Methodology for Modeling of the Mechanical Part of an Anti-lock Braking System by Bond Graph

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Abstract-- **A system is a structured combination of elements related to each other to form a coherent entity which has one or more functions. Several researchers are interested in systems studies which may be in many ways placed around the modeling, simulation and improvement of systems according to evolving needs. This communication is part of the modeling mechatronic systems domain, using a systemic approach. It is a contribution to the study of anti-lock braking systems (ABS) in order to find a methodology for modeling and simulation of complex, nonlinear and multi-disciplinary systems, by exploiting the bond graph (BG) formalism. Thereby supervise these functional behaviors.**

Index Terms--**Analysis and modeling, mechatronic systems, anti-lock braking system, Bond Graph.**

1. INTRODUCTION

The systemic is a new discipline that combines the theoretical, practical and methodological approaches, relating to the study of what is recognized as too complex to be tackled in a reductionist way, laws or emergent properties characterizing the system or mode observation problems, representation, modeling or simulation of a complex totality [1-4].

Modeling is the process of developing a model, which is a representation of the architecture and the function of the system [5]. One of the objects of a model is the ability to predict the effect of changes in the system. On the one hand, a model should be a close approximation of the real system and integrating the most of its characteristics. On the other hand, it should not be too complex in order to be treated mathematically or numerically.

The mechatronic systems are complex systems. Which are it is the integration of mechanical and electromechanical systems (mechanical components, machinery, precision mechanics..) with electronic systems (microelectronics, power electronics, sensors, actuators) and information technology (systems theory, modeling, automation, software, artificial intelligence) [6], [7].

Nowadays, mechatronic systems, mostly involve several disciplines. Robotics can be considered the father, or the ancestor of mechatronics. Today mechatronics goes well beyond the framework of robotics and affects many applications very present in areas in our daily lives, as well as in industry [8]. It affects more and more the world of transport and in particular the automotive sector.

The complexity of such systems requires the use of systemic tools allowing on one hand a fair system modeling and helping to design or improve existing systems on the other hand. The decomposition of the system to study several subsets, which can be studied separately, permits to facilitate the modeling process.

This communication provides a description of the anti-lock braking system (ABS) operating modes and the partial modeling of this system by using the bond graph (BG) methodology.

2. ANTI-LOCK BRAKING SYSTEM

The ABS is active safety equipment which helps the driver to maintain directional control of the vehicle by preventing the wheels from locking during braking intense episode [9], [10].

The ABS braking systems are not all configured the same way; some prevent blocking of the four wheels whereas others avoid only blocking of the rear wheels [11], [13]. All ABS systems, however, operate by monitoring wheel speed. If a potential blockage of wheel is detected, it applies or rapidly releases the brake on that wheel. All ABS systems use four main components: the wheel speed sensors, the hydraulic part, the braking pressure modulator and the electronic control unit.

A. *Wheel speed sensors*

The wheel speed sensors are inductive proximity detectors. They monitor the rotational speed of the wheels and the vehicle. When the sensors detect that the wheels even one of the wheels no longer rotates, although the automobile continues the movement, it means that the wheels are locking. The signals delivered by the sensors are processed by a digital electronic system in the sensors.

B. Hydraulic part

The brake control is affected from the master cylinder; the centerpiece of the system which is connected to the brake fluid reservoir. When the driver presses the brake pedal, the force is transmitted to the brake booster, which then transforms this power to the master cylinder. So the strength of the supports is the one that determines the braking power.

C. The braking pressure modulator

The braking pressure modulator has the function of modulating the hydraulic pressure to the wheel cylinders or calipers. The assembly modulator contains the solenoid valves of the hydraulic system, a motor pump and two accumulators.

The solenoid valve is a controlled hydraulic valve, managing the transition between the master cylinder, the wheel cylinder and the oil tank. These positions are arranged and organized by the electronic brake control module with electrical signals of different intensities, powering the coils to create electromagnetic forces.

