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Reduction of Electric Energy Consumption in Drives with Controlled Gear Ratio

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A novel method of reducing energy consumption by electric drive systems operating under strongly variable loads is proposed. It involves the use of a gearbox with a controlled gear ratio that is changed during the implementation of complex motion profiles. Positive results of preliminary simulation studies were experimentally confirmed by testing a modified drive system of an orthotic robot with three variants of the gear ratio: two different values of a constant gear ratio and a controlled gear ratio. A dedicated test stand and experimental methods are discussed. The obtained experimental results confirmed the effectiveness of the proposed method, namely that the energy consumption was reduced by 8% and 14.1% when using the gearbox with a controlled gear ratio.

topics: electric drive systems, energy consumption, controlled gear ratio

1. Introduction

Nowadays, more and more devices powered by electric drive systems draw energy from sources of limited capacity, mainly from batteries and accumulators [1–4]. The operating time of these devices depends on the characteristics of the energy sources on the one hand [5], and on the level of energy consumption of the powered device on the other [6, 7]. For several years, the authors' interests have focused on the issues of improving the design and control algorithms of devices so that they perform their functions with the lowest possible energy consumption [8–11]. The inspiration to undertake this type of work was the participation in the "ECO-Mobility" project, within which a prototype of an orthotic robot was developed and launched [12]. It is a medical device powered by a set of batteries, the main function of which is to restore motor functions to disabled people with paresis of the lower limbs [13]. An important element of these works was the simulation study of the influence of selected physical characteristics of users, parameters of the gait performed by the device, and, above all, selected design features of electric drive systems on the energy demand of the robot's actuators [14–17]. Lower energy consumption allows for longer operating time on a single battery charge, which translates into the ability to cover a greater distance while performing the walking function. Analysis of simulation test results for various designs of actuators has shown that it is worth considering the possibility of reducing the amount of energy consumed by the robot's drive systems by using a controlled gear ratio. The preliminary results of simulation studies of the drive system modified in this way have shown that adding a control variable to the drive system in the form of a gear ratio changed in a precisely defined, programmed way, opens up the possibility of reducing energy consumption when the robot performs the walking function [18, 19]. The obtained simulation test results became the inspiration to confirm these phenomena experimentally. For this purpose, it was necessary to build a dedicated test stand for conducting research on the drive system with a controlled ratio for use in electro-mobile devices.

2. Materials and methods

2.1. Functional concept of the stand

When developing the functional concept of the constructed test stand, the following requirements were adopted:

(i) controlled implementation of a step change in the gear ratio in the test stand,
(ii) program control of the value and direction of the torque loading the tested drive,
(iii) integration of control and measurement systems in order to ensure their synchronization during the tests.

Figure 1 shows a block diagram of the functional concept of the test stand adopted for its implementation.

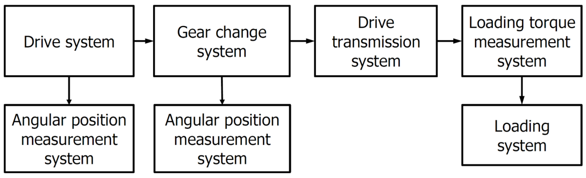

Fig. 1. Functional block diagram of the test stand.

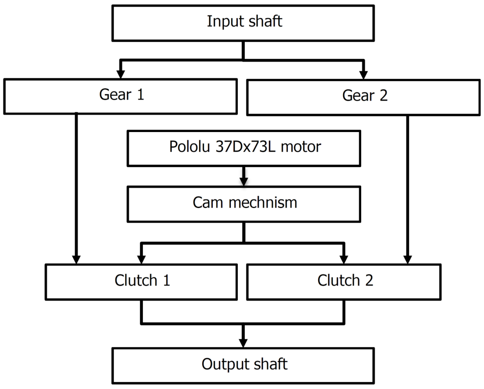

Fig. 2. Block diagram of the gear change system.

