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ELECTROMAGNETIC LOCKING DEVICES OF CAR HANDLING UNITS

Summary. This paper contains the design of a testing device, which was constructed for the purposes of checking functional properties of the innovative solutions of variants of electromagnetic locking devices with potentials of replacing current mechanical brakes used for stopping pallets with loaded cars in parking houses developed by the company KOMA - Industry s.r.o. The testing device consists of two positioning tables, whose moveable parts are anchored perpendicular to each other in the frame of the testing device. An electromagnet and a solenoid generating the force needed for stopping the motion of the pallet is connected to the moveable part of the upright positioning table. The brake ramp made of a ferromagnetic material has a hole at its top surface into which the pin of the solenoid is inserted and is attached to the horizontal moveable part of the positioning table. This paper presents holding force values of the electromagnet, which were obtained by experimental measuring on the created testing unit.

Keywords: braking of manipulation units, electromagnetic force, testing device

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1. INTRODUCTION

With the increasing number of vehicles, it has become necessary, due to the lack of conventional parking spaces, for an efficient way of dealing with short- and long-term vehicle storage. Over the past decade, the dimensions of cars have increased considerably, unlike the ground plan dimensions of parking spaces. In many countries, the dimensions of parking spaces remain standardised to the same dimensions, which is one of a number of problems in the current situation of parking of vehicles [12]. The dimensions of parking spaces in the Czech Republic are determined by the standard [9], where perpendicular parking spaces measure 5 metres in length and 2.5 in width.

Parking houses are possible efficient alternatives for parking, where the vehicles are parked on several floors above each other. The most efficient option in terms of parking area utilisation is parking houses harnessing fully automated systems that transport the vehicle located on the pallet from the dispatching area to an appropriate cell space of the block parking rack with the use of lifting and manipulation devices. One or more pallets with parked vehicles can be inserted into a given parking rack cell.

When a block parking rack cell is designed for storing more pallets with vehicles in a row, the lower surfaces of the pallets, or the lower running surfaces of the cells, are generally provided with rollers to limit movement resistance (shear friction replaced by rolling friction). Prevention of spontaneous movement of stored pallets in the cells is solved by fixation means, by mechanical brakes or locking devices using the pulling or pushing forces of an electromagnet.

2. MECHANICAL PALLET LOCKING BRAKES

The two design variants of mechanical brakes of the pallet brake system designed by KOMA - Industry s.r.o., which are used in the Parking House Brno Kopečná; are listed in [1]. Both of these mechanical brake variants consist of the following three basic components: the brake body, the pulley bracket and the compression spring.

The theoretically derived generated forces and kinematic ratios, which act during processes of guiding /pushing the parking brake pulley into or out of the circular recess in the brake ramp section, are presented in [3].

In [5], a test device is presented, which was designed to experimentally determine the true values of the forces acting vertically on the body of the brake of the pallet locking system.

The purpose of mechanical pallet brakes [1] is to lock the pallet (which is located closest to the front vertical plane of the rack cell by which the pallets are inserted into the cell) in place. This prevents the pallet (and the pallets behind it) from moving and moving in a horizontal plane in the direction of the longitudinal axis of the rack cell. The locking of the pallet in a precise position is a prerequisite for smooth operation in a fully automated parking house system, with a computer-controlled automated vehicle loading and unloading process using sophisticated technological equipment.

If the cell to be occupied by a pallet contains one pallet already (in an exact position relative to the length of the stacker cell, anchored by the pallet brakes), the pallet moving in is guided (with the help of “mechanical locking teeth”) past and then in reverse motion (by the motion mechanism of the transporting device) inserted into the “lock teeth” of the already stored pallet. By means of these mechanical locks (consisting of two teeth on each of the two sides of the pallet, which are situated perpendicular to the longitudinal axis of the rack cell), the adjacent pallets are mechanically interconnected. Then, the pallet feed chain (mechanically interconnected with the pallets already stored in the respective rack cell) is pushed horizontally into the cell by means of a telescopic shifter.

3. INNOVATIVE PALLET BRAKE DESIGN

The proposed innovative solution is a locking device, which does not use mechanical brakes [13], but a mechanism based on the principle of holding or pushing an electromagnet.

