

LABORATORY MODELS – SOLUTIONS FOR THE STUDY OF THE HYBRID ELECTRICAL SYSTEMS OF TRACTION AND SUPPLY, WITH APPLICATIONS IN CARS

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Abstract: *The paper presents two structures of hybrid operation systems, alongside the design data, and the facilities that they permit. In addition, the supply solutions are presented with various combinations of electric power sources.*

1. INTRODUCTION

The car, in its classical form, has exceeded its centenary. Some one hundred years ago, the Ford cars had already become an actuality – and that was only the beginning! The engine outdid the electric motor with respect to the propulsion system of the car, the Ford mark A got the better of the electric car, discovered around 1834, on account of the advantage represented by the primary energy source, i.e. oil.

The road covered by the car ever since has been tantamount to permanent innovation, as a direct consequence of its commercial success. The spreading of cars has seen an unbroken evolution, with only few hitches, as the car has become today a means of transportation without which economic life – and not only it – would be hard to conceive. Economy is dependent on the existence of cars in two ways: that of the transport effected by it, and that of the proportion of the population busy in the automotive industry. The interventions of the various states in support of the car industry, especially in the current crisis periods, stand proof to its impact within the sphere of labor force. Dr Dieter Zetsche, president of the European Automobile Manufacturers' Association (ACEA) and chief

executive of German carmaker Daimler AG, remarked that the entire European automotive industry provides 2.2 million direct jobs, and indirect employment for almost 10 million families [1].

Yet, as nothing in actual existence is perfect, the car also assumes disadvantages. The pollution cars produce has manifold consequences on the environment, and, implicitly, on man, who is in fact its beneficiary.

Oil, ever since its recognition as the main primary source for the means of transportation, has become a bone of contention, which generates regional, or even world-wide tension. That aspect, doubled by the pollution produced by its burning, and the prospect of the depletion of the existing oil resources, have determined an intensification of research in the field of finding the sources likely to replace the tank filled with petrol or diesel fuel. As it happened in several other cases in the past, hopes went towards the electric sources. Still, as the accumulator fails, this time too, to be an optimal variant, a compromise was reached, i.e. the hybrid electric vehicle, or HEV. In an HEV, the electric motor is used, in addition to the engine, while the accumulator occurs alongside the petrol tank, in the car supply. The appearance of the electric

motor in the propulsion system can be likened to the advent of the transistor as part of the electric equipment of cars; far from being a mere attempt or a transitional solution, the transistor represented the only way to achieve today's complex systems of conducting the processes of supply and combustion in engines, which was meant to concomitantly solve the problems of pollution and consumption. On the other hand, other electronic and mechatronics equipments conduce to increased comfort and driving security. Therefore, not only did the transistor fail to disappear from the technology of the automotive electrical equipments, but it has also become a unanimously accepted reality. A similar destiny can be predicted for the electric motor in car propulsion, resulting in its increasingly forceful recognition.

The signal for a revolution in automotive technology was given by the launching of the HEV Toyota Prius. The electric hybrid car variant is a convenient bridge towards the purely electric variant, an already accepted compromise, which can give [2]:

- to carmakers, a respite allowing them to choose the suitable technology in keeping with an infrastructure capable of rapid development;
- to the oil suppliers, a period of relative calm, determined by the existence of a market for their products, as the transition to a different variant is not made abruptly;
- a temperate attitude from the oil suppliers;
- a dynamic evolution of R-D in the field of the energy sources: that of the batteries of accumulators and/or the combustion hydrogen piles;
- a way to speed the dynamics of economic life, new horizons.

Car manufacturers announce the immediate, or proximal, launching of new car variants.

The issue of manufacturing several HEV variants assumes more than one modalities: starting from an already existing platform, and redesigning the propelling, supply and process-conducting systems or/and simulation [7]; realizing a new design; using the laboratory functional models [8], [9], [10], on a larger or smaller scale; combined methods.

We have used, as part of the work conducted within the research Centre ELECTROMET of the University in Pitesti, the technology based on realizing a laboratory

functional models, which is a combination between a HEV powertrain and a part of dynamometer. This laboratory model is closer by a real vehicle. Another laboratory stands [8], [9], [10], are pure electric to far from real vehicle.

