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Performance of power-assist transport cart drive

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ABSTRACT

The aim of this paper is to evaluate the performance parameters of a novel power-assist drive unit dedicated to intralogistics equipment. The drive unit under investigation comprises an industrial wheel driven by a BLDC motor, mounted on a fork with a plate, enabling connection to devices such as a pallet cart. The unit is equipped with an additional drive responsible for lifting the wheel when the cart is moved manually. During preliminary tests, the forces required to move the pallet trolley were determined based on the type of floor, the type and orientation of the caster wheels, and the load. For each of the tested loads, the smallest forces were recorded for a trolley with wheels aligned with the direction of travel on a smooth floor, while the largest were observed for wheels positioned perpendicular to the intended direction of travel on a coarse-aggregate floor. To evaluate the performance of the power-assist drive unit, a test stand was built, and a detailed testing program was developed, taking into consideration the pulling (pushing) force and power consumption of one unit and a set of two electric drive units mounted on a pallet trolley. Analysis of the obtained results leads to the conclusion that the proposed drive can significantly reduce physical effort in manual transport, especially in intralogistics operations. The presented device allows for moving a trolley weighing more than 600 kg, regardless of the type and initial setting of the wheels or the smoothness of the floor.

Keywords: electric drive unit, pallet trolley, power-assisted cart, pulling force, pushing force.

INTRODUCTION

Despite the constantly increasing degree of industrial automation, many logistics processes related to production still require manual labor. Warehouse operations, such as unloading and moving pallet shipments, as well as supplying production stations within the factory, are often carried out using manual carts or trolleys. To ensure the safety and health of employees, there are several standards and restrictions limiting manual transport from an effectiveness perspective. The ISO standard [1] determines some formulas limiting force and safety limit for pulling and pushing depending on travel distance, task frequency and factors resulting from the risk analysis, including type of activity and handle height. This standard recommends a safe limit of sustained force for two-handed pushing of 230 N for men and 130 N for women, while for pulling, these values are 10 N higher. Moreover, each country has its own legal regulations. For example, in Poland, the maximum force required to initiate the movement of an object is limited to 300 N for pushing and 250 N for pulling, while the permissible weight of a load moved on a trolley on flat terrain with a hard pavement cannot exceed 450 kg per employee, including the weight of the cart/trolley [2].

The above limitations result from ergonomics and numerous studies on the physical capabilities of the human body. Published research has shown that the maximum push strength for males is about 250 N in a standing position, while for females it is 140 N [3]. It should be emphasized that maximum push/pull forces are strictly dependent on individual factors such as body composition, body balance, joint strength, and even shoe-floor friction [4]. Other studies highlight additional factors influencing the biomechanical load on the shoulders and lower back during pulling or pushing, such as the weight of the object, the number of hands used, and the handle height [5].

The protection of employees performing transport work is not limited to legal restrictions alone. The authors of [6] proposed a system that utilizes force sensors and online cameras to detect unsafe pulling and pushing actions. The system records the employee's posture, determining whether it is safe.

The above examples clearly demonstrate the need to support human work during manual transport, especially with heavy loads (over 450 kg [2]), in order to reduce physical effort and meet legal requirements. One way to achieve this is by using devices that augment human power. The study in [7] examined a method of transporting heavy objects using a humanoid robot. Such robots can successfully replace humans in warehouse work and operate more efficiently than standard conveyor or sorting systems. Currently, there is significant development in the field of walking support robots [8]. While their primary use is in modern nursing assistance and rehabilitation, some solutions may also be applied in other areas, such as supporting transport work. Such solutions have a wide range of applications; however, it should be noted that, due to their level of advancement, large-scale use under industrial conditions is not economically viable. When analyzing the market for devices that aid manual transport, it becomes clear that power-assist drives [9–12] – similar to the solution presented in this article – are the most popular. These universal solutions can be applied in various areas of life and technology. Researchers are also investigating other solutions, such as in-wheel motors [13] or differential drive robots with swivel casters [14], to enhance manual transport.

The use of power-assisted carts or trolleys impacts workplace ergonomics. In [15], researchers analyzed the effects of robotic walkers on gait dynamics during assisted walking. They observed that walker-assisted walking differs significantly from normal walking, particularly in terms of the accelerations acting on the upper body. Given this, it is unsurprising that many studies are currently focused on adaptive control of power-assist devices. For example, in [16], the authors propose two control methods for driving a power-assisted cart designed for walking assistance, which adjust the cart's motor output efficiently in response to changes in the environment. Both methods control the cart based on the estimated hand force. Similar solutions are discussed in [17, 18]. A slightly different approach was presented in [19], where the authors described a mode-switching algorithm for autonomous mobile robots (AMR) that transitions from autonomous navigation to manual operation based on body sway.

