Improving the environmental safety of vehicle operation by using flywheel batteries

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Abstract. Despite the fact that according to the largest international organization “Our World in Data”, air pollution mortality is decreasing - mainly due to improved indoor air - this type of environmental pollution is one of the world's leading risk factors. In 2017 approximately 5 million people around the world died from diseases caused by air pollution – strokes, lung cancer, etc. The prevailing part (about 40% of the world's air pollution) occurs when vehicles are used, mainly personal vehicles, which means that it is necessary to develop measures to improve the environmental friendliness of the use of vehicles. Since the exhaust gases of automobile engines contain a large amount of air pollutants, it is possible to limit their emissions by developing and implementing hybrid vehicles with flywheel energy accumulators. The article considers the dimensionless dependence of the current acceleration of the car to its maximum acceleration in the presence and absence of a flywheel in the system, and checks the reliability of the dependence on the stand.

1. Introduction
At the moment, in accordance with new environmental standards and changes in legislation, consumers' interest in cars powered by internal combustion engines is gradually decreasing. There is an increasing number of cars that run either entirely on electricity or in a hybrid way. Hybrid cars use two sources of energy - for example, combustible petroleum products and electricity. The effectiveness of the use of hybrid vehicles has been repeatedly confirmed by multiple studies by scientists from different countries [1 - 6].
2. Main part
By considering the principle of operation of hybrid vehicles, it is necessary to point out that in such vehicles, the power units work together, transferring power to the wheels through a complex transmission. Usually, the electric motor helps the combustion engine when the car is lifting, starting its work, in the process of overtaking. The main engine speed is reduced, wear is slowed down, fuel consumption is reduced, and dynamics remains the same or improves. The principle of operation of some hybrids allows the car to start on electric traction. The best models can travel up to 50–100 km without starting an internal combustion engine - in the city they drive silently, with zero exhaust emissions [7].

There are also hybrid cars in which one axle is driven by a gasoline engine and the other by an electric one. This allows you to increase cross-country ability and improve controllability without complicating the car's layout and almost without increasing the cost of its maintenance [8].

But the active introduction of hybrid vehicles with an electric battery leads to the need to dispose of spent batteries, which has a negative impact on the environmental situation [9-12]. In their production is included a lithium bromide, which is hazardous to human health, as well as cobalt and nickel. Scientists from the American Chemical Society (ACS) have already provided evidence that the compounds contained in lithium-ion batteries are harmful to soil bacteria [13].

Recently, hybrid power plants with braking energy recuperation have become widespread in the world, which reduce energy losses by up to 50%, depending on the frequency of the braking process [14], [15]. In practice, various types of energy accumulators are used, which are most often installed between the motor and the generator, such as electrical, flywheel, mechanical and others [16], [17].

2.1. Perspective energy storage devices
Most often, energy storage devices are subdivided into electrochemical ones, which convert electrical energy into chemical energy of substances, and physical energy storage devices, which transform into mechanical energy.

Electrochemical energy storage includes capacitive storage, molecular energy storage, inductive storage, storage batteries, superconducting inductive storage, etc [18].

Capacitive energy storages are one of the most powerful types of energy sources. They are highly reliable and transfer efficiently stored energy. Low-power chargers can be used to charge them. But due to the low specific energy intensity, it is difficult to create capacitive energy storage devices with stored energy exceeding 10 MJ.

The most common batteries are lead acid. Batteries are considered to be relatively cheap. The main disadvantages are considered to be heavy weight and size, sensitivity to negative temperatures and a limited number of discharge cycles.

Nickel-cadmium batteries are more energy efficient and can also operate at low temperatures. But recently their use has been limited due to the non-environmental friendliness of production and disposal.

Lithium-ion batteries have some advantages - they have a high energy density, a large number of operating cycles. However, they have problems with the storage and operation of the battery at low temperatures and also lose their properties when charged after partial discharge of the battery.

Heat accumulators are capable of storing thermal energy and do not require frequent addition of fuel. The main disadvantages are considered to be long heating, significant dimensions and weight - this creates difficulties in their transportation and assembly.

Unfortunately, at low temperatures, typical of most regions of our country, the properties and resource of all electrochemical storage devices are significantly deteriorated, which does not allow them to be effectively used. Therefore, an important task is to develop such a drive that meets the requirements for durability, reliability and overall dimensions.

