PROBABILISTIC EVALUATION OF ABS MANEUVER FAILURE FOR AN ELECTRONIC BRAKE SYSTEM BY TOLERANCES ANALYSIS

Lucian Eugen ROŞCA[1], Ioan BONDREA[1]

ABSTRACT The ABS system for passenger vehicles as a mechatronic safety critical real-time system comprises a high number of components in a complex architecture (mechanics, hydraulics, electronics and software). Braking system hydraulic inlet valve switch event is the crucial point of the ABS control chain and prevents the driver from locking the vehicles wheels on a hard braking maneuver. Statistical tolerance analysis based on Monte Carlo simulation is applied in this study to determine the influence manufacturing variations and external factors during real life exploitation over the braking system in an ABS control maneuver for a large set of produced units. Results in this paper presents a probabilistic evaluation of the control chain robustness during an ABS maneuver in terms of system performance dependency in respect to components tolerances, to offer an overview of the performance margin for a large population of a produced units.

KEYWORDS Antilock braking system, evaluation of failure, probabilistic evaluation, tolerances analysis

1. INTRODUCTION

Antilock braking system as a safety critical mechatronic system is mass-produced and mandatory equipment required in all new passenger cars sold in the EU since 2007. In case of a failure during ABS control, vehicle wheels will lock and lead to a longer stopping distance and poor or no steering control on most of the road surfaces. An ABS failed maneuver can be only a timely failure but may have severe impact including accidents with loss of human life. Malfunction of an ABS control has to be prevented by design and must guarantee the optimal performance of the system in any circumstances. The complexity of antilock braking system architecture makes this task difficult even for manufacturers with considerable experience. In the architecture of the braking system a large number of different components like mechanical, hydraulic, electronic and electrical, are coupled together, all controlled by software in order to prevent the vehicle wills from locking up during a hard brake maneuver [1]. Braking system faults have been analyzed for the hydraulic part of the system [2] and communication systems between components [3] to emphasize the importance of integrating redundant counterparts in order to guarantee optimal performance in exploitation and to expose the limits of validation techniques traditionally used for guarantee the robustness of a complex mechatronic system.

In the mass production each system component has a certain amount of deviation from its nominal design values and because of unavoidable effect of manufacturing variation; an accepted tolerance limit is defined for each component in the design phase. This limit should guarantee full operation according to the top level requirements.

Regarding mechanical mechanisms and assemblies different algorithms and techniques have been developed for tolerance allocations and evaluation of their effect on functionality by statistical tolerance analysis methods like Monte Carlo simulation in order to relax or strengthen certain component tolerance limit requirements having the goal of finding a balance between reducing cost of manufacturing and ensure quality [4-7].

In complex systems like the electronic brake system with a very high number of active components that have tolerances, the overall probability of the combination that all worst case conditions are met in the same time becomes low with rising number of components. Nevertheless a study over the effect of system tolerances and environmental conditions later defined in the paper which as well have a probabilistic variation is required for fully guarantee system robustness during operation.

In this paper the probability that an ABS maneuver control will fail under normal everyday exploitation conditions is evaluated by statistically analysis of the system components tolerances,

[1] ULBS, Bd. Victoriei 10, Sibiu, 550024, Romania

including the effect of externals factors like environmental conditions.

Starting from the above perspective the structure of the paper is as follows. Section 2 introduces the overall braking system description and ABS control algorithm. In Section 3 to 6, the design of the ABS control chain is divided in sections. A section is defined as the part where energy is transported in the same form or in other words, a section boundary is where the energy form is altered. The section boundary means a loss of efficiency while transforming energy from one form into another. Definition of the parameter in evaluation together with their statistical distribution are presented and later used as inputs for the Monte Carlo simulation. Paper section 7 defines the environmental conditions which hold parameters like ambient temperature in the engine compartment and parameters of electrical network for supplying the system with electrical energy. Section 8 introduces the mathematical model of the simulation and defined scenarios together with the Monte Carlo simulation flow chart, are defined in section 9 and 10.

Paper section 11 and 12 concludes with presenting the results of the simulations and the conclusions of this research.