This article focuses on a novel power-assist drive unit (PADU), which can be mounted on any handcart to assist its manual operation. The presented drive unit has a wide range of applications, including medical transport and baggage handling systems. It can be particularly useful in various intralogistics processes, enhancing the efficiency of manual transport. There are two basic configurations of the PADU system: with one drive unit placed in the geometric center of a trolley equipped with four castor wheels or with two units mounted on the sides of the trolley. Due to its design, the system is very easy to change the operating mode from assisted to manual and vice versa. Thus, it offers similar application possibilities to solutions available on the market [9–12].

This article aims to test the operational parameters of the PADU attached to a pallet trolley to evaluate its design assumptions and its ability to reduce physical effort during transport operations. To the authors' knowledge, this is the first research publication in this field.

The structure of the article is organized as follows. Section 2 describes preliminary tests of the force needed to set the pallet trolley in motion. Section 3 discusses the design of the power-assist drive unit, the test stand, and the test program. Section 4 presents the obtained performance results graphically and provides analysis, and Section 5 provides a summary.

PRELIMINARY TESTS

The aim of the preliminary tests was to determine the actual force needed to set the pallet trolley in motion, with the results serving as reference data to verify the effectiveness of the PADU operation. The research program involved equipping the pallet trolley with three different sets of industrial caster wheels commonly used in intralogistics (Fig. 1a) and measuring the force necessary to move the trolley straight ahead (F_p) and to make a turn (F_R). In the first case, the force sensor was mounted along the symmetry axis of the trolley (Fig. 1b), and in the second case, it was mounted at the corner. The force sensor was equipped with an additional pointer that determined the maximum force measured during a given measurement.

Three sets of caster wheels, differing in diameter and tread material, were tested. The first set comprised wheels made of polyamide PA6 with a diameter of 200 mm; the second set were wheels with a diameter of 160 mm, with an ergonomic tread made of polyurethane (ergo); and the third set were wheels with a diameter of 160 mm, featuring a flat polyurethane tread. Additionally, various cases of wheel alignment before setting the trolley in motion were examined. In the first case, the wheels were aligned in the direction of movement (Fig. 2a), and in the second case, they were perpendicular (Fig. 2b). Moreover, the influence of the trolley's load on the force required to set it in motion was examined by loading it with weights of 670 kg and 1290 kg (randomly selected pallet shipments). The tests were conducted in series of five individual measurements on two different types of industrial concrete floors: smooth and coarse aggregate. The test results are shown in Figures 3 and 4.

The results presented in Figure 3 clearly show that moving the trolley on a coarse-aggregate floor requires more force than on a smooth concrete floor. For a smooth floor and a load of 670 kg, it is easiest to move and maneuver the trolley using wheels with a flat polyurethane tread, while for a load of 1290 kg, it is easiest to move the trolley using polyamide wheels and to turn it with wheels that have a flat polyurethane tread. It is unsurprising that as the load on the trolley increases, the values of the F_P and F_R forces also increase. However, what is puzzling is that in some cases, the value of the F_R force was greater than the F_P force.

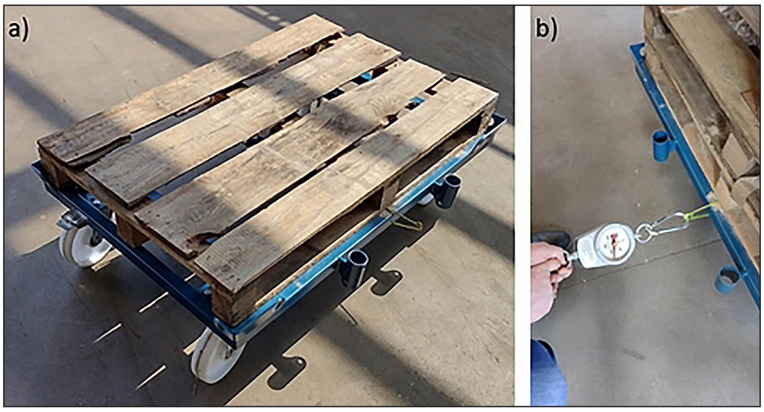

Figure 1. Preliminary tests of the force needed to set the pallet trolley in motion: (a) pallet trolley equiped with poliamide wheels, (b) the way of measuring force

