Theoretical Research and Laboratory Experimental Tests Regarding the Dynamic Behavior of Hydraulic System for Energy Recovery at the Braking of Motor Vehicle

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Abstract

The paper presents some results from the theoretical research and from the laboratory experimental tests regarding the dynamic behavior of one Romanian hydraulic system for the energy recovery, presented in the last edition of the conference. Laboratory tests of the hydraulic system for recovering energy were made on a testing stand, special designed and built, also, presented in the previous edition of conference. The theoretical and experimental results demonstrate the possible performances of the hybrid vehicle and that the energy recovery hydraulic systems are good means to increase energy efficiency of the road motor vehicles.

KEYWORDS: energy recovering systems, hybrid motor vehicles, regenerative drive systems, hydrostatic regenerative systems

1. Introduction

As it known, in the braking phase of the motor vehicle, the kinetic energy accumulated in the accelerating phase is converted in the thermal energy, which is, normally and irremediable, wasted in atmosphere. This has a strong negative impact over the environment, over global warming and over the resources of fossil fuels. To reduce the fuel consumption and to limit the gas emission, the automotive manufacturers have developed less polluting vehicles, with reduced consumption of fuel. In this category are included, also, beside of the motor vehicle which use the renewable and green energy, the motor vehicles with hybrid propulsion systems, as a new propulsion innovative technology. The main objective is the recovering the kinetic energy of the motor vehicle, in the braking phases, and reusing these recovered energy in the starting and acceleration phases, in order to increasing energy efficiency of vehicles. Starting from this reason, have appeared the kinetic energy recovery systems. There are many kind of energy recovery systems, but the most known are those electrics and hydraulics, where the main component is the electric or hydraulic machine, that is able to work as a generator, in the braking phase, and as a motor, in the starting phase.

The Romanian technical solution for an energy recovery system, which was presented in the last edition of the conference /1/, is a mechatronics system, which contains: a hydro-mechanic subsystem, an electronics subsystem, an informatics subsystem and, also, a control subsystem, all conceived as a mechatronics system /2/.

The implementation/installation of the kinetic energy recovery system, on one motor vehicle, transforms the vehicle in a thermo-hydraulic hybrid vehicle, compound by a mechano-hydraulic system for kinetic energy recovery and, also, an existing system thermo-mechanical transmission. Therefore, the dynamic behavior of the vehicle had to be analyzed for the whole hybrid motor vehicle, including the energy recovery system.

2. The installation of the energy recovery system on motor vehicle

Figure 1 shows the constructive and functional concept of the designing and the installation of the energy recovery hydraulic system on motor vehicle /3/.

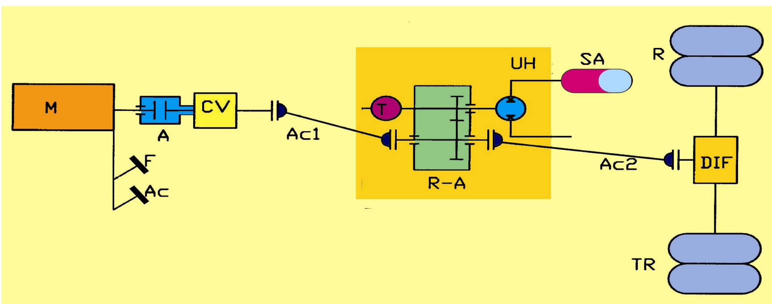


Figure 1: The installation of the energy recovery system on motor vehicles

The energy recovery system consists, in essence, of a hydro-mechanical module which includes a variable displacement hydraulic machine UH, that can operate both in pump mode during braking, and in motor mode, during start-up/acceleration of motor vehicle.

The hydro-mechanic module R-A is connected in a parallel line with the existing thermo-mechanic drive line of the vehicle, through the engine M and clutch A, in order to capture and store (SA) the kinetic energy of vehicle, in the braking phase /3/.

The implementation/installation of the energy recovery system can be done on motor vehicles that have a long Cardan axle between the gearbox CV and the differential mechanism DIF, by replacing it with two shorter axles. Mechanical connection between the Cardan axles Ac1 and Ac2 and the hydro-mechanic module R-A is permanently and is achieved through a mechanical transmission, which adapts the rotational speed of the Cardan axle to the operating rotational speed of the hydraulic machine/unit UH in the system. Depending on the specific conditions provided by the motor vehicle, on which the recovery system is installed, the coupling outlet and mechanical transmission can be placed at the end of the Cardan axle Ac1, close to the gearbox, at the end of the Cardan axle, close to the rear drive train TR, or between the gearbox CV and the drive train TR, by splitting the Cardan axle. The hydraulic unit is a hydraulic machine of variable displacement/geometric volume, which can vary between 0 and a maximum value (V_g=max). Axial piston hydraulic unit can be removed from the zero displacement position, only when the vehicle goes forward. When it goes into reverse, the displacement of the unit remains zero (Vg = 0). The energy recovery system comprises a hydraulic station to achieve the circuits, as well as the transducers (T) required for measuring, monitoring and controlling of braking (F) and acceleration (Ac) phases /4/.

