Development of eco-friendly mechanized rotary parking lots with a flywheel energy storage device

Leila Abdullina¹, Vladislav Smirnov², Anna Alimova³, Alina Kalistratova² and Alexander Kravets⁴

¹Department of Theory of machines and mechanisms, Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5/1, Moscow, 105005, Russian Federation
²Department of Ecology and Industrial Safety, Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5/1, Moscow, 105005, Russian Federation
³Department of wheeled vehicles, Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5/1, Moscow, 105005, Russian Federation
⁴Department of Jurisprudence, Russian Foreign Trade Academy, ul. 4A Pudovkina, Moscow 119285, Russian Federation

E-mail: abdullina_98@mail.ru

Abstract. Perspective type of mechanized parkings is a multi-storey rotary parking system. It is the most efficiency type, but it costs relatively high per unit of parking space. Lower speed of transportation of cars in comparison with other parking types slightly influences on productivity, because an efficiency of work of the device is firstly defined by duration of stages of loading and unloading of cars. The main disadvantage of multi-storey car parks compared to conventional parking lots - is the need for increasing costs for the operation of the lifting device. One of the methods of improving the energy efficiency of lifting and transport machines is the development of structures with energy recuperation. It allows the kinetic energy of the moving parts at the stage of braking to be accumulated in the battery, and to get used for acceleration when performing the next movement. The article describes the mechanism of a rotary-type parking lot with a flywheel energy storage device, and its principle of operation. The characteristics of a flywheel energy accumulator are well suited to the task. In terms of the specific energy reserve per unit of weight, the flywheel battery effectively competes with the electric one, differing from it by a higher working life. Also, its properties do not deteriorate at low operating temperatures. The justification of the choice of the required parameters of the flywheel, the analysis of its shape and the choice of material from which the flywheel can be made.

1. Introduction

Currently, in large cities, the number of cars significantly exceeds the number of available parking spaces. The most acute problem is the temporary location of vehicles near public objects, such as office buildings or large shopping centres. Cars are parked unsystematically, obstructing the passage of vehicles and the movement of pedestrians. Unorganized storage of cars leads to a degradation in the quality of the surface layer of the atmosphere [1], which adversely affects the health of people living in near areas [2]. Also, parking cars on the street along the roadway reduces the throughput of the...
motorway and leads to an increase in the emission of carbon dioxide into the environment due to non-ecological operating modes of engines.

2. Relevance
Focusing on all of the above, the issue of developing car parks that can solve the urgent task of compact storage of vehicles is of particular importance. One of the methods for solving this problem is the use of new multi-storey car parks instead of single-storey ones. Such car parks use the land plot with the greatest efficiency, protect vehicles from rainfall and also reduce the harmful effects of cars on the environment - the features of the engine during cold start and warm-up lead to a multiple increase in carbon dioxide emissions, which does not occur when using multi-story indoor car parks, which maintains a constant temperature. Multi-storey, as well as other multi-parking lots allow developing and implementing a whole range of measures to ensure environmental safety [3].

At the moment there are a large number of varieties of multi-story parking. To build the theoretical basis of this work were widely used different engineers works. For example, Gnezdilov’s S.G. work: “Overview of parking space mechanization means” and “Development of classification and terminology in the field of mechanized car parks”. In these works he examined underground multi-level automated parking systems for cylindrical, tower, elevator types of cars [4, 5]. His work gave us a detailed description of flowcharts transfers of vehicles, which are transported by the parking lot, and their design, classification, etc. It should be noted, that he principles of parking systems are the same for all parking lots of similar types.

The dissertation by Bystrov E.O. had a great influence on the development of the topic of multi-level parking lots in Russia. “Development of a methodology for the optimal design of the metal structure of a car lift of a revolving type of a multi-level car park” [6], is a work, in which the author described the design of a multi-seat rotary car park of a revolving type, calculated the loads acting on its nodes, showed (using the economic calculation the advantages of a multi-story parking over a one-story parking), made recommendations for designing multi-seat parking lots.

For more detailed immersion in the topic you can research patents: US5049022A, US2899087A, US3063579A and other.

3. Purpose of the study
The purpose of this study was to propose a solution to improve the operation of a multi-storey rotary car park, as well as to increase its efficiency and environmental friendliness.

4. Main part
There are a large number of different versions of multi-storey car parks. First of all the choice of execution depends on the cost of the parking space, as well as the available parking space and convenience of use. A perspective variety of mechanized parkings is a rotary parking system. It is the most efficiency type, but it costs relatively high per unit of parking space. The lower speed of transportation of cars in comparison with analogues slightly affects the overall performance, since the efficiency of the device is primarily determined by the duration of the stages of loading and unloading cars.