It was assumed that a direct current (DC) motor would be used as the input drive, cooperating with a newly developed gearbox enabling switching between two gear ratios during system operation. It was decided to connect the output shaft of the gearbox to the drive transmission system, which was taken from the prototype of the orthotic robot. To be able to conduct tests under variable load conditions, it was necessary to develop a dedicated loading system cooperating with the output of the tested drive. In order to accurately measure the loading torque and the possibility of its regulation, a torque measurement system is placed between the loading motor and the tested drive transmission system. It was decided to use two angular position measurement systems in the stand. The first one is used in the motor angular position control system, while the second one, located behind the gearbox with a controlled ratio, is designed to measure the angular position of the output shaft of this gearbox.

2.2. Development of functional systems

Based on the adopted concept of the test stand, individual functional systems were developed.

2.2.1. Gear change system

The purpose of the gear change system is to switch between two gear ratios during the operation of the entire drive system. This transmission

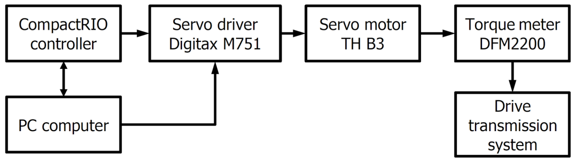

Fig. 3. Block diagram of the loading system.

consists of an input shaft on which the wheels of two parallel gear transmissions are rigidly mounted. The cooperating wheels of these transmissions are mounted on bearings on the output shaft and therefore do not transmit power directly to it. This is achieved by two friction clutches, the pressure of which is provided by springs based on a trolley controlled by a cam switching system, which is driven by a Pololu 37Dx73L 24V 79RPM #4696 DC motor. The ratio of the first gear is $i_1 = 1$, while the ratio of the second gear is $i_2 = 2.125$. Figure 2 shows a block diagram of the gear change system.

2.2.2. Loading system

The adopted structure of the loading system include the elements presented in the diagram (Fig. 3). To generate the load torque, a direct alternating current (AC) servo motor THB324NMBDXFB200 from Dynamic Motion Systems was used. It allows for generating a continuous torque of up to 15.7 Nm and at the peak up to 34 Nm. The maximum speed of this motor is 555 rpm. The Digitax HD M751-02200120A10 servo driver is powered by 230 V, supports the angular position transducer built into the motor and has been configured to control the torque generated by the motor based on an analogue control signal in the range of ± 10 V. The signals controlling this servo drive come from the digital-to-analog converter of the CompactRIO controller.

2.2.3. Drive transmission system

The stand used a modified drive transmission system that was used in the prototype of the orthotic robot developed as part of the "ECO-Mobility" project. It consists of a T5 toothed belt transmission, a Hiwin 1R165 ball screw and a 06B-2 double-row chain transmission (Fig. 4). The total gear ratio of this gear set is $i_p = 128.8$. Due to the transmissions used, the drive transmission system has a limited range of motion. The output shaft of the system can move in the range of 0°–108.7°, which translates into the movement of the input shaft in the range of 0°–14000°. A detailed description of this transmission was presented in [17].

2.2.4. Drive system

The adopted structure of the drive system and its control system include the elements presented in the diagram (Fig. 5).

The main element of the motor control system is the SID 116 programmable DC motor driver. It is powered by a stabilized power supply with a voltage of 28 V and a current capacity of 20 A. A dedicated application running on a PC is used to control and program the driver. The CompactRIO programmable controller generates an analog voltage signal according to the developed angular position trajectory. The driver operates in a closed-loop position control mode using the signal from the rotary incremental encoder mounted on the motor shaft.

2.2.5. Angular position measurement system

In the motor control path (Fig. 6), an incremental encoder marked RE30 was used and mounted on the motor shaft. The signal from this encoder is recorded by the digital input module of the CompactRIO controller and further used in the feedback loop of the SID116 motor driver.

The second angular position measurement system used in the stand is designed to determine the current position of the output shaft from the variable ratio gear (Fig. 7). In this case, the Termipol HY38-360HS incremental encoder was selected, from which the digital signal is recorded by the CompactRIO controller.

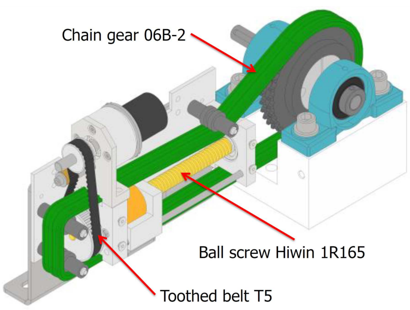

Fig. 4. 3D model of the drive transmission system.

