The prospects of using flywheel energy accumulators in the lifting and transport industry

N N Barbashov and A A Barkova

1 Department, 2nd Baumanskaya st., 5/1, Moscow, 105005, Russian Federation

E-mail: anastasiia_barkova@mail.ru

Abstract. The increase in the energy consumption of lifting and transport machines in transient operating mode requires the creation of mathematical models and, on their basis, the development of recommendations for increasing economy. Important reasons for reducing the economy of lifting machines are changes in speed and load, deviations from the optimal value and causes an increase in energy dissipation. Another reason for the increase in lost energy is the process of machines with a loss of kinetic energy during their shutting-off. Increasing the economic showings of machines is possible by reducing its nominal power, which leads to a deterioration in dynamic qualities. A promising method of increasing the economy of machines is using of braking energy recovery, its accumulation and using during further acceleration. In this case, the increase of efficiency occurs without reducing the dynamic qualities and showings of the machine.

1. Introduction

Since the significant increase in energy consumption in the Russian Federation, the government adopted the "Energy Strategy of the Russian Federation for the period up to 2035," which indicates a number of main internal problems, including the technological lag of the Russian fuel and energy complex from the level of developed countries and a high level of dependence on imports of some types of equipment, materials and services. Analysis of the dynamics of waste generation showed that the largest volume for the period under study falls on the type of activity "mining"[1].

In order to bring the country's energy sector to a higher, qualitatively new level that maximizes the dynamic socio-economic development of the Russian Federation, the strategy identifies a number of necessary measures, including the promotion of research and development work to increase energy efficiency, and high-efficiency recovery technology as priority technology.

The main reasons for the increase in energy consumption by construction, road and lifting vehicles are their operation in undisclosed modes with frequent alternation of acceleration and braking [2]. In hybrid power settings, the usage of energy recovery can reduce energy losses by up to 50% depending on the frequency of braking processes. Recently, various types of electric and flywheel energy accumulators have been increasingly used in practice in the lifting and transportation industry. More than 20 manufacturers and many research centers are researching flywheel energy batteries, as well as developing prototypes.

Currently, the recovery of braking energy is most often carried out in two ways:
• Using an electric drive in a transport machine and energy recovery with an electric battery. This direction has advantages for applications in electric vehicles. A weak point in the development of this direction is an electric battery with a limited discharge and charging cycle. If it is using in electric vehicles is obvious when recharging once a day, then its using when working with an unidentified acceleration-braking cycle is problematic. Also, certain difficulties arise when using an electric battery in the cold season, for example, the work of loaders in warehouses in unheated rooms.
• Using a flywheel energy accumulator \[3,4\] consisting of a flywheel, a vacuum chamber, and bearings. Mathematical model of the bearing takes into account the centrifugal and Coriolis forces \[5,6,7\]. Since such energy storage devices do not require the conversion of kinetic energy to other types of energy and meet the requirements for specific energy intensity and charging speed \[8\]. Even in electric vehicles, attempts to use flywheel batteries to work in the urban traffic cycle were successful. This success was facilitated by the insignificant amount of pumped energy in one cycle and the high motor resource of mechanical energy recovery devices.

To solve the current problems, it is necessary to develop the theoretical foundations of possible methods for reducing the energy consumption of lifting and transportation machines in unspecified operating modes. In addition, the usage of hybrid lifting and transportation machines has a positive impact on environmental improvement. A large role is played by the complete stop of the ICE during idle in the closed room. And the usage of batteries of significantly lower capacity than in electric vehicles simplifies the problem of recycling used batteries \[9\].

Under the constant increase in cargo transportation and sub-loading and unloading operations, the task of increasing the productivity of lifting machines and reducing the cost of their operation becomes especially urgent.

For example, with an average cycle time of 2 minutes, a crane performs about 250 cycles per shift. According to studies, the loss of kinetic energy of one crane with a lifting capacity of 20t reaches 10,000 kJ per shift.

Energy balance of lifting-transport machine operating in acceleration mode with optimal gear ratio is shown in figure 1. The area of the circle of the diagram is proportional to the useful work of the engine, taken as 100%, and the areas of individual segments are proportional to the shares of the use of this energy. When operating in the "acceleration-braking" mode, the fuel consumption of the lifting and transportation machine increases sharply since the energy loss during braking accumulated during acceleration is much greater than the friction loss and is commensurate with useful work. Therefore, the using of braking work for useful purposes and its transfer to the battery during energy recovery is the most effective method of increasing the economy of machines.

![Figure 1](image)

**Figure 1.** The energy balance of the lifting machine in the "acceleration - braking" cycle: a - the mechanism of movement, b, c - the beginning and end of the descent of cargo.
The use of a flywheel battery allows to significantly reduce energy losses and increase the efficiency of lifting and transportation machines in undisturbed operating modes.

2. Calculation
Consider more detail an unspecified mode consisting of acceleration cycles and subsequent braking of the machine.