D. Electronic control unit

It is the electronic control unit (ECU) which receives the information from the wheel speed sensors. In the modern ABS system, the ECU and the hydraulic units are integrated. The ECU detects any signs of rapid deceleration of a wheel and commands the electronics unit to act on the electrovalves [14].

The following figure shows the four parts constituting the ABS braking system.

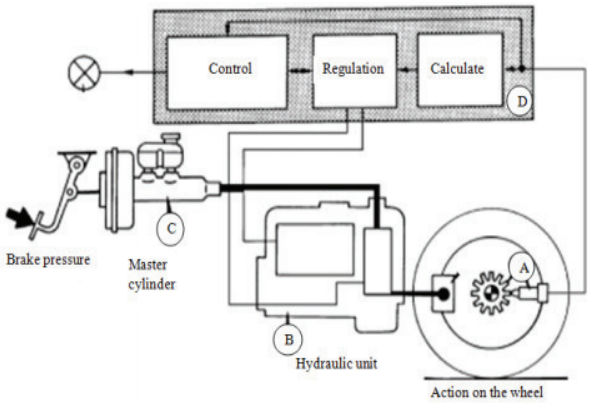


Fig. 1. ABS brake system components [15].

3. RESEARCH WORKS ON ABS MODELING

The work on the braking system and its components require special and meticulous attention, because its malfunction leads to endanger human life. Also, the quality of work and components, spare used must it be always a major concern [10], [16]. Since the 70s, an increasing number of scientists have been interested in the braking systems; the following paragraph shows some research on the ABS braking system.

Marcel-Stefan Geamanu (2013) [17], has modeled and simulated the dynamic behavior of the wheel of a car in the braking condition with an ABS system after estimating model parameters.

Cem Unsal (1999) [18], has proposed a design based on a nonlinear observer for controlling the vehicle traction he designed a sliding mode controller to keep wheel slip during braking with an ABS system. Direct feedback from the state is replaced with non-linear observers to estimate the vehicle speed from the system output.

Li Bing-lin, and Wan Mao-song (2015) [19], have analyzed the braking process of the vehicle and the principle of operation of the antilock system (ABS), they used the method AME Sim and the control strategy based on the PID controller to determine the model of the hydraulic system for a vehicle with a single wheel.

Chankit Jain, Rahul Abhishek and Abhishek Dixit (2014) [20], have explained the system of dynamic equations of the wheel during ABS braking, they used a Simulink model and the PI control strategy to maintain the slip rate and simulate the speed and the braking distance of the vehicle.

Mohamad Heerwan Bin Peeie, Hirohiko Ogino and Yasuo Oshinoya (2016) [21], have proposed a model that combines the ABS braking system and the control braking with recuperation, to improve the braking performance of small electric vehicles. Hydraulic ABS unit is installed at the front tire, whereas a motor in the wheel at the rear, then they simulated the performance of this model.

Hongtao Zhang, Wei Han, Lu Xiong, and Songyun Xu (2016) [22], have studied the integration of the hydraulic part and the electronic part of the ABS braking system to design an electrohydraulic system, they proposed a control unit (HCV), which is composed of six on-off electrovalves of the high debit to control the hydraulic pressure wheel cylinders, then they have set up a simulation model of the designed system.

4. DYNAMIC EQUATIONS OF THE MASTER CYLINDER

This communication is interested in modeling the master cylinder; it is the mechanical part that produces the pressure set point for the ABS braking system.

The master cylinder of a hydraulic braking system transforms the force applied by the driver for actuating the brakes on the wheels. To meet the requirements of the legislation, each vehicle must have two separate brake circuits; the master cylinder is designed as tandem units where there are two pistons in one cylinder, with two separate rooms which are nominated the primary and secondary chambers.

When the driver presses the brake pedal, the booster is a device that converts the force in a pressure set point to the master cylinder that transforms this pressure to the wheels by means of all which form the hydraulic unit.