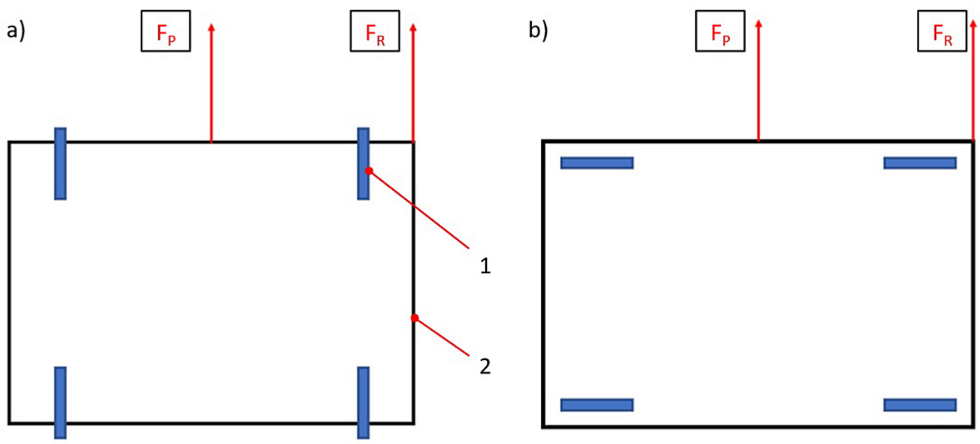

Figure 2. Preliminary tests scheme: (a) for wheels oriented in the direction of force, (b) for wheels perpendicular to the direction of force; F_P – pulling force, F_R – rotating force; 1 – caster wheels, 2 – pallet trolley frame

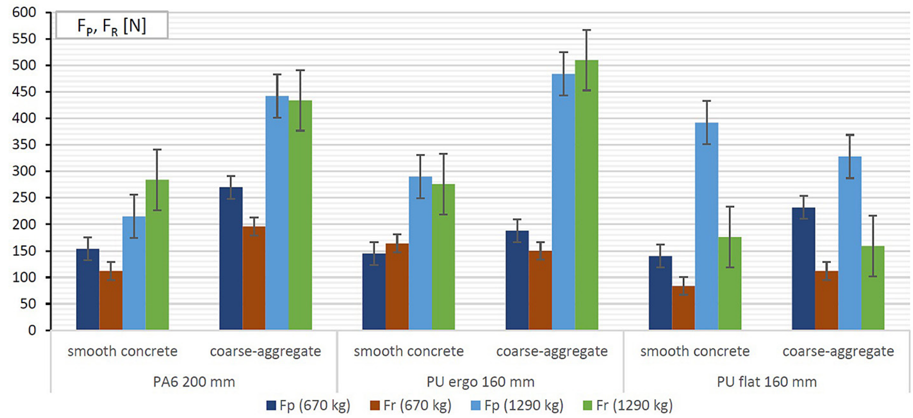

Figure 3. Average values of forces F_P and F_R for a trolley with weels oriented in the force direction

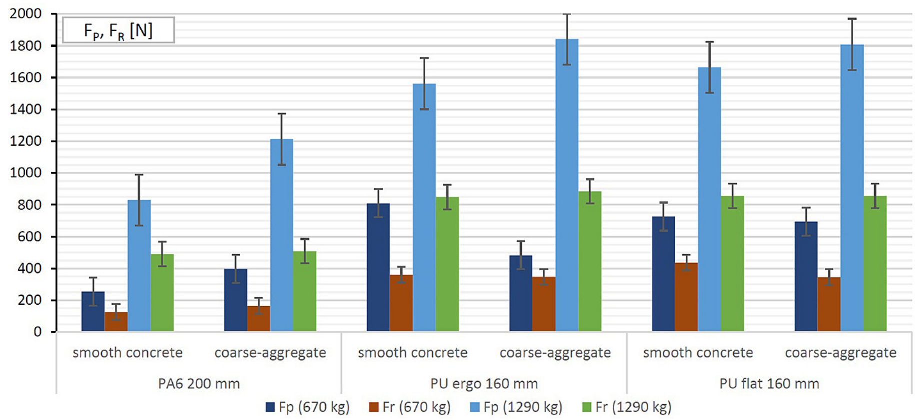

Figure 4. Average values of forces F_P and F_R for a trolley with weels perpendicular to the force direction

The reason for this phenomenon is the fact that the tests were carried out on floors characterized by high unevenness (waviness), which, on the one hand, could result in a large variation in the results obtained, but on the other hand, fully reflected the actual operating conditions of pallet trolleys.