2. A CONCEPTION OF REALIZING A LABORATORY MODEL

A classic vehicle can be assimilated to the model in Figure 1, where the drive/traction engine develops angle speed Ω_E and a torque M_E . In keeping with the transmission ratio i_1 in the gearbox, the torque will be, at the exit from the latter, M_i , and the angle speed Ω_i . In the differential D the final ration will be i_f , and the wheel torque M_R , and the angle speed Ω_R .

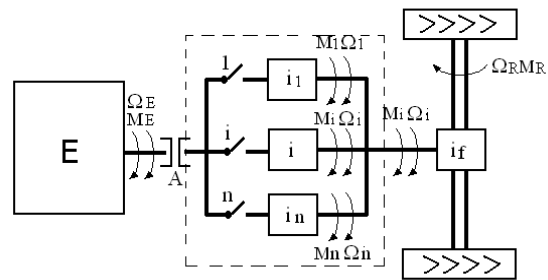


Fig.1. The structure of the classic car

We have modeled the mass of the vehicle by means of a flywheel, the inertial moment of which is calculated out of energy considerations: the kinetic energy of the car at speed v_a should be equal to the kinetic energy of the flywheel at the angle speed Ω_v imposed:

$$\frac{1}{2} J_v \Omega_v^2 = \frac{1}{2} m_a v_a^2 \quad (1)$$

If we consider the relationship holding between v_a , the angle speed of wheel Ω_R , and the running radius of wheel r_R , we will get:

$$J_v = m_a \left(\frac{\Omega_R}{\Omega_v} r_R \right)^2 \quad (2)$$

$$J_v = m_a \left(\frac{\Omega_E}{i \cdot \Omega_v} r_R \right)^2 \quad (3)$$

where:

Ω_E – the angle speed of the engine

i – the total transmission ratio from the engine to the wheel, in this case $i = i_i \cdot i_f$.

In order to get a flywheel as small as possible, it is imperative that Ω_V should be as high as possible, while it cannot exceed the rotation ratio of the engine.

It is also recommendable that ω_V should observe the relationship:

$$\frac{\Omega_E}{i_i} = \Omega_V \quad (4)$$

In other words, we can conduct the modeling of the vehicle through a flywheel driven by a rotation ratio Ω_V placed within the interval:

$$\Omega_R \leq \Omega_V \leq \Omega_E \quad (5)$$

In making the initial calculation of the flywheel, we started from $m_a = 300 \text{ kg}$ and $v_a = 15.55 \text{ m/s}$ imposing that $\Omega_V = 50\pi \text{ rad/s}$. Under such conditions, the resulting inertial moment was $J = 2.94 \text{ kgm}^2$.

Once the flywheel realized (Fig. 2), the question arises if the modeling can be done, with the same device, of a different vehicle of mass m_{a1} and speed v_{a1} , other than the initial ones:

$$\begin{aligned} m_{a1} &= k_m \cdot m_a \\ v_{a1} &= k_v \cdot v_a \end{aligned} \quad (6)$$

where:

k_m – represents the mass ratio m_{a1}/m_a ;

k_v – represents the ratio of the speed of the two cars: v_{a1}/v_a .



Fig.2. The balancing flywheel

The flywheel must be driven to another angle speed Ω_{V1} , such that:

$$m_{a1} \cdot v_{a1}^2 = J \cdot \Omega_{V1}^2 \quad (7)$$

It follows that:

$$\Omega_{V1} = \Omega_V \cdot k_v \cdot \sqrt{k_m} \quad (8)$$

Consequently, providing that the engine is capable to do it, one other vehicle can be modeled with respect relation (8). It can be noted that the flywheel security (especially related to the material used) must be in the designer's attention. Thus, the angle speed must not exceed the some admissible limits.

Basically, the greatest impact on the new resulting angle speed Ω_{V1} is represented by coefficient k_v . The above reasoning indicates that such a flywheel can model a larger category of small-class vehicles. So, this could justify the used solution, even it is rather hard to implement.