3. The theoretical research by mathematical modeling and PC simulation

The research objective of the theoretical research and of the laboratory experimental tests is the knowledge of the dynamic behavior of the energy recovery hydraulic system, before the its mounting on the motor vehicle and, also, to establish the level of performance of each components of the system and, also, for entire hybrid vehicle.

For the theoretical research, the authors used the *MATLAB with Simulink* and, also, *AMESim* simulation Program and for experimental tests they used the LabVIEW and TEST POINT and a special endowment from test laboratory.

For testing of the energy recovery hydraulic system, in laboratory conditions, there was necessary to design and physically develop a test stand, able to reproduce the characteristic working modes of a hybrid motor vehicle with the ability to recover kinetic energy during braking. The test stand, which was conceived, also, as one mechatronic system, was presented in the last edition of the conference /2/.

3.1. Theoretical results obtained by simulation in MATLAB with Simulink

The energy recovering hydraulic system was designed to be implemented on one Romanian automotive, well-known as ARO 243 type, which has a 4x4 driving system. The designing of the energy recovering hydraulic system was made starting from the constructive and functional features of this middle motor vehicle, which were used for the simulation of the dynamic behavior of the resulted hybrid vehicle. Using the classical moving equations and MATLAB with Simulink Program, were elaborated mathematical models and the simulation programs for the starting and braking phases and, follow the simulation, had been obtained a lot of graphical variations for the main parameters /3/, some interesting of them are presented in the figures from below.

In the figures from left below, there are presented some theoretical results of interest regarding the dynamic behavior of the motor vehicle at its hydraulic start-up, and in the figures from right below, there are presented some theoretical results of interest regarding the dynamic behavior of the motor vehicle at its hydraulic braking.

At the beginning, it consider that the hybrid vehicle will be moved exclusively by hydraulic means, when the hydrostatic energy comes from the hydro pneumatic accumulators, where it is stored for reuse at the maximum pressure 250 bar. The variation of start-up velocity is done in **Figure 2** and the variation of the pressure inside of accumulators vary as in **Figure 3**, until is reached the minimum pressure at 100 bar.

In this time, the variation of kinetic energy of the motor vehicle is continuously increasing, while the hydraulic power from **Figure 4** has a maximum value just for 2/3 from maximum working pressure /3/. The variation of energy efficiency of hydraulic propulsion of the motor vehicle is shown in **Figure 5** and is around (70-60) %.

The second simulation were made for the braking phase, when it consider that the motor vehicle has a initial velocity approximate with 12 m/s (43 km/h), equal with maximum velocity developed in the hydraulic start-up, described above, having the same kinetic energy captured by the vehicle in the starting phase. The variation of the braking velocity is done in **Figure 6**, which shows a continuously degreasing, while the kinetic energy, accumulated in the starting phase, is degreasing too. In this time, the pressure inside of accumulators, shown in **Figure 7,** is increasing only to maximum value of 140 bar, less than the initial pressure of 250 bar. The **Figure 8** shows the degreasing of the power at wheel and at pump, in the braking phase. The increasing of energy recovered in braking phase is similar with evolution of the coefficient of braking energy recovery, shown in **Figure 9.** His maximum is around of 65%.

