

FROM THE POTTER'S WHEEL TO MODERN AUTOMOBILES (The flywheel through the ages)

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Abstract. The present paper is a survey of super-flywheel usage over centuries. Several aspects of use of super-flywheel for accumulating kinetic energy in industry and vehicles as additional source of energy are considered. The possibilities for recuperation of energy during the braking modes of vehicle for the most common cycles of urban transport (“European” and “American”) have been determined. The efficiency of such an energy recovery system is evaluated, of course, but keeping in mind its pros and cons. Some results of the author activity in the field of usage of Super-flywheels, the author’s collaborators and Ph. D. students, developments and achievements of leading world companies are enlisted.

Keywords: flywheel, super-flywheel, Kinetic Energy Resovery System (KERS), hybrid propulsion systems, urban cycles of the vehicle.

1. INTRODUCTION

In industry and transport technology, the flywheel in most cases is a rotating body with significant main moment of inertia [kgm^2] compared to the other parts of the mechanical system.

Its first analogue has been known since ancient times as the pottery’s wheel, where the sculptor drives his work table directly with foot or by means of elementary crank–fork mechanism, Fig. 1.

During the first industrial revolution about two hundred years ago, after the appearance of the steam engine, the flywheel was a vital element of it. Its initial purpose was to overcome the so-called dead positions, and subsequently it carried out the energy transfer within a period of the stationary (steady

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state) motion to ensure a certain degree of non-uniformity of the angular velocity of the main shaft of the machine.

Due to relatively low speeds of that time, the dimensions of the flywheels are significant, Fig. 2.



Fig. 1. Pottery wheel

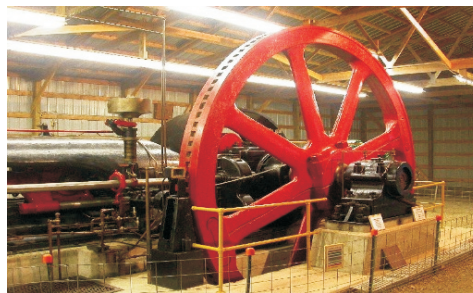


Fig. 2. The flywheel of steam engine

With increasing operating speeds, its dimensions are reduced remarkably. At present, in explicit form, as a separate machine element it exists in construction of almost every energy or technological machine – Internal Combustion Engines (ICE), piston pumps, compressors, presses, dies, pins, etc.

In the sixties of the last century, the idea of using the kinetic energy when stopping the vehicle by accumulating it in a high speed flywheel, called “super-flywheel” arose. One of the apologists for this idea is Prof. D. W. Rabenhorst from the “Johns Hopkins” University, USA, who created a research laboratory whose main activity was to study the application of super-flywheels in vehicles technology and industry [1–2].

The conditional speed limit between classic and high-speed flywheels is 1000 [1/s] (10000 [tr/min]) [3]. The first are usually monolithic, made of cast iron or steel, and practice has proven their safety from the point of view of risk assessment, i.e. the stresses generated by the centrifugal inertial field are far from the permissible ones for the respective material. Their predominant form is usually a disk, most often in combination with a clutch, recently they are rarely seen as a ring with spokes and a hub [4].

Modern super-flywheels have the shape of a disk made of coiled threads or ribbons or a combination of these. The materials from which they are made are mainly composites of the type of C-phazer HT with an allowable tensile stress of 2370 [MN/m²], or C-phazer IMER – 3450 [MN/m²], or mostly a bundle of carbon threads in a polymer or graphite C–C matrix, with even higher additional stresses.

2. MODERN SUPER-FLYWHEELS; MAIN CHARACTERISTICS

It is relatively easy to prove that the ideal flywheel for energy storage should be light and made of material with great strength. If we consider a thin toroidal thread, rotating with an angular velocity ω around its main axis of inertia, a one dimensional stressed state (tensile) can be assumed with great confidence, which has the form:

$$\sigma_{on} = \rho v^2, \quad (1)$$

where ρ [kg/m³] is the density of the material, v [m/s] – peripheral linear velocity.

The specific energy capacity K_e of the thread represents the ratio of the accumulated energy to its mass, i.e.:

$$K_e = \frac{E}{m} = \frac{1}{2} v^2 \quad \text{or} \quad K_e = \frac{1}{2} \frac{\sigma_{on}}{\rho}, \quad (2)$$

which confirms the above statement, or in the case of a real flywheel K_e is directly proportional to σ_{on} [N/m²] and inversely proportional to ρ [kg/m³] of the material

$$K_e \Rightarrow \frac{\sigma_{on}}{\rho}. \quad (3)$$

Several other coefficients have been introduced in the theory of super-flywheels, namely:

– energy density coefficient

$$K_p = \frac{E}{V} \quad \left[\frac{\text{kJ}}{\text{m}^3} \right], \quad (4)$$

where E is the largest possible value of accumulated energy [kJ], V – flywheel volume [m³];

– the form factor K shows how efficiently the material is used, and for a flywheel with the equal speed shape, this coefficient is assumed to be unity [4];

– speed coefficient

$$\xi = \frac{\omega}{\omega_0}, \quad (5)$$

where ω is the allowable angular speed of the flywheel, and the same speed of the toroidal thread for the same material, ω_0 – the same speed of the toroidal thread for the same material;

– coefficient of specific power

$$K_m = \frac{P}{m} \quad \left[\frac{\text{W}}{\text{kg}} \right], \quad (6)$$

i.e. maximum power per unit mass.

