ELECTROHYDRAULIC BRAKING SYSTEMS FOR ELECTRIC AND HYBRID VEHICLES - SIMULATIONS AND EXPERIMENTS

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The paper presents the operation principle and the performance of the electrohydraulic braking systems, starting with the first modern generation and reaching the last types used on the most performant electric and hybrid vehicles. Modeling, digital simulation and experimental identification are used to point out the degree of mechanical, electrical and hydraulic complexity of the most important achievements in the field. The number of patents covering the automotive speed limits systems is incresing continously, but the complexity of the digital control and the diagnosis systems limits the number of types used în practice. The wide number of debugging systems based on a single kind of basic knowledge is not enough to identify the source of problems generating errors and accidents occuring in driving a modern car. The open CAN systems have to be used in conjunction with interdisciplinary diagnosis teams built in time, and using a database of fair technical reports. From this point of view, this papers underlines the need of complex technical studies supported by the companies toghether with the high level technical universities.

Keywords: electric and hybrid vehicles brakes, structures, dynamic performances, energy saving possibilities

1. Electrohydraulic brakes evolution

The first important progress in increasing the automotive bracking security was achieved in our century by CONTINENTAL [1] through introducing hybrid inputs (mechanical and electromechanical) of the flow control valve included in a vacuumatic booster (Ate Mk 25). Much more, the vacuum chamber was doubled, and a linear potentiometer was set up in contact with the second disk membrane (Figs. 1 and 2). A long series of

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dynamic braking and steering test were succesfully performed with a VOLVO XC90 car [2], [3].

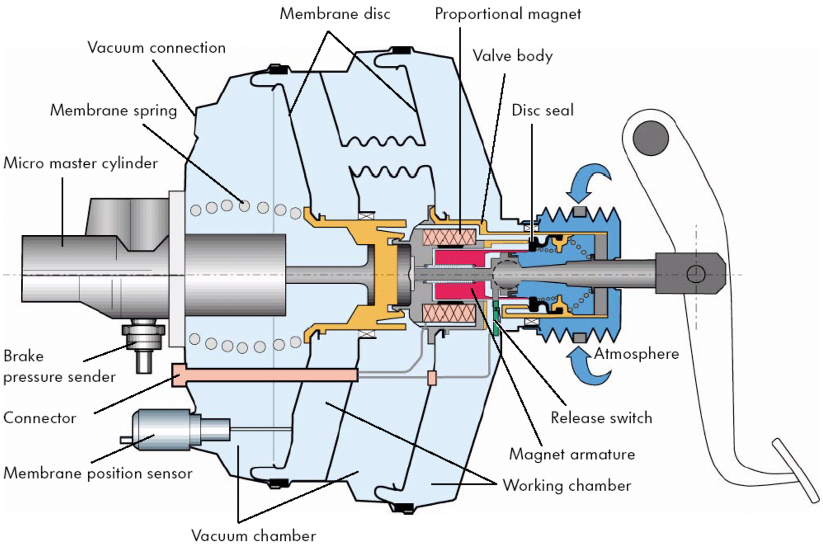

Fig. 1. Lateral view of the first hybrid multifunctional electrohydraulic brake [1]

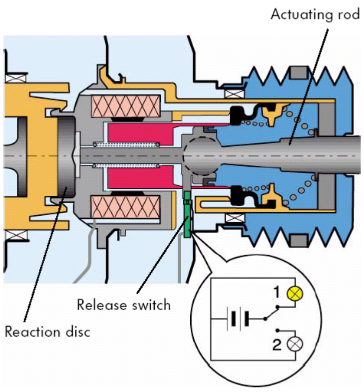

Fig. 2. Proportional force solenoid and stroke control switches

All the attempts to create dangerous steering and braking situations (figs. 3 and 4) were rejected by the EHBA together the ABS system. The concentration of all the piezoelectric accelerometers in a single robust sensor offers a proper set of simultaneous information. Consequently, this type of brake booster is still used not only for economic reasons. For example, the new hybrid cars with turbocompressors are using a small electrical driven vacuum volumetric pump connected to the brake front chamber. ABS system response, regarded by the pressure applied on the calipers is shown in Fig. 5. The hydraulic brake acts by successive pulse. During an emergency braking of the car from a velocity of 65 km/h with a deceleration of 6.48 m/s^2 the pressure pulses have an average frequency of 82 Hz. Fig. 5 clearly shows the action of the emergency braking system (EBA).

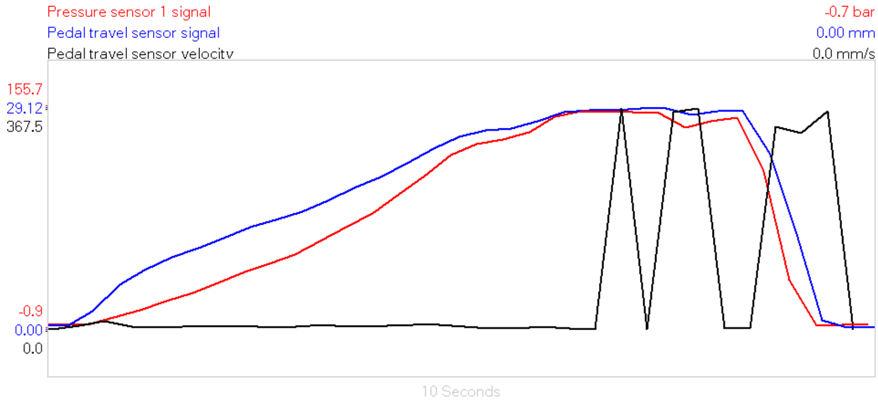

Fig. 3. Brake pressure, pedal travel and pedal travel velocity during a normal braking action