The main disadvantage of multi-storey car parks compared to conventional parking lots - is the need for increasing costs for the operation of the lifting device. The vehicles lifting and lowering mechanism operates in an unfavorable “start-stop” mode, which leads to an increase in electricity consumption [7]. Recently, hybrid power plants with recovery of braking energy (which reduce energy loss by up to 50% depending on the frequency of the braking process) have become widespread in the world [8, 9]. In practice, engineers usually use various types of electric, pneumatic and flywheel energy batteries.

For the recovery of braking energy, electric batteries are widely used, which are actively used in the automotive industry and lifting and transport equipment. Unfortunately, at low temperatures characteristic of most regions of our country, the properties and resource of electric batteries are
significantly deteriorating, which does not allow them to be used effectively for rotary parking. Therefore, the best option is to use a device that would ensure the recovery of braking energy using a flywheel energy accumulator, which is most often installed between the motor and generator [10].

In terms of the specific energy supply per unit weight, the flywheel accumulator effectively competes with the electric one, differing from it by a higher service life [11, 12]. However, electrical energy is the most convenient for use by the consumer. Therefore, it is advisable to combine the flywheel battery with a reversible electric machine, controlled by a computer.

In the rotary car park, kinetic energy is exchanged between the flywheel and the cradle drive with the cars located on it using an electric control device. It simultaneously acts on the traction electric DC motor and an additional reversible electric DC machine associated with the flywheel. When lowering the unbalanced mass of cars, an additional reversible electric DC machine connected to the flywheel operates in electric motor mode and is powered by a traction electric motor, which operates in generator mode and spins the flywheel.

At the same time an additional reversible electric DC machine works in generator mode when this machine is lifting an unbalanced mass of cars, it reducing the flywheel's rotation speed and turning its kinetic energy into electrical energy, which is powered by a DC traction motor. Its control is carried out by an electric control device connected to a power supply network, to a traction motor and a reversible electric DC machine.

Figure 1. presents a diagram of a device for implementing the proposed method of operation of a rotary parking lot with the recovery of braking energy and a device for its implementation, where:

1 - rotary parking; 2 - traction engine; 3 - gear; 4 - coupling; 5 - bevel gear; 6 - bevel gear; 7 - a cylindrical gear; 8 - a cylindrical gear; 9 - a leading asterisk of a chain transmission; 10 - driven chain sprocket; 11 - chain; 12 - a cylindrical gear wheel drive cradles; 13 - reversible electric machine direct current flywheel drive; 14 - flywheel; 15 - control device; 16 - power supply network; 17 - housing, 18 - electrical circuit.

On the figure 2 the general view of the rotary car park under consideration is presented. The numbers indicate: 19 - a placed car, 20 - a platform (cradle) for a car.

The use of a flywheel battery allows reducing energy losses and increasing the efficiency of rotary car parks in unsteady operating modes [12].

**Figure 1.** Recuperation scheme.

**Figure 2.** General view of the rotary car park.
Let us evaluate the effect of integration a flywheel into the system, its influence on the power consumption. To solve this problem, it is required to design a small flywheel, for which the following relations will be true [13, 14]:

\[ E = \frac{1}{2} I \cdot \omega^2 \]  

(1)

Where \( E \) - is the kinetic energy, \( I \) - is the moment of inertia, \( \omega \) - is the angular velocity of the flywheel.

For a solid cylinder, the moment of inertia can be calculated as:

\[ I = \frac{m}{2} = \frac{r^4 \cdot \pi \cdot h \cdot \rho}{2} \]  

(2)

Where \( h \) - is the height of the cylinder, \( r \) - is the radius, \( \rho \) - is the density of the material of the cylinder.

![Figure 3. Appearance of the flywheel.](image)

In practice, the more complex form of the flywheel (figure 3) is often used, it looks as a hollow cylinder located on the shaft. In this case, the moment of inertia can be written as follows:

\[ I = \frac{m}{2} = \frac{\pi \cdot h \cdot \rho}{2} \left( r_1^4 - r_2^4 \right) \]  

(3)

where \( r_1 \) - is the outer radius, \( r_2 \) - is the inner radius.