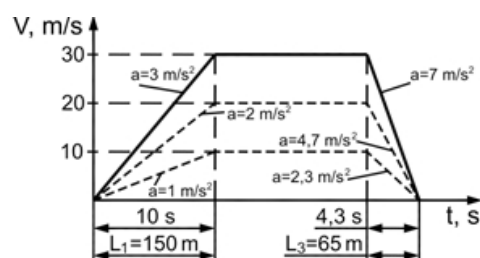


Fig. 3. The elementary speed cycle



Fig. 4. Flywheel of the “Jyrobuss”

For the first time, the flywheel as a primary source of energy is used to propel a trolley between the stops, with intermediate energy loading there, working in so-called elementary speed cycles, Fig. 3. This is the first application into a means of transport that became in Switzerland in the seventies of last century with the so-called “Jyrobuss”, Fig. 4. The flywheel, made in the shape of a large steel disk, which together with the electric motor is enclosed in a steel casting to reduce aerodynamic losses and safety. Figure 5 shows the modern KERS for City-Bus.

For the needs of the physical study of the plasma, a system has been implemented by means of which a rotor with a mass of several to 5E5 kilograms is braked in a very strong electromagnetic field, gaining the name “Tokamak”, the flywheel of which is shown in Fig. 6.

Figure 7 depicts a quasi-cylindrical super-flywheel consisting of a steel thread freely wound on solid aluminum spokes ending with a rectangular fork [4]. In this construction, virtually each single strand is loaded in tension only,



Fig. 5. Kinetic Energy Resovery System (KERS) for Passenger-buss [5]

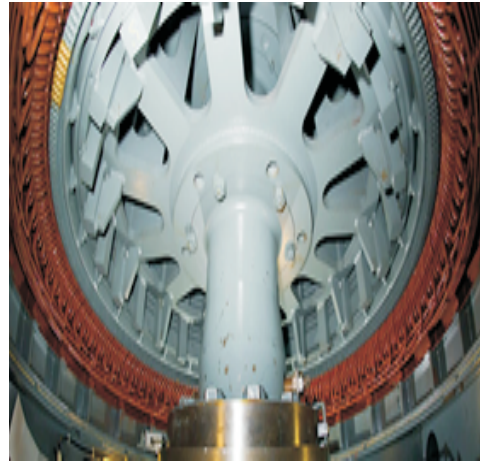


Fig. 6. "Tokamak's" rotor

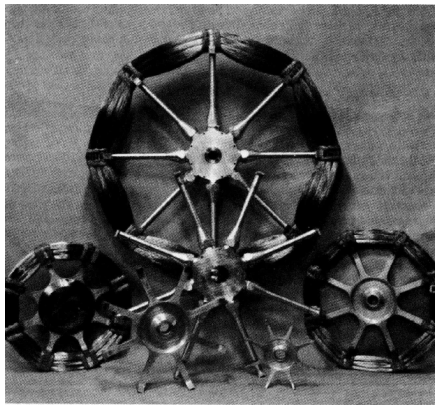


Fig. 7. Quasi-cylindrical super-flywheel

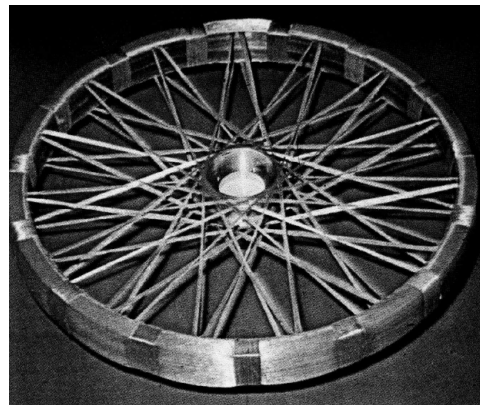


Fig. 8. Kevlar super-flywheel

see (1). The rectangular forks have the purpose of keeping the threads in the axial direction.

In Figure 8, a super-flywheel is produced by winding Kevlar fibers on a thin epoxy resin cylinder and again elastic Kevlar fibers are used for spokes [4].