The flywheel also models one of the advance resistances, namely the resistance to acceleration. There follow the modeling of the other components of the advance resistances: resistance to running, air resistance, and uphill resistance. That was made by means of a generator with separate excitation. The latter power, P_G , has to be:

$$\begin{aligned} P_G \geq & f \cdot m_a \cdot g(\cos \alpha)v_a + 0,5\rho c_x A_f v_a^3 + \\ & + m_a g(\sin \alpha)v_a \end{aligned} \quad (9)$$

where:

f – the coefficient of running resistance, 0.009;

g – gravitational acceleration, 9.81 m/s^2 ;

α – the angle of longitudinal slope of the road, $\alpha = 10^\circ$;

v_a – the speed of the car, 15.55 m/s ;

ρ – the air density, 1.16 kg/m^3 ;

c_x – the air resistance coefficient, 0.335;

A_f – the surface of the maximal transversal section of the car, 1.8 m^2 .

With the above data, the following values are obtained for the three terms of the above

relation: 406.806 W; 1315.0324 W, 7157.4348 W.

For our model, we did not consider uphill resistance, hence with the first two terms, our generator must have a power of:

$$P_G \geq 405.616 + 1315.0324 = 1.72 \text{ kW} \quad (10)$$

At this moment, we use a 2kW synchronous generator with electromagnetic excitation, which is the right solution if we take into account its efficiency rate.

If we also modeled uphill resistance, the power of the generator should increase significantly. At any rate, the above calculated value can be decreased. Supposing that, in uphill motion, the maximal speed is 12.5 m/s, for our example, we get approximately the necessary power of 5.754 W. Thus, an electric car of 8 kW could model all the advance resistances, while its reversibility, motor – generator, would be imposed for both modeling uphill and downhill motion.

The ratio between the angle speed of the flywheel and that of the wheel result from relation (2):

$$i_\Omega = \frac{\Omega_R}{\Omega_V} = \frac{1}{r_R} \sqrt{\frac{J_V}{m_a}} \quad (11)$$

For instance, considering $r_R=0.280$ m, it follows that $i_\Omega=0.353553$.

For any given pair of wheel values: angle speed $\Omega_{R(i)}$ – torque $M_{R(i)}$, the resulting values of the angle speed $\Omega_{V(i)}$ of the flywheel, respectively of the torque $M_{V(i)}$ at the axis of the flywheel:

$$\begin{aligned} \Omega_{V(i)} &= i_\Omega^{-1} \cdot \Omega_{R(i)} \\ M_{V(i)} &= i_\Omega \cdot M_{R(i)} \end{aligned} \quad (12)$$

The values $\Omega_{R(i)}$, $M_{R(i)}$ can be obtained for various cycles through simulation with ADVISOR, and those of $\Omega_{V(i)}$, $M_{V(i)}$ with relation (12), Tab.1. The calculation was made for $\Omega_{V(i)}$, $M_{V(i)}$ considering the value $i_\Omega=0.3535$.

Table 1.

Cycle	v_a (m/s)	$\Omega_{R(i)}$ (rad/sec)	$M_{R(i)}$ (Nm)	$\Omega_{V(i)}$ (rad/sec)	$M_{V(i)}$ (Nm)
UPIT20	8.94	31.7694	19.3298	89.87	6.833
UPIT25	11.17	39.7376	24.4263	112.4118	8.63
UPIT26	11.62	41.3332	25.5815	116.9256	9.04
UPIT27	12.069	42.9296	26.782	121.441	9.46
UPIT29	12.96	46.1245	29.3189	130.479	10.36

The model of the car is shown in Figure 3, where TM is the torque transducer, and M is the corresponding display device, V is the flywheel, Fr is an additional electric brake, and G is the generator for modeling advance resistances.

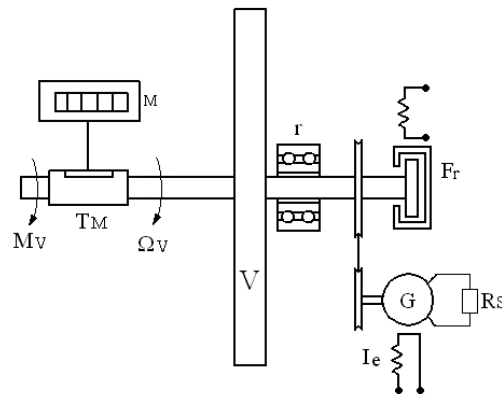


Fig.3. Car model

3. THE HYBRID OPERATING SYSTEM

The operating / driving system is made up of two power sources: an electric motor (M), and an engine (E), which has each the possibility of operating separately or jointly, according to the principle expounded in Figure 4.