2. BRAKING SYSTEM HYDRAULIC LAYOUT AND ABS FUNCTION DESCRIPTION

The hydraulic electronic control unit (HECU) installed in vehicles has many active components which can be divided in three categories: mechanics, hydraulics and electronics. In Fig. 1, is presented the hydraulic layout of a standard braking system with two separate circuits, starting from master cylinder pressure towards wheels calipers together. Inlet ABS valves are highlighted in this layout and described in detail in next section. During braking maneuver hydraulic pressure is created by the driver when pressing the brake pedal. The displacement of the master cylinder leads to high pressure brake fluid flow through the circuit towards the wheels calipers. To prevent the wheels to lock, the ABS function employ electro-mechanical controlled hydraulic-valves to regulate the brake pressure during hard braking. This is done using four valves present in each circuit, two valves for each wheel called inlet and outlet valves. Inlet valves are normally open valves, brake fluid flows through it when the valve is not activated and outlet valves are normally close valves which means that brake fluid will flows trough only when the valve is activated. During an ABS maneuver pressure is increased, decreased or held using the controlled electro mechanical hydraulic valves. When a wheel sensor detects a wheel that may lock pressure increase must be stopped immediately and this is done by activating the inlet valve. In this moment the driver is prevented from increasing furthermore the pressure and to lock the wheel. This stage of the ABS control chain is called pressure hold, no more pressure increase is possible because inlet valve is activated and outlet valve is close in its normal state. Depending on the road surface it may be the case that pressure has to be decreased, in this case outlet valve is activated and fluid is released into a chamber called low-pressure accumulator. From here an electro-hydraulic return pump, pumps the fluid back into the brake fluid reservoir. This pressure regulation repeats during an ABS maneuver as long as a wheel tends to lock.

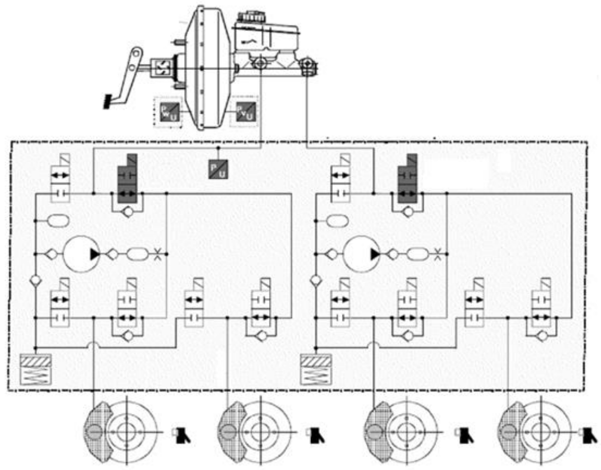

Figure 1. Braking system hydraulic layout

3. COMPONENTS OF ABS CONTROL CHAIN AND DEFINITION OF THE SYSTEM TOLERANCES

In order to identify the system components which may affect braking system performance during ABS maneuver due to tolerances, the ABS control chain is divided into sections. A section boundary is defined as the part in the system where energy is transformed from one form into another. In Fig. 2, is presented the identified sections and its main components which are sensible to tolerances. Vehicle supply voltage and ambient temperature are considered as environmental conditions outside of the system but nevertheless included here as a section of the system. System electrical architecture is considered as section two where electronic components and software come together to control the inlet valve. In this section electrical current controlled by a PWM flows through the valve coil creating a magnetic field necessary for valve actuation. In section tree the ABS inlet valve represents the hydraulic and mechanical component of the system architecture which is responsible for brake fluid pressure regulation. In this section magnetic force of the coil leads to valve tappet displacement from its normal open position to its close position which will stop fluid to flow through the valve.

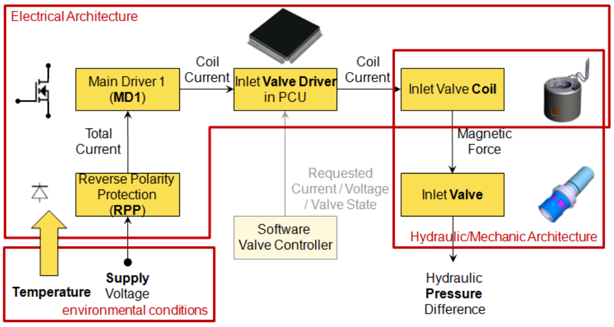

Figure 2. Defined system boundaries

Definitions of the parameter in evaluation together with their statistical distribution are presented next for each considered system section.

4. SYSTEM ELECTRICAL COMPONENTS TOLERANCES AND SHAPE OF THEIR DISTRIBUTION

From the tolerances point of view electronic and electrical components exhibit a variation in the ohmic resistance from two reasons, one is variation due to mass production imperfection and second is due to temperature. A braking system electrical architecture is a very complex one and because the focus of evaluation is tolerances analysis only components which can affect the current flow intensity are schematic represented as resistances in Fig. 3. To activate an ABS inlet valve the system is connected to the vehicle battery and current flows through several components like reverse polarity protection (RPP) and main driver (MD1), inlet valve driver, towards valve coil and circuit ends with a connection to the ground (GND). The system has four valves connected in parallel, the below figure show the components end their nominal resistance are shown. For the evaluation all four inlet valves are considers active and all the other valves shall be off.

For each electrical component of the system in the design phase a nominal value is establish together with a specified range of deviation allowed in the mass production and considered as good quality to enter in the assembly process. How the deviations are distributed in this range depends on the manufacture process of the electronic components and is controlled and measured for an established number of components exiting the production line resulting in a certain shape of the distribution. Table 1, shows for each selected component the specified nominal, minimum and maximum value together with the shape of the distribution and temperature coefficient.