Figure 9 shows a modern super-flywheel wound from pre-stressed carbon threads in a polymer or graphite matrix on an aluminum hub.

Figure 10 depicts the sequential operations of resin coating carbon or glass fibers rings already produced in polymer matrices and subsequent compression

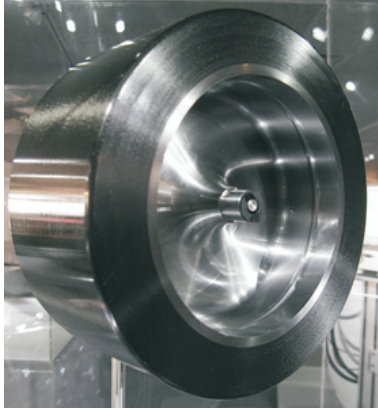


Fig. 9. Modern super-flywheel from preliminary stressed carbon threads

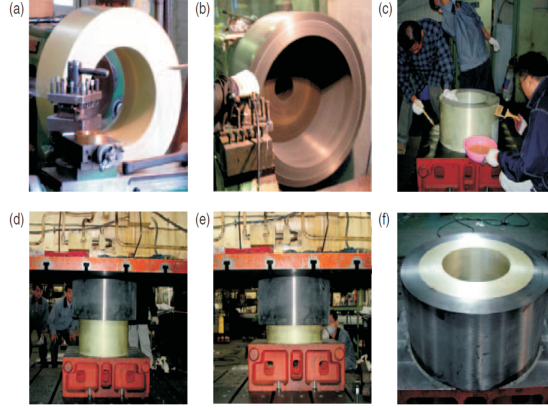


Fig. 10. Sequential operations in the production of a contemporary super-flywheel

[6–7]. To achieve large values of radial and tangential stresses in the rings, a force of the order of 0.1 to 1 [MN] is applied depending on the size of the flywheel and its angular velocity.

3. THEORETICAL CONSIDERATION

3.1. Notation and basic dependencies

The energy per unit mass of the vehicle obtained by the main engine, required for its acceleration and movement at a constant speed, can be represented by the expression:

$$E_{\dot{v}>0} = \frac{1}{\eta_1} \sum_{i=1}^{n-1} \left\{ \frac{\delta}{2} |v_i^2 - v_{i+1}^2| + g(f \pm \sin \alpha) \int_{t_i}^{t_{i+1}} v \, dt + k_v \int_{t_i}^{t_{i+1}} v^3 \, dt \right\}, \quad (7)$$

where the intervals t_i, t_{i+1} are these in which the acceleration is positive or zero in [s]; g [m/s²] is the ground acceleration; $f = 0.008 \div 0.012$ [–] is the rolling friction coefficient; k_v [1/m] is the aerodynamic drag coefficient of the vehicle, $k_v = (3 \div 5) 10^{-4}$ [1/m]; η_1 [–] is the efficiency coefficient of the transmission, $\eta_1 = 0.75 \div 0.92$; $\delta = 1.06 \div 1.1$ [–] is the coefficient of rotating mass.

The energy per unit mass that could be recovered when the vehicle is

stopped in an analogous way is represented by the relationship:

$$E_{\dot{v}<0} = \eta_2 \sum_{i=1}^{n-1} \left\{ \frac{\delta}{2} |v_i^{*2} - v_{i+1}^{*2}| - g(f \pm \sin \alpha) \int_{t_i^*}^{t_{i+1}^*} v \, dt - k_v \int_{t_i^*}^{t_{i+1}^*} v^3 \, dt \right\}, \quad (8)$$

where the time intervals t_i^*, t_{i+1}^* [s] are similar to above, i.e. the acceleration is negative; η_2 [-] is the efficiency coefficient of the transmission – from the running wheels to the battery, (0.60–0.85).

The relationship (8) represents what part of the input energy for acceleration and constant speed – the expression (7), can be restored in some kind of accumulator. The ratio of the energies for one urban cycle E – the relationship (8), to E – the expression (7), is a recuperation coefficient k_r that shows how much of the input energy can be restored in some kind of accumulator:

$$k_r = \frac{E_{\dot{v}<0}}{E_{\dot{v}>0}} 100$$

$$= \eta_\Sigma \frac{\sum_{i=1}^{n-1} \left\{ \frac{\delta}{2} |v_i^{*2} - v_{i+1}^{*2}| - g(f \pm \sin \alpha) \int_{t_i^*}^{t_{i+1}^*} v \, dt - k_v \int_{t_i^*}^{t_{i+1}^*} v^3 \, dt \right\}}{\sum_{i=1}^{n-1} \left\{ \frac{\delta}{2} |v_i^2 - v_{i+1}^2| + g(f \pm \sin \alpha) \int_{t_i}^{t_{i+1}} v \, dt + k_v \int_{t_i}^{t_{i+1}} v^3 \, dt \right\}} 100, \quad (9)$$

where $\eta_\Sigma = \eta_1 \eta_2 = (0.4 \div 0.8)$.