The power split device is the key device in the issue of coupling two power sources.

A synthesis of the possibilities of coupling power sources can be found in [3].

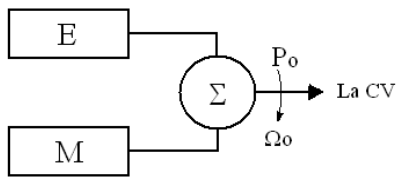


Fig.4. The principle scheme for the pairing of two power sources

The coupling solution of two power sources based on the planetary mechanism is shown in Figure 5.

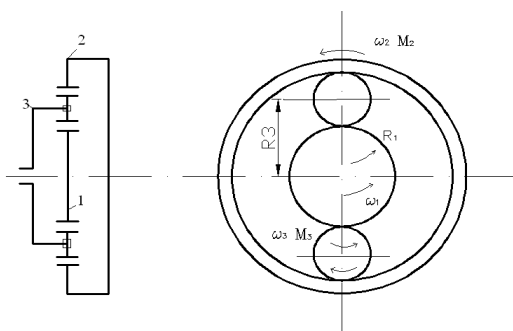


Fig.5. Solutions of coupling power sources with summation of rotation ratios

Our solution is based on a differential mechanism whose structure is presented in Figure 6, a. Its practical realization is presented in Figure 6, b [4].

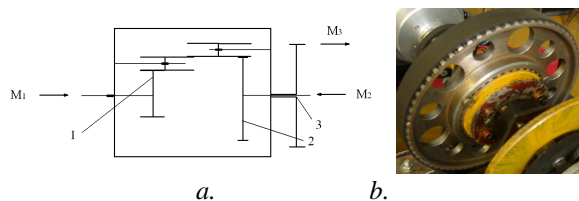


Fig.6. The solution of the psd realized: a – planetary mechanism designed – kinematic structure; b – planetary mechanism realized model

The principle scheme of the stand is presented in Figure 7[4].

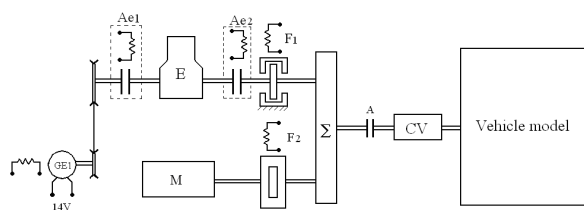


Fig.7. The principle scheme of the stand

The engine has access to both ends of the exit shaft. A *GE1* generator is coupled, at one of its ends, by means of an electromagnetic clutch. The other end of the heat engine is coupled to the power split device Σ , through clutch *Ae2* and the electromagnetic brake *F1*.

The engine *M* is connected to the second entry of the differential mechanism Σ . A mechanic clutch *A* allows uncoupling the drive system from the flywheel. A gearbox *CV* enables to change the gear level. The flywheel operates generator *GE2*, whose excitation is programmable, with a view to modeling the advance resistances of the car.

The system of electromagnetic clutches *Ae1*, *Ae2*, and the electromagnetic brakes allow doing the necessary combinations for the construction of the large-series hybrid variant, respectively the parallel hybrid, operating only with the engine, operating only with the engine.

The mathematic model is deduced starting from the scheme in Figure 8 [5]. The calculus notations are, respectively: *e* – engine (heat engine); *m* – motor (electric motor); *psd* – power split device (the summation device); *c* – the crown of the *psd* mechanism; *b* – belt (transmission belt); *p* – the primary shaft of the gearbox; *s* – the secondary shaft; *fd* – final drive (main transmission); *v** – vehicle “reduced” to the equivalent planetary shaft.