The mechanical part comprises an oil tank distributed by the two hydraulic chambers and a set of elements represented by figure 2.

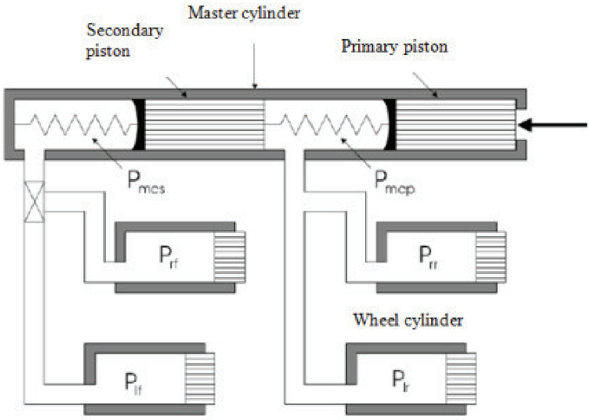


Fig. 2. Constitution of the mechanical part [16].

F_{spring} : the force exerted on the spring for coefficients k1 and k2.

x_{mcp} and x_{mcs}: compression springs in the primary and secondary chamber.

The variation of volume is modeled by these two equations.

In permanent regime the mathematical model of the master cylinder is presented by the following equations:

$$F_{spring1}=F_0+k_1(x_{mcp}-x_{mcs}) \quad (1)$$

$$F_{spring2}=F_0+k_2.x_{mcs} \quad (2)$$

$$\mathrm{Pmcp} = \frac{Fpedal - \mathrm{Fspring1} - Frestriction}{Amc} \quad (3)$$

$$\mathrm{Pmcs} = \mathrm{Pmcp} - \frac{(\mathrm{Fspring2} + Fsrestriction)}{Amc} \quad (4)$$

Where:

Pmcp: the pressure in the first chamber of the master cylinder.

Pmcs: the pressure in the secondary chamber of the master cylinder.

$$\frac{\mathrm{dv_r}}{\mathrm{dt}} = Cq.\sqrt{\mathrm{Pmcp} - \mathrm{pr}} \quad (5)$$

$$\frac{\mathrm{dv_{ra}}}{\mathrm{dt}} = \mathrm{Cq}.\sqrt{\mathrm{Pmcs} - \mathrm{pr}} \quad (6)$$

Where:

Cq: Valve orifice coefficient.

Pr: Reservoir pressure.

Vra and Vr the exchanged volumes enter master cylinder and the reservoir, these volumes circulate in the circuits of braking.

$$x_{mcp} = \frac{\mathrm{Vr}}{\mathrm{Amc}} + x_{mcs} \quad (7)$$

$$x_{mcs} = \frac{\mathrm{Vra}}{\mathrm{Amc}} \quad (8)$$

It is important to give the mathematical model representing the master cylinder's relationship with its environment particularly with the brake disc.

The mathematical model of the master cylinder and drum brake is expressed in equations (9) and (10) [21].

$$\rho gAmcHp - K(xp - xd) - kp.xp - dp.\frac{dxp}{dt} = mp\frac{d^2xp}{dt^2}. \quad (9)$$

$$k(xp - xd) - kd.xd - df\frac{dxd}{dt} = md\frac{d^2xd}{dt^2} \quad \text{when } \mathrm{xp(t)} = \frac{Vra(t)}{Amc} \quad (10)$$

Where: Amc is the master cylinder section, Hp is the pressure of the highest point of the tank, kd and kp are the coefficients springs, dp and df are the damping coefficients in oil, mp and md are the masses of the pistons of the master cylinder and the movable portion of the drum brake also xp et xd are the compressions of the springs in master cylinder and the drum brake finally ρ is the brake oil density [25], [26].

5. BOND GRAPH MODELING OF THE MASTER CYLINDER

BG method to treat chains of energy and information, this is an oriented graph showing dynamic variables, which translate the energy transfers between systems. They are based on power relationships. It helps to understand the energy transfers and focuses particularly on structural properties of complex systems as it highlights the causality in the resulting model.