The coefficient k_r as a function of $v_{\max}$ (maximum velocity) in consecutive series of elementary cycles is shown in Fig. 11, as well as at zero slope of the road ($\alpha = 0$), $\eta_\Sigma = 0.72$, $k_v = 4 \times 10^{-4}$ [1/m], $\delta = 1.1$ and different rolling frictions f [m] and two slopes of the road in Fig. 12

For modelling and simulating the energy consumption of transport vehicles of the million city in the world database there are several scientifically and empirically established high-speed transport cycles, the most successful of which are the so-called “European” and “American” ones, Figs 13 and 14 [8]. For a specific energy-realized urban transport cycle, the car mileage is defined by the integral:

$$L_i = \int_0^T v(t).dt, \quad (i = 1 \dots N). \quad (10)$$

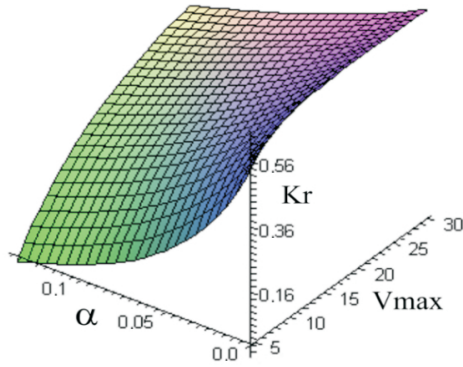


Fig. 11. k_r as a function of α and $v_{\max}$

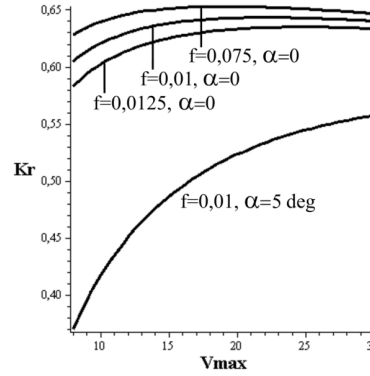


Fig. 12. k_r as a function of $v_{\max}$, α and f

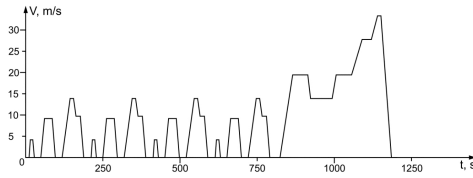


Fig. 13. “European” urban cycle

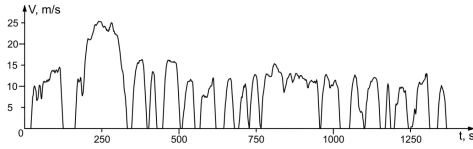


Fig. 14. “American” urban cycle

In a specific cycle, the mileage of an electric classic automobile with the structure diagram shown in Fig. 15, containing electric battery – 1, inverter – 2, frequency-controlled asynchronous motor – 3, clutch – 4, reducer – 5, and running wheels, without recuperation of energy during braking depends on the balance of the energies:

$$Q \cdot \eta_{\text{bat}} \cdot \eta = N \cdot E_{V \bullet \geq 0}, \quad (11)$$

where Q is the capacity of battery [kWh]; N is the number of cycles [-]; m is the mass of the vehicle [kg]; T is the time of the cycle [s], η_{bat} and η are the efficiencies of the battery and the mechanical losses, respectively, [-].

The mileage of the electro-mobile for the two specific urban cycles “Eu” and “USA” can be calculated by means of the relationship:

$$L = N \cdot L_i = N \cdot \int_0^T v(t) \cdot dt, \quad (12)$$

where L is the mileage for one cycle [km].

For example, at $m = 100$ [kg], $f = 0.01$ [-], $\eta_b \cdot \eta = 0.85$ [-], $Q = 20$ [kWh] $= 7.2E7$, $\alpha = 0$ [-], the mileage per one charge, for the two urban transport cycles the following results are obtained:

$$L^{\text{Eu}} = 169.9 \text{ [km]} \text{ and } L^{\text{USA}} = 165.4 \text{ [km]}.$$

The results obtained experimentally are very close to those of the leading automotive company [8, 9].

When regenerating for a part of energy by stopping of the vehicle with structure including a battery – 1, inverter – 2, frequency controlled electro motor-generators – 3 and 5, gear reducer – 4 and flywheel – 6, Fig. 16, the energy balance can be expressed as:

$$Q \cdot \eta_{\text{bat}} \cdot \eta = N \cdot E_V \cdot \prec 0. \quad (13)$$

With an average coefficient of recovery $k_r = 0.45$, for the two urban cycles the following results are calculated:

$$L^{\text{Eu}} = 196.5 \text{ [km]} \text{ and } L^{\text{USA}} = 205.9 \text{ [km]},$$

which is a percentage increase from 16.6 [%] and 24.5 [%], respectively, and proves the expediency of using the energy from stopping the vehicle.