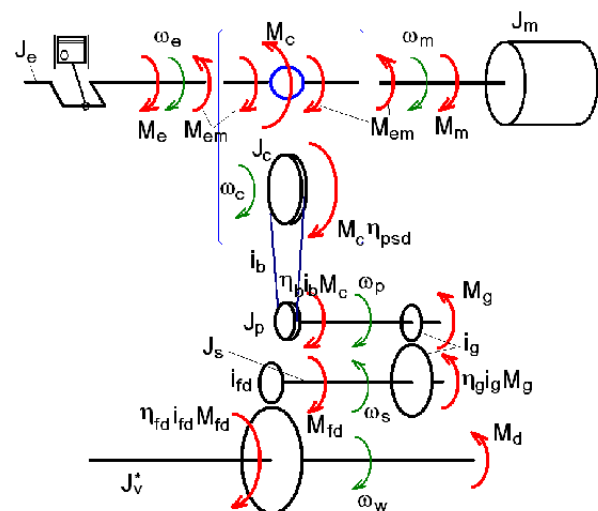


Fig.8. Scheme for deducing the differential equations of the stand

After writing the equations of dynamic equilibrium (d'Alembert's principle) for each single shaft, we get:

$$\begin{cases} J_e \frac{d\omega_e}{dt} = M_e - M_{em} \\ J_m \frac{d\omega_m}{dt} = M_m - M_{em} \\ J_c \frac{d\omega_c}{dt} = \eta_{psd} M_c - M_{c1} \\ J_p \frac{d\omega_p}{dt} = \eta_b i_b M_{c1} - M_g \\ J_s \frac{d\omega_s}{dt} = \eta_g i_g M_g - M_{fd} \\ J_v^* \frac{d\omega_w}{dt} = \eta_{fd} i_{fd} M_{fd} - M_d \end{cases} \quad (13)$$

And, considering the kinematic constraints:

$$\begin{cases} \omega_c = \frac{1}{2} \cdot (\omega_e + \omega_m) \\ \omega_c = i_b \omega_p \\ \omega_p = i_g \omega_s \\ \omega_s = i_{fd} \omega_w \\ \omega_w = \frac{v}{r_r} \end{cases} \quad (14)$$

There follows, after a series of calculations:

$$\begin{cases} (4\eta_{psd} J_m + J_c^*) \cdot M_e - J_c^* M_m - 2J_m M_c^* = \\ = [4\eta_{psd} J_e J_m + J_c^* (J_e + J_m)] \cdot \frac{d\omega_e}{dt} \\ (4\eta_{psd} J_e + J_c^*) \cdot M_m - J_c^* M_e - 2J_e M_c^* = \\ = [4\eta_{psd} J_e J_m + J_c^* (J_e + J_m)] \cdot \frac{d\omega_m}{dt} \end{cases} \quad (15)$$

The ordinary differential equations (15) represent the motion equations of the hybrid drive system. Let us notice a few facts:

♦ due to the planetary mechanism, in both its sides equal moments are established (marked M_{cm}). The crown moment (or the moment of exit from the mechanism) is double that value;

♦ since the summation mechanism (i.e. the power-split device) essentially introduces an

additional degree of freedom into the mechanism, it follows that the propulsion system is governed by two differential equations (instead of only one, as in the conventional system);

♦ due to the symmetric character of the organization schema of the propulsion system (with the two engines positioned on either side of the planetary mechanism), the respective motion equations of the two engines are symmetric in indices e and m. This is apparent in the equations that make up the system (15).

3.1 The hybrid variant with CVT

Another hybrid variant is in the preparatory stage, namely the variant with a continuous transmission gearbox (CVT), which will assume the structure in Figure 9 [6].

Between the psd and the engine is placed a gearbox with continuous variation. The engine was replaced with a more powerful engine. At the exit from the psd there is a two-speed gearbox.

The new variant allows the complete automation of the stand, and conducting all the standard tests.

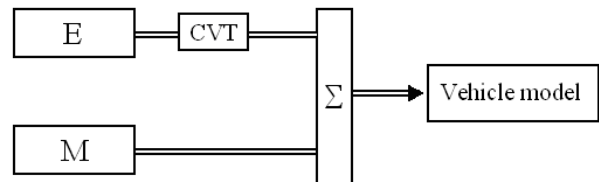


Fig. 9. The principle scheme of the stand with CVT

3.2 Supply with the hybrid electric power source

In the electric power supply scheme two basic sources are designed: a set of batteries, B and a Fuel Cell (see FC system in Figure 10).