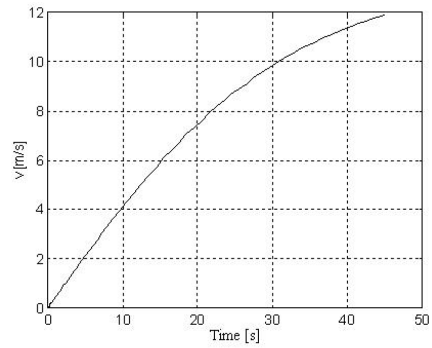


Figure 2: The start-up velocity

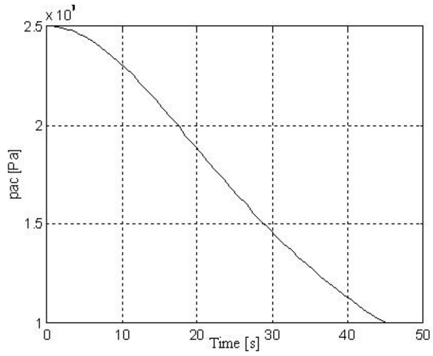


Figure 3: The pressure in accumulators

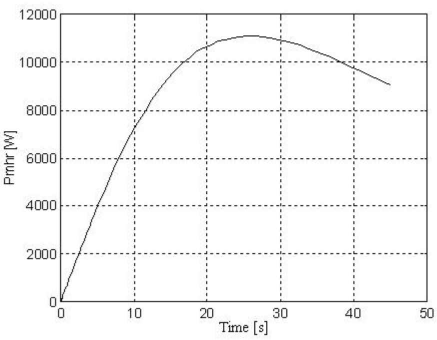


Figure 4: The power of hydraulic motor

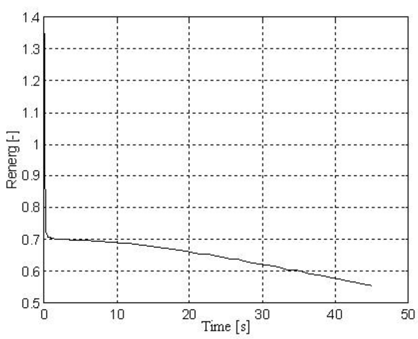


Figure 5: Energy efficiency of hydraulic propulsion

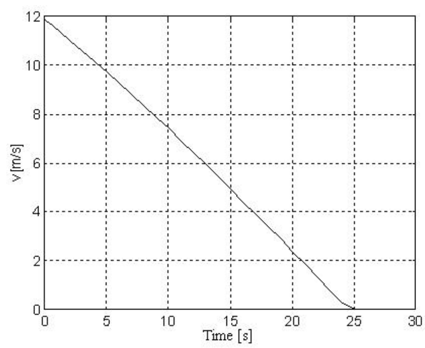


Figure 6: The braking velocity

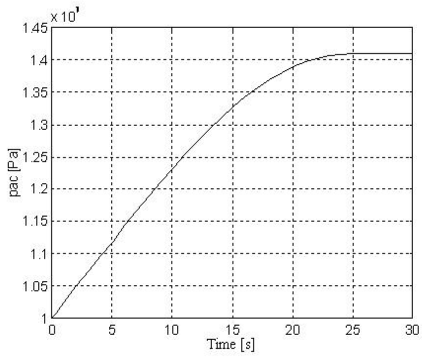


Figure 7: The accumulators pressure

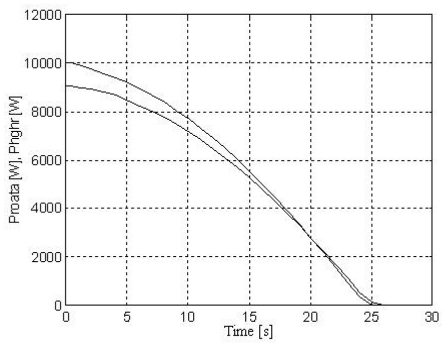


Figure 8: The powers at wheel and pump

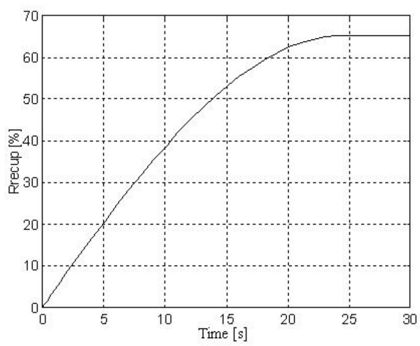


Figure 9: Coefficient of braking energy recovery

3.2. Theoretical results obtained by simulation in AMESim program

The simulation networks presented in this section have been developed and analyzed by modules using *AMESim* numerical simulation software. To achieve the simulation network of the hybrid vehicle with thermo-hydraulic propulsion system, the next models have been used: the model of the engine, the models of the elements that convey energy from the vehicle to the ground (drive wheels and free wheels), the model of the differential mechanism, the model of the gearbox, the model of the clutch and the model of hydraulic machine. The final model was the model of the hybrid vehicle with thermo-hydraulic propulsion system, represented in **Figure 10.** The simulation model contains a torque transducer, installed between the gear box and the differential mechanism, which works inside of a closed loop and which aims to have the possibility for adjustment of the motor vehicle velocity, in order respect the referenced velocity from EPA data file (the first 500 seconds from standard profile EPA, which has 1350 s). With this torque transducer, it can select the time/period when the hydrostatic machine works as pump or as hydraulic motor, in function of the couple polarity.