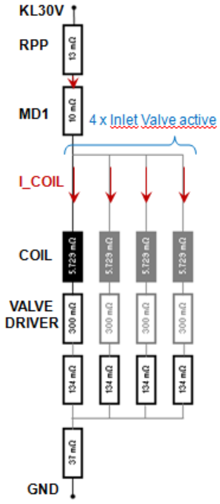

Figure 3. System electrical components schematic represented as resistances

Table 1. Electrical components tolerance

Name	Nominal (@20°	Temperature Coeff. α	Min (-3σ)	Max (-3σ)	Shape
RPP	13 mΩ	0,00350 /K	-10% (-30%)	30%	Gauss/Equal
MD1	13 mΩ	0,00350 /K	-10% (-30%)	30%	Gauss/Equal
Coil	mΩ	0,00392 /K	-0.50%	4.50%	Gauss-Cut
Valve Driver	300 mΩ	0,00350 /K	-30%	30%	Gauss
PCB Valve	134 mΩ	0,00392 /K	n.a.	n.a.	Not statistical
PCB Common	37 mΩ	0,00392 /K	n.a.	n.a.	Not statistical

Figure 4, 5 and 6 presents the tolerance statistical distribution shape for each component. In case of main driver and reverse polarity protection shape is a Gaussian shape on the sides and flat equal distribution between the interval of 0 and 20% deviation from the nominal. Valve driver resistance has a Gaussian distribution with main value to zero deviation and a +/- 30% accepted deviation. Coil resistance has also a Gausian shape but with cut limits the assumption is that in production some of the. Shape of the distributions is obtain by measuring the electric resistance of 1000 samples for component and is assumed to be representative for any higher number of components.

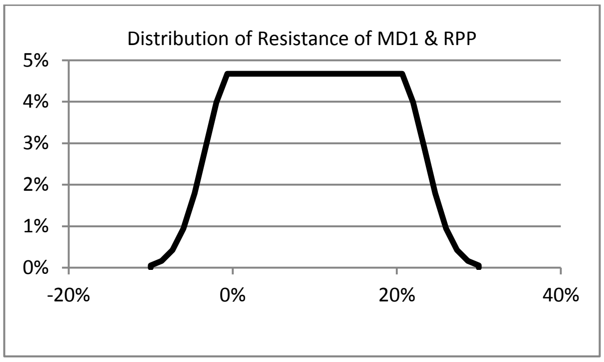

Figure 4. Shape of the distribution for main driver and reverse polarity protection

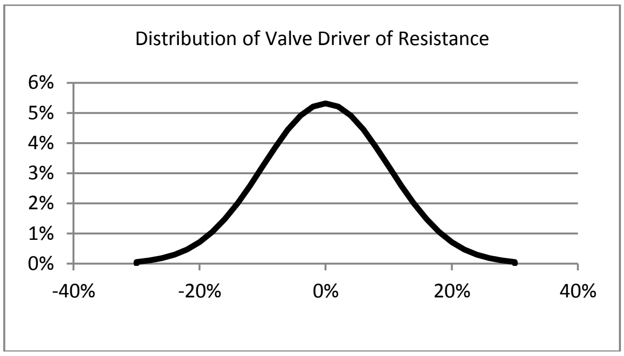

Figure 5. Shape of the distribution for valve driver resistance

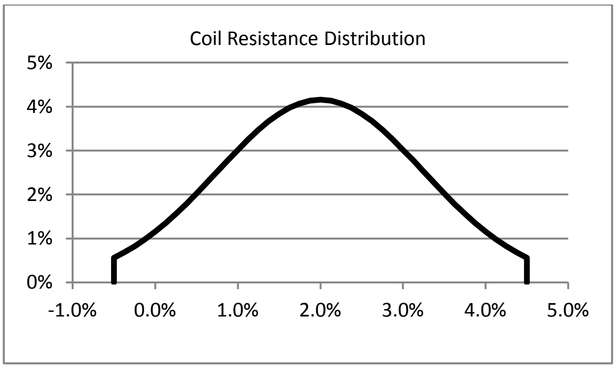

Figure 6. Shape of the distribution for valve coil resistance

5. MAGNETIC, HYDRAULIC & MECHANICAL ARCHITECTURE DEFINED TOLERANCES AND SHAPE OF THEIR DISTRIBUTION

The current value which flows trough valve coil invokes a magnetic field which creates a mechanical force on the valve tappet. The mechanical tolerances and position of the assembled parts can create an additional resistance in the magnetic circuit. This is taken into account and is represented by a loss of current ΔI_COIL assumed as equally distributed shape between 0mA and 50mA.