Fig. 1 shows the 2D and 3D design of the testing device, which demonstrates the two innovative principles of pallet locking. The testing device stand (created version – Fig. 3) consists of a welded steel frame structure 1 (Fig. 1), two positioning tables 2, 3 [2] and locking device components.

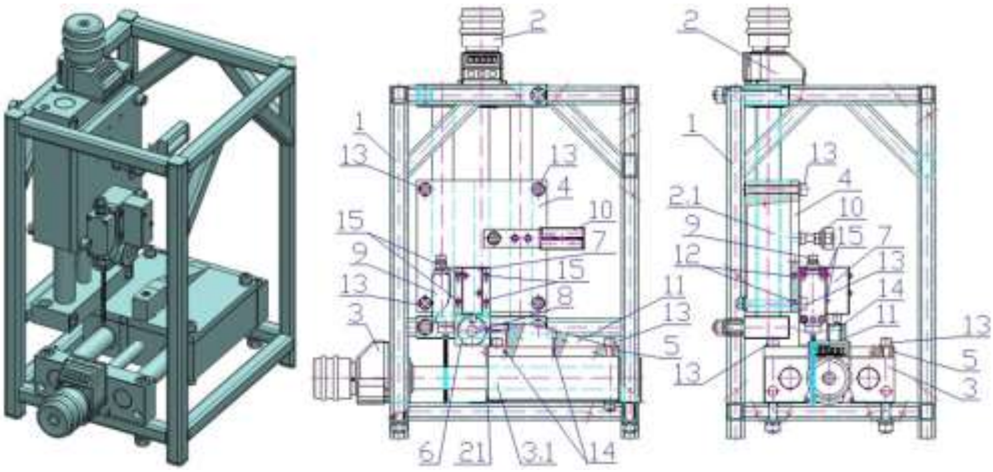

Fig. 1. 3D model and 2D design of the testing stand of the locking device

The vertical positioning table 2 is attached to the steel frame structure 1 using four screws.

A bracket 6 is attached with two M5 x 25 screws 12 to the face surface of the plate 4 (Fig. 1), which is by means of 4 M10 x 20 screws 13 attached to the moving part 2.1 of the vertical positioning table 2 (Fig. 2). The push solenoid 7 (that is, a long coil, consisting of threads of identical lead of copper wire of the same circular cross-section along the whole length, stored in a metal frame) is mounted onto the face of the bracket 6 by four M3 x 5 screws 15 and a holding electromagnet 8 is also attached to the bracket 6 with screw M4 x 15 23.

The brake ramp 11 is attached by two screws 14 to plate 5 (Fig. 2) of the horizontal positioning table 3. Due to the change of position of the moving part 3.1 of the horizontal positioning table 3 at some point, the arm 21 comes into contact with limit switch spring 9 [6]. When gradually moving the moving part 3.1 of the horizontal positioning table 3, the bottom row of electrical contacts [10] of limit switch 9 close on limit switch 9 due to the deflection of the spring on limit switch 9.

Limit switch 9 is provided with two electrical contacts placed one above the other, which are mechanically interconnected. When the limit switch spring is not deflected 8, the current flows through the upper row of closed contacts, which is visually represented on the signalling panel 10 of the test device by a red LED. When the spring of the limit switch 8 is deflected, the upper (previously closed) contact and the lower contact on the signalling panel

10 are opened, the green LED light switches on and the supply voltage is applied to the push solenoid coil 7 and the electromagnet coil 8. A magnetic field is formed around both coils by a passing direct current.