At the beginning, the simulation was made only for the motor vehicle with thermo-mechanic propulsion, without the energy recovery system. In **Figure 11**, is shown the evolution of the EPA reference velocity and real velocity of the vehicle, where it can see that the evolutions of this two velocities are very closely. The **Figure 12** shows the variation of the acceleration of the vehicle and in the **Figure 13** is presented the variation of the longitudinal velocity of the vehicle, which has only positive values, and the torque variation on driving gear input, which include the negative values. This means that, in the braking phase, a torque comes to energy recovery system which can drive the hydrostatic machine, this being in a pump work mode.

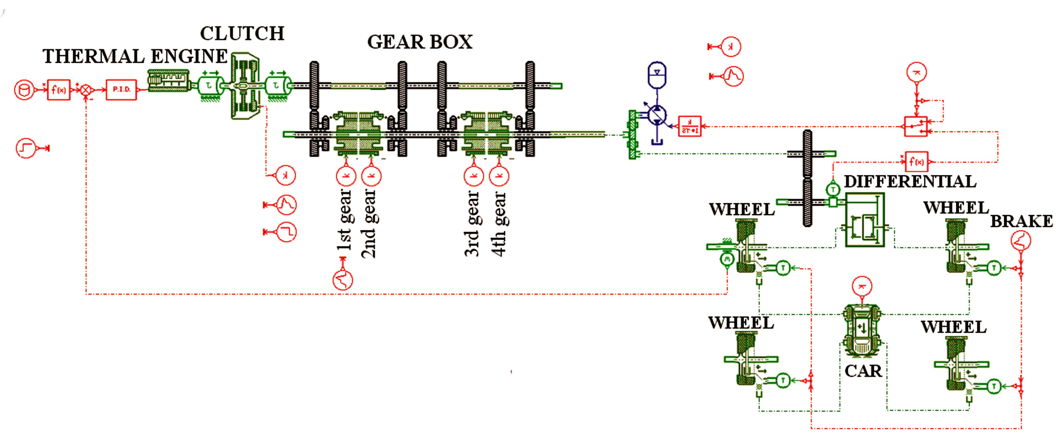


Figure 10: The simulation model of the hybrid vehicle

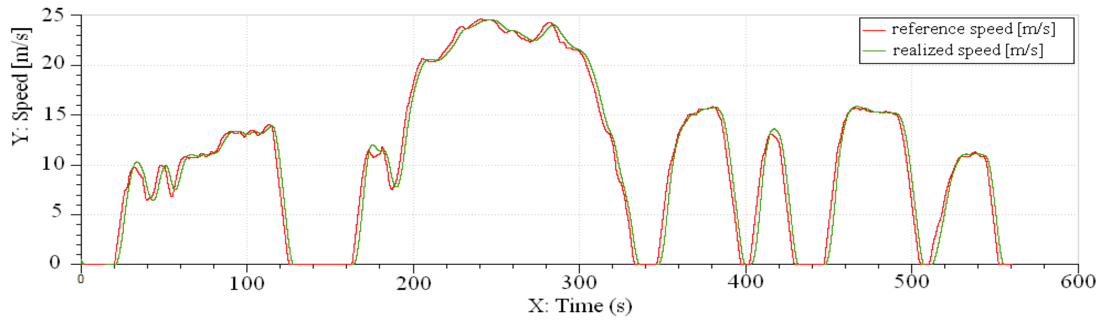