As expected, moving a pallet trolley with wheels oriented perpendicular to the direction of the applied force (Fig. 4) requires more force than in the previous case (Fig. 3), both for straight movement (F_P) and turning (F_R). The values of both forces are clearly higher on the coarse-aggregate floor (max. 1800 N), but it is noteworthy that in this case, there is a greater difference between the F_P and F_R values. In each of the tested variants, the value of the F_P force is approximately twice as high as the F_R force, and the lowest values were recorded for wheels with a diameter of 200 mm made of polyamide. As mentioned earlier, the data obtained from the preliminary research will be used to verify the effectiveness of the PADU operation, as presented in the next section.

SUBJECT AND SCOPE OF RESEARCH

The design of the power-assist drive unit (PADU), which is the subject of this research, is shown in Figure 5. The device consists of an industrial wheel (8), driven by a BLDC motor (2) via a planetary reducer (1) and a timing belt transmission (6). These components are mounted in block bearings (10), which are attached to a two-piece body (7, 12) connected by horizontal connectors (9). The entire assembly is mounted with pins on a fork (4), equipped with a plate that enables PADU to be mounted on various vehicles, trolleys, or devices – such as a pallet trolley. Movement of the trolley equipped with PADU is possible when the wheel is pressed with appropriate force against the ground. This is achieved using a set of compression springs (11), one end of which is attached to an axis connected to the fork (4) and the other to one of the horizontal connectors (9). It should be emphasized that the compression springs are mounted on a threaded pin and are based on nuts. Thanks to this, it is possible to adjust the pressure force. When manual movement of the trolley is required, PADU can be raised to the upper position by a mechanism consisting of a camshaft (14) driven by a BLDC motor (3) via a planetary reducer and timing belt transmission (5). Then the spring assemblies (11) are compressed and the PADU is locked in the raised position thanks to the special shape of the camshaft (14). Notably, the wheel drive can only be engaged when the inductive sensor (13) detects the correct position of the camshaft, which corresponds to contact between the wheel and the ground. For added convenience, a manual lever (15) is provided, allowing PADU to be lifted or lowered without the need to engage the electric drives.

The use of PADU to assist the movement of a pallet trolley requires two drives placed in such a way that the wheel axes remain concentric. This configuration enables not only forward movement but also turning, by varying the rotational speed of the driven wheels. To ensure the rectilinear of the trolley's movement path when driving straight, rotational speed feedback is used, enabling the synchronization of both PADUs. An example application of this solution is shown in Figure 6.

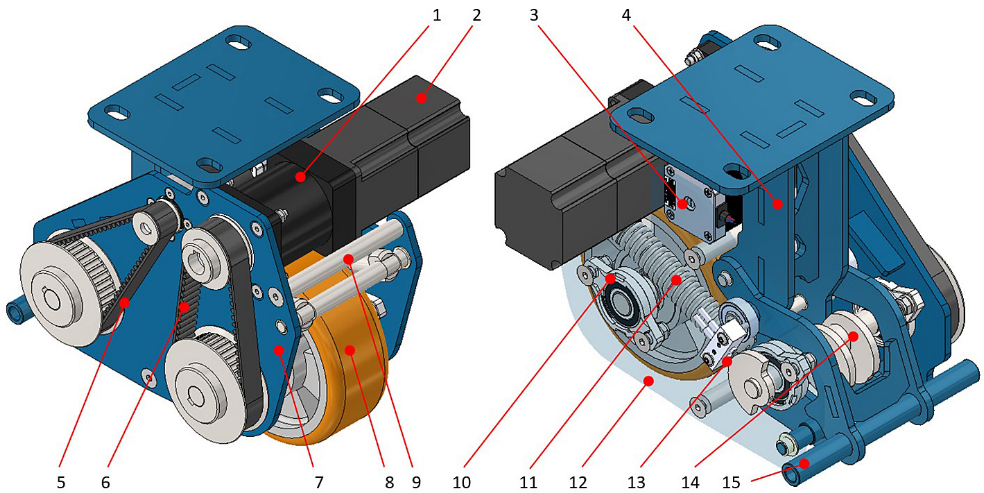

Figure 5. Power-assist drive unit (PADU) for intralogistics equipment: 1 – planetary gear reducer, 2 – BLDC motor (wheel drive), 3 – BLDC motor (up/down drive) with planetary gear reducer, 4 – fork with mounting plate, 5 – belt transmission (up/down), 6 – belt transmission (wheel), 7 – left body, 8 – wheel, 9 – horizontal coupler, 10 – block bearing, 11 – spring, 12 – right body (transparent view), 13 – inductive sensors and cam, 14 – camshaft, 15 – handle (up/down manual operation)

