply a curve of best efficiency on torque-speed map of the engine. The electric motor works as a supporting unit providing lacking power or transforming power excess depending on current conditions.

5. Simulation model

The simulation model of the hybrid-electric propulsion system was elaborated in Matlab-SIMULINK environment. The general block scheme of the model is shown in Fig. 6. The simulation model was created to develop motor control algorithms in the system. It enables analysis of a hybrid operation with different power-supply scenarios. Particular scenarios describe principles of the power distribution for both engines in several flight phases: take off, climbing and cruise. The developed simulation model consists of four basic blocks:

- piston engine block,
- electric motor block,
- control block,
- load block

The piston engine is modeled with the static output torque characteristics – the torque is a function of engine speed and throttle opening.

The electric motor with permanent magnets (BLDC) is described by the torque constant k_i and voltage constant k_v (for calculated induced voltage). Considering the accuracy of a piston engine description, this approximation is sufficient. BLDC electric motor experimental studies confirm that.

The controller is designed to provide a possibility of automatic controlling of both drive units. Required throttle position was calculated using the optimum performance characteristic of the engine – thus the primary scenario is an operating within the area of highest engine efficiency. The controller can also be switched to manual mode for the development of other scenarios (e.g. minimizing the energy drawn from batteries).

The loading subsystem consisting of the propeller connected through a transmission, is described by external characteristics for various phases of flight: take off, climbing and cruise.

The input data for the simulation model are:

- required propeller rotational speed
- stage of flight

- altitude
- value of voltage source (in manual mode of throttle position changing)

The output parameters are:

- engine torque
- motor torque
- required current values,
- voltages
- piston engine specific fuel consumption.

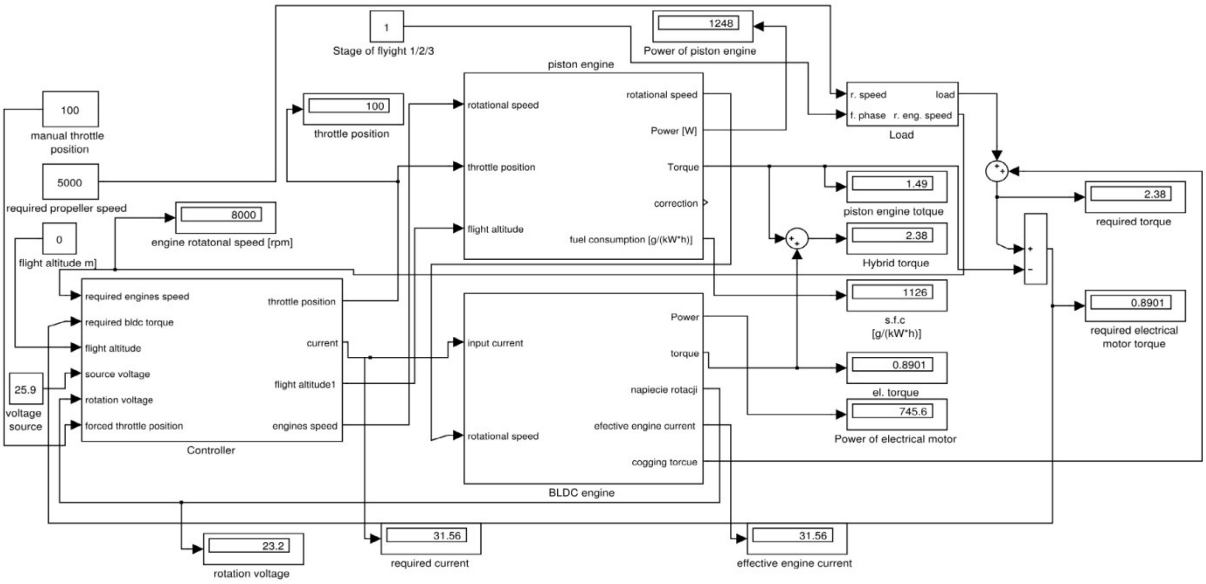

Fig. 6. Matlab-SIMULINK scheme of the propulsion system model

6. Simulation results

Simulations were performed for three stages of flight: take off, climbing, cruise. Two power supply scenarios were included to determine control requirements for both drive units. The scenarios are depicted with Sankey diagrams in Figures 7 and 8. Due to a low current required for charging (long battery charging time) and poor efficiency of energy recuperation to the batteries the aspect of a piston engine optimization for the second scenario was not analyzed.

Fig. 7. Scenario without energy recuperation

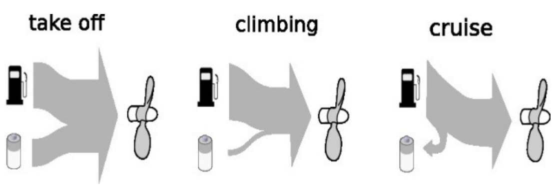

Fig. 8. Scenario with energy recuperation

Figure 9 presents the values of the power required by the propeller (with transmission) and the power levels of both drive units. According to the first scenario the electric motor is used only during take off and climbing. In the take off phase the electric motor provides about 38% of the power required by the propeller while during the climbing phase it is only about 3% of total power.