Figure 7. Valve coil

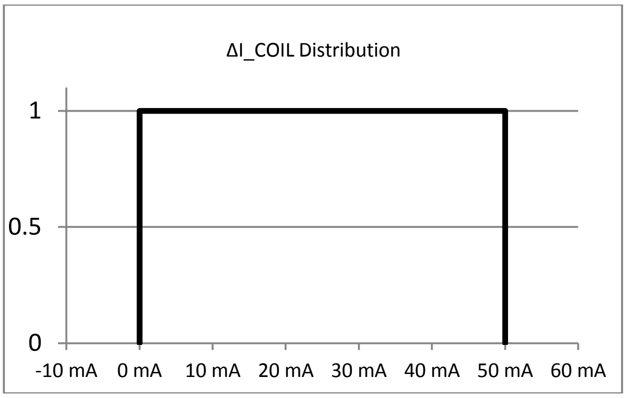

Figure 8. Shape of distribution for current loss

The mechanical tolerances of an ABS vale are given by the spring elasticity coefficient, friction inside the moving elements of the valve and parts geometrical tolerances. The influence of the mechanical tolerances of the ABS inlet valve is defined as the electrical current intensity I_{COIL}[mA] required to close a valve within 20[ms] against a certain pressure (delta pressure over inlet valve) and is given by the so-called limit current characteristic for all pressure ranges in figure 9. The average characteristic is defined as a nominal valve and limit current minimum and limit current maxim characteristic represents the accepted range for which a valve is considered accepted from the quality point of view.

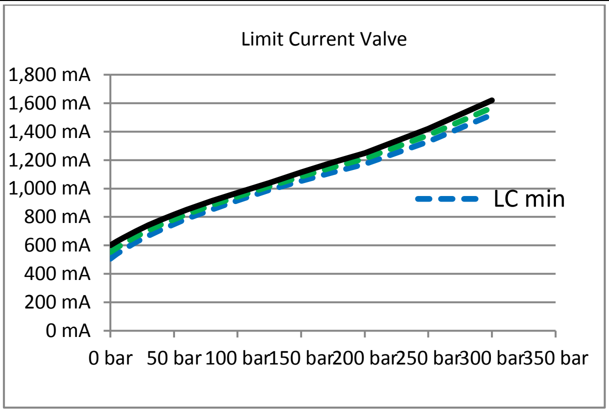

Figure 9. Limit current characteristic

The valve tolerance distribution between minimum and maximum is assumed Gaussian type. Nominal equals the average and maximum, minimum equals -2σ, max equals +2σ.

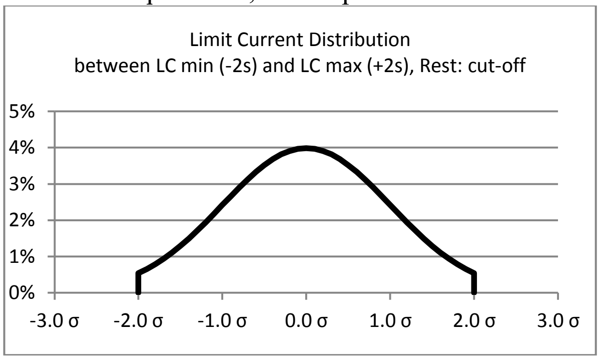

Figure 10. Valve limit current distribution

6. ENVIRONMENTAL CONDITIONS DEFINED TOLERANCES AND SHAPE OF THEIR DISTRIBUTION

The environmental conditions hold the parameter temperature. All electrical components change their internal resistance with temperature. For the electrical components the temperature of the valve driver, main driver and reverse polarity protection shall be assumed equal with ambient temperature plus 10C:

$$T_{MD1,RPP,VD} = T_{ambient} + 10C$$

With the probability of TCS the coil can be pre-heated. Therefore, statistically depending on TCS maneuver probability the temperature of the coil shall be:

$$T_{COIL} = T_{ambient} + \Delta T_{pre-heat}$$

In all other cases the temperature of the COIL shall be in general assumed as:

$$T_{COIL} = T_{ambient}$$

For the statistical tolerance analysis distribution of the temperature in the engine compartment where the braking system is installed is shown in Figure 11.

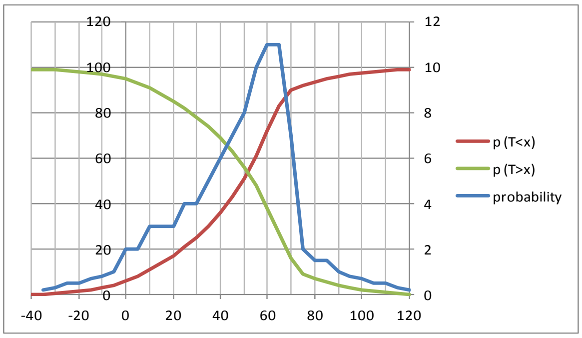

Figure 11. Shape of temperature distribution during vehicle lifetime

7. DESCRIPTION OF SUPPLY VOLTAGE, DEFINED TOLERANCES AND SHAPE OF THEIR DISTRIBUTION

Braking system ECU is connected to the vehicle supply voltage via cable harness. Figure 12 shows a simplified electrical circuit and the current flow from the battery towards ECU and the connection to the ground together with external current load of other consumers in the vehicle (e.g. electrical power steering) which may occur during ABS maneuver, which is cannot be delivered by the generator immediately due to latency during changing load.