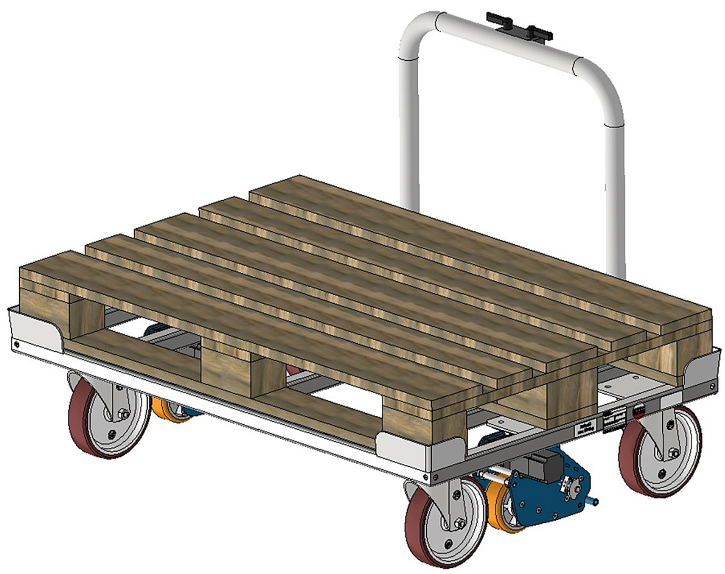

Figure 6. Pallet trolley with PADU system

To determine the performance of PADU, a research program was developed. This program involves measuring the pulling force and electric power consumption of the PADU system for five different test cases. For research purposes, a test stand, shown in Fig. 7, was constructed. It consists of a vertical T-slot Table 1, to which a pneumatic actuator (2) with a clogged chamber is attached, acting as a pneumatic spring. A strain sensor (3) was mounted on the piston rod, with its outputs connected to a data acquisition system, measuring the force exerted by the pallet trolley (4), equipped with two PADUs, on sensor (3). The electric current flowing to the device and the voltage from the source were recorded using an oscilloscope. Tests were conducted on the left PADU (Fig. 8), the right PADU, and both PADUs operating simultaneously. In the single-PADU tests, the trolley was positioned so that the axis of the force sensor aligned with the longitudinal axis of the drive wheel. For the tests with both PADUs operating simultaneously, the trolley was positioned so that the axis of the force sensor aligned with the trolley axis of symmetry (force measurement halfway between the PADUs). Additionally, to prevent the trolley from being lifted by the springs that press the PADU to the floor, it was symmetrically loaded with two steel plates. In the first series of tests, the performance was evaluated under conditions with no slippage between the drive wheels and the floor, with motor

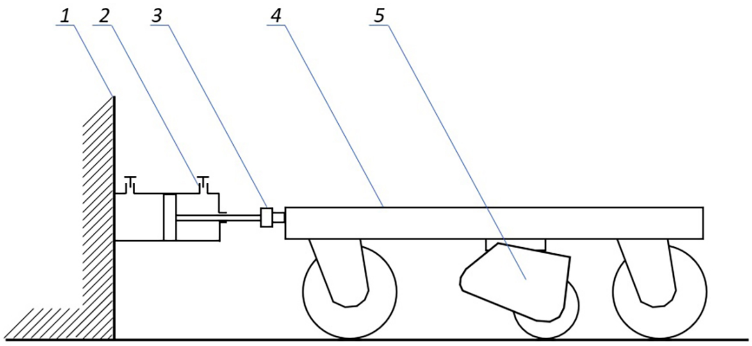

Figure 7. Test stand: 1 – vertical T-slot Table, 2 – pneumatic cylinder, 3 – strain sensor, 4 – pallet trolley, 5 – power-assist drive unit