To simplify the calculations, it is accepted the idealization of the cycle, consisting in the fact that the values of the total given moments of the forces $M_\Sigma$ and the moments of inertia of the links $J_\Sigma$ are taken constant in the acceleration and braking sections, so the movement on them is uniform with constant accelerations:

$$
\varepsilon_{dr} = \frac{M_\Sigma dr}{J_\Sigma}
$$
$$
\varepsilon_{des} = \frac{M_\Sigma des}{J_\Sigma}
$$

Since the speed and kinetic energy are zero when the mechanism is stopped, the value of the change of the latter will be equal to the value of the kinetic energy reserve at the beginning of braking:

$$
T_{in} = \frac{J_\Sigma \omega_{in}^2}{2}
$$

where: $\omega_{in} = \omega_{max}$ - is the initial velocity before braking.

Braking of the mechanism can be carried out in various ways, for example, switching the engine to generator mode and recovering the generated energy. Some electric motors have this capability. In this case, the engine is switched to the "dynamic" braking mode, and the operation of the applied decelerating torque $M_{des}$ can be accumulated and usefully used. If during braking the engine is switched off ($M_{dr} = 0$) and decelerating torque $M_{des}$ is applied, the total torque takes the form:

$$
M_\Sigma = M_{harm.str} + M_{use.str}
$$

The total shutdown operation will be negative:

$$
\sum A_{br} = \int_{\phi_{ac}}^{\phi_{br}} (M_\Sigma br) d\phi
$$

where: $M_\Sigma = M_{dr} + M_{des}$ – total equivalent moment, $M_{dr}$ – equivalent moment of engine.

Modules of operations during acceleration and during shutdown are equal to each other:

$$
|\sum A_{ac}| = |\sum A_{br}|
$$

Assuming that acceleration and braking are carried out at constant values of the given moments of forces and moments of inertia, a connection between the driving moment during acceleration and the braking moment during shutdown can be found, as well as the angular coordinate of the $\phi_{sw}$ of switching from acceleration to braking:

$$
(M_\Sigma ac)\phi_{ac} = (M_\Sigma br)\phi_{br}
$$

where: $\phi_{ac} = \phi_{sw}$ – path traversed by the reduction link during acceleration: $\phi_{br}$ – path traversed by the reduction link during braking.
The above equation is an energy condition of the idealized acceleration-braking cycle. Under the accepted assumptions in the "acceleration-braking" cycle, the movement is equally accelerated or equally slow with constant accelerations:

$$\varepsilon_{ac} = \frac{M\Sigma ac}{J_\Sigma}$$

$$\varepsilon_{br} = \frac{M\Sigma br}{J_\Sigma}$$

where: $J_\Sigma$ - total equivalent moment of inertia.

The maximum $\omega_{\text{max}}$ speed in the cycle can be found from the condition of equality of the maximum value of kinetic energy and the operation of driving forces, for example, by the equation of motion in the energy form:

$$T_{\text{max}} = \frac{J_\Sigma}{2} \omega_{\text{max}}^2 = \left( \sum A_{ac} \right) = (M\Sigma ac) \varphi_{ac}$$

where: $\omega_{\text{max}} = \sqrt{\frac{2(\sum A_{ac})}{J_\Sigma}}$ - maximum speed during one cycle.

Thereafter the relationship between the $\omega_{\text{max}}$ and the angular path in the cycle can be found:

$$\varphi_{cycle} = \varphi_{ac} + \varphi_{br}$$

The driving time in the idealized cycle can be found as the sum of the acceleration and braking time:

$$\tau_{\text{cycle}} = \tau_{ac} + \tau_{br}$$

where: $\tau_{ac} = \frac{\omega_{\text{max}}}{\varepsilon_{ac}} = \frac{\omega_{\text{max}}f_\Sigma}{M\Sigma ac}$ - acceleration time,

$$\tau_{br} = \frac{\omega_{\text{max}}f_\Sigma}{M\Sigma br}$$. deceleration time.

For real lift vehicles, the engine power is less than the brake power, so the braking time is usually less than the acceleration time:

$$\varphi_{ac} = \frac{f_\Sigma \omega_{\text{max}}}{2(M\Sigma ac)}$$ - the way acceleration,

$$\varphi_{br} = \frac{f_\Sigma \omega_{\text{max}}}{2(M\Sigma br)}$$ - the way braking.

Therefore, the dynamics of the acceleration-braking cycle is largely determined by the acceleration time, depending on the "excess" engine power and the given maximum speed $\omega_{\text{max}}$. The dependence of the dynamic qualities of the machine in the form of a ratio $\frac{\tau_{ac}}{\tau_{min}}$ on the share of engine power use during acceleration $k_w = \left( \frac{M_{str}}{M_{dr}} \right)^{SW}$ is presented in the form:

$$\frac{\tau_{ac}}{\tau_{min}} = \frac{1}{(1-k_w)}$$

$$\frac{\varphi_{ac}}{\varphi_{min}} = \frac{1}{(1-k_w)}$$

where: $\tau_{min} = \frac{\omega_{\text{max}}f_\Sigma}{M_{dr}}$ - minimum possible acceleration time of the machine without load.
3. Conclusion
The acceleration-braking cycle has the highest dynamic qualities at constant values of force moments in individual sections.

Studies prove that the use of energy recovery during braking allows not only to maintain high dynamic qualities of machines, but also to significantly improve economic qualities.

The development of the basis for the design and effective use of lift-transport machines with a flywheel energy accumulator is an important and promising task of modern mechanical engineering.

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