The physical storage of electricity mainly includes two types of complexes: kinetic energy storage (flywheels) and gravitational energy storage [19].

In a flywheel accumulator, energy is accumulated and stored in the form of the kinetic energy of the flywheel or its perspective design - a super flywheel, and is released in the form of mechanical rotational
energy. Thus, the type of energy is conserved without conversion, which significantly increases the overall efficiency of the battery. Compared to other energy storage methods, flywheel energy storage systems have a long service life, typically over 20 to 25 years.

Often, a flywheel energy storage unit is combined with devices for converting the type of energy - hydraulic, pneumatic, electric machines, forming an energy storage system. The most widespread are energy storage systems with electric reversible machines (engine-generator) [20].

A flywheel energy storage device based on a super flywheel has one of the highest specific power indicators among existing energy storage devices. And when using modern high-strength materials, for example, graphene tapes (paper), the flywheel battery has the highest specific energy index of all storage devices.

In terms of the specific energy reserve per unit weight, the flywheel accumulator effectively competes with the electric one, differing from it in a higher service life [21]. However, electrical energy represents the greatest convenience for the consumer. Therefore, it is advisable to combine a flywheel battery with a reversible electrical machine controlled by a computer. The flywheel battery is most often installed between the motor and the generator [22].

The flywheel energy accumulator has been found to be the most efficient for use in various fields, including the transport and material handling industry (EERA (European Energy Research Alliance)). Therefore, the best option for this project is the use of a device that would provide braking energy recuperation using a flywheel energy accumulator.

During the Soviet era, according to the results of studies of city buses with hybrid units and variators under the leadership of N.V. Gulia, it was found that fuel consumption is reduced by using flywheel batteries by about half, and the toxicity of exhaust is several times. Advantages and disadvantages of using flywheel energy accumulators have been the subject of research by both Russian and foreign scientists, while increasing the efficiency of installations when using flywheels has been proven [23], [24].

2.2. A hybrid car with a flywheel energy accumulator

This article discusses the scheme of a hybrid car with a flywheel energy accumulator. The ERA international community conducted a study of energy storage methods and confirmed that it can be safely disposed of, which means that it is the most environmentally friendly among other batteries [25].

The recovery of braking energy and its storage in the flywheel is carried out by changing the gear ratio of the variator that connects the flywheel to the transmission of the machine. A dynamic model of a machine with a variable gear ratio is shown in the figure 1.

Figure 1. Block diagram of a machine with a flywheel energy accumulator: 1 - the moment of inertia of the flywheel; 2 - the moment of inertia of the transmission of the machine; 3 – the variator.

There is a need to evaluate the dynamic qualities of a machine with a flywheel energy accumulator, which functions accord to a rational dependence. This estimate can be made using the law of conservation of kinetic energy in differential form which can be written as:

\[
M^\theta_e = J^\theta_k \left( \frac{d\omega_2}{dt} \right) + \left( \frac{dJ^\theta_2}{d\omega_2} \right) \left( \omega_2 \right)^2 / 2
\]  

(1)
where \( J^g_\Sigma = J_2 + \left( U_{12} \right)^2 J_1 \) - the total moment of inertia of the machine, given to the transmission shaft, \( U_{12} = \frac{\omega_1}{\omega_2} = U(t) \) - instantaneous gear ratio of the variator between the transmission shafts and the flywheel, \( M^g_\Sigma \) - the given moment of driving forces and resistance.

With the values given discounted total moment of inertia to the output shaft of the transmission of the machine after replacing variables the given value of the total moment of forces according to the law of conservation of kinetic energy in the differential form takes the form:

\[
M^g_\Sigma = e_2 \left( J_2 + U_{12}^2 (\omega_2) J_1 + U_{12} (\omega_2) \left[ \frac{dU_{12} (\omega_2)}{d\omega_2} \right] J_1 \omega_2 \right)
\]

Since the resulting differential equation is nonlinear, its solution was sought by numerical integration on a computer. When you perform a numerical calculation of the dynamic properties of a car with braking energy recovery, the ratio of the current acceleration of the transmission drive shaft to its maximum value \( (e_2)_{\text{max}} \) at the beginning of acceleration:

\[
\frac{e_2}{(e_2)_{\text{max}}} = \left( 1 + U_{12}^2 (\omega_2) J_2 + U_{21} (\omega_2) \frac{dU_{12} (\omega_2)}{d\omega_2} J_1 \right)^{-1}
\]

Simulated results are shown in figure 2:

**Figure 2.** Dependence of the ratio of the current acceleration of the machine shaft to its maximum value on the ratio of the current speed to its maximum value for energy recovery (curve 1) and without energy recovery (curve 2).