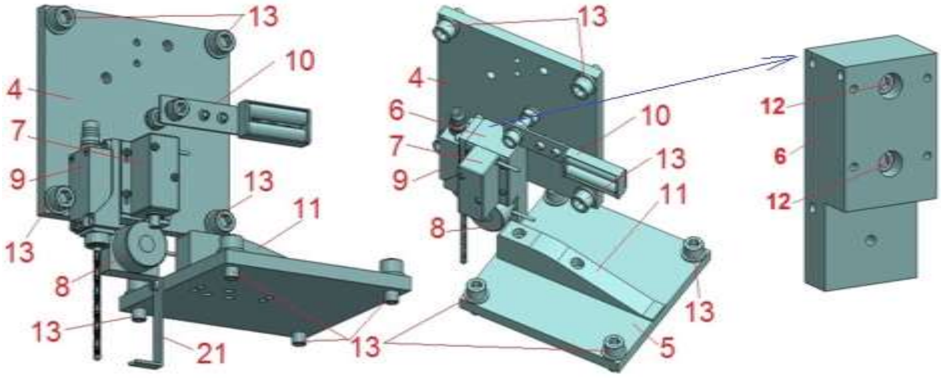

Fig. 2. The innovative pallet locking design - locking device

The magnetic field around the push solenoid coil 7 generates a force that extends outwardly from the coil core, which leads to a pin. The pin, when the core is ejected from the push solenoid coil 7, is inserted into the opening of the brake 11, thereby preventing further movement of the moving part 3.1 of the horizontal positioning table 3, thus, simulating pallet locking of an electromagnetic locking device.

Fig. 3. The constructed test stand site of the innovative pallet locking design

The magnetic field around the coil in the core of the holding electromagnet 8 generates pull strength. If the electromagnet 8 is located in the desired position, then the pull strength of the electromagnet 8 acts on the lateral surface of the brake 11, thereby preventing further movement of the moving part 3.1 of the horizontal positioning table 3.

The constructed model of the pallet locking device utilising holding, pushing or pulling forces of the electromagnet is shown in Fig. 3.

4. PULL STRENGTH OF THE ELECTROMAGNET

To have trouble-free operation when guiding the pallet to the parking position in the rack cell, rolling along the roller track, the maximum distance between the side of the brake ramp 11 and the face of the electromagnet 8 must be kept. The maximum distance y [m] of the electromagnet 8 from the brake ramp 11 is strongly influenced by the holding force $F_{M(y)}$ [N].

The dependence of the holding force on the distance of the electromagnet from the ferromagnetic plate (side surface of the brake ramp 11) is described by Maxwell's equation (2).

Electrical current I [A] passing through the electromagnet excitation coil 8, is a source of magnetic field of a certain magnetic intensity and also produces a magnetic induction flux Φ_m [Wb]. This magnetic flux is proportional to the current I [A]. The steady-state current I [A] is given only by the voltage U [V] and the resistance R [Ω] of the spool and does not depend on the anchor position. Because the coil current is proportional to the magnetic voltage of the electromagnet, only a small amount of force is required to retain the anchor, hence, a small current. Pull strength F_M [N] of a DC solenoid can be expressed by the relation (1).

$$F_M = \frac{B. S}{2. \mu_0} \text{ [N]} \tag{1}$$

where B [T] - magnetic induction, S [m^2] - contact surface of magnet with washer, μ_0 [H. m^{-1}] - vacuum permeability.