The objective is to reproduce graphically all physical phenomena taken into account in the modeling hypothesis. At this level, the bond graph tool enables with its graphical nature, using a single language, highlighting the nature of the power exchanges in the system, such as storage phenomena, processing and power dissipation.

The order and type of dynamics of the system are deducted directly from the model. With its evolving nature, the graphical structure of the resulting model may be modified by a simple addition of bond graph elements [27-31].

The basic requirement is that the brake servo shall be sufficiently sensitive to provide the braking pressure. The determination of the pedal and booster parameters is studied by researchers [24], [25], [32]. The following figures represent the responses of these devices to different set points.

Once the strength of the driver increases, it will continue until it reaches the maximum of atmospheric pressure, called Knee point. These two curves showing the non-linearity of the system, in this case the bond graph model can be a transformer MTF of which the transformation ratio is a non-linear function. In our case we will take a transformation ratio around an operating point which represents a fixed action on the pedal.

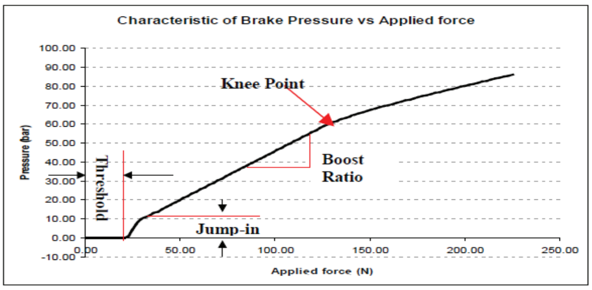


Fig.3 Characteristics of brake pressure and brake pedal applied force [24].

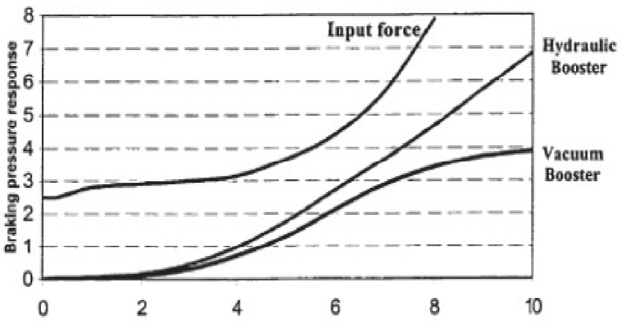
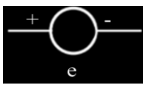
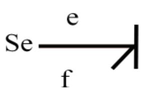
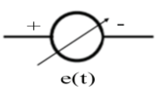
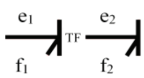
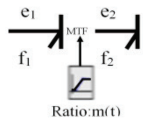
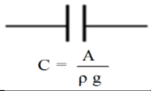
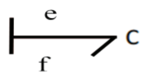
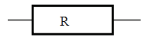
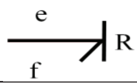
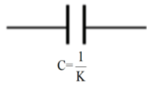
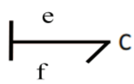
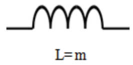
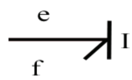


Fig.4 Characteristics of the vacuum and hydraulic booster [32].

To determine the bond graph model of the ABS system and based on several references interested in modeling systems by Bond graph formalism [33-35], we present the models of each element of the mechanical part of this system in the following table:

TABLE I

The master cylinder elements of the ABS

Element	Equivalent electrical model	Bond Graph model
The fixed Force		
The variable force		
Pedal		
Booster		
Reservoir		
Restriction		
Springs		
Mass of the piston		

The next step of the modeling is to assemble the previous elements by contacting them with junctions "0" if submitted by a common effort and by junctions "1" if they are traversed by the same flows. The bond graph model is given by the following figure:

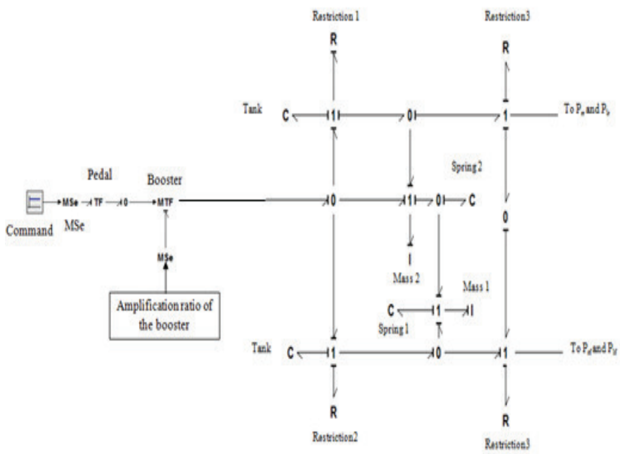


Fig. 5 Bond graph model of the master cylinder ABS.

The simulation is a tool used by the researcher, engineer, military, etc. to study an action on an element. In this part we have simulated the behavior of the master cylinder for a driver force set point value 100 N, the simulation results are shown in the following figures.

Figure 6 presents the pressure evolution in the master cylinder; Figure 7 presents the compression of the spring 1 in the master cylinder and Figure 8 presents the compression of the spring 2 in the master cylinder.

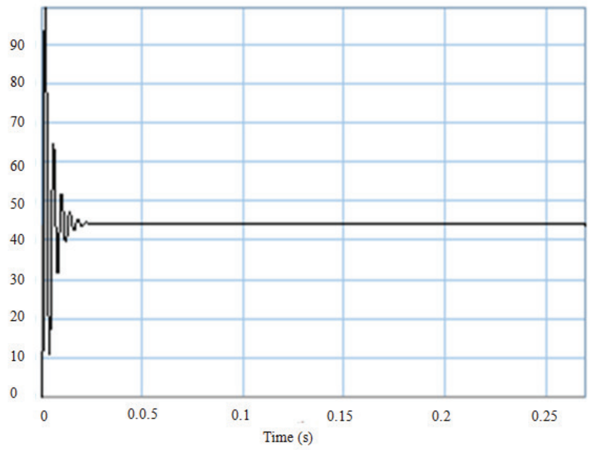


Fig. 6 Pressure evolution in the master cylinder.

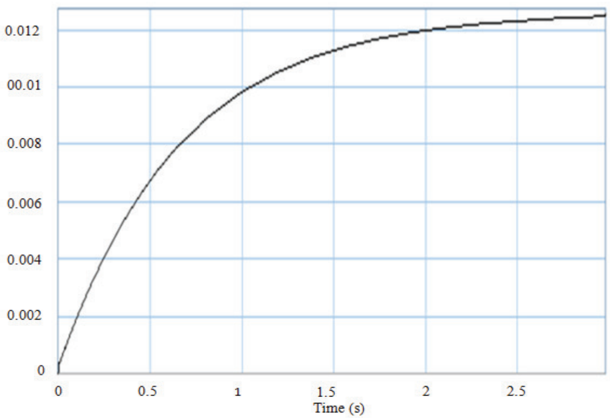


Fig.7 Compression of the spring 1 in the master cylinder.

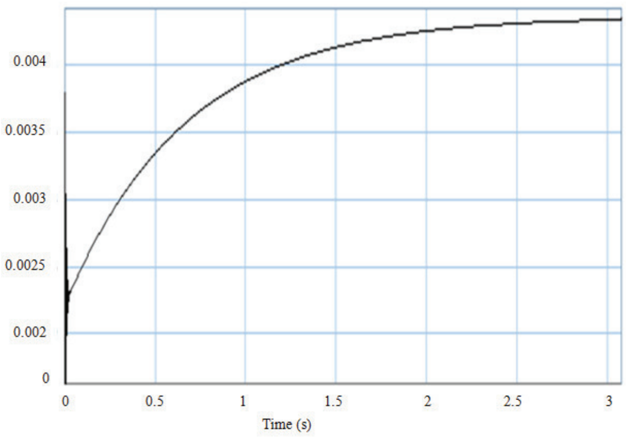


Fig.8 Compression of the spring 2 in the master cylinder.