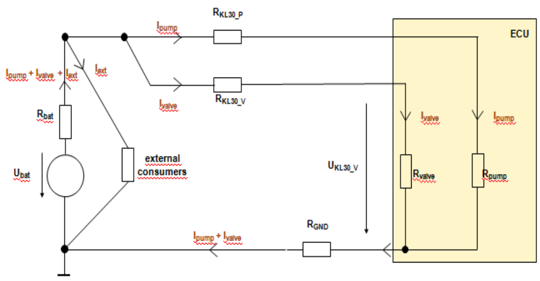

Figure 12. Simplified electrical circuit of vehicle for supplying braking system with voltage

Electrical supply circuit components exhibit a voltage drop over the circuit which may vary due to their tolerances from manufacturing process and ambient temperature variations during operation. Table 2 shows similar as in the system components case the specified nominal, minimum and maximum value of the accepted deviation range for each component together with the shape of the distribution and temperature coefficient.

Table 2. Electrical supply circuit components tolerances

Name	Nominal (@20°C)	Temp. Coeff. α	Min	Max	Shape
U_{bat}	13V	0 /K	8V	18V	See Fig. 12
R_{bat}	4mOhm	0 /K	2mOhm	15mOhm	See Fig. 12
$R_{contact}$	1.0mOhm	0 /K	0.5mOhm	3.5mOhm	See Fig. 12
R_{fuse}	3.5mOhm	0 /K	3.5mOhm	3.5mOhm	Fix
R_{cable_KL30V}	15mOhm	0,00392 /K	15mOhm	15mOhm	Fix
R_{cable_GND}	5mOhm	0,00392 /K	5mOhm	5mOhm	Fix
I_{valve}	10A	n/a	10A	10A	Fix
I_{pump}	**f(ΔP)**	**n/a**	**bar+4A]**		**See ***
I_{ext}	**10A**	**n/a**	**10A**	**70A**	**See ***

The distribution of battery voltage (U_{bat}) is taken from BMW specification and is shown in Fig. 13.

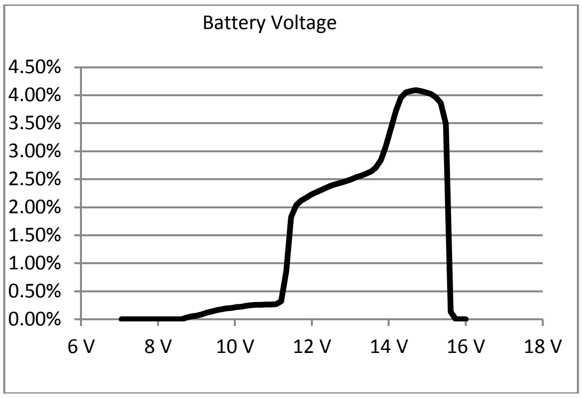

Figure 13. Probability distribution for vehicle battery voltage

A statistical distribution of the internal battery resistance R_{bat} is unknown, assumptions are made R_{bat} = 15[mOhm] as maximum resistance including battery contacts, and a triangular distribution shape. ECU contact resistance: R_{max}=3.5mOhm, R_{nom}=1mOhm, leaning triangular distribution shape, no temperature dependency. KL30_V cable harness: length = 2m, diameter: 2.5mm² (=15mOhm@20°C), no statistical distribution, only temperature dependency. GND cable harness length=1m, diameter: 4mm² (=5mOhm@20°C), no statistical distribution, only temperature dependency.

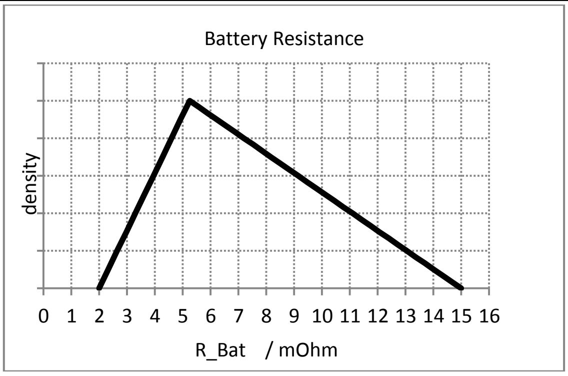

Figure 14. Probability distribution for vehicle battery internal resistance

Valve current is assumed simplified as constant 10[A]. In ABS maneuver situation this reflect 8x1.25A (1.25A allow more than 200bar on an average inlet valve). Usually not all valves are switched at the same time. The most likely situation is pressure hold, where all inlet valves are active and all outlet valves are inactive.