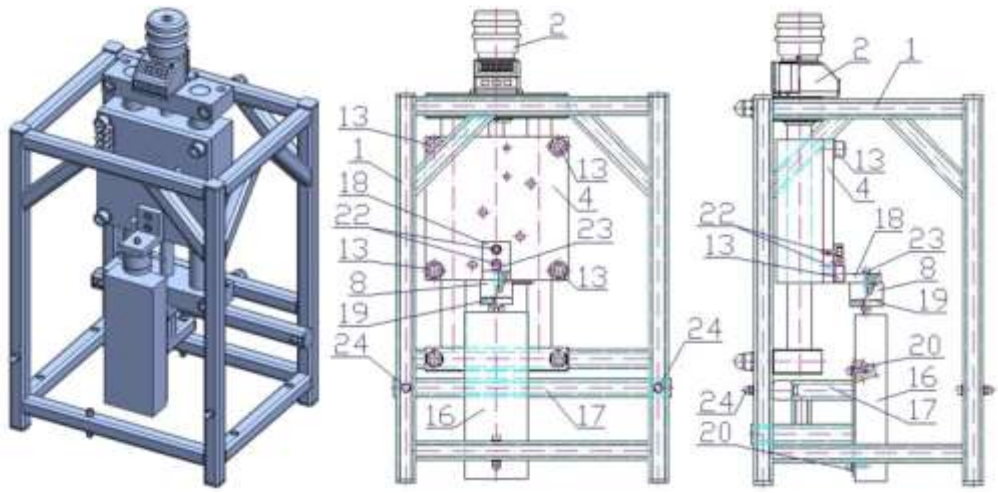

Fig. 4. 3D model and 2D design of measuring station

If we add magnetic induction, magnetic voltage and magnetic resistance of the air gap into the relationship (1), we will in ideal conditions, when the whole magnetic flux is closed without dispersion by the geometric air gap, obtain the force dependence $F_{M(y)}$ [N] on the stroke y [m], or pull strength characteristic of the electromagnet in the form of (2).

$$F_{M(y)} = \frac{F_m . \mu_0 . S}{2. y^2} \text{ [N]} \tag{2}$$

where F_m [N] - magneto-motor force, y [m] - distance of magnet electromagnet from ferromagnetic pad (plates of circular cross-section 19).

From relationship (2), it follows that dependence of pull strength $F_{M(y)}$ [N] of the electromagnet is inversely proportional to the square of the size y [m] of the air gap. The foregoing considerations assume that the entire magnetic flux given by the excitation magnetic voltage is involved in the generating pull strength. In reality, there is dispersion in the magnetic circuit. Therefore, the actual magnetic flux in the air gap, as well as the pull strength of the $F_{M(y)}$ [N] electromagnet, will be smaller. Dispersion increases as the magnetic induction in the air gap increases.

At the measuring station (Fig. 7), construction design on Fig. 4, experimental measurements were performed to obtain true values of holding force $F_{M(y)}$ [N] of the direct current solenoid 8 [4] (holding force 180 N, operating voltage 12 V DC, maximum current 0.5 A) depending on the distance y [m] and the magnitude of current I [A] flowing through the solenoid coil.

The holding force $F_{M(y)}$ [N] (Fig. 6), of electromagnet 8 was detected by a digital load cell 16 that was attached to the face of the welded bracket 17 by screws 20 (Fig. 4). Values of holding force $F_{W(y)}$ [N] of the electromagnet 8 measured by the digital load cell 16 were recorded on a PC in the software Force Logger, ver. 1.01 (Fig. 5). Bracket 17 was attached to the steel frame 1 by three screw connections 24. The holder 18 of the electromagnet 8 was connected with two screws 22 to the face of plate 4.

Fig. 5. The holding force of the electromagnet, detected by a digital load cell, was recorded on a PC by the Force Logger software, ver. 1.01

By changing the position of the moving part 2.1 of the vertical positioning table 2 the distance y [m] of the solenoid 8 between the ferromagnetic plate of circular cross-section 19 was set, and the ferromagnetic plate was screwed onto the threaded part of the digital load cell 16.

The Solenoid coil 8 was supplied with DC voltage and current of 0.1 A to 0.4 A from laboratory power supply P230R51D (Fig. 7) [11], which is equipped with two sources with continuous voltage regulation in the range of 0 to 30 V, with the possibility of setting the current limitation from 0.1 to 4 A.

Values of holding force $F_{M(y)i}$ [N]; read from the digital load cell display 16 for a given distance y [m] and current I [A] flowing through the solenoid coil 8; were recorded (for i = 3 repeated measurements under the same conditions) by Tabs. 1 to 4.

Tab. 1

The holding force of the electromagnet depends on the distance from the ferromagnetic plate, current flowing through coil I = 0.4 A

$y.\ 10^{-3}$ [m]	i	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8
$F_{M(y)i}$ [N]	1	137	38	17	10	7	6	4	3	2
	2	136	36	16	10	8	5	4	3	2
	3	137	36	17	10	7	5	4	3	2
$F_{M(y)}$ [N]		136.7 ± 1.4	36.7 ± 2.9	16.7 ± 1.4	10.0 ± 0.0	7.3 ± 1.4	5.3 ± 1.4	4.0 ± 0.0	3.0 ± 0.0	2.0 ± 0.0