Figure 11: The evolution of the EPA reference velocity and real velocity

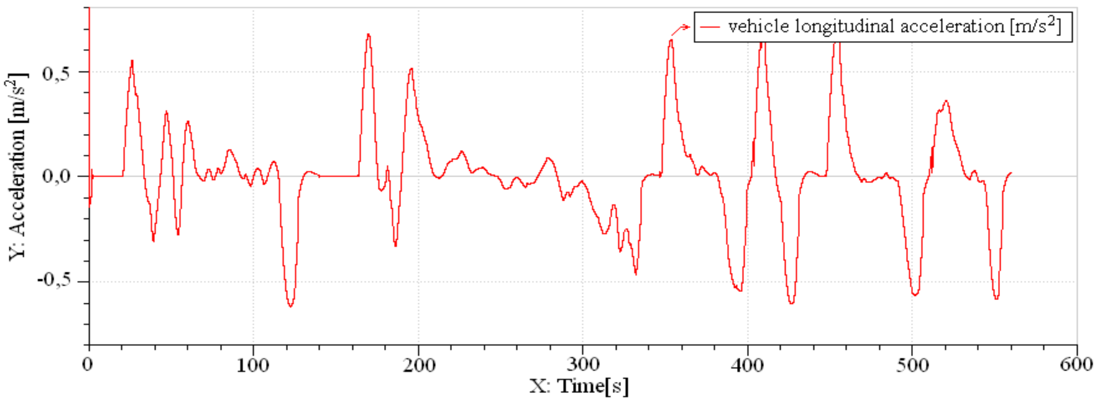


Figure 12: The evolution of the motor vehicle acceleration

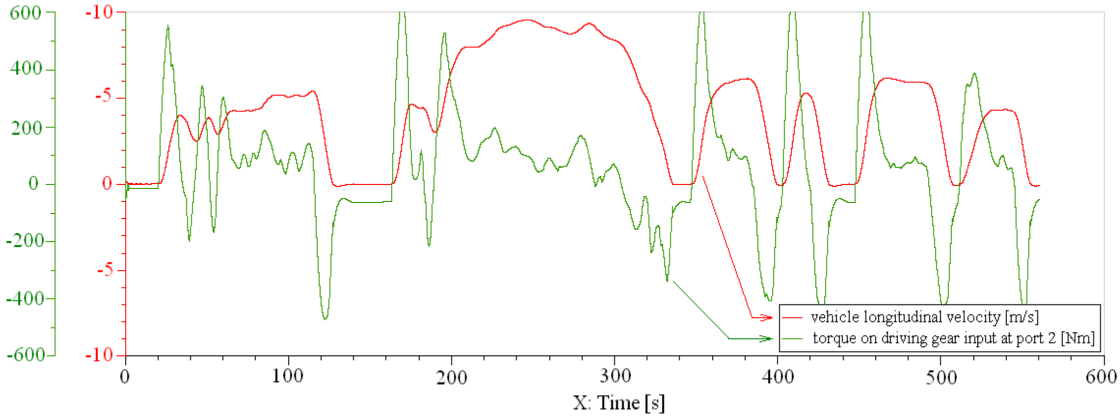


Figure 13: The variations of the vehicle velocity and the torque on driving gear input

In the second phase of the simulation, the hybrid vehicle is considered with the energy recovery hydraulic system in activity. In **Figure 14**, where are presented the variation of the equivalent torque of hybrid system, reduced on engine shaft, *with and without* using of energy recovery system. It can see the supplementary torque from the energy recovery system. In **Figure 15**, is shown the variation of the accumulators input flow and in the **Figure 16** pressure variation inside of the accumulators.

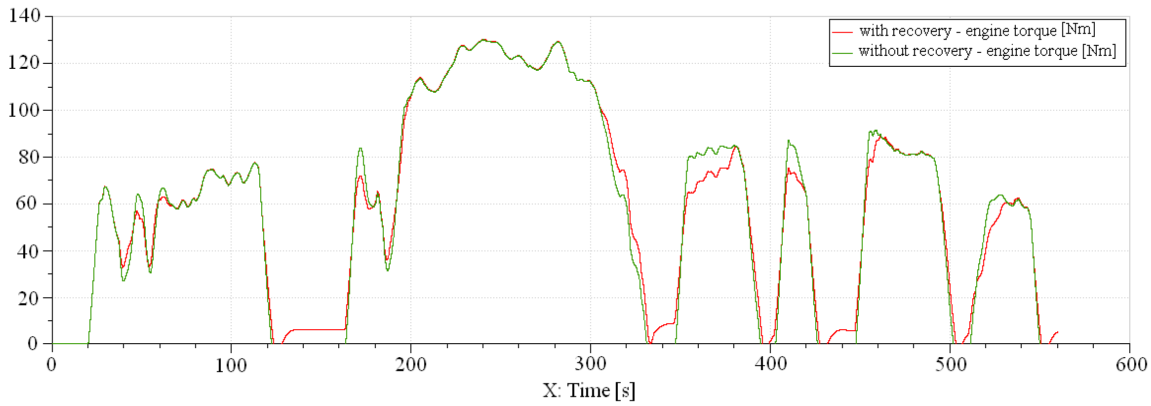


Figure 14: Variation of the engine output torque, without/with energy recovery system