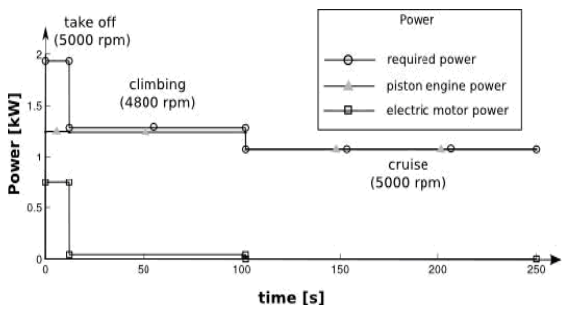

Fig. 9. Power required and power provided from the engine and from the motor without battery charging

In the second scenario (Fig. 10), the first two stages do not differ from each other – the electric motor and the piston engine operates at the same levels. During the cruise phase the piston engine is additionally loaded by the electric motor operating as a generator. 48 W of additional output power of the piston engine during battery charging is required. This amount of power is almost negligible hence the shift in engine operating point (and its efficiency) is slight.

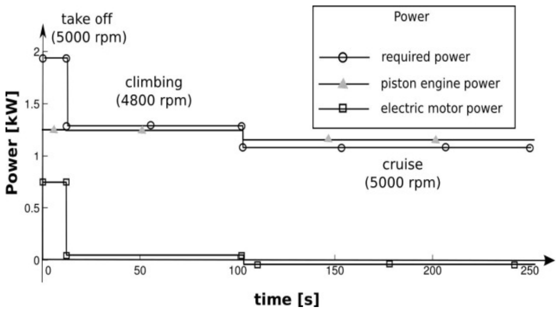

Fig. 10. Power required and power provided from the engine and from/to the motor with battery charging

The charging process continues until the battery is fully charged or the phase of flight is over. After applying simple energy dependences, taking into account the battery efficiency equal to 60%, assuming the maximum charge current equal to 100% of battery capacity charging time is approximately three times longer than the total time of discharge (Fig. 11.).

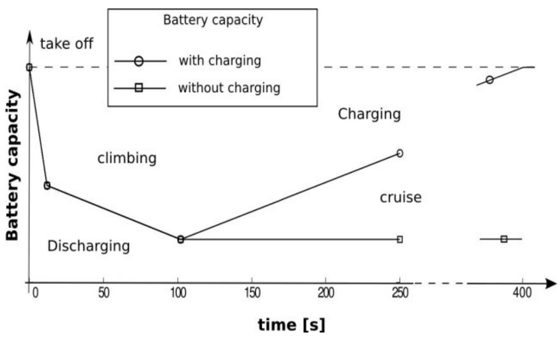

Fig. 11. Battery capacity changes

The cost of the additional load of the piston engine by the electric generator is shown in Figure 12 as the absolute fuel consumption. With the assumed flight data, the absolute cost of charging was about 6 g of fuel.

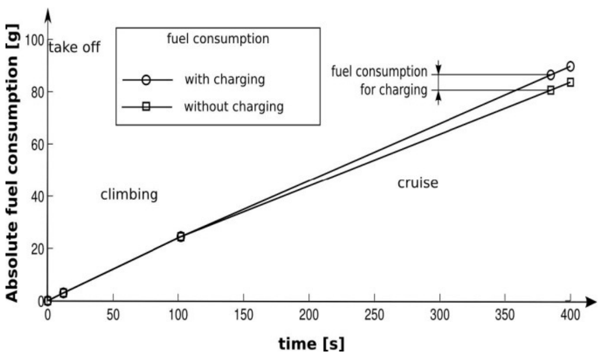

Fig. 12. Fuel consumption for both scenarios

7. Conclusions

The results presented in this paper are the initial stage of simulation model work-out. A further development of the model will be conducted as well as its adjusting to the physical system (that is currently under elaborating).

A hybrid-electric propulsion system has certain advantages over the conventional systems. It can operate at various modes, which results in better fitting to external conditions and assumed purposes after determining the algorithms that provide the most optimal power management and high efficiency of energy utilization.

Although primary objective of this work was to determine the usability of hybrid-electric drive for the UAV in an aspect of optimizing an energy flow, particular contras should be pointed out. One of the most significant disadvantages is the increase of mass. A hybrid-electric drive is assembled of greater number of components (in comparison to a conventional drive – e.g. one based on piston engine only) so the overall mass of the hybrid system is greater. That is a serious problem in reference to aerial vehicles, where the weight issue is crucial in the field of flying object performances and payload capabilities. Another problem related to the mass is a total volume of the entire system which is also greater in case of hybrid drive. It negatively influences the realizability of a spatial arrangement of the propulsion system components within a flying object fuselage. Aside from mass and volumetric matters, a complexity of the entire system is significantly increased which is an undesirable outcome.

Although the results presented do not show comparison between hybrid and conventional drive yet, they point out that there is a more efficient way of distributing and utilizing an energy to meet the desirable requirements. This may benefit with an increase of range and flight duration in reference to small unmanned flying vehicles.

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Nomenclature/*Skróty i oznaczenia*

UAV Unmanned Aerial Vehicle/*bezzałogowy aparat latający*

BLDC Brushless Direct-Current (Motor)/*silnik bezszczotkowy prądu stałego*

PWM Pulse-Width Modulation/*modulacja szerokością impulsu wypełnienia*

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