When applying a 100N force on the brake pedal the pressure evolution in the master cylinder begins by rapid undulations, then stabilizes at a value of 44 bars which conforms with the curve of Figure (3), we also see that the compression of the first spring is 12 mm by against the second spring length is reduced only 4.3 mm.

6. CONCLUSION

The simulation model allows mainly studying the behavior of the mechanical part of a fixed supporting force. This allows internal supervision of these parts and providing information on the evolution of several variables. This information can be used to improve the response time and minimize vibration or amplify the braking pressure.

Any model contains parameters modifying his behavior and variables permitting the prediction of its evolution. In some cases, these variables and parameters can be measured directly (for example, the wheel rotation speed). In other cases, the interest parameters must be estimated by using the model equations or by observation of responses.

After simulating the model in degraded mode by modifying these parameters, we can integrate a system to simulate the effects of the partial or total degradation of the mechanism to minimize the danger to human life.

This communication concerns the modeling process, which uses the graphic language, going through the development of dynamic models and opening to simulation, in order to be capable at first to orient, then in secondly to act on the system.

REFERENCES

[1] B.S Blanchard, W.J Fabrycky, W.J Fabrycky, "Systems engineering and analysis", paerson international edition 1990.

[2] S. Eggins, "Introduction to systemic functional linguistics" 2004 - books.google.com.

[3] F. Moussa, C. Kolski, M. Riahi, "Analyse des dysfonctionnements des systèmes complexes en amont de la conception des IHM : apports, difficultés, et étude de cas", Faculté des Sciences de Tunis, Université de Valenciennes et du Hainaut-Cambré, 2006.

[4] C. Bernard, "Le processus de décision dans les systèmes complexes : une analyse d'une intervention systémique", université du Québec, 2006.

[5] A. Maria, "Introduction to modeling and simulation", Proceedings of the 29th conference on Winter simulation, pp. 7-13, Washington DC, Maryland, USA, 1997.

[6] J. Cousin "Modélisation des Systèmes Mécatroniques" université numérique et technologie Saint Etienne, 2009.

[7] H. Belhadaoui,"Conception sûre des systèmes mécatroniques intelligents pour des applications critiques", Centre de Recherche en Automatique de Nancy, 2011

[8] G. Hamza, "Contribution aux développements des modèles analytiques compacts pour l'analyse vibratoire des systèmes mécatroniques", universités, Sfax Tunisie, Paris Saclay, Centrale Supelec France, 2016.

[9] T. Zhi-Hui, C. Zhen-Fu, P. Xiao-Fei, G. Xue-Xun, and P. Shuang-Hong, "Development of Integrated Electro-Hydraulic Braking System and Its ABS Application", international journal of precision engineering and manufacturing, march 2016.

[10] L. Liang Xujian, L. Xiangyu Wang, Y. Liu, J. Song and X. Ran, "Transient switching control strategy from regenerative braking to anti-lock braking with a semi-brake-by-wire

system", International Journal of Vehicle Mechanics and Mobility, January 2016.

[11] T. K. Bera, K. Bhattacharya, A.K. Samantaray, "Evaluation of antilock braking system with an integrated model of full vehicle system dynamics", Department of Mechanical Engineering, Indian Institute of Technology, India, Elsevier 2011.

[12] T. B Hoang, "Observateurs commutés et compensation de retard pour les systèmes d'antiblocage des roues",Université paris sud, 2014.

[13] Z. Hongchang, Z. Yunqing and C. Liping, Hardware-in-the-Loop Simulation of Pneumatic Antilock Braking System Based on Modelica, International Journal of CAD/CAM Vol. 10, N°1, pp. 29~37, 2010.