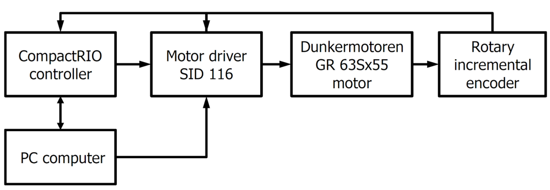

Fig. 5. Block diagram of the structure of the drive system with the control system.

2.2.6. Load torque measurement system

The value of the torque loading the tested drive system is determined using the NCTE 2200 magnetostrictive torque meter, which allows for measuring static and dynamic torque in the nominal range up to 75 Nm, and the peak value is up to 97.5 Nm. Its linearity error, including hysteresis, is below 1% of the measurement range, the bandwidth is 1 kHz, and the permissible speed is 5 thousand rpm. The output signal from the transducer is a voltage value in the range of 0–5 V. This signal is then recorded by the analog-to-digital converter of the CompactRIO controller (Fig. 8).

2.2.7. Electrical quantity measurement system

The current consumed by the motor is measured by a current transducer using the Hall effect. It is powered by a symmetrical stabilized power supply with a voltage of ±15 V. The voltage measurement signal is low-pass filtered with a cut-off frequency of $f_g = 159$ Hz and then recorded using the analog-to-digital converter of the CompactRIO controller.

The voltage on the motor wires is filtered by a low-pass filter with a cut-off frequency of $f_g = 159$ Hz, which results from the need to average

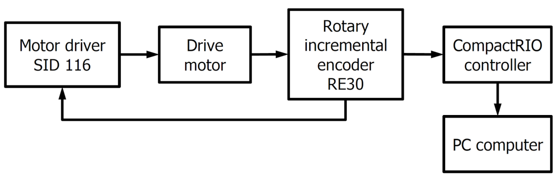

Fig. 6. Block diagram of the system for measuring the angular position of the motor shaft.

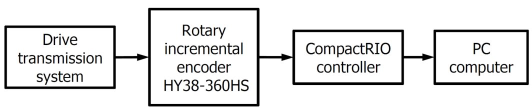

Fig. 7. Block diagram of the system for measuring the angular position of the output shaft of a variable ratio gear.

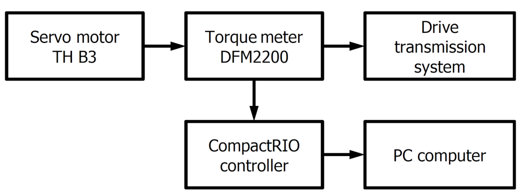

Fig. 8. Block diagram of the load torque measurement system.

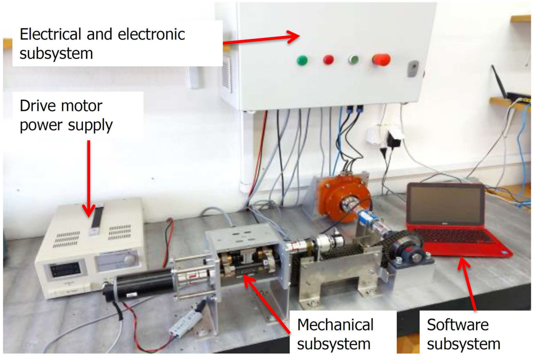

Fig. 9. Subsystems of the test stand.

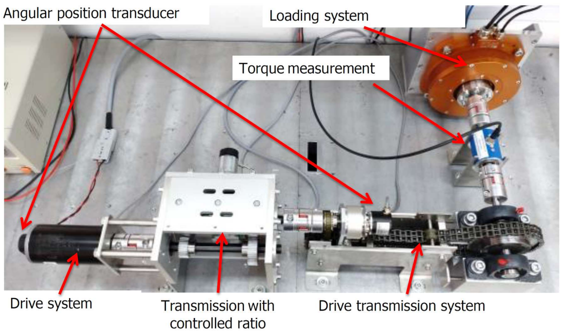

Fig. 10. Mechanical subsystem of the research stand.