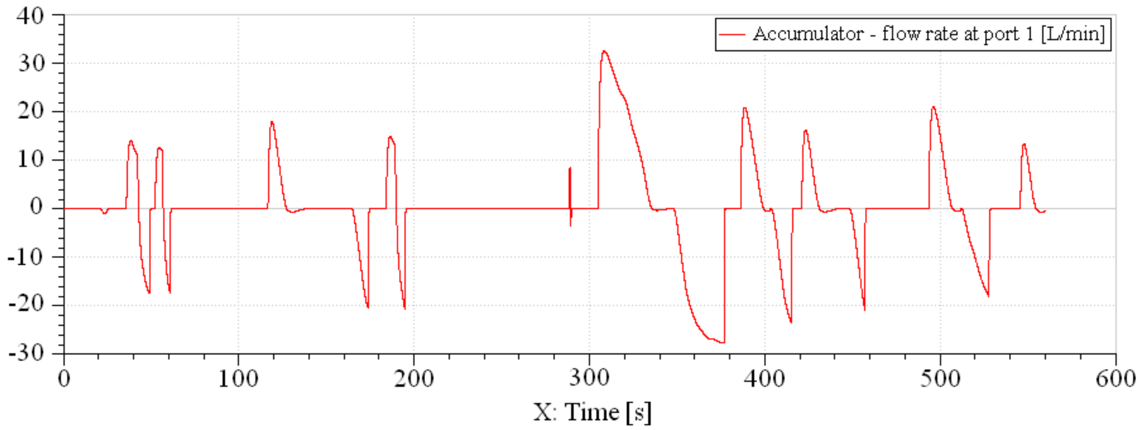


Figure 15: The variation of the accumulators input flow

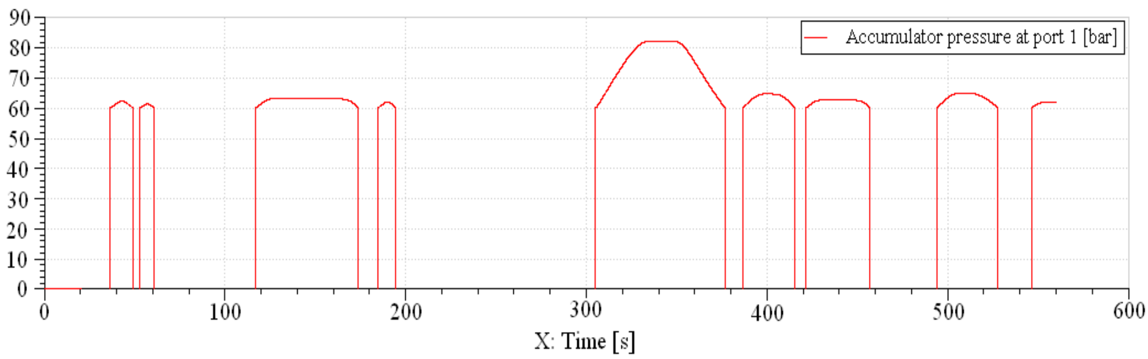


Figure 16: The pressure variation inside of the accumulators

4. Laboratory experimental tests using the real-time simulation network

In order to testing of dynamic behavior of the hybrid motor vehicles by using of the real-time simulation network, is necessary to do this in two steps. For developing the real-time simulation, in the first step have to create the co-simulation subsystem and in the second step, will be used the hybrid simulators model, which connect, in terms of informatics, the mathematical models and components of physical systems.

4.1. The creating of the co-simulation network

For achieving the co-simulation networks, there have been used the above presented model, developed by means of AMESim software. This was coupled to a simulation supervisory application of this work, developed by the authors, by means of LabVIEW programming language. In **Figure 17** can be seen the co-simulation subsystem, the process model being coupled to the application developed in LabVIEW and loaded on a NI PXI industrial computer, through the communication process implying sharing of memory. For communication between two systems, had been used TCP/IP protocol.

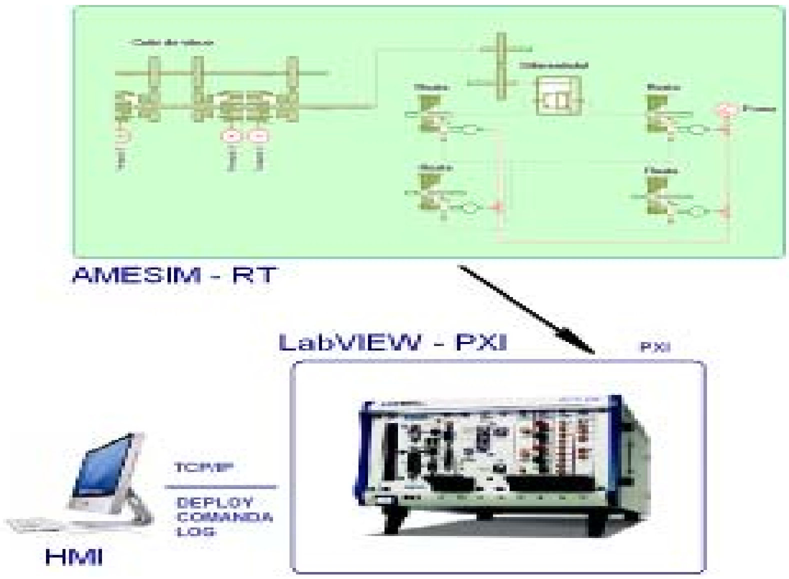
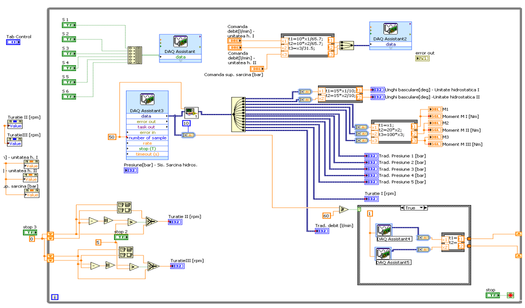
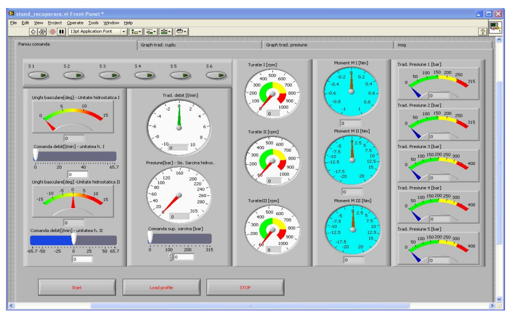