Then the kinetic energy stored by the flywheel can be calculated as [15]:

\[ E = \frac{\pi \cdot h \cdot \rho}{4} \left( r_1^4 - r_2^4 \right) \cdot \omega^2 \]  

(4)

From the Eq.4 it follows that it is necessary to increase radius to increase the energy stored by the flywheel. However, this will lead to a significant increase in overall dimensions and mass. Another possible solution is to increase the speed of the flywheel, which is primarily limited by the strength of the material from which it is made [16]. Mechanical characteristics of various materials are shown in table 1.
Table 1. Mechanical characteristics of various materials.

| Material            | Tensile Strength, MPa | Density, kg/m³ | Specific Strength, MPa/(kg/m³²) |
|---------------------|-----------------------|----------------|---------------------------------|
| Alloy steel         | 1500                  | 7800           | 0.190                           |
| Aluminium alloys    | 600                   | 2700           | 0.220                           |
| Titanium alloys     | 1500                  | 4500           | 0.300                           |
| Tungsten alloys     | 1500                  | 19300          | 0.078                           |
| Composites:         |                       |                |                                 |
| Boron aluminium     | 1400                  | 2700           | 0.520                           |
| Carbon aluminium    | 1000                  | 2300           | 0.430                           |
| Carbon fibre, CFRP  | 1400                  | 1550           | 0.900                           |
| Organoplasty        | 1500                  | 1380           | 1.090                           |

The maximum speed limit at which a flywheel may operate is determined by strength of the rotor material, called tensile strength $\sigma$ [17, 18]. A suitable safety margin must be maintained, to keep the stress experienced by the rotor below the strength of the rotor material. The maximum stress of a thin rotating ring is given by:

$$\sigma_{\text{max}} = \rho r^2 \omega^2$$  \hspace{1cm} (5)

Where $\sigma_{\text{max}}$ is the maximum stress and $\rho$ is the density of the flywheel material. More complex equations are available for different rotor geometries, but the maximum stress is always proportional to $\rho$, and the square of peripheral speed, equal to $r\omega$. The effect of rotor geometries can be accommodated by introducing a shape factor $K$. The maximum specific energy and energy density are then given by:

$$\frac{E}{m} = K \frac{\sigma_{\text{max}}}{\rho} [J/kg]$$  \hspace{1cm} (6)

$$\frac{E}{V} = K \sigma_{\text{max}} [J/m^3]$$  \hspace{1cm} (7)

Eqs 6-7 indicate that the specific energy (energy per mass unit) and energy density (energy per volume unit) of the flywheel are dependent on its shape, expressed as shape factor $K$.

The shape of a flywheel is an important factor for determining the flywheel speed limit, and hence, the maximum energy that can be stored. The shape factor $K$ is a measurement of flywheel material utilisation [17].

Figure 4 shows the values of $K$ for the most common types of flywheel geometries.

![Figure 4. Different flywheel cross sections [17].](image-url)
The ratio of the recuperated energy $E_{rec}$ to the full energy used in a rotary parking $E$ when establishing the flywheel energy storage device for given $K$, using (6) and assuming the value $m = 1$kg is shown in table 2:

| Material           | Ratio value $\frac{E_{rec}}{E}$ |
|--------------------|----------------------------------|
|                    | $K=0.5$ | $K=0.305$ | $K=0.606$ | $K=1$  |
| Alloy steel        | 0.096   | 0.058     | 0.116     | 0.192  |
| Aluminum alloys    | 0.111   | 0.017     | 0.134     | 0.222  |
| Titanium alloys    | 0.166   | 0.101     | 0.202     | 0.333  |
| Tungsten alloys    | 0.038   | 0.023     | 0.047     | 0.077  |
| Composites:        |         |           |           |        |
| Boron aluminum     | 0.259   | 0.158     | -         | -      |
| Carbon aluminum    | 0.217   | 0.132     | -         | -      |
| Carbon fibre, CFRP | 0.451   | 0.283     | -         | -      |
| Organoplasty       | 0.543   | 0.331     | -         | -      |

Based on the results:

Figure 5. Dependence of the recovery ratio for various materials and flywheel shapes.

Figure 5 shows the dependence of energy recovery on the material and shape of the flywheel, allowing you to select the flywheel that best meets the requirements.

5. Conclusions

The studies confirm the results of studies of other scientists [19, 20], and prove that the use of energy recovery during braking allows not only to maintain high dynamic qualities of the rotary parking mechanism, but also significantly increase its efficiency.

The methodology for calculating the main parameters of the energy storage brake system and determining the parameters of the flywheel accumulator are shown.

The analysis of the ratio of mass, shape and material of the flywheel in order to identify the most profitable option in terms of regenerative qualities and efficiency.
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