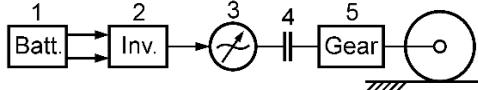


Fig. 15. Structure of a classic electric car

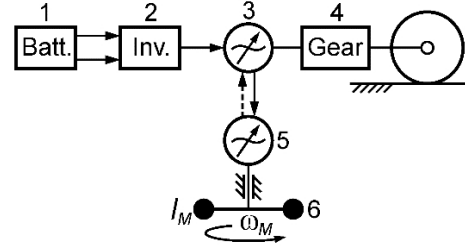


Fig. 16. Electric car with KERS

3.1.1. Dynamical problems

A characteristic feature of the modern kinetic accumulators is that they work in a transient mode when the angular velocity changes in the range $(0.3 - 1.0) \omega_{\text{max}}$ at a very small gradient in the region between the first and second resonances.

This is due to the high speeds and the rigid suspension of the flywheel. The presence of unstable frequency zones in the region of the first resonance can be demonstrated theoretically and experimentally.

Figure 17 depicts a dynamic model of a rotor suspended in a homogeneous elastic-dissipative field with six degrees of freedom.

After changing the quasi-static transition (in both directions – speed increase/decrease) through the main resonance by the average method, the moments of the driving and resisting forces are plotted in Fig. 18. The two unstable frequency zones are shown with the different colors (green – magnification; blue – reduction) [10–11].

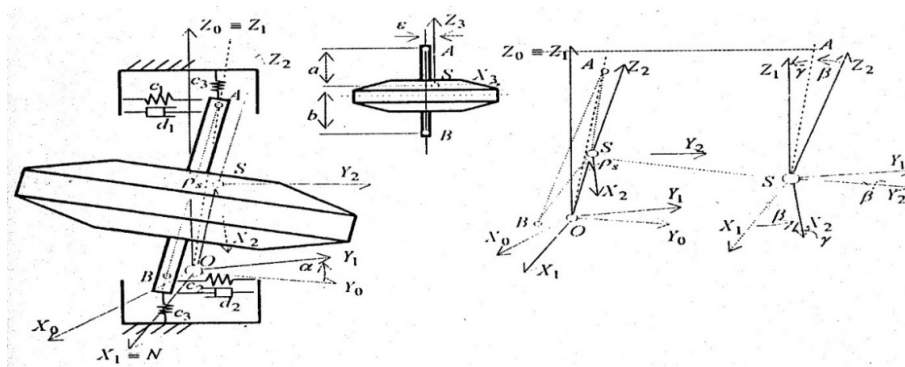


Fig. 17. Dynamic model of elastically suspended super-flywheel

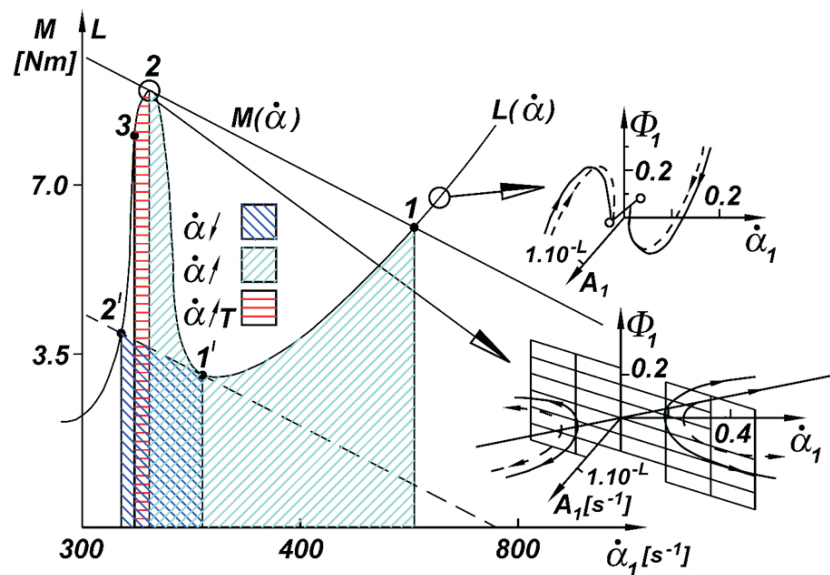


Fig. 18. Unstable frequency zones

3.1.2. Experimental research and analysis

In the Laboratory of Kinetic Accumulators of the Faculty of Industrial Technology (FIT) of the TU–Sofia, a computerized system (stand) was built, animated and brought in life for simulated field studies of KERS for a city bus with volumetric hydrostatic machines. Its main elements and hydraulic scheme are shown in Figs 19 and 20, respectively, [12].