The arithmetic mean $F_{sM(y)}$ [N] of measured values of holding forces $F_{M(y)i}$ [N] was calculated with the help of relation (3), using relation (4), the deviations $\Delta_{i(y)}$ [N] of measured values $F_{M(y)i}$ [N] from the arithmetic mean $F_{sM(y)}$ [N] was obtained.

$$F_{sM(y)} = \frac{\sum_{i=1}^{n} F_{M(y)i}}{n} \ [N] \tag{3}$$

$$\Delta_{i(y)} = F_{M(y)i} - F_{sM(y)} \ [N] \tag{4}$$

The sample standard deviation $S_{vo(y)}$ [N] of the arithmetic mean $F_{sM(y)}$ [N] was calculated using relationship (5) [7], and the standard deviation $S_{o(y)}$ [N] of the arithmetic mean $F_{sM(y)}$ [N] [8] by relation (6) [7].

$$s_{vo(y)} = \sqrt{\frac{\sum_{i=1}^{n} \Delta_{i(y)}^2}{n-1}} \ [N] \tag{5}$$

$$s_{o(y)} = \frac{s_{vo(y)}}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n} \Delta_{i(y)}^2}{n.(n-1)}} \ [N] \tag{6}$$

In the table [7] of critical values of Student's distribution, the chosen risk was set to be 5%, and therefore $t_{\%,n}$ [-], for the number of measurements “n = 3” and the risk α = 5% the Student's coefficient is $t_{5\%,3} = 4.3$.

Tab. 2

The holding force of the electromagnet depends on the distance from the ferromagnetic plate, current flowing through coil I = 0.3 A

$y.\ 10^{-3}$ [m]	i	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6
$F_{M(y)i}$ [N]	1	112	17	9	6	4	3	2	1
	2	114	18	9	6	4	3	2	1
	3	114	17	9	7	4	4	2	0
$F_{M(y)}$ [N]		113.3 ± 2.9	17.3 ± 1.4	9.0 ± 0.0	6.3 ± 1.4	4.0 ± 0.0	3.3 ± 1.4	2.0 ± 0.0	0.7 ± 1.4

The error margin $\kappa_{(s)}$ [N] was calculated by relationship (7).

$$\kappa_{(y)} = t_{5\%,3} \, . \, s_{o(y)} \ \text{[N]} \tag{7}$$

The last row of Tabs. 1 to 4 contains the results of the measured holding force values $F_{M(y)}$ [N], given by relation (8).