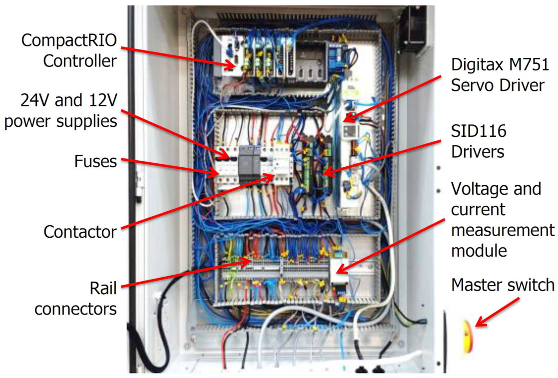

Fig. 11. Electrical and electronic subsystem of the test stand.

the rectangular voltage waveform with a pulse width modulation controller. The obtained voltage waveforms are recorded using the analog-to-digital converter of the CompactRIO controller.

2.3. Subsystems of the test stand

A research stand was designed and built to conduct research on a drive system with a controlled gear ratio. Figure 9 shows a photo of the stand with its subsystems marked.

2.3.1. Mechanical subsystem

The mechanical subsystem was mounted on a laboratory table, which enabled the stable assembly of all components and simplified their mutual positioning. This subsystem consists of a drive system, a gear change system, a drive transmission system, a loading system, angular position transducers and a torque measuring system (Fig. 10).

2.3.2. Electronic and electrical subsystem

For control and data acquisition, an electronic and electrical subsystem was developed, consisting of a CompactRIO programmable controller, a load motor servo driver, two drivers of a gear changing motor and a drive motor, a module for measuring the supply voltage and the current consumed by the drive motor. It also contains additional components needed for the subsystem to operate, such as power supplies, fuses and connectors. The components are mounted in an industrial control cabinet (Fig. 11).

2.3.3. Software subsystem

To operate the test stand, a control program was developed in the LabView environment, which enabled the generation of waveforms of the set angular position: sinusoidal, sawtooth and constant value, and of the loading torque: sinusoidal, linear and constant value. It also allowed for the control of the gear change in both manual and automatic mode at a set time of the test. Additionally, the course of position, loading moment and gear ratio could be read from a previously prepared file. All values measured by the electronic system were recorded on a PC, which enabled their later processing and analysis.

3. Launch of the test stand

After assembling the test stand, all components were adjusted and tuned. This included, among others, tuning the parameters of the loading motor and the drive motor drivers. The next step was to calibrate the control and measurement systems, in particular the loading system. The results of this work are shown in the graph below (Fig. 12).

This characteristic is linear within the nominal motor torque, i.e., 15 Nm. Outside this range, it begins to deviate from the linear course, which was decided to be corrected in the control program.

In the next stage, dynamic tests were carried out for the angular position and loading torque curves (Fig. 13).

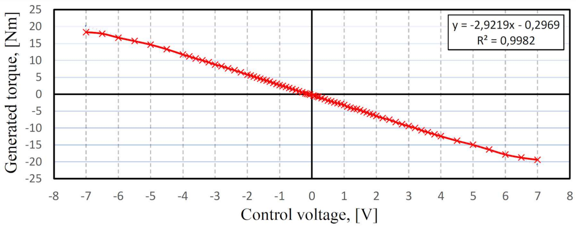

Fig. 12. Characteristics of the loading system.

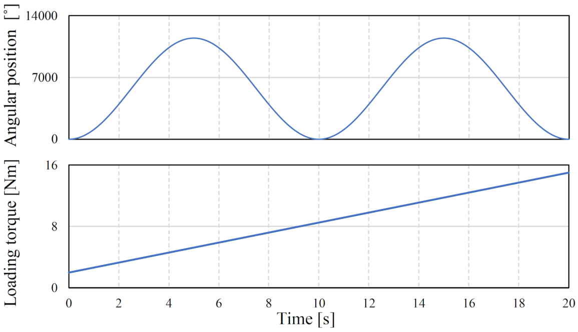

Fig. 13. Graphs of angular position and loading torque during tests.