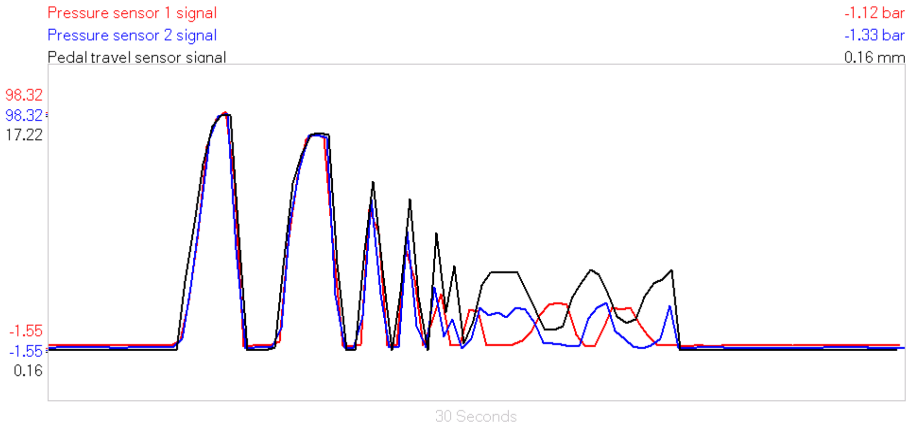

Fig. 4. Braking pressure (in red) and the brake pedal stroke during driving with over-steering

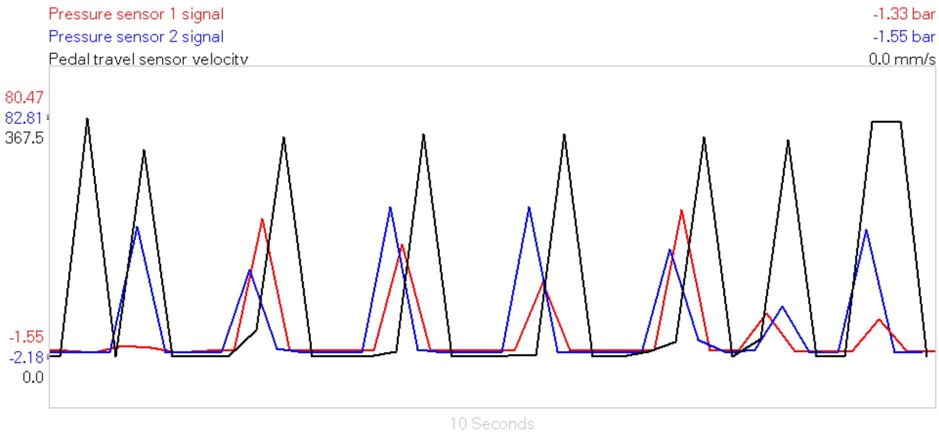

Fig. 5. Braking pressure, pedal travel and speed during emergency brake (EBA)

2. Second generation of electrohydraulic brakes

The first step in avoiding the use of a vacuum source (engine admission gallery or a vacuum pump) was the parallel driving of the brake pump piston. Some automotive components companies patented different electro-mechanical systems. The iBooster [4-5] created by Bosch Company (figs. 6-9) can be used with all drivetrain configurations and is particularly suited to hybrid and electric vehicles. The control principle used by iBooster is similar to that of vacuum brake boosters: a flow valve controls the air supply to provide a boost to the force applied from the driver‘s foot. The actuation of the brake pedal is detected via an integrated differential travel sensor and this information is sent to the control unit. This unit determines the control signals for the electric motor, while a three-stage gear unit converts the torque of the motor into the necessary boost force. The power supplied by the booster is converted into hydraulic pressure in a standard master brake cylinder. The electromechanical design of the iBooster also offers a host of benefits for driver assistance systems. Using the electric motor, the iBooster can build up the pressure independently, without the need for the driver to apply the brake pedal. Compared with typical ESP® systems, the required braking pressure is built up three times more quickly and is adjusted with much greater accuracy through the electronic control system. This offers significant benefits for automatic emergency braking systems. In combination with the ESP® from Bosch, the iBooster provides the braking system redundancy required by automated vehicles for safety reasons.

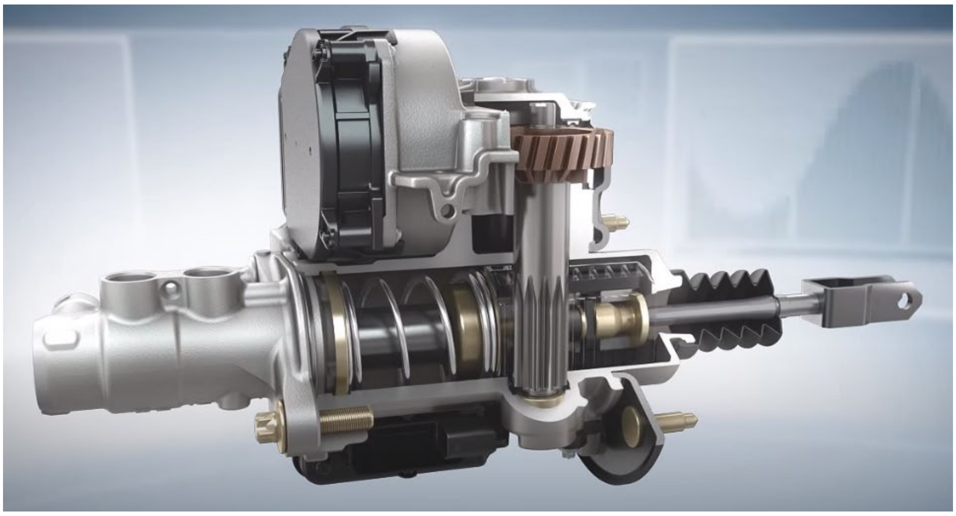

Fig. 6. Bosch 1st generation of vacuum-independent brake booster [4]