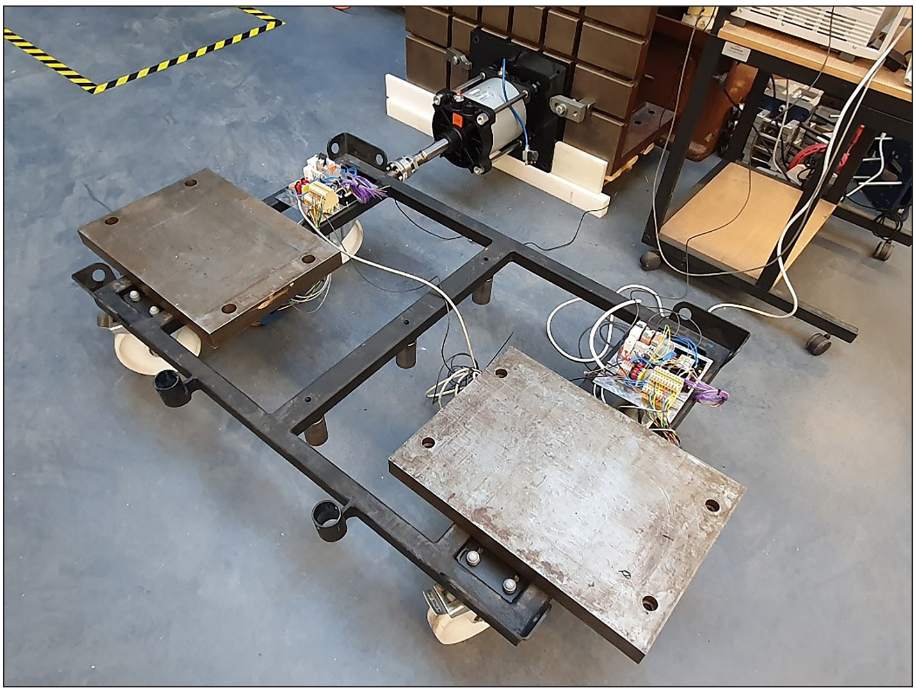

Figure 8. Testing the pushing force of left PADU

operating parameters ensuring the required force to support the trolley movement while optimizing electrical power consumption. Subsequently, the tests were conducted when slippage occurred between the wheels and the floor.

TEST RESULTS

Figures 9–13 present the results of experimental tests for different PADU – trolley configurations. The force with which the trolley presses on the sensor was recorded, along with the electrical power demand of the individual PADUs. In the first test, the average force generated by the left PADU (Fig. 9) was 158.6 N, and the average force generated by the right PADU (Fig. 10) was 158.3 N. The power corresponding to these forces was 59.35 W for the left PADU and 60.46 W for the right PADU. The average current drawn by the left module was 2.46 A, and by the right module was 2.5 A. It should be emphasized that the cyclical variability of the current diagram results from the power controller used, which charges and discharges the capacitive filter cyclically. Therefore, it is important to analyze the average current value, and therefore power.

Similar tests were carried out for a situation in which the wheels of one PADU lost traction