Curve 1 shows that the acceleration of the vehicle \( e_2 \) decreases as its speed \( \omega_2 \) increases, this is typical for solving the first-degree linear equation, which is describing the transient acceleration of a transport vehicle with an internal combustion engine. The physical meaning of this reduction in acceleration towards the end of the movement when accelerating with energy recovery is that by the end of the movement there is a decrease in the kinetic energy of the flywheel and, of course, a decrease in the driving forces. Curve 2 describes the behavior of the same machine at a constant value of the transfer function, which corresponds to acceleration without energy recovery and the absence of a term with a derivative in the equation. Thus, the difference between the values \( e_2 \) of curves 1 and 2 shows how
much acceleration is reduced in the absence of mechanical energy from the flywheel battery operating in engine mode during acceleration. This is natural, since the total power of the main engine and the upper-stage flywheel engine in this case is lower.

A stand for conducting experimental studies was designed and manufactured to test the derived equations.

The scheme of the experimental modeling installation does not have a motor and speed sensors of the links. Measurement of the flywheel rotation angles was performed using a computer after high-speed photography of the movement of the mechanism. The flywheels of the four-ring mechanism exchange energy between themselves by braking one and accelerating the other. The experimental setup is started by setting one of the flywheels in motion. It is not possible to use an individual motor for this purpose, since the movement of the flywheels is reversible with a change in the direction of rotation after stopping.

In the experiment, the angular position of the flywheel was determined, and the gear ratio of the mechanism was determined by differentiating one angle of rotation of the flywheel from another angle, that is:

\[ U_{12} = \frac{d\varphi_1}{d\varphi_2} \]  

Then the law of changing the gear ratio by the angle of rotation of the rocker arm of the mechanism was obtained by calculation and experiment, was compared with the calculated gear ratio between the two rockers of the four-hinge mechanism.

**Figure 3.** Photo of the experimental stand mechanism.

The initial angle corresponding to the extreme (dead) position of the mechanism was assumed to be zero. On each frame, a line was drawn from the axis of rotation of the flywheel to the center of the crank attachment, from which the angle of rotation of the flywheel was counted. Stages of processing an experiment on a computer:

**Figure 4.** Initial position of the mechanism. A.
After that, the angles were measured in increments of 0.04 for each new position. To do this, a line was drawn in each subsequent frame connecting the flywheel rotation axis with the crank mounting axis. The angle between the zero position line and the line marking the disk position on each frame was then measured, as shown in figures B, C, D.

The obtained results of processing two cycles of the experiment on a computer were presented in the figure 8.
Figure 8. Example of experimental dependencies of the oscillations of the flywheel before carrying out the approximation.

Graphs of superimposed oscillations are plotted based on the obtained calculation and experimental data. The deviation of the obtained curves from the theoretical data does not exceed 8%, which is an acceptable order of error [26]. Thus, it is possible to make a conclusion about the possibility of using a flywheel battery in hybrid cars to improve their environmental friendliness, this conclusion is confirmed by the experiment.

It should be noted that if it is necessary to construct a uniquely shaped flywheel according to the original design, it is possible to use additive technologies. Modern printers print at high speeds and are much cheaper than casting experimental flywheel molds in factories. In particular, by modeling a flywheel on a 3D printer, you can get the appearance and combinations of parameters that are relevant for a specific experiment on laboratory facilities [27].

3. Conclusions
1. A flywheel battery can reduce the acceleration time, as well as reduce the total operating time of the internal combustion engine, especially in places of forced stop at the time of driving in the city cycle mode.
2. The use of a hybrid power plant in a vehicle provides significant fuel savings and reduces environmentally harmful emissions.
3. Flywheel energy accumulators have a simple design, high resource, and their disposal causes less damage to the environment than the disposal of electrochemical batteries. 1. The study and calculation of the carbon footprint of hybrid solar-wind installations is an urgent task, the solution of which will help to understand the degree of influence of alternative energy on the environment.

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