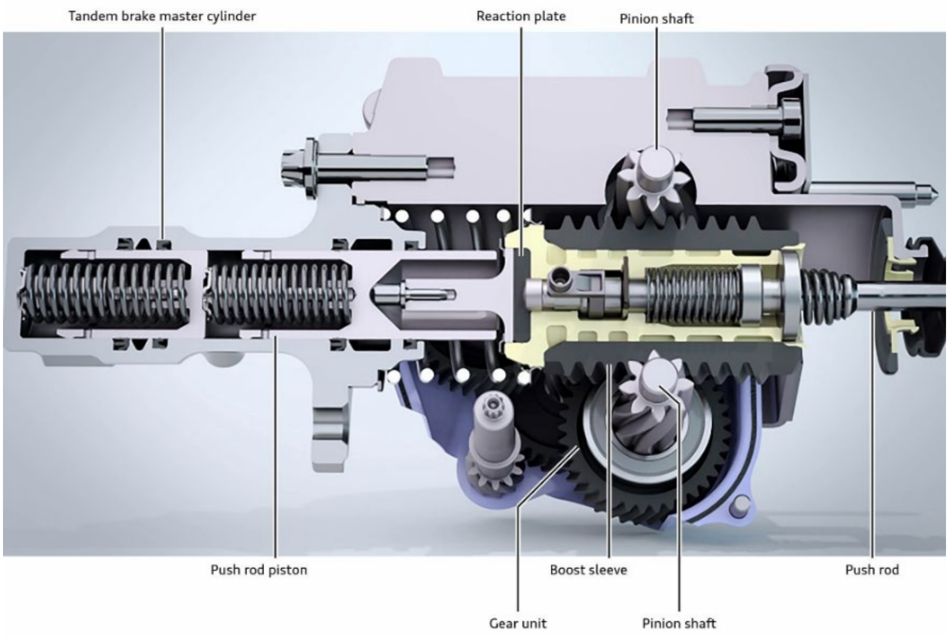

Fig. 7. Main section of the vacuum-independent brake booster IBooster

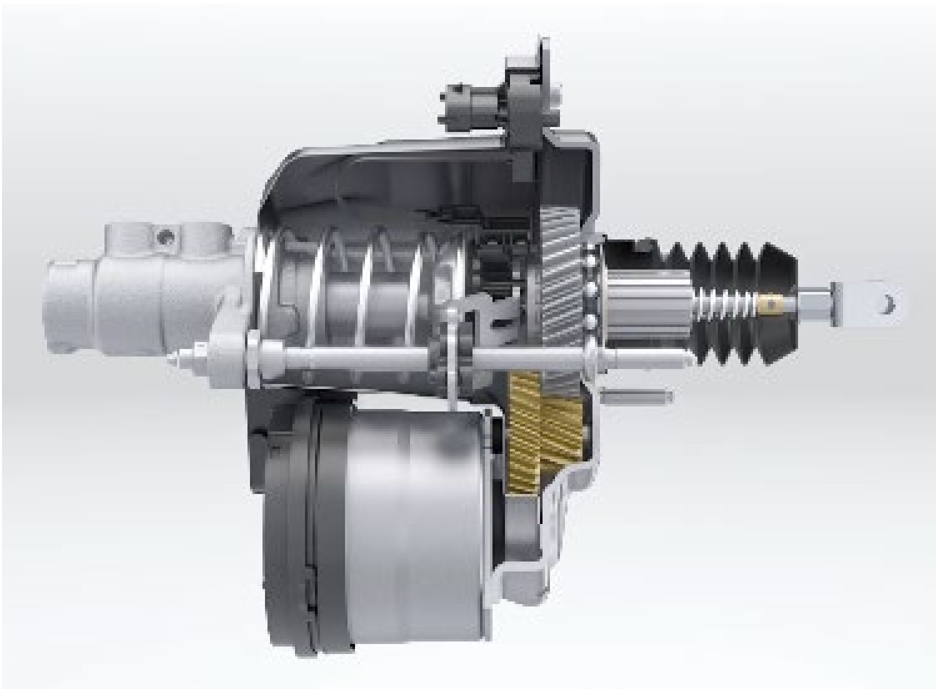

Fig. 8. Cut view of the second generation of IBooster [5]
(Vacuum-independent brake booster)

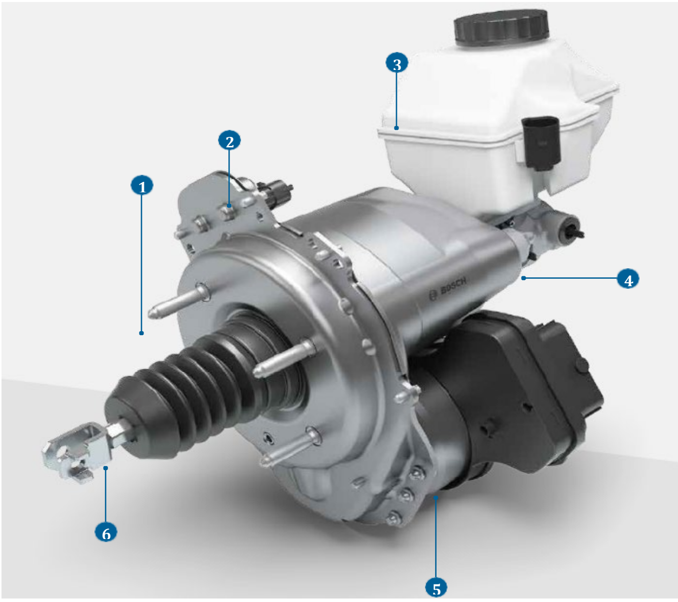

Fig. 9. Overall view of the second generation of iBOOSTER: 1-vehicle interface; 2-differential travel sensor; 3-reservoir with level sensor; 4-tandem master cylinder; 5-power pack (motor and electronic control unit; 6-input road [5]

Another electromechanical drive system (Fig.10) was developed by Continental Corporation for electrical vehicles [6]. The torque of a small high speed brushless motor is multiplied be a three stages gear mechanism (Fig.10).