During ABS the system hydraulic pump is activated and in this context represents a load to the vehicle supply voltage. Current necessary to activate the pump depends on brake pressure. As a necessary input for the calculation of the voltage at KL30V the pump current is needed. Here, it is assumed that the EBS pump requires a current depending on the pressure as described below:

The statistically chosen ΔP for the maneuver shall be used as pump pressure but at least 100bar(=24A). It is assumed, that for high ΔP the driver pressure is nearly equal to ΔP. It is assumed that for low ΔP at least high-µ with a driver pressure of 100bar is given. Pump current is statistical depending via pressure with no temperature dependency.

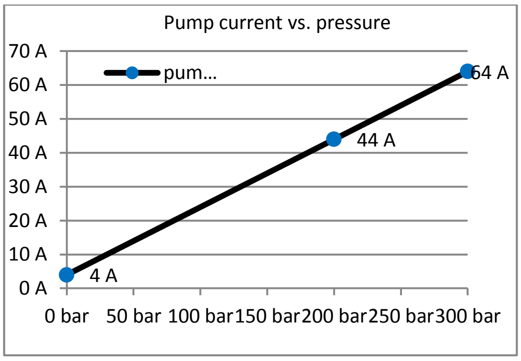

Figure 15. Pump current characteristic vs. pressure

8. DEFINITION OF THE MATHEMATICAL MODEL

To prevent from a wheel to lock during a hard breaking maneuver the hydraulic inlet valve is switch to its close position as described in ABS maneuver in chapter 2. To activate the in the valve the current which passes through the valve coil I_{COIL} [mA] creates a magnetic field, which through the magnetic circuit invokes a mechanical force over the valve tappet. The electrical current intensity I_{COIL} is the output of the system electrical architecture schematically described in chapter 2.1. In the proposed analysis the influence of the system components among other external factors are translated as electrical losses: voltage drop over components, current loss, magnetic loss, therefore mathematical model consist in calculation of the actual current intensity which passes through the valve coil as a function of voltage drop, supply voltage and temperature:

$$I_{COIL} = f\left(T_{Ambient}, U_{Supply}, R_{MD1}, R_{RPP}, R_{VD}, R_{COIL}\right) \quad (1.1)$$

From the system electrical architecture the amount of current which reach the valve coil equals with the amount of voltage which reach the ECU (U_{ECU}) divided by the sum of all resistances expressed in equation 1.2.

$$I_{COIL} = \frac{U_{ECU}}{R_{MD1}(T_{MD1}) + R_{RPP}(T_{RPP}) + \frac{1}{\sum \frac{1}{R_{VD,inletValve}(T_{VD}) + R_{COIL,inletValve}(T_{COIL}) + R_{PCB}(T_{amb})}} + R_{PCB}(T_{amb})} \quad (1.2)$$

Voltage which reaches the system ECU is needed in order to calculate I_{COIL} in the equation (1.2). Electrical network for the supplying the system with electrical energy can influence the amount of voltage which reach to the ECU connector due to voltage drop over its components and therefore U_{ECU} is calculated in respect with the network supply voltage architecture represented in Fig. 11 and ambient temperature in equation 1.3.

$$U_{ECU} = U_{bat} - \left(I_{pump} + I_{valve} + I_{ext}\right) * R_{bat} - I_{valve} * R_{KL30} - \left(I_{pump} - I_{valve}\right) * R_{GND} \quad (1.3)$$

In eq. 1.3 additional consumers like electrical current needed to run the system hydraulic pump (I_{pump}) are taken in consideration together with I_{ext} which represents the consumer for the power steering.

$$U_{KL30\_V} = U_{bat} - \left(I_{pump} + I_{valve} + I_{ext}\right) \cdot R_{bat} - I_{valve} \cdot R_{KL30\_V} - \left(I_{pump} + I_{valve}\right) \cdot R_{GND}$$
$$R_{KL30\_V} = 3 \cdot R_{contact} + R_{Fuse} + R_{cable\_KL30V}(T)$$
$$R_{GND} = R_{contact} + R_{cable\_GND}(T)$$
$$R(T) = R(20°C) \cdot \left(1 + \alpha \cdot (T - 20°C)\right)$$

To determine the limit pressure P_{limit} based on the calculated I_{COIL} value is looked up in the limit current curve presented in valve current vs. pressure characteristic.

9. STATISTICAL TOLERANCE ANALYSIS BASED ON MONTE CARLO SIMULATION

To Monte Carlo simulation is a statistical method used here to analyze the impact of manufacturing variations and external perturbations over the braking system performance. In the previous section the mathematical model determines the braking system response as pressure limit P_{limit}[bar] for a fixed component values. The Monte Carlo simulation method involves an iterative process of running the mathematical model for a specified number of times. Each iteration of the simulation is done with different input parameters randomly varied between specified tolerances limits according to the specified statistical distribution presented in chapter 2. In this analysis a population sample of 1 million produced braking units is considered and the result of Monte Carlo simulation reveals the statistical distribution of the system response. In Fig. 15 a structural overview of the Monte Carlo simulation is presented. Parameters which can be varied are divided in two categories the external (environmental parameters, battery voltage, temperature) and system components.