After a start command – the energy storage system, energy transfer between the main and secondary (simulating the mass of the vehicle) flywheels starts

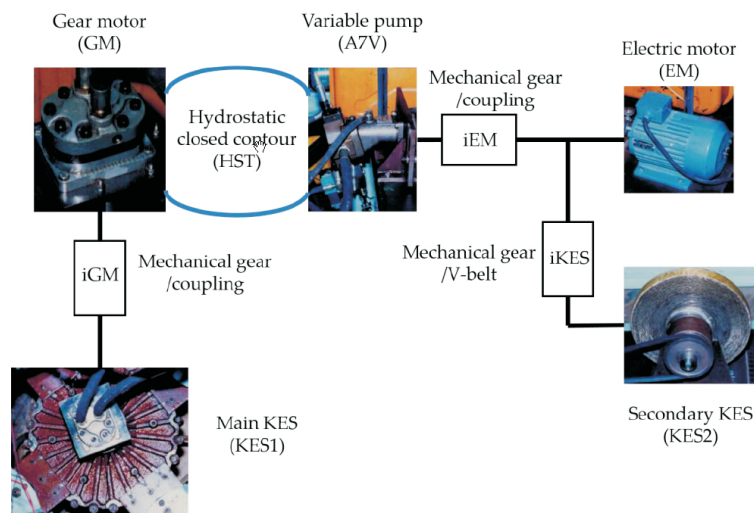


Fig. 19. Structural scheme of the test Stand

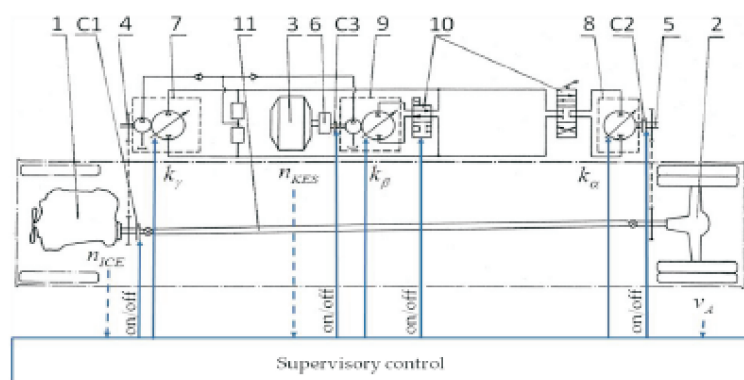


Fig. 20. Hydraulic scheme of the Stand

to work at a preset speed cycle and the protocol for the specific experiment is automatically issued.

To prove the existence of an unstable frequency zone of the forced vibrations at a monotonically increasing angular velocity (the green area in Fig. 18), a recording of the horizontal oscillations (see Fig. 21) in the upper bearing of the main flywheel was made (main KES in Fig. 19) [11].

The verification was made by superimposing the preset speed cycle – with solid lines, and the one realized by the “vehicle” – with the lines of asterisks, Fig. 22, [12].

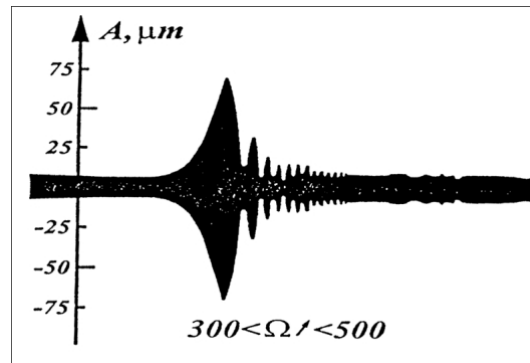


Fig. 21. Experimental record of transition through the first resonance

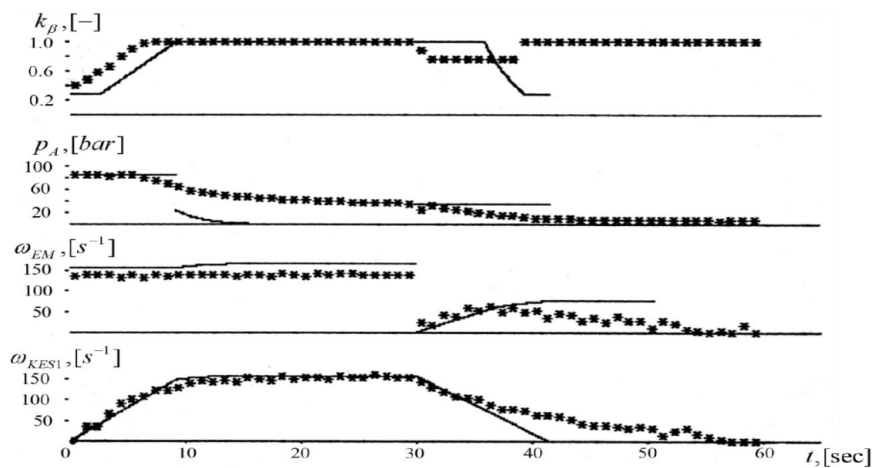


Fig. 22. Comparative analysis results; approximate theoretical model – solid line; experimental data – ****