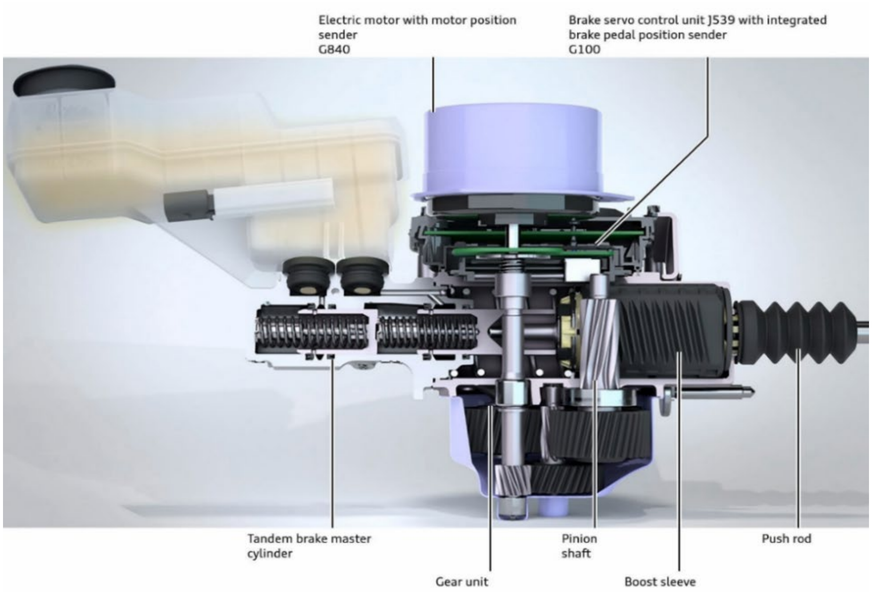

Fig. 10. Electrohydraulic brake servocontrol unit [6]

4. Last generation of EHB

The brake regulation system MK C1 (figs. 11 and 12) is being used on an Audi e-tron model for the first time [7-10]. This system represents a further level of development of existing (conventionally constructed) brake regulation systems. The main new feature is the integration of a tandem brake master cylinder, brake servo (via electromechanical components including regulation), ESC regulating systems (including ABS, EDL, and TCS) and brake "blending" in one module. This achieves a significant weight reduction (about 30%) compared to conventionally constructed brake systems. In addition, system availability is improved thanks to the reduced number of individual components. From a functional perspective, the system offers dynamic advantages when building up pressure. It also provides the driver with a brake pedal feeling which remains constant, even when recovery is taking place.

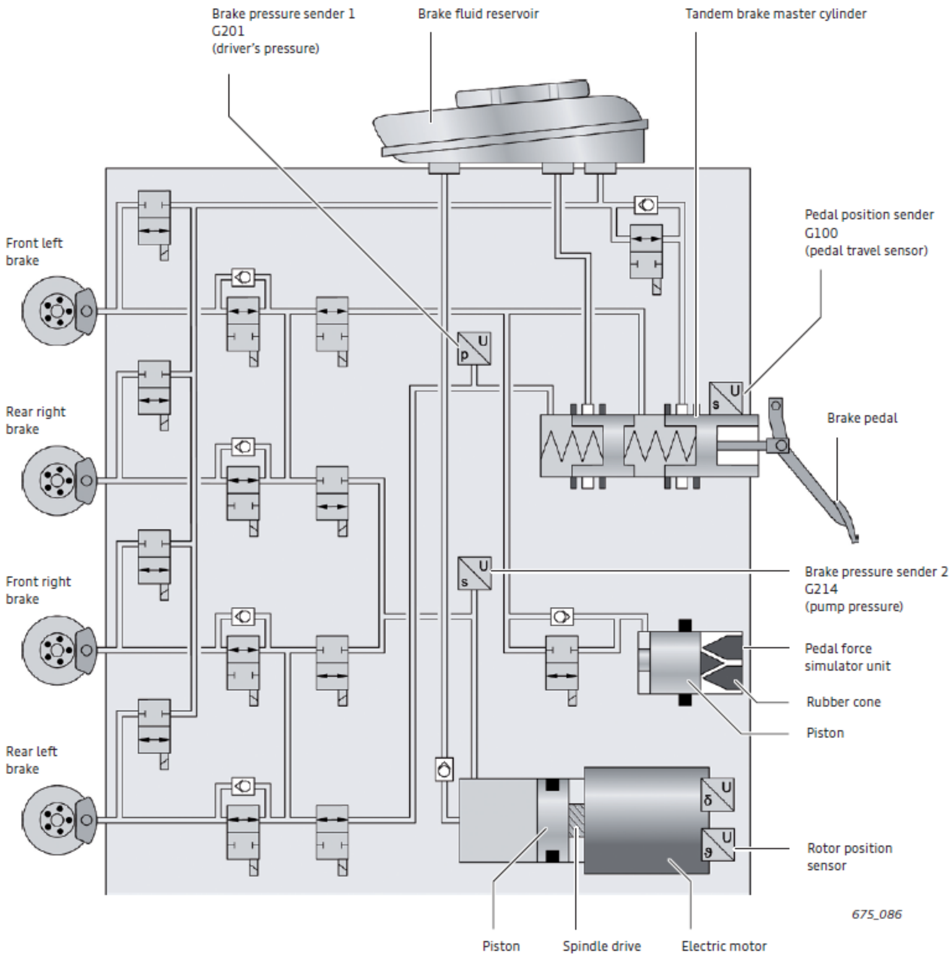

Fig. 11. The brake regulation system MK C1

In the brake pressure build-up phase via electric motor pump unit (linear actuator), driver presses the braking force simulator (normal braking procedure). The module includes a “classic” tandem brake master cylinder whose piston is operated by the driver via the brake pedal. The pedal/plunger travel is registered by the pedal position sender G100. If pedal operation is detected, the control unit J104 actuates isolating valves 1 and 4, which then block the relevant wires. At the same time, a solenoid valve is energized, thereby allowing energy to pass through. Because the isolating valves have blocked the wires, the “brake pressure” initiated by the driver does not reach the brakes. Instead, the pressure acts on the piston of the pedal force simulator unit due to corresponding valve being open. The piston is pressed against a rubber cone and a steel spring which take up the force progressively.