$$F_{M(y)} = F_{sM(y)} \pm \kappa_{(y)} \ \text{[N]} \tag{8}$$

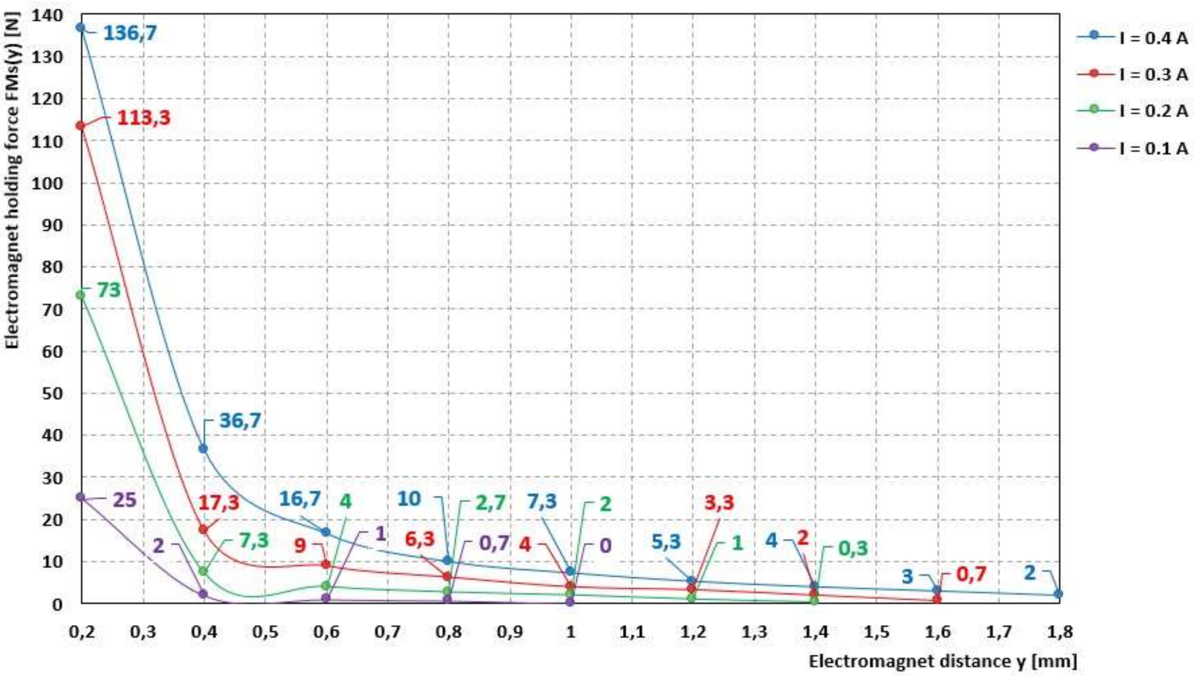

Fig. 6. The holding force of the electromagnet depending on the distance from the ferromagnetic plate

Tab. 3
The holding force of the electromagnet depends on the distance from the ferromagnetic plate, current flowing through coil I = 0.2 A

$y.\ 10^{-3}$ [m]	i	0.2	0.4	0.6	0.8	1.0	1.2	1.4
$F_{M(y)i}$ [N]	1	75	7	4	3	2	1	0
	2	71	8	4	2	2	1	1
	3	73	7	4	3	2	1	0
$F_{M(y)}$ [N]		73.0 ± 5.0	7.3 ± 1.4	4.0 ± 0.0	2.7 ± 1.4	2.0 ± 0.0	1.0 ± 0.0	0.3 ± 1.4

Tab. 4
The holding force of the electromagnet depends on the distance from the ferromagnetic plate, current flowing through coil I = 0.1 A

$y.\ 10^{-3}$ [m]	i	0.2	0.4	0.6	0.8	1.0
$F_{M(y)i}$ [N]	1	26	2	1	1	0
	2	24	2	1	0	0
	3	25	2	1	1	0
$F_{M(y)}$ [N]		25.0 ± 2.5	2.0 ± 0.0	1.0 ± 0.0	0.7 ± 1.4	0.0 ± 0.0

Fig. 7. Constructed measuring station of holding force of the DC electromagnet

5. CONCLUSION

This paper presents the principle of an electromagnetic locking device, which uses holding forces generated by a DC electromagnet or core pushing force from the solenoid anchor for locking the pallets parked in cells of automated parking houses.

A testing device was designed and subsequently constructed to demonstrate possible ways of holding and preventing spontaneous movement of handling units parked in rack cells of fully automated warehouses. The motivation behind the construction of the testing equipment was to offer a reliable alternative parking brake solution to the mechanical parking brakes that are currently being used in automatic parking houses constructed by KOMA - Industry s.r.o.

The drawback of electromagnetic braking devices utilising the electromagnet handling units to lock the electromagnet handling units is the need to maintain a minimum distance between the electromagnet face and the opposing ferromagnetic part installed on the handling unit where the electromagnet holding force acts.

Error-free vehicle loading/unloading; placed on a steel pallet provided with rollers on its lower surface, into/from a parking rack cell on a selected floor; computer-controlled automated parking house processes can only be achieved by precisely guiding the pallet to/from the parking position by a sophisticated loading device. A conveyor is usually used as a loading device where a chain or a toothed belt is the pulling element. The pallet with the vehicle is moved out of the parking position when the pallet's grip holder is engaged by a gripping element connected to the conveyor chain. Due to the dimensions and constructional design of both gripping elements, of designed racks and pallets used in parking houses, it is necessary to ensure sufficient manufacturing and assembly accuracy to allow the two gripping elements to snap together. The precise locking of the gripping elements is greatly influenced by the length of insertion of the pallet into the rack cell, which must not change during parking. A change in the position of the parked pallet due to the effects that occur in the interior of the parking house, which may change the position of the pallet, can be with great probability and be avoided using the proposed principle of the electromagnetic braking/locking device.

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