4. SUPER-FLYWHEELS IN TRANSPORT AND INDUSTRIAL IMPLEMENTATION

Non-stationary and stationary accumulators based on the KERS are found in:

4.1. Transport vehicles as additional energy sources

- Figure 23: Heavy vehicles with a speed of flywheel 6500 [1/s] encapsulated in a vacuum medium. Power transfer to and from flywheel is based on electro-magnetic torque transmission with a power of up to 60 [kW]. The overall mass of the unit is reported 15 of about 20 [kg] [13–14].

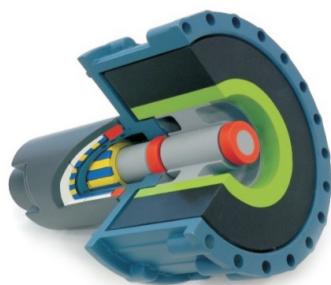


Fig. 23. KERS for heavy vehicle

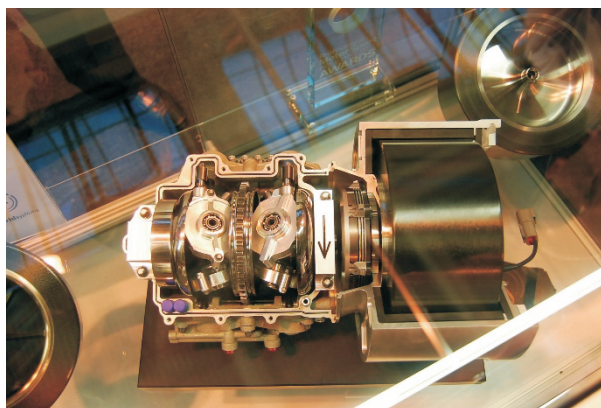


Fig. 24. Super-flywheel in “Formula” one

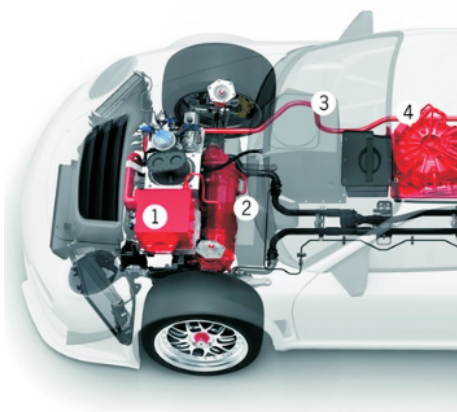


Fig. 25. Porsche 911 GT 3 R Hybrid – Super-Flywheel [15]: 1 – electrical appliance; 2 – electro motor/generators; 4 – flywheel with motor/generator up to 80 [kW] over three to five seconds. All unit has a volume $4 \cdot 10^{-2} \text{ [m}^3\text{]}$

- Figure 24: “Formula’s car” with Friction Continuous Variable, including the power flow in parallel with ICE [15]. Energy charging takes place after the car has entered the corner due to the need for a sharp reduction in the speed and after leaving the curve, the kinetic accumulator will be able to add extra power in the order of 60 [kW].
- Figure 25: Sports car for rich customers including classic rear-wheel drive with ICE, front transmission with two reversible electric machines, control, cooling, lubrication, and safety systems, power electronics, and a super-flywheel, the heart of which is the rotor with motor/generator [7, 16].

4.2. Stationary based power

- Figures 26 and 27: At the beginning of the century, stationary kinetic accumulators with a maximum power in the range of 10 to 400 [kW] were put into regular production and offered by several companies on the market. They generally consist of a flywheel, motor/generator, a preserved vacuum, control system, as well as an electrical input-output (constant and alternating current with standard parameters) [15, 17–18].