The counter force which the driver feels on the pedal corresponds to the force which would be felt with a conventional brake regulation system. The force applied by the driver is measured by a pressure sensor (brake pressure sender 1 G201) and the pedal travel by a movement sensor. Depending on these measured values, the control unit J104 energises the electric motor, whose rotational movement is transmitted to the pump piston via a spindle drive. Because the pressure supply valves 2 and 3 are open, the pressure built up by the piston movement reaches the brakes. The pressure built up by the electric motor/piston unit is measured at a second location (brake pressure sender 2 G214) and reported to the control unit. The synchronous electric motor features electronic commutation and is therefore equipped with a rotor position sender. The control unit uses the the spindle drive ratio to calculate the piston position on the basis of the rotor position and the number of rotations.

Fig. 12. Electrohydraulic brake MK C1 used on AUDI e-TRON E55 (2018) [4-5]

MK C2 (Fig.13) is Continental’s second-generation brake-by-wire system which integrates the master cylinder (MC), brake booster and control systems

(ABS and ESC) into a single compact and lightweight module. MK C2 makes a major contribution to drive with efficient regenerative braking [6]. Other hightech automotive corporation as TOYOTA developed similar concepts [11-12].

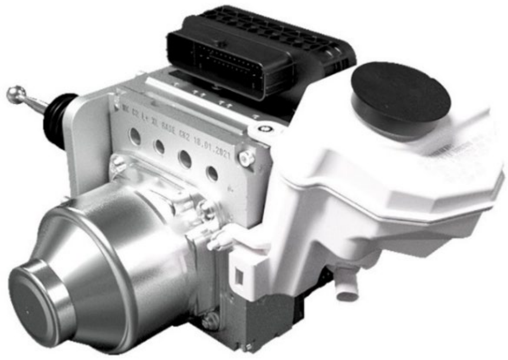

Fig. 13. Last type of EHB type MK C2 (2022) prepared for more complex autonomous driving

5. Modeling and simulation of the EHB scheme of MK C1

The best way to predict the performances of such a complex hybrid system is the numerical simulations with languages including realistic models of all the components. The authors are currently using Simcenter Amesim [13-14] which is completed with some structural parameters of the control system of the brushless motors used for driving the small size pums needed for braking systems. The basic simulation network from Fig. 14 was used to predict the MK C1 dynamics. General simulation languages as Simulink need a huge amount of theoretical work and progressive validations to offer good practical results [15-18].

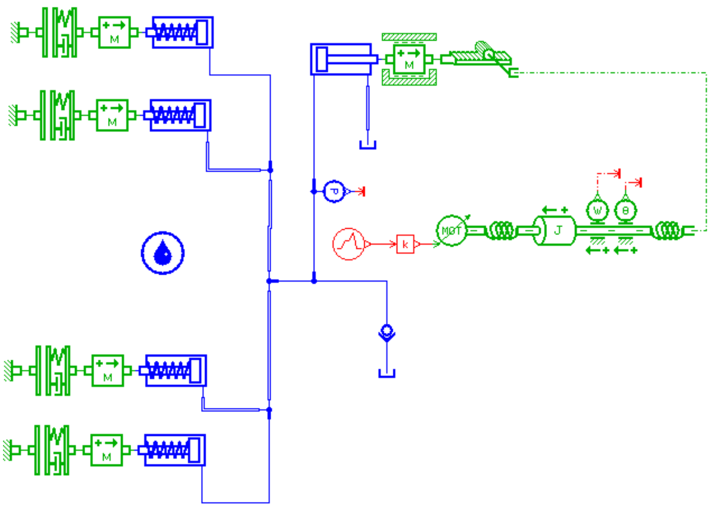

Fig. 14. Simulation network of the EHB MK C1 for a normal common braking procedure

The normal fluid circuits for a common braking process are shown on Fig. 15. All the ABS servovalves are available for supplying the 6 calipers on each wheel, but only two ESP servovalves are normally open.

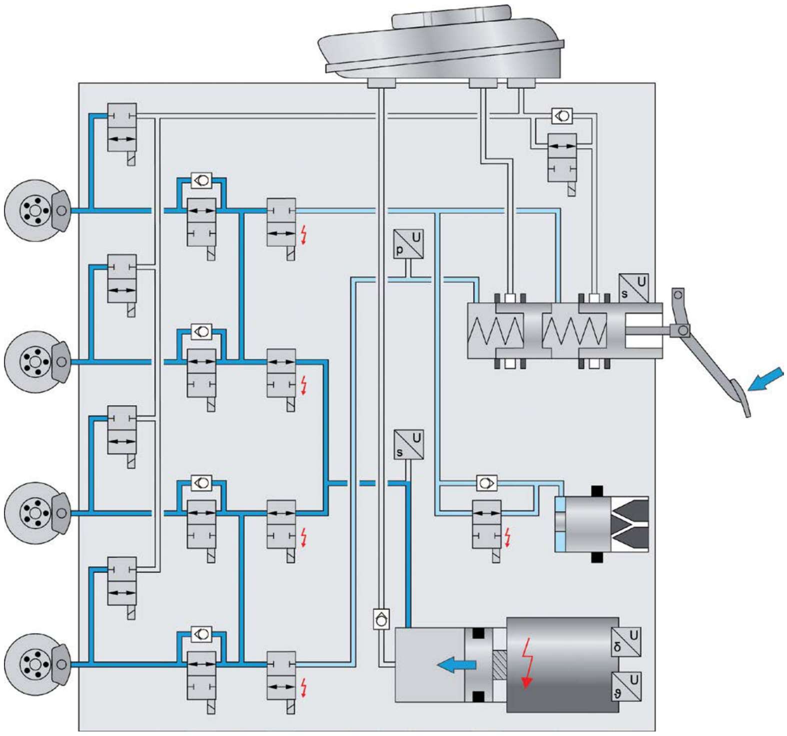

Fig. 15. EHB scheme of MK C1 used on tested Audi e-tron type GE including ABS control unit

The duty cycle of the system, introduced by the pedal travel sensor is specified in Fig. 16.

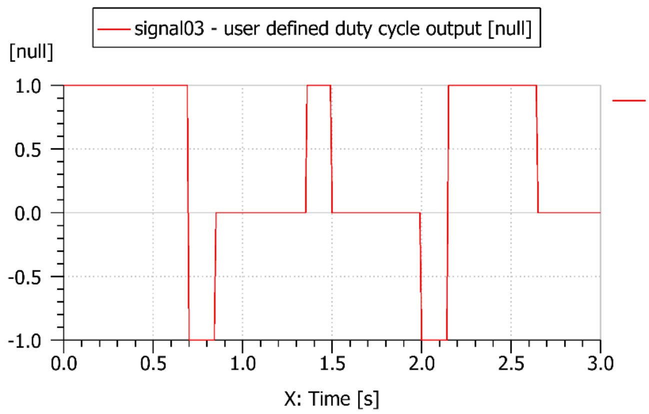

Fig. 16. The duty cycle output introduced by the pedal travel sensor

The results of the simulations are presented in the following diagrams (17…22), showing very useful details of following the process.

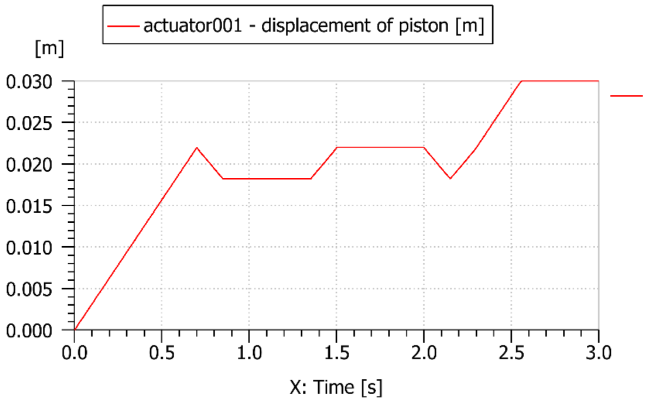

Fig. 17. Displacement of the pump piston actuated by the brushless motor by a spindle drive

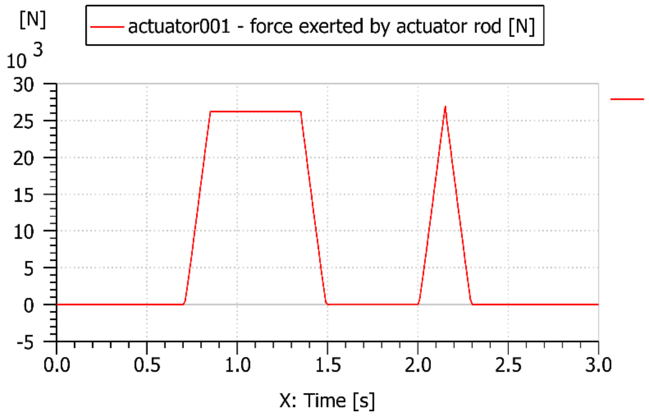

Fig. 18. Force exerted by the electromechanical actuator on the pump piston

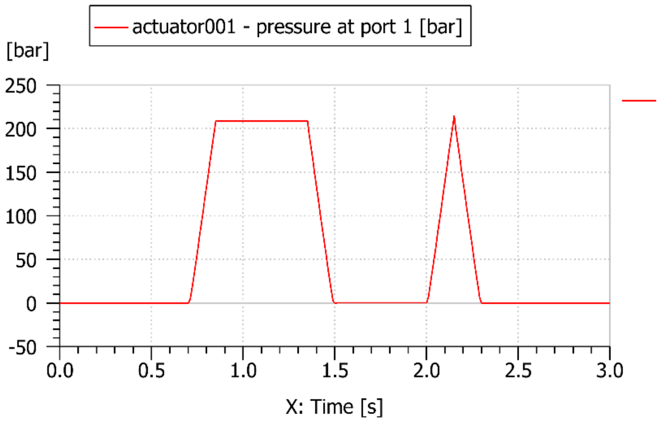

Fig. 19. Pressure variation in the delivery port of the electromechanical pump

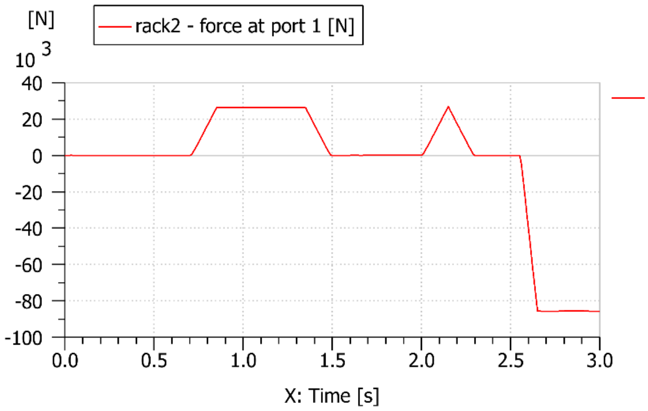

Fig. 20. Pressure force applied on the pistons of a fixed caliper of the front axle (6 pistons of 30-36-38mm)

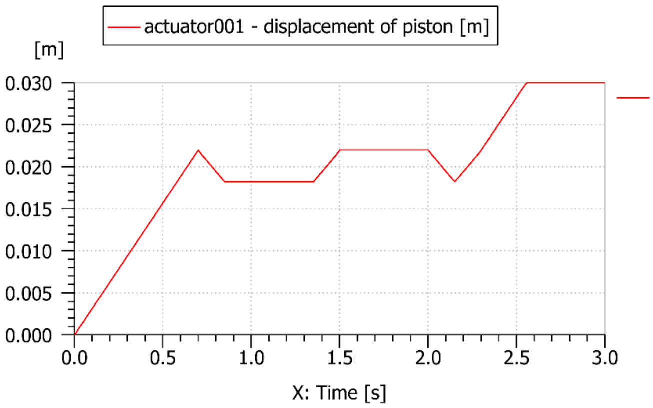

Fig. 21. Typical axial displacement of the bigest caliper piston (max. 30μm)

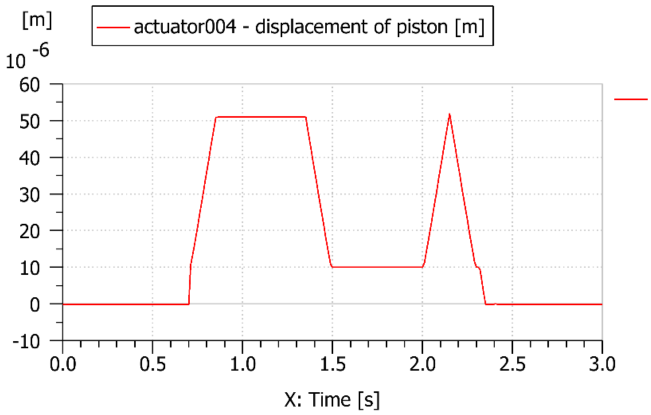

Fig. 22. Axial displacement of the smalest pistons of a front caliper (30mm)

6. Some experimental validations of the simulation model

The understanding the all braking process needs much more investigations, but the presented ones were globally validated by some experimental researches carried out on a AUDI e-tron 55 full electric car running on a good quality highway (from Bucharest to Ploiești) during a few quasi-identical driving cycles. An overal view of the front space of the tested vehicle (Audi e-tron 55) is presented in Fig. 23. The MK C1 module is protected by a shield in the driver side of the front space.

Fig. 23. Front space of the tested full electric car (free of front engine hood for inspection)

The following diagrams from Figs. 24…29, obtained by periodical acceleration and braking orders applied on the braking pedal, are found in good agreement with the ones obtained by numerical simulation.

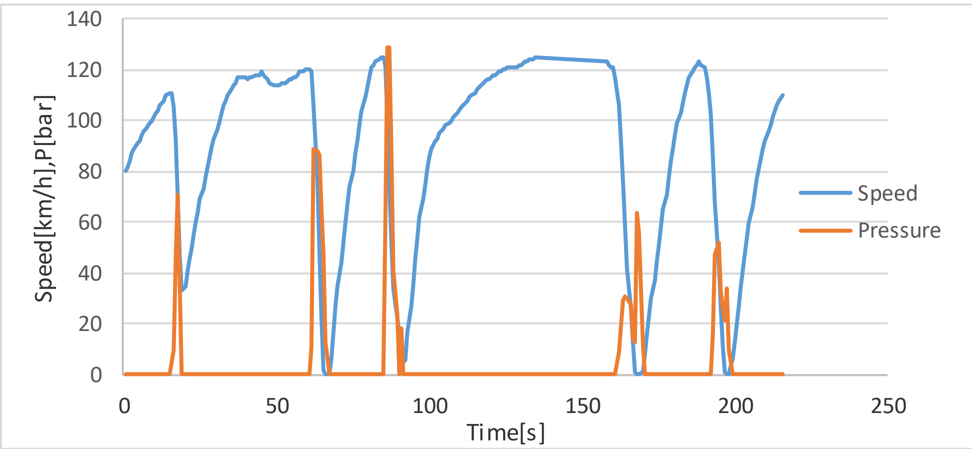

Fig. 24. A typical accelerating-braking test performed on the highway

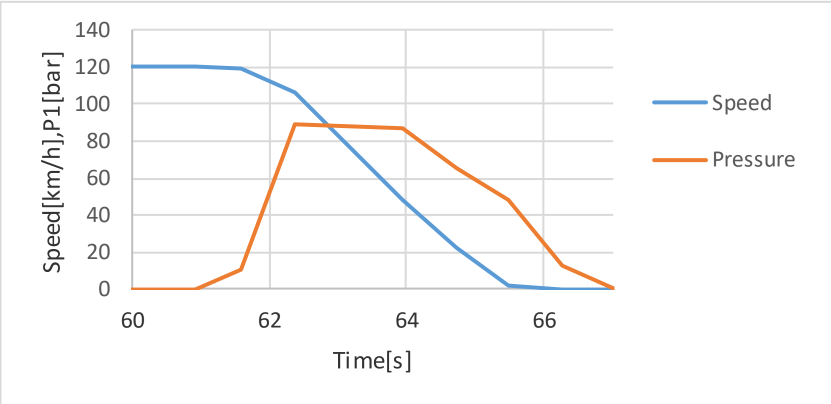

Fig. 25. Real variation of the velocity during a emergency braking process (about 4s)

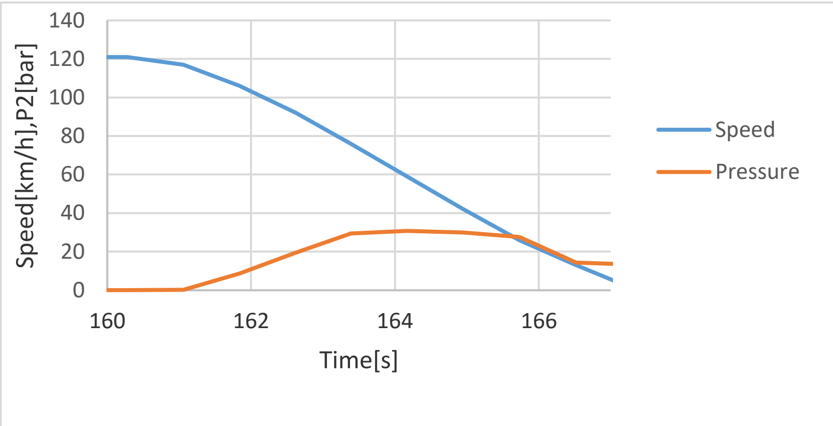

Fig. 26. Real variation of the velocity during a common braking process (typical 8s)

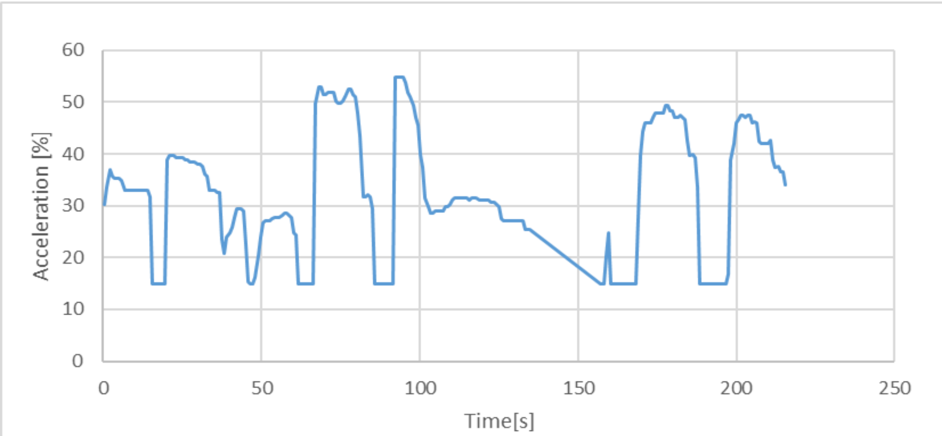

Fig. 27. Longitudinal acceleration of the car in a typical test cycle

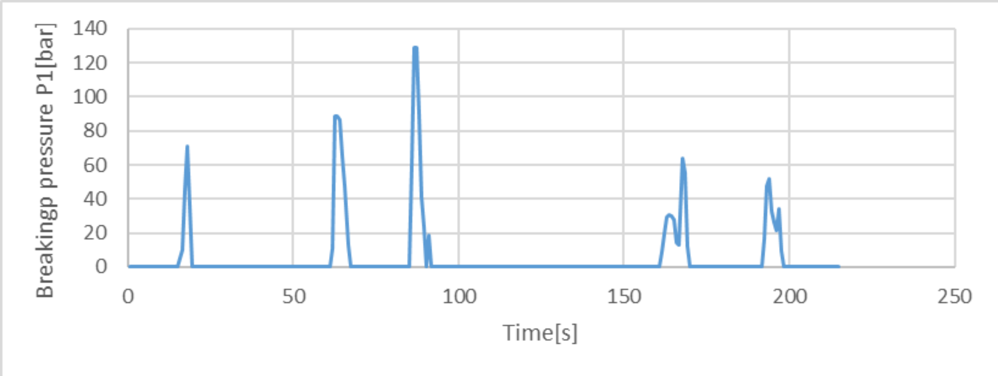

Fig. 28. Real braking pressure from calipers (P1) during a typical test

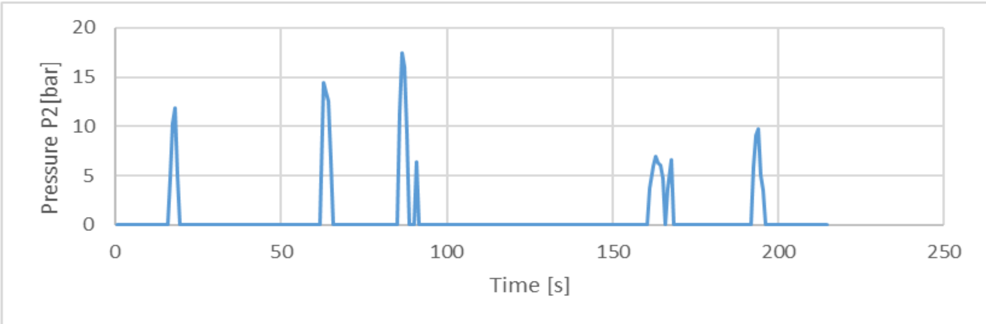

Fig. 29. Pressure in the delivery port of the second chamber of the piston pump (P1) during a typical test

The pressure generated by the driver is multiplied by a ratio of about 130 bar/17bar =7.6! The vehicle speed is reduced continously from 120 km/h to zero without shocks in four seconds without activating the ABS system!

7. Conclusions

The constant increasing of the security demands for the automotive domain will oblige all the car manufacturers to extend the number of sensors associated with the driving security systems, and consequently - the mass manufacturing of the electromechanical braking unities. A stong interest is shown to the regenerative braking systems, as TESLA Corporation is promoting by Brembo Company [19]. From the wide introducing of the ABS systems in 2000, the mass and the price of these modules was cut at least four times! However, the need of a stable market of sensors, transducers, software etc. will limit the progress in the field, dominated by new economic options. This paper is an example of the efficiency of simulation languages during the design preliminary phase, but in close connection with the technical specifications of all the components. The fine tuning of all the software involved in hybrid control systems can be performed with high efficiency by the collaboration between the designers and the maintenance high level staff [20-21].

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