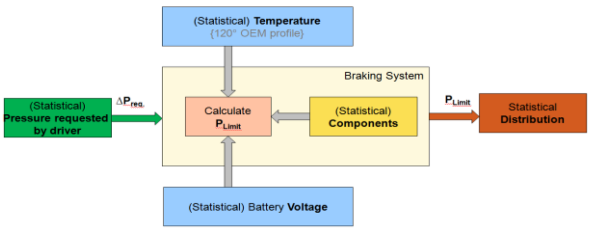

Figure 16. Structural overview of the Mote Carlo evaluation

A flow chart of the Monte Carlo simulation is presented in figure 17 where graphically shows the steps of the simulation:

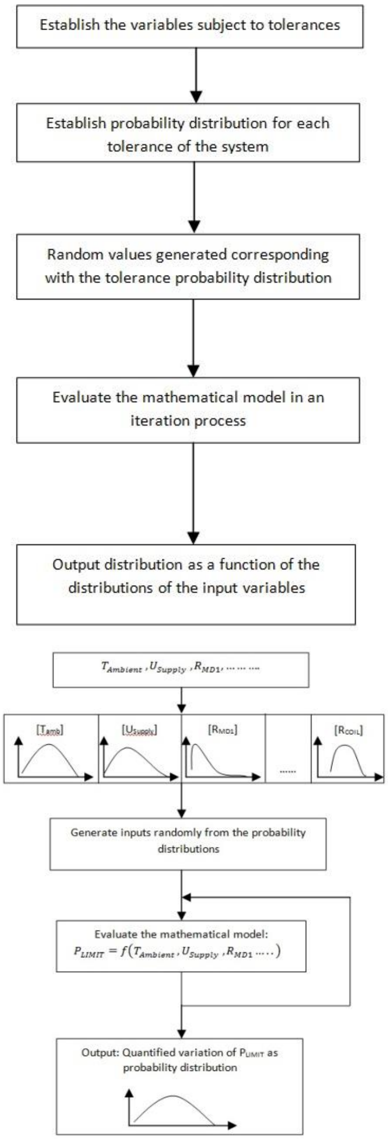

Figure 17. Monte Carlo simulation flow chart

- The first step defines the simulation scenarios by establishing the parameters which will be varied during simulation. For example in order to highlight the influence of temperature variation over the system response only this parameter will vary between its defined limits during simulation and the rest of model parameters will remain fixed. In next chapter the parameters selected to be varied in each simulation scenario are chosen by having the goal of highlighting different aspects of the system performance.
- After that the parameters which will be varied during simulation are established, the corresponding probability distributions are loaded into a database. The probability distributions have been explained in chapter two for each component considered as subject to variation.
- The Monte Carlo simulation is applied for a population sample of 1 million produced braking units, therefore model needs to have one million input values for each parameter which has to be varied. For this reason a set of one million values needs to be generated for each parameter according to their distribution by using a random number generator. The result of this step is a pool of data with 1 million values for each parameter.
- The next step of the simulation evaluates the mathematical model in an iteration process. For each of the iteration the model takes as input a different set of parameters selected in a random way.
- When the total number of iterations has been performed the impact of the tolerances on the ABS valve actuation is presented as a statistically distribution of the pressure limit P_{limit}

10. DEFINITION OF SIMULATION SCENARIOS

An ABS failure occurs when the valve fail to close against the brake pressure created by the driver during a hard braking maneuver. For the ABS inlet valve control chain this means that a failure exists if the hydraulic pressure P_{Driver} is higher than P_{limit} against witch the system is design to perform the valve actuation valve will fail to close leading to a locked will. P_{limit} depends on the braking system tolerances and environmental condition of the exploitation. Table 3 defines how the evaluation of braking system P_{limit} is depicted. System limit pressure is calculated for cases I, II, III and IV for fixed tolerances values in different scenarios. First and second case scenario simulates the worst case conditions for both, system components and environmental conditions. Here the system control chain components maximum accepted deviations values for tolerances are considered together with a maximum temperature of 90[°C] / 110[°C]. For this scenarios a battery voltage of 10[V]/9[V] is considered which simulates a week battery installed in the vehicle. The calculation of P_{limit} for these two cases will reveal maximum pressure against which the ABS valve can still be switched under worst case components tolerances and worst case exploitations conditions. The next scenario calculates the P_{limit} for a worst case ABS unit but this time under normal exploitation conditions where ambient temperature has a value of 60°C and a strong battery installed in the vehicle with a voltage of 13[V]. In simulation number IV an ideal barking system unit is evaluated under worst case external conditions. For this purpose system components tolerances are set to theirs nominal value and temperature at the maximum of 110°C with a power supply voltage set to a minimum of 9[V].