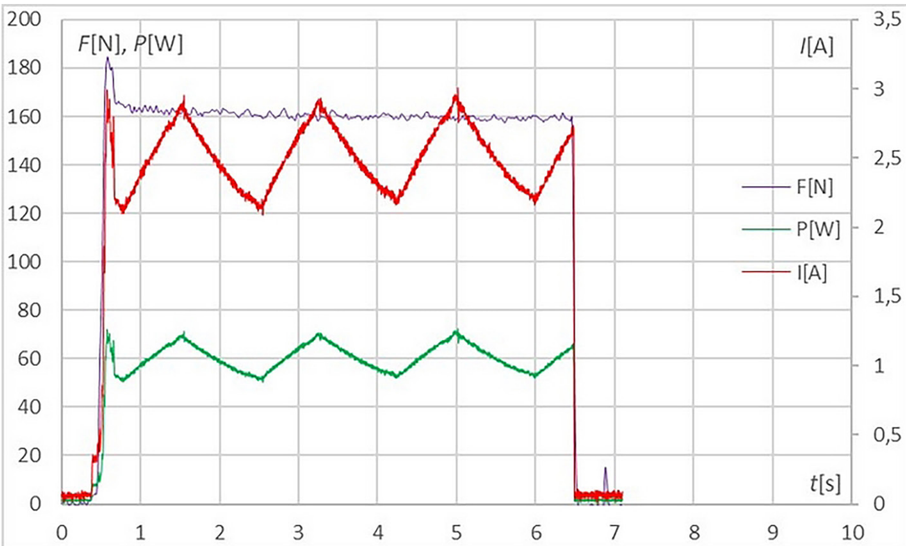

Figure 9. Pushing force and power consumption for the left PADU without slip

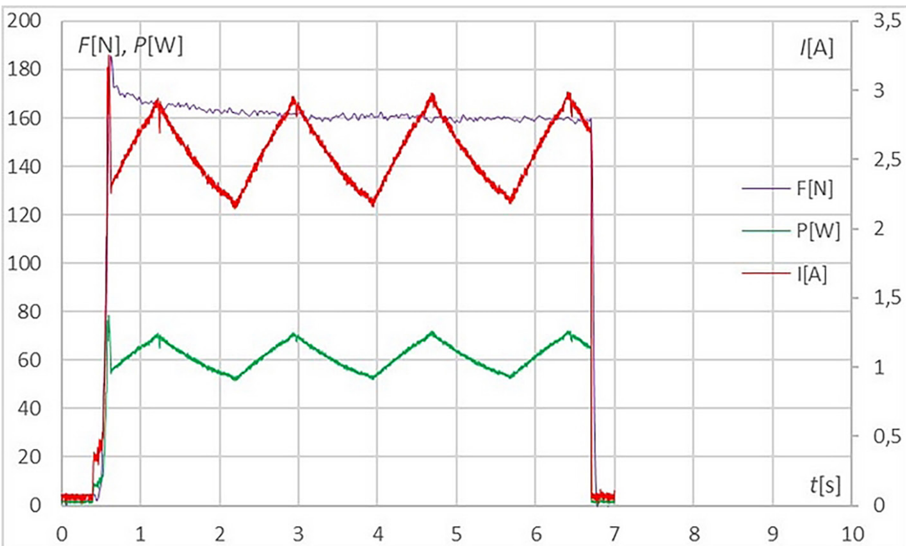

Figure 10. Pushing force and power consumption for the right PADU without slip

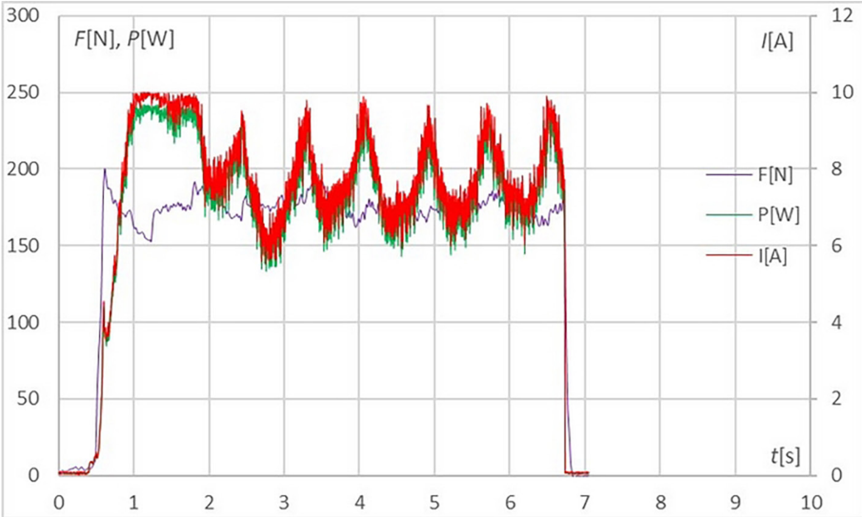

Figure 11. Pushing force and power consumption for the left PADU with slip

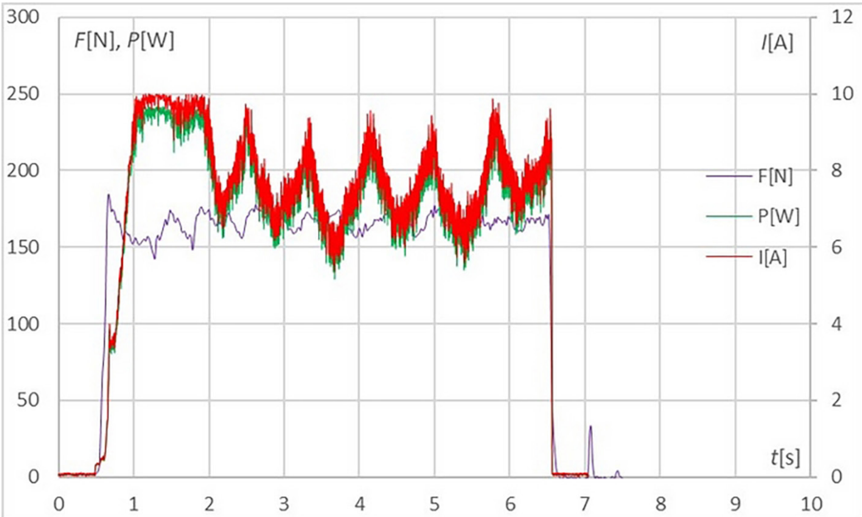

Figure 12. Pushing force and power consumption for the right PADU with slip

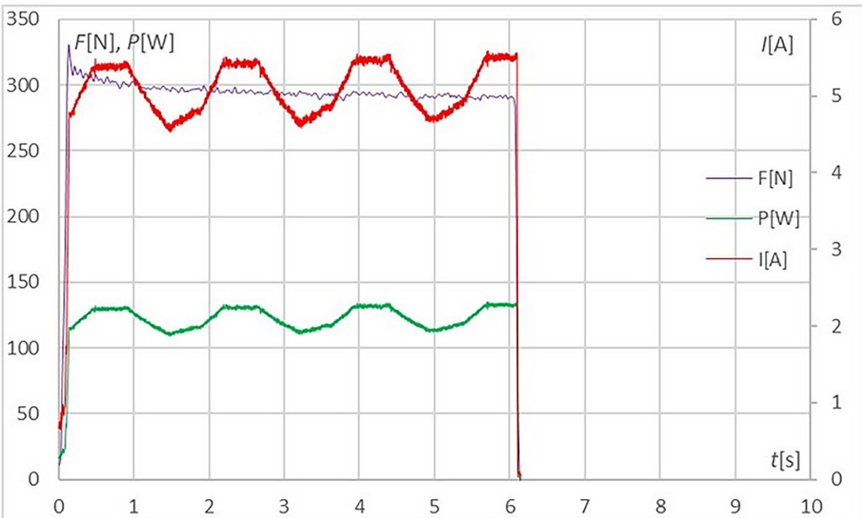

Figure 13. Maximum pushing force and power consumption for the both PADUs without slip

during operation and were spinning. The results are presented in graphs in Figures 11 and 12.

Despite a sharp increase in the power of the left drive to 183.66 W and the right drive to 181.38 W, the forces generated by the drives did not change significantly. The current consumption also increased for both drives, averaging 7.6 A for the left module and 7.5 A for the right module. The main reason for the increased energy consumption during wheel slippage is overcoming the resistance resulting from sliding friction between the wheel and the floor. The slippage forces the current regulator to operate much more aggressively in order to maintain the appropriate rotational speed. This suggests that operating in conditions that may cause the drive to lose traction could negatively impact the battery life of the modules.

Finally, the pushing forces of both electric drive units operating simultaneously were tested. An example test chart is presented in Figure 13.

The recorded average pushing force was 288.9 N, with a total drive power of 20.2 W. The current required to maintain the total drive power was 4.526 A.

CONCLUSIONS