Figure 17: Co-simulation subsystem

In **Figure 18**(a), can see the block diagram of application and in **Figure 18**(b) the stand operator interface, that allows governing of the simulation process and visualization of data obtained during simulation. The application contains component which controls the hydrostatic equipment within the simulation network, by adjustment of hydrostatic unit capacity, opening and closing of way directional control valves.



(a) Block diagram of data acquisition



(b) Interface of stand functioning

Figure 18: The application developed in LabVIEW language

4.2. The testing of the dynamic behavior using co-simulation network

To know the dynamic behaviour of the energy recovery system, in laboratory conditions, it was used the numerical simulation with control loop equipment, or concept of "real-time simulation" of a system, involving the simultaneous use of a mathematical model and a physical part of the system. Modern methods of experimentation imply the existence at least one numerical calculation equipment. The necessity of using electro-hydraulic converters, for control and adjustment of various physical parameters confirms this. The ability to "load" the numerical calculation systems, with "virtual models" of systems developed using advanced modelling languages, increases more their flexibility, as it can be seen in **Figure 19.**

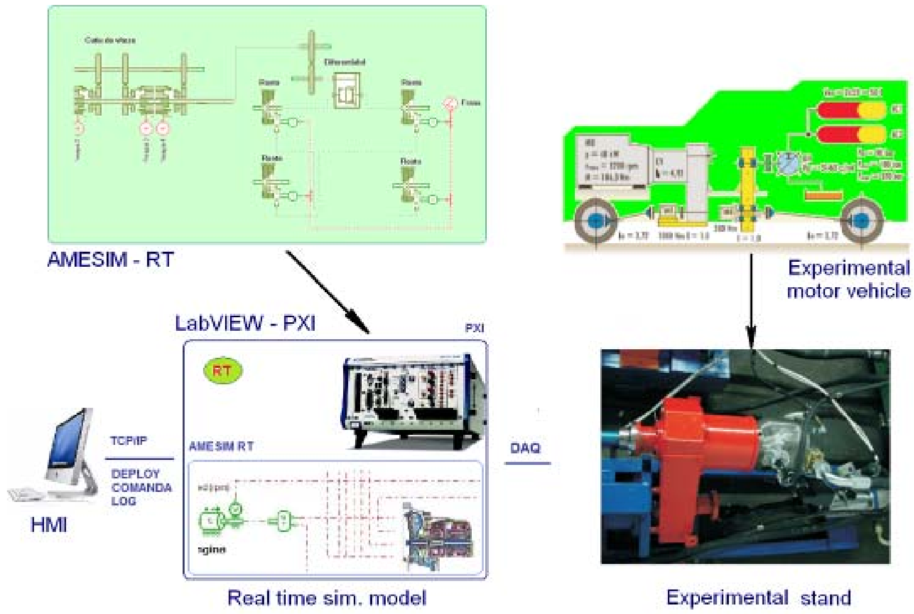
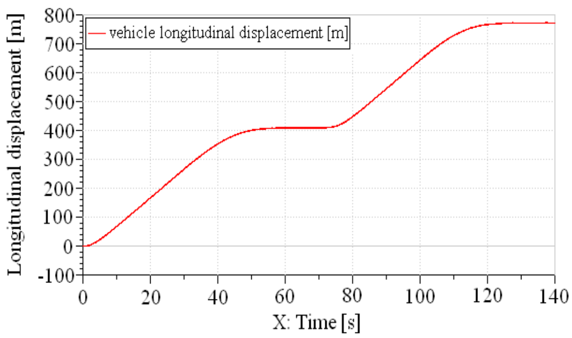