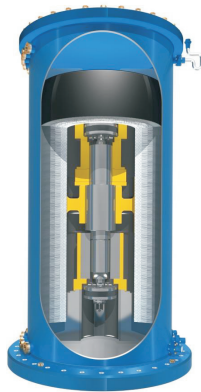


Fig. 26. Wind power station

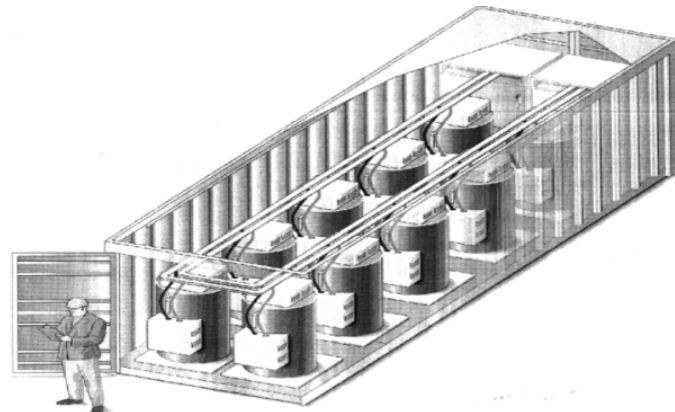


Fig. 27. Package of KERSW

- Figure 28: As a variety of substations along the large railway highways with direct-current power supply, as well as various lifting facilities (hydraulic elevators, container-handling equipment at large ports, Uninterruptible Power Systems, stationary storage power devices with general purpose, etc.) [19–22].

Kinetic accumulators are very suitable for this purpose thanks to the possibility of transferring large powers, in which case their price does not grow



Fig. 28. Substation along the largest railway high-lines

directly proportional to the power – something inherent in other accumulator systems (with ultra capacitors, electro-chemical ones etc.).

They have proven their right to exist, and similar substations have already been built along main railway lines – highway, in the USA and EU (Spain) with power up to 500 [kW].

In the eighties of the last century, under leadership of Prof. Iv. Popov Corresponding Member of BAS, an electric car (MAHOCAR) with kinetic energy accumulator was designed and produced in our country for the needs of Flexible Production Systems (GAPS in Bulgarian) [23–24].

The design and manufacture of an asynchronous motor/generator with frequency control for embedding in the flywheel, inverter and capacitor battery were assigned to specialists from the Institute of Electro Industry (IEI).

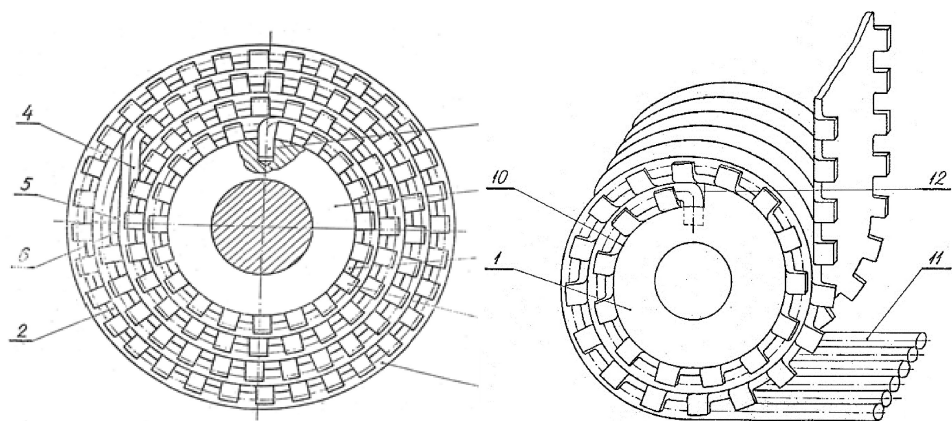


Fig. 29. Super-flywheel with pre-tensioned threads and strips

Colleagues from TU–Sofia made a flywheel (dimensions $\Phi = 0.85$ [m], $L = 0.65$ [m], $\Omega = 600$ [1/s]) from pre-tensioned steel threads and strips, a system for security and suspension on the platform electric car “BOLKANCAR”, Fig. 29. Prof. Popov’s requirement was that everything be produced with Bulgarian materials, or he liked to express himself “with orthodox materials” [7, 25].

The natural tests and 72-hours operation were conducted according to Bulgarian Standards at the Base of the IEI in the city of Zemen.

5. CONCLUSION

It may sound fantastic to use kinematic accumulators (KERS) instead of peak power stations (plants), replacing the well-known “pumped-accumulator” ones. Instead of pumps/turbines, pipelines, lake, dam wall, etc., a kinetic accumulator with a monolithic flywheel about ten meters and a maximum rotation speed of 80 [1/s] with a built-in reversible electric machine, canned vacuum, inverter, control system etc. can be installed underground. With these dimensions of KERS, the accumulated energy would be of the order of 3E3 mega joules (about hundred at a maximum tension in the flywheel up to 1E3 mega watts in the course of one hour), at a maximum tension in the flywheel up to 1E3 [MN/m²], which is completely acceptable for high-strength steels.

Another future application of KERS would be in space, where losses would be minimal (natural vacuum, weightlessness, etc.).

The elimination of the largest drawback of kinetic accumulators – their discharge over time as a result of the frictional forces in the bearing assembly and aerodynamic losses, with the application of modern technologies and materials, will perhaps open the way for their even wider use in technique.

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