The power-assist drive unit presented in this article is designed to assist manual transport. Thanks to its design, it can work with any transport device, such as a pallet trolley. The PADU performance tests showed that, when using two drives on one trolley, it is possible to achieve a pushing (or pulling) force of approximately 290 N, which is consistent with the standards and legal regulations mentioned in the introduction. The presented set of drives will allow for the complete replacement of human effort when moving straight and maneuvering trolleys equipped with any set of industrial wheels (among those tested) on a smooth concrete floor with a load of up to 1300 kg. It should be noted that this applies only when the trolley's wheels are aligned with the direction of movement. However, when the wheels of the trolley are set perpendicularly, the force generated by the PADUs is insufficient to fully replace human effort, though it will still provide significant support.

Analyzing the PADU's performance, it can be concluded that using two units on one trolley can produce a maximum pushing force of 540–590 N, assuming the maximum force exerted by an operator is within the standards and regulations (250–300 N). This makes it possible to move a trolley weighing more than 600 kg regardless of the type and initial setting of the wheels and the smoothness of the concrete floor, making this solution ideal for use in production and warehouse halls. It should be emphasized that when using PADU to support the manual transport of heavier goods (over 1000 kg), it is recommended to equip the trolleys with wheels with a less flexible tread, e.g. made of polyamide.

The PADU module discussed in the article addresses the needs of the intralogistics industry. Within the framework of the presented project, models can be designed for heavier loads or more challenging surfaces. The results presented in this work provide an excellent basis for further research, particularly in the areas of battery selection and system optimization regarding electric power demand and wheel slip prevention algorithm.

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