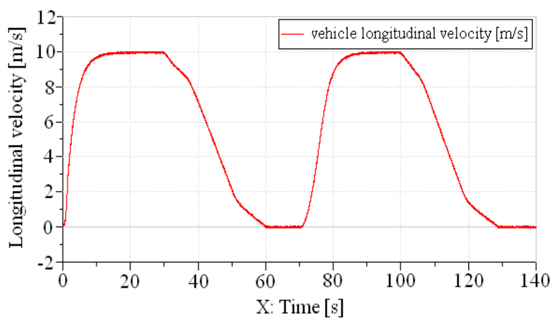
Figure 19: The hybrid network of real-time simulation for tests in laboratory conditions

The system includes a numerical model simulating the dynamic behavior of a motor vehicle with thermo-mechanic propulsion, a process computer of PXI (from *National Instruments*) family, an experimental stand and a system for regular acquisition of data in the analyzed process. The purpose of this analysis is to be excited correspondingly, based on specific input data into the mathematical model, the *power components of the experimental stand* by means of the process computer, in order to be quantified the *amount of energy* that it can recover under simulated operation conditions.

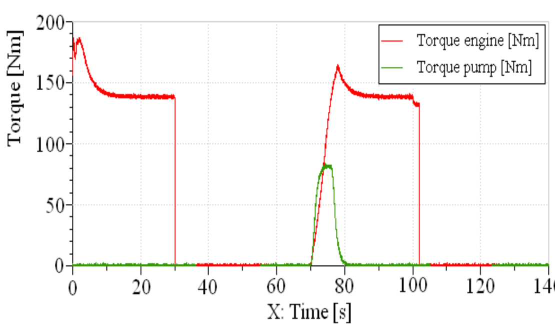
To perform experiments in the simulation model has been removed simulation of the electro hydraulic subsystem. In place of this component, there has been introduced into the model, information gathered from the testing stand, which contains the physical component of the electro hydraulic subsystem. The next technological parameters on the stand have been introduced into the model: rotational speed at the shaft of hydrostatic unit and torque obtained at the shaft of the unit. From the simulation model, a command has been sent to the physical unit on the stand, by means of which has been emulated the heat engine. The command has been sent as that rotational speed achieved at the shaft of hydraulic motor (which emulates, on the testing stand, the real heat engine) to be dependent on its torque, according to the torque/rotational speed functional curve, imposed in the simulation model. Adjustment of rotational speed at the drive shaft has been performed by appropriate variation of the hydrostatic unit capacity. In parallel, computer component of the mechatronic stand has controlled the devices on the stand so that the simulation model on the PXI industrial computer to record a certain cyclogram during 140 s: consisting, in the first time, in a acceleration by thermal engine, followed by hydraulic braking with energy recovery and, finally, a new acceleration by thermo-hydraulic hybrid propulsion system. In **Figure 20** are presented the data obtained from experiments of real-time simulation for testing of hybrid motor vehicle with kinetic energy recovery system. Thus, in **Figure 20**(a), is shown the variation of the stroke and, in **Figure 20**(b), the velocity of the vehicle. In **Figures 20**(c), it can see the torque of the equivalent system of engine and, also, the torque of the hydrostatic unit. In **Figures 20**(d), is evolution of acceleration.



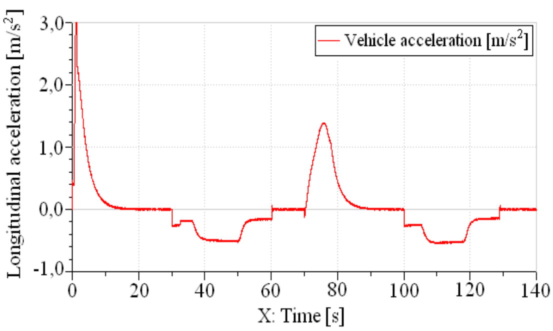
(a) Evolution of stroke of motor vehicle



(b) Evolution of velocity of motor vehicle



(c) Torque engine and torque pump



(d) Evolution of acceleration of vehicle

Figure 20: Data obtained from experiments of real-time simulation

5. Conclusions

The paper makes a very short presentation of one Romanian energy recovery system, which was subjected on theoretical research, by mathematical modeling and numerical simulation, and, also, on an experimental tests by real-time simulation.

The theoretical results demonstrate the possible performances and emphasized a good dynamic behavior of the hybrid motor vehicle that includes an energy recovery hydraulic system, is a good solution to increase energy efficiency of the vehicles.

The experimental tests, which were made on a special testing stand, by co-simulating, using the concept of "real-time simulation" of a system, confirmed the theoretical results and highlights the possibility to be quantified the *amount of energy* that can be recovered, under the simulated operation conditions.

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