[14] G. Jingang, J. Xiaoping and L. Guangyu, "Performance Evaluation of an Anti-Lock Braking System for Electric Vehicles with a Fuzzy Sliding Mode Controller", Energies 2014.

[15] A. Demri, "Contribution à l'évaluation de la fiabilité d'un système mécatronique par modélisation fonctionnelle et dysfonctionnelle", Univ. d'Angers, 2009.

[16] N. Geromel, "ATV braking system: Introduction and system modeling Aalto", university, Matikainen 2014.

[17] M. Stefan Geamanu, "Estimation and Dynamic Longitudinal Control of an Electric Vehicle with In-wheel Electric Motors", Laboratoire des Signaux et Systèmes, SUPELEC,,Paris, 2013.

[18] C. Unsal, "Sliding mode measurement feedback control for antilock braking systems", IEEE transactions on control systems technology, vol. 7, N°2, march 1999.

[19] L. Bing-lin, W. Mao-song, "Study on the Control of Anti-lock Brake System based on Finite State, International Conference on Advances in Mechanical Engineering and Industrial Informatics", China, 2015

[20] J. Chankit, R. Abhishek, D. Abhishek, "Linear Control Technique for Anti-Lock Braking System", Journal of Engineering Research and Applications, 2248-9622, Vol. 4, Issue 1, August 2014, pp.104-108.

[21] M. Heerwan Bin Peeiea, O.Hirohiko and Y. Oshinoyab, "Skid control of a small electric vehicle with two in-wheel motors: simulation model of abs and regenerative brake control", international journal of crashworthiness, mars 2016.

[22] Z. Hongtao, W. Han, Lu. Xiong, Xu. Songyun, "Design and Research on Hydraulic Control Unit for a Novel Integrated-Electro-Hydraulic Braking System", IEEE Transportation Electrification Conference and Expo, Asia - Pacific (ITEC) June 1 - 4, Busan, Korea, 2016.

[23] K. Chun Huang and S. Ming-Chang, "Design of a hydraulic anti-lock braking system (ABS) for a motorcycle, Journal of Mechanical Science and Technology", Springer 2010.

[24] H. Ping HO," The influence of braking system component design parameters on pedal force and displacement characteristics", University of Bradford, 2009.

[25] F. Tianku, "Modeling and performance analysis of ABS systems with nonlinear control", University Montreal, Canada 2000.

[26] I. Filipovic , B. Pikula and D. Prelcec, "A detailed Model for Simulation of hydrodynamic processes in hydraulic braking system with ABS on motor vehicles", Journal of Scientific Research & Reports,2016.

[27] A. Mughal, "Elements of Bond Graph real time modeling, simulation and control of dynamical systems", Springer, 2016.

[28] M. Van Hoa Nguyen, "Synthèse de tolérance pour la conception des systèmes mécatroniques : Approche par bond graph inverse", Université de Lyon, 2014

[29] P.J. Cheng, H.P. Huang, "Robust fault detection and isolation using bond graph for an active-passive variable serial elastic actuator", International Journal of Robotics and Automation (IJRA), Volume (6): Issue (2), 2015.

[30] L. Cauffriez, S. Grondel, P. Loslever, C. Aubrun, "Bond Graph modeling for fault detection and isolation of a train door mechatronic system Control Engineering" , Elsevier, 2016.

[31] M. Arab Djeziri, "Diagnostic des Systèmes Incertains par l'Approche Bond Graph", Ecole Centrale de Lille, 2007

[32] Y. Konishi, "Development of hydraulic booster Unit for Active Brake Control", SAE Paper 980602, 1998.

[33] W. Borutzky, " Bond graph methodology: development and analysis of multidisciplinary dynamic system models", books.google.com, 2009.

[34] A.K Samantaray, BO. Bouamama, "Model-based process supervision: a bond graph approach", Springer, 2008.

[35] B. Ould Bouamama, D. Tanguy Geneviève, "Modélisation par bond graph Application aux systèmes énergétiques", Techniques de l'Ingénieur, 2008.