The set of batteries (16 batteries x 12V, 24Ah) made of Pb, capsulated, mounted in a ventilated room. The Fuel Cell has a power of 8 kW, with a voltage varying within the limits of 47-76V, and the working current within the limits of 0-170A.

Through switch a1, the set of the batteries B can be coupled in parallel to FC, and through

a2, to the main voltage terminals. The two switches, a1 and a2, must not be connected simultaneously.

The main load of these sources is represented by the drive engine of stand M.

In the electrical schema, Figure 10, another two electric generators appear: GE1 and GE2. GE1 can operate when the engine works, either in the situation of simulating a series hybrid or in the situation when it does not work in the economic points, and its coupling is necessary, as well.

GE2, being driven by the same shaft on which the flywheel is mounted, accomplishes two parts – that of a generator intended to recover energy on braking, and that of a brake intended to model the advance resistance of the car. A switch a_f, actuated at the same time as the brake pedal, introduces the recovering circuit, which uses an ultracapacitor (110F, 48V).

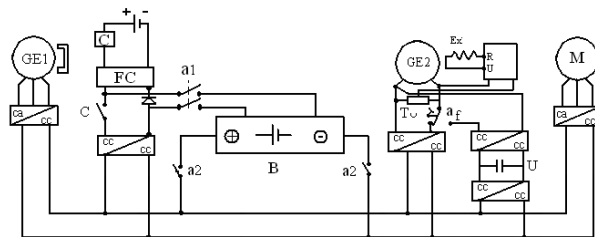


Fig. 10. Hybrid supply scheme

Figure 11 shows an image of the system of electric sources.



Fig. 11. Image of the sources of electric power supply, and the adjoining converters

4. USE OF THE STAND

The stands allow the functioning in electric regime, classical and HEV.

We can also determine: the complex characteristics of the engine in order to establish the optimal functioning points; the characteristics of the electric motor in the same aim; the influence of the functioning of the electrical motors in normal regime and in an extended regime, that is the change the relation between the functioning regime with constant torque respectively constant power [11], the best supply sources etc..

We present the so determined characteristics of the engine, Figure 12.

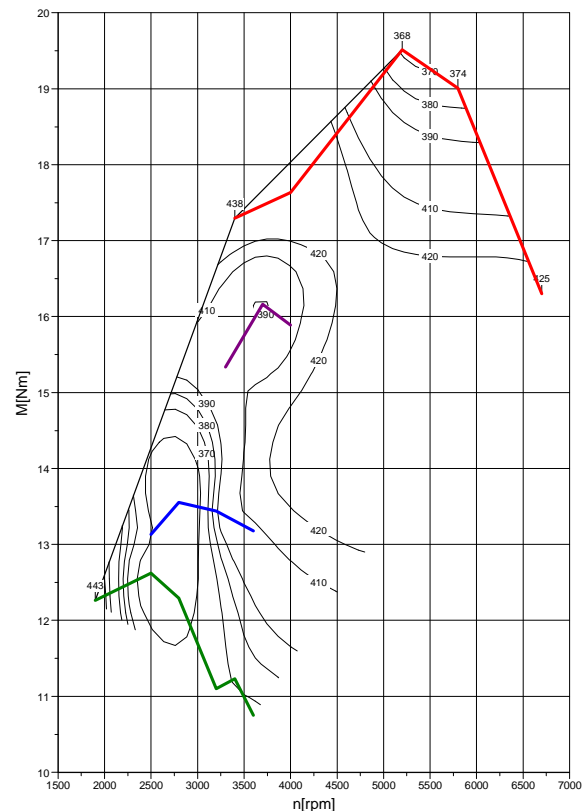


Fig. 12. Complex characteristics of torque and specific fuel consumption on depending on speed.

5. CONCLUSIONS

The current research base at the ELECTROMET research centre at the University in Pitesti allows us to conduct both tests on the hybrid operating systems, and on the energy supply systems. The fact that the working stand is equipped with efficient elements allows the

researchers there to conduct further studies to find the best structures for both the operating systems, and the energy supply systems.

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