In simulation case V statistical inputs are used for the system components tolerances only and external parameters are set to the fix value of extreme conditions 110[°C] ambient temperature and 9[V] for the power supply voltage. The aim of this evaluation is to reveal by how much the systems performance is reduced for a population of one million produced braking units under realistic conditions of mass production all used under worst case exploitation conditions.

The defined conditions in case VI simulate as close as possible the reality. Statistical inputs are used for all parameters which are subject to variation.

The aim of the last case scenario is to simulate performance of a worst case unit throughout its lifetime by setting fixed worst case tolerances for the braking unit components and statistical variation for the environmental parameters.

Table 3. Evaluation defined scenarios

Considered Effects	Simulation case I /II	Simulation case III	Simulation case IV	Simulation case V	Simulation case VI	Simulation case VII
Control chain components tolerances and distribution	Worst case	Worst case	Nominal	Statistical	Statistical	Worst case
Temperature	90°C /110°C	60°C	110°C	110°C	Statistical	Statistical
Supply voltage	10V/9.0V	13V	9V	9V	statistical	statistical
Result of evaluation	Calc. P_{limit}	Calc. P_{limit}	Calc. P_{limit}	Statistica distribution for P_{limit}	Statistica distribution for P_{limit}	Statistica distribution for P_{limit}

11. SIMULATION RESULTS

During an emergency braking on a dry surface driver creates a brake pressure with the help of the buster between 180 and 200[bar]. For evaluation reasons two thresholds are defend, one at 200[bar] and one at 180[bar]. These two thresholds are used in order to evaluate the braking system performance. If system ABS valve can switch the valve against a pressure higher than 200[bar] optimal performance is guaranteed. For the range between 180 and 200[bar] ABS brake unit performance is in a safe range but performance is reduced and for a system where P_{limit} is under 180[bar] safety cannot be guaranteed.

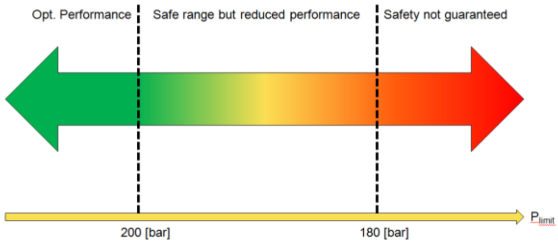

Figure 18. Defined thresholds for performance evaluation

The results of the simulations case scenario 1 and 4 present the evaluation of system valve switch event for fixed tolerances of the system and fixed environmental conditions.

The Simulation case I and II, reveals that for worst case tolerances of the components correlated with a low voltage battery and a high temperature, ABS switch can be done only against a maximum pressure of 140[bar]. In this situation if driver will create a higher pressure during an emergency brake the valve will fail to switch and vehicle wills will lock. In this case safety is not guaranteed.

In the simulation III is evaluated the same worst case tolerances of the components but this time in ideal environmental conditions. The pressure against the valve can switch exceeds by far the 200[bar] threshold. For this case performance can be 100% guaranteed. The result shows how much the effect of the environmental condition really contributes to the system performance.

For the simulation case IV the aim is to evaluate a perfect braking unit (no deviations for the components) under worst case condition of exploitation. The valve switch is guaranteed for pressures up to 230[bar]. For this case scenario robustness of the ABS control chine is as well guaranteed. As a conclusion the results of the simulations performed with fixed parameters show a low system performance obtained when worst case component tolerances are correlated with worst case environmental conditions.

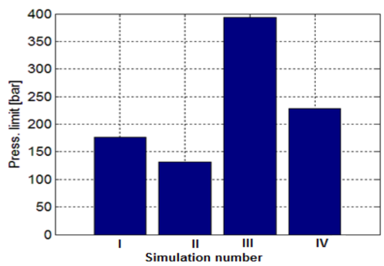

Figure 19. Simulations result for fix parameters of the tolerances

Monte Carlo simulation result for the scenario case V, allows us to conclude over the impact of extreme environmental conditions over a population sample of 1 million braking units produced. Results reveal that in this conditions the lowest system pressure limit against which ABS valve can be switch is 180[bar] and validates that any of the produced samples will perform in the safety range.

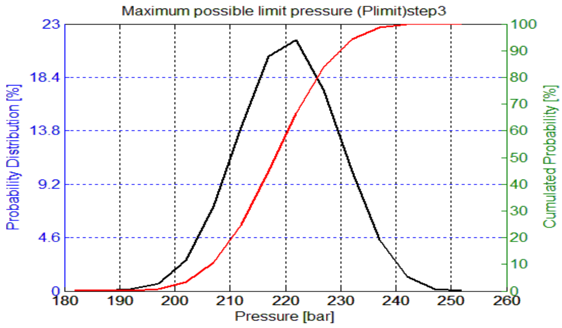

Figure 20. Monte Carlo simulation result case scenario V

Result for the scenario case V (figure. 20) all parameters a varied statistically and reveal that lowest system pressure against which valve can be switch is 200[bar]. This case scenario represents a realistic analysis over the entire produced braking units