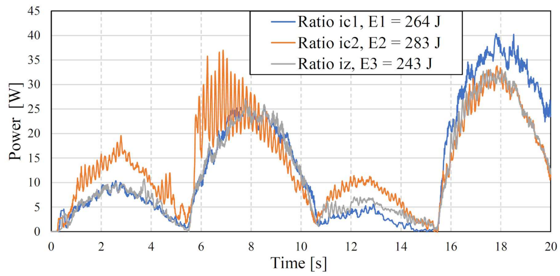

Fig. 14. Power curves and values of electrical energy consumed for the three analyzed gear ratio variants.

TABLE I

Comparison of energy consumed by the tested drive system for three gear ratio cases.

	Gear ratio		
	$i_{c1} = 128.8$	$i_{c2} = 273.8$	i_z (variable)
energy consumed	264 J	283 J	243 J
energy reduction with variable gear ratio i_z	−8%	−14.1%	–

The tests were carried out for 3 cases:

(i) Constant gear ratio with a total value of i_{c1}.

$$i_{c1} = i_p \times i_1 = 128.8, \times 1 = 128.8, \tag{1}$$

where i_{c1} is the total gear ratio during the test, i_p — gear ratio of the drive transmission system, i_1 — gear ratio in a variable gear ratio system.

(ii) Constant gear ratio with a total value of i_{c2}

$$i_{c2} = i_p \times i_2 = 128.8 \times 2.125 = 273.8, \tag{2}$$

where i_{c2} is the total gear ratio during the test, and i_2 — gear ratio in a variable gear ratio system.

(iii) The gear ratio i_z was changed in the 15th second of the test

$$i_z = \begin{cases} i_{c1} = 128.1, & t \in \langle 0\,; 15 \rangle, \\ i_{c2} = 273.8, & t \in (15\,; 20 \rangle, \end{cases} \tag{3}$$

where i_z is the value of the variable gear ratio during the test, and t — test time [s].

Figure 14 shows the power consumption curves for the 3 tested cases.

Analysis of these graphs allows us to conclude that in the initial phase of the study when the load was low, lower values of the i_{c1} ratio provided lower power consumption. The larger i_{c2} ratio, in addition to increasing power consumption, caused less stable drive operation. After increasing the load in the second phase of the test, the situation was reversed and lower power consumption occurred in the case of the larger i_{c2} ratio. The course recorded for the case of variable gear ratio i_z allowed combining the fragments of the operation of both gear ratios with the lowest power consumption.

For all studied cases, the total energy consumption during the study was summarized. The obtained test results are presented in Table I.

The obtained results show that changing the gear ratio during the drive function allowed for a significant reduction in energy consumption. The use of the solution with the variable ratio i_z resulted in an 8% reduction in energy consumption compared to the constant gear ratio i_{c1}. In comparison with the second constant gear ratio i_{c2}, the reduction in energy consumption after using the variable ratio i_z was even greater and amounted to 14.1%.

4. Conclusions

The obtained results of preliminary studies indicate a large potential of the method proposed by the authors to reduce energy consumption. The use of a gearbox with a variable, controlled ratio allowed for a significant reduction in the amount of electrical energy consumed by the tested drive compared to solutions with a constant ratio. In relation to the first constant ratio, the reduction in energy consumption was 8%, and in relation to the second as much as 14.1%. Such a significant reduction in energy consumption is particularly valuable in the case of devices powered by batteries, as it allows them to work longer before the next required charging of cells. For this reason, work on the proposed method of reducing energy consumption should be continued.

The authors see further opportunities to reduce the energy demand of drive systems, both by improving the algorithms for controlling the gear change and by improving the method for selecting the values of these gears. Additionally, the research will take into account the possibility of recovering energy in the generator parts of the drive motors, which will ensure further reduction in energy consumption.

Thanks to the construction of the stand, further work will be possible, including development of algorithms for adaptive change in gear ratio of drive systems in response to changes in their operating conditions. This will have a wide application in the use of electro-mobile devices, such as mobile robots, electric wheelchairs, electric city buses [7], scooters [20], and electric cars.

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