Hardware In the Loop with Electro-Hydraulic Brake System

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Abstract - The paper describes the procedure our research group followed to prototype an Electro-Hydraulic Braking system (EHB). The first step consisted in developing a model of the system, by using the softwares AMESim® and Simulink®. Then the Pedal Force Emulator (PFE) was designed in detail and built. A Hardware-In-the-Loop (HIL) bench was used to test the prototype. The same procedure was followed for the hydraulic unit. The aim of the activity consisted in trying to adapt the standard components of a traditional braking system to develop a low cost EHB. Also failsafe valves to connect the driver to the wheel calipers in case of fault were used to create a reliable failsafe system in order to improve system reliability.

Key-words – Prototyping, Braking Systems, failsafe, reliability, modeling and testing.

1 Introduction

EHB [1] is getting the first step towards "Brake by Wire", due to the reliability problems connected with Electro-Mechanical Brakes (EMB) and the electric power requested by purely electric brakes. EMB cannot be used on current vehicles, since they would need 42V electric systems due to the consistent required electric power. As a consequence, EHB is the best compromise between the request for Brake-by-Wire and the layout of actual cars. EHB is characterized by a Pedal Force Emulator (PFE), giving the driver the proper force feedback. A displacement sensor measures pedal travel and sends its signal to the CPU of the system. It decides the pressure level for each caliper; it is modulated by a hydraulic control unit, formed by an accumulator and some electro-valves, similar to those of common Electronic Stability Program (ESP) systems. The accumulator is fed by a pump, similar to that of an ESP. Two valves for each wheel can put in communication the hydraulic accumulator with the wheel calipers when wheel pressure has to be raised, or the wheel caliper with the tank in the case wheel pressure has to be reduced. Pressure modulation is performed through a comparison between the desired pressure level and actual pressure level, measured by a sensor located in the hydraulic unit. This sensor measures the pressure level at the exit of the hydraulic unit towards the caliper. Wheels pressure sensors cannot be mounted directly on the calipers, due to the complexity in the architecture of such a system and especially to the fact that the calipers and the hydraulic unit can be built by different suppliers. In the system there are two or more failsafe valves, connecting at least front calipers with PFE in the case of a detected fault. The advantages of such a system over traditional brake systems should be a better performance during panic brake manoeuvres, since the delays due to booster behaviour are absent at all. Secondly, a completely free modulation of the pressure levels of the four calipers can be performed. Thirdly, ESP work can be improved, since wheels pressure can be modulated in a very precise manner due to the pressure sensors located in correspondence of the output ports of the hydraulic unit, absent in a standard ESP. Also Anti-Lock Braking System (ABS) behaviour can be improved by EHB, due to wheels pressure information. It can be useful for a better estimation of the friction coefficient between the tires and the ground, since wheels locking at low pressure level would mean a low friction level, and wheels locking at a high pressure level would mean a high friction coefficient. Last advantage of EHB over standard brake systems consists in the freedom of determining the pedal feeling according to the will of the designer, independently of the volume displacement properties of the components of the braking system. According to the control algorithm, it is possible to impose different pressure levels, for the same values of pedal travel, as a function of the kind of manoeuvre. For example, during a parking brake manoeuvre, it is better to have a very little jump-in, vice versa in the case of a panic brake. The main disadvantage of EHB in comparison to standard brake system is its high cost; in the research activity described in this paper, an EHB prototype was built by using standard brake system hardware for the hydraulic unit, to evaluate the performance of a low cost EHB system.

2 The pedal force emulator

PFE was the first component our research group designed. It consists of the Tandem Master Cylinder (TMC) of a common brake system, and a component designed "ad hoc" (Figure 1). TMC primary piston receives the force by the driver; TMC output ports are connected to the failsafe valves (closed when the driver pushes the pedal and no fault is detected) and the component of Figure 1, the heart of PFE, giving the driver the desired force feedback. The TMC is useful only in the case of a fault to pressurize brake fluid for the calipers; it has no function in brake manoeuvres without faults detected in the system. Nowadays simulation is a fundamental tool to reduce cost and time during the design process. PFE was modelled by using the commercial software AMESim®, together with the TMC [2]. According to subjective analysis of pedal feeling, it was demonstrated that common drivers would prefer a brake feeling softer for low values of pedal travel and stiffer for high values of pedal travel [3] than in common braking systems. Target of our activity has been to obtain such a pedal feeling through a simple and cheap device. This target was reached by using a system formed by two pistons and two springs (Figure 1). The piston on the left is a hydraulic piston, pushed by TMC brake fluid pressure; this piston gets in contact with a second piston. The spring between the two pistons is a common TMC spring; it is characterized by a pre-charge to guarantee that the system can go back to the initial condition when the driver does not push brake pedal any more. The initial backlash between the two pistons guarantees a proper initial travel with a very low force feedback perceived by the driver, according to the specification for a low stiffness of the system in the first part of pedal travel. The second spring, between the second piston (in the right part of Figure 1) and the external structure, guarantees the proper feedback force for middle values of pedal travel. For high values of pedal travel, force feedback is due to the conical bump stop in Cellasto®, in the right side of Figure 1. Force feedback to the driver is a little influenced by the pre-charge of TMC springs, since TMC pistons have a travel corresponding to the closure of the communication between the working chambers and the tank. Also friction forces due to TMC pistons and PFE pistons have an influence on PFE force feedback. All these factors could be evaluated through simulation; as a consequence, the experimental optimisation process of the system could be minimized.

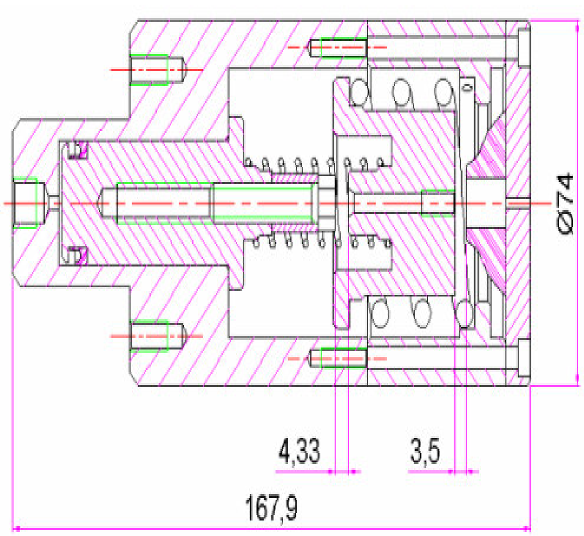


Figure 1 – Politecnico di Torino PFE prototype

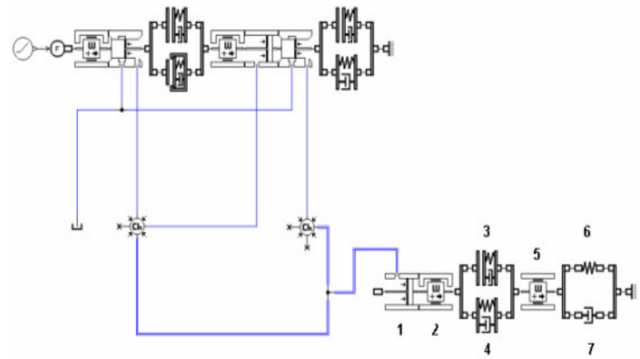
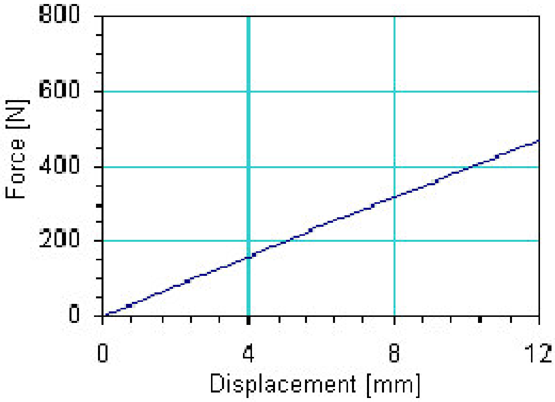


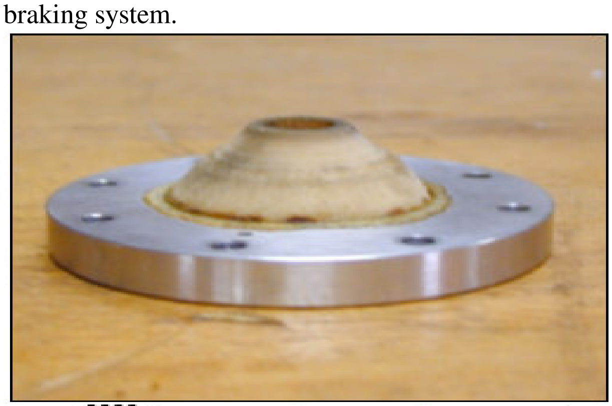
Figure 2 – AMESim® model of Politecnico di Torino PFE

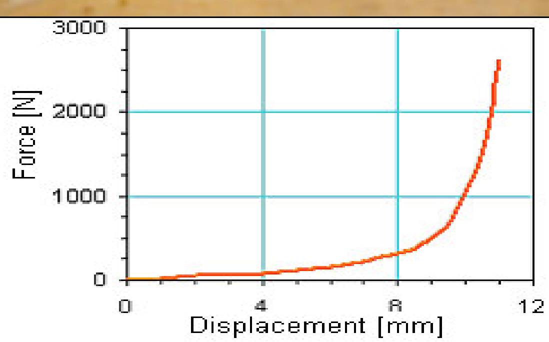
Figure 2 is the sketch of an AMESim® simple model of Politecnico di Torino PFE; at the top of the drawing it is possible to observe the model of a standard TMC, characterized by the two working chambers, and the two output ports. The elements indicated with the numbers 1-7 are the typical components of this pedal force emulator. The hydraulic piston corresponds to the hydraulic chamber indicated as 1, with the mass corresponding to the body 2. Through AMESim®, it is possible to attribute a value for Coulomb friction force, stiction force and damping force for each moving mass. It is of fundamental importance to obtain a realistic result. The spring indicated as 4 is the spring between the two pistons, a standard TMC pre-charged spring. The block 3 represents the contact stiffness between the two pistons, which appears as soon as they get in contact. 5 is the second piston, acting on an equivalent stiffness, corresponding to the effect of the helicoidal spring and the endstop in Cellasto®. By using the model only for the part of the standard TMC, it was possible to verify the correspondence between the simulation and the experimental results through Politecnico di Torino braking systems test bench [2]. Of course, it was of fundamental importance to measure and insert in the TMC model, to obtain realistic results, all the geometric parameters of the real TMC. The second step consisted in performing a predictive analysis of the results corresponding to the complete PFE.



Figures 3, 4 – PFE second spring (between the piston and the carcass): photograph and force – displacement characteristic

Figures 3,4 show PFE reaction spring, located between the piston and the carcass; Figure 4 is the linear experimental force-displacement characteristic of the spring. A very complex tuning was required to set the shape of the end stop in Cellasto® in the proper way, to obtain the desired characteristic (Figures 5 and 6). Figure 7 contains all the elements of the pedal force emulator; the rods indicated as ‘A’ were used to tune the proper pedal feeling, since they permit to define the exact initial distance between the pistons of PFE. Figure 8 shows the connection between the two pistons, whereas the elements (1) and (2) of Figure 9 were used to measure the exact displacement of each of the two pistons of PFE during the first experimental tests. The cap of PFE had a hole to make pass rods ‘1’ and ‘2’, each connected to one of the two pistons. A precise displacement sensor was connected to the elements ‘1’ and ‘2’ outside PFE to detect the internal motions of the system. Figure 10 shows the packaging of the PFE, which is characterized by reduced size in comparison to the booster and a TMC of a traditional braking system.





Figures 5, 6 – The bump stop in Cellasto with the experimental characteristic

A devoted test bench was built to test PFE and then the hydraulic unit of Politecnico di Torino EHB. The bench was based on Hardware-In-the-Loop simulation. An xPC Target system was used to make work in real time the Simulink® blocks used to control the bench and to process the signals from the sensors. Input-output boards by National Instruments were used as acquisition system. A hydraulic actuator pushed TMC primary piston, determining the displacement of the elements inside PFE. The time history of the displacement of the hydraulic actuator was imposed by a manoeuvre selector implemented in Simulink®. A devoted hydraulic unit was used to control the actuator. An electro-valve DHZO 4/4 by Atos controlled the motion of the actuator. A PID controller sent its signal to the solenoids of the electro-valve as a function of the difference between the desired and the real displacement of the hydraulic actuator.

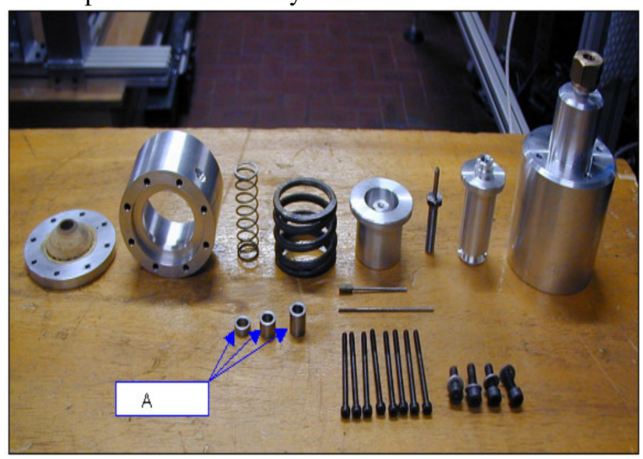
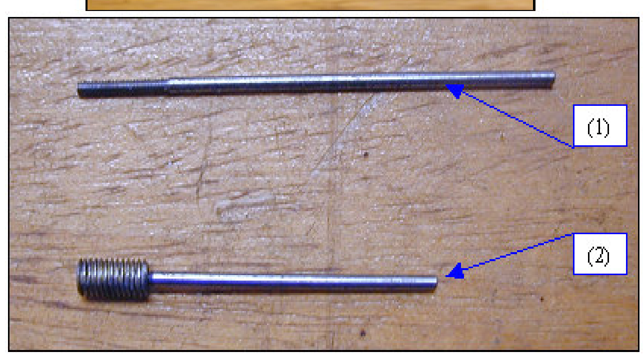
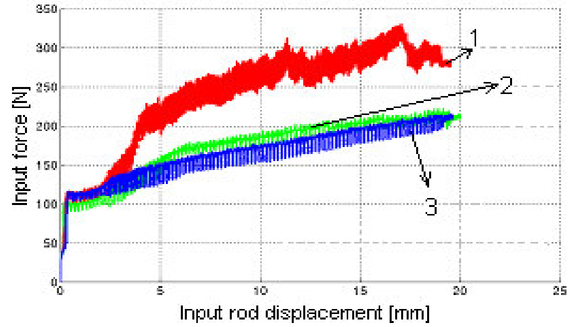


Figure 7 – Components of Politecnico di Torino PFE



Figures 8, 9 – The pistons of Politecnico di Torino PFE and the rods used to measure piston displacements during the tuning of the system

The displacement of the actuator was measured by a potentiometer, located in correspondence of the Tandem Master Cylinder Unit of the PFE. A load cell measured the force between the actuator and the TMC. As a consequence, any kind of manoeuvre could be implemented in the bench. During the first experimental tests, a lot of parameters appeared of fundamental importance to guarantee a correct result. One of them was the friction force between the first piston of PFE and the carcass. Devoted tests were implemented to determine friction forces between the pistons and the carcass, not to have a too big hysteretic behaviour in the force-displacement characteristic. Devoted tests were conceived (Figure 11) to measure friction forces inside PFE. The test of Figure 11, indicated as 3, consisted in pushing the primary piston of the only TMC, having open output ports, to verify the amount of the friction forces and of the pre-charges of the springs of TMC stand-alone. The second step consisted in performing the same manoeuvre, this time having the first piston of PFE (mass number 2 of Figure 2) inserted in the carcass, with the contemporary absence of the springs 4 and 6 of Figure 2. The difference in force between the results of the second and the first test corresponds to the friction forces due to the sliding of PFE piston inside the carcass. In Figure 11 it is possible to analyse the difference in behaviour between two pistons having a different level of superficial roughness (curve 1: high roughness, curve 2: low roughness), inserted in holes executed with different tolerances. It is evident the importance of a big precision in the realization of the components and in assembling them. Through a lot of similar tests, it was possible to find out the best backlash between the hydraulic piston and the carcass not to have consistent friction forces and a fast consumption of the system, due to friction phenomena. Figure 12 summarizes the behaviour of Politecnico di Torino PFE, for two different tunings of the system, obtained by changing the rods indicated as ‘A’ in Figure 7 (curves 1 and 2). The complete accordance between the experimental results and the AMESim© model used to design the system is evident. Figure 12 contains also a comparison between Politecnico di Torino force-displacement characteristic and that presented and used as target in [1] by Bosch. Our research group decided to maintain a pedal feeling quite near that of a traditional braking system, with a maximum pedal travel only a little smaller than that of a standard brake system.



Figures 10, 11 – Politecnico di Torino PFE and the first experimental results

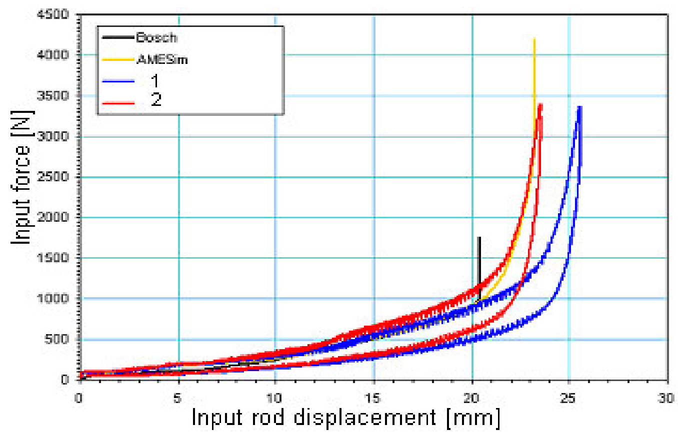
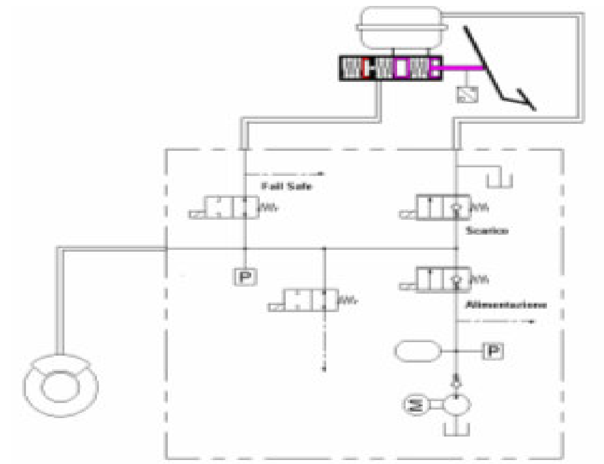
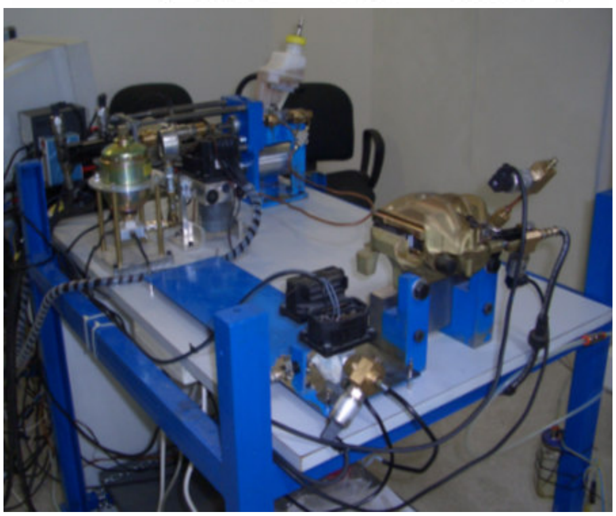


Figure 12 – PFE experimental characterization; Bosch: reference presented in [1], AMESim®: simulation result; 1, 2: experimental results with different elements ‘A’ (Figure 7)

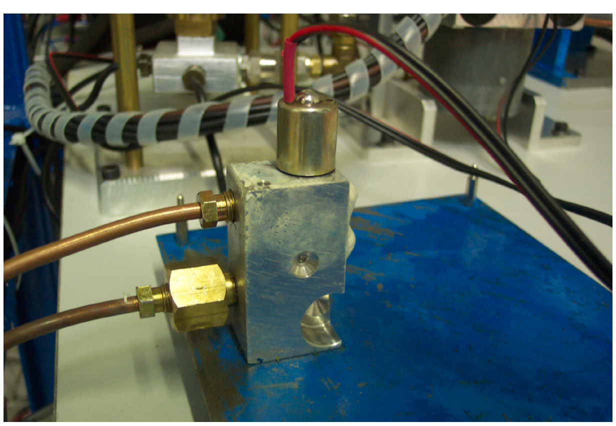
3 The modulation

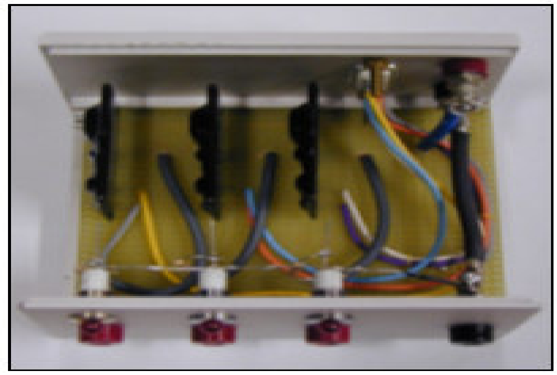
The following step in the activity consisted in developing the hydraulic control unit for a prototype of EHB system also, by using the hardware of commercial ABS/ESP systems. Our research group decided not to use expensive proportional electro-valves, to perform this activity, but standard ABS/ESP electro-valves, characterized by an on-off behaviour. The task of this activity consisted in verifying the possibility of modulating in a very precise way wheels pressures only by using cheap on-off valves. To reach this goal, a prototype of an EHB system for a single caliper was built, according to the simulation activity presented in [2]. It was used the Non-Isolated scheme for EHB hydraulic circuit. It consists of a unique hydraulic circuit for the whole system; the main advantage is the simplicity of the system; the main disadvantage is the fact that a fault in the accumulator provokes a dangerous decay in the performance of the brake system, even if the failsafe valves are activated, since the nitrogen of the accumulator could migrate in the whole brake system. It would provoke a reduction of brake fluid Bulk modulus, and the impossibility to create a pressure in the wheel caliper. A devoted accumulator was designed; it was pre-charged by a standard ESP pump unit. Figure 13 is a scheme of the Non-Isolated circuit for a single wheel EHB system. Figure 14 is a photo of EHB test bench; all the standard sensors of EHB were mounted: accumulator pressure sensor, wheel caliper pressure sensor at the output port of EHB hydraulic unit, PFE pressure sensor, in addition to PFE displacement sensor. Two failsafe valves were inserted in EHB hydraulic circuit: the first, a standard for all EHB systems, was used to connect TMC to the wheel caliper in the case the failsafe algorithm detects a fault, the second one was used to disconnect TMC from PFE in case of fault, not to have too consistent values of pedal travel. Figure 15 shows the first failsafe valve, cut from a standard ESP unit. It is possible to see the solenoid, in the upper part of the figure.





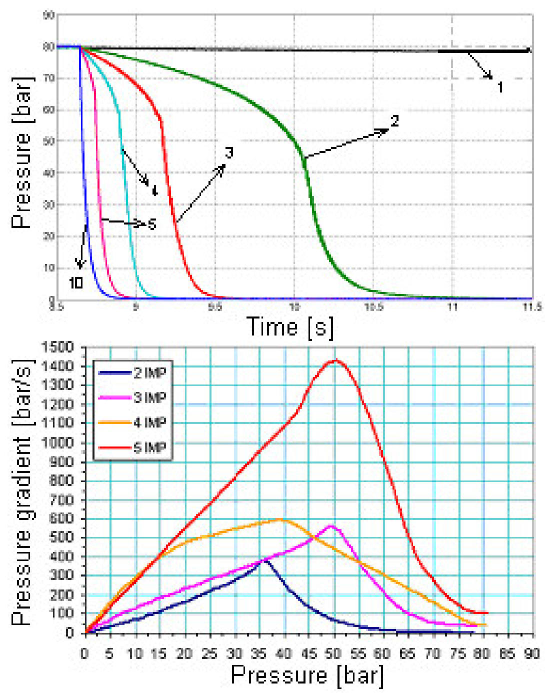
Figures 13, 14 – Scheme of the Non-Isolated circuit and a picture of Politecnico di Torino EHB test bench





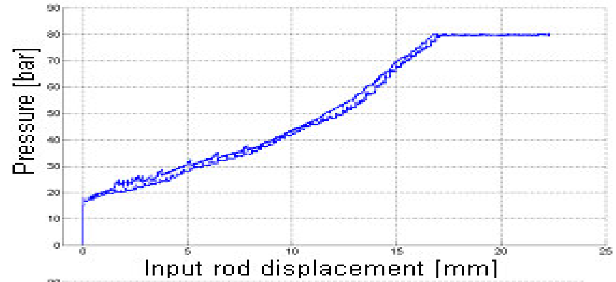
Figures 15, 16 – A failsafe valve in Politecnico di Torino EHB test bench and the electronic device devoted to the control of the electro-valves

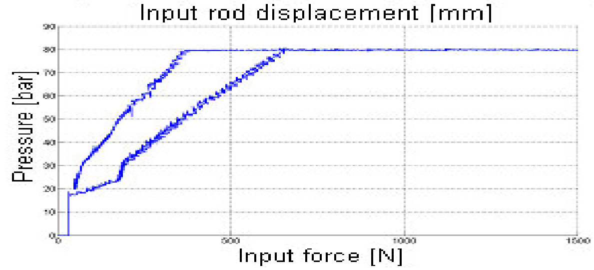
The first test were devoted to detect if it is possible having a smooth modulation of standard ESP electro-valves, also during slow brake manoeuvres, not to have consistent wheels pressures oscillations, due to the on-off opening of the electro-valves. A PWM (Pulse Width Modulation) technique was tested, by building a devoted electronic box (Figure 16) characterized by a system of high performance relays, having turn on and turn off times minor than 1 ms.



Figures 17, 18 – First experimental results obtained through the modulation of the electro-valves

Different kinds of modulation were tested, for example by changing the typical frequency of modulation. As a consequence of a lot of experimental tests, an optimal modulation frequency of 100 Hz was found. Figure 17 is about a sequence of several modulation tests at the PWM frequency of 100 Hz; an initial pressure level of 80 bar was imposed at the wheel caliper. In the following part of the test, a different number of electrical pulses, each having the duration of 1 ms, during each cycle of modulation were imposed on the pressure reduction valve. Each 0.01 s, 1, 2 ,3 , 4, 5 pulses of 1 ms were imposed, corresponding respectively to lines 1, 2, 3, 4 and 5 of Figure 16; in the test showing the biggest pressure gradient, the pressure discharge valve was maintained fully open (line 10 of Figure 17). Optimisation of modulation regarded also a different distance imposed between the pulses, for the same duration of the opening of the discharge valve, during a PWM cycle. In fact, for example, if you have to impose 3 pulses within a period of 10 ms, it is possible to generate them in the first part of the period of modulation, or to distribute them during the period. The experimental results showed that it is useful to impose the most consistent possible distance between the pulses to have a reduction of pressure oscillations at the wheel caliper. These oscillations could give origin to a decay of the feeling of comfort transmitted by the vehicle to the driver. The results of all these tests originate look-up-tables, similar to that shown in Figure 18, plotting the obtainable pressure gradients as a function of actual pressure, for different values of pulses within one PWM cycle. These look-up-tables are used by EHB control algorithm, to determine the modulation of the electro-valves, as a function of caliper pressure and desired pressure gradient. Another task consisted in creating a second order transfer function to estimate caliper pressure, measured in the test bench by a devoted sensor, on the basis of EHB hydraulic unit output port pressure sensor. In a real application of EHB, only this second sensor would be present on the car. In fact, as it was explained previously, it would not be realistic to modify wheel calipers by adding a pressure sensor for EHB system. Wheel calipers can be produced by different suppliers than EHB hydraulic unit; as a consequence, it will not be possible to mount wheels pressure sensors for EHB directly at the calipers. The transfer function takes in account the dynamics due to the pipes. Figures 19 and 20 were obtained by implementing a complete base brake control algorithm; these pictures are experimental results got with Politecnico di Torino test bench, having imposed a reference pressure similar to that of a standard booster. They are about a semi-stationary brake manoeuvre, at a TMC input rod speed of 3 mm/s. EHB control algorithm compares reference pressure and output pressure from the hydraulic unit; on the basis of the difference, it takes a decision about the modulation level for the electro-valves, by using a look-up-table based control algorithm. It is clear the low level of amplitude of pressure fluctuations, due to the correct modulation of the electro-valves and the correct estimation of wheel caliper pressure. In Figure 20, it is evident an initial step in pressure, similar to the jump-in of standard brake boosters. Further work has been carried out to evaluate the performance improvement in panic brake manoeuvres; a Brake-Assist control algorithm was implemented, too. A detailed analysis based on PC simulation together with a whole vehicle model was performed to evaluate the possible performance increase of ABS and ESP control algorithms due to the improved pressure modulation and to the additional sensors typical of EHB. During ABS modulation, a standard brake system is characterized by pressure oscillations at the calipers with an amplitude of about 20 bar; by using an EHB system, it was possible to reduce these oscillations at a level of 10-15 bar only, giving origin to an improvement of the stopping distances.





Figures 19, 20 – Experimental results of Politecnico di Torino EHB system

4 Conclusions

EHB seems to be a promising evolution of standard brake systems. It should guarantee a better dynamic response during panic brake manoeuvres. In addition, Pedal Force Emulator should improve pedal feeling in comparison with traditional systems. A HIL test bench was implemented to test Politecnico di Torino PFE and to design the control algorithm for EHB. It was possible to find out a control algorithm capable of minimizing pressure oscillations due to the on-off behaviour of standard ESP electro-valves. Further work will be necessary to improve the reliability of the system, especially from the point of view of the high pressure accumulator durability. Finally, it will be necessary to implement an EHB test bench by using four wheels callipers, and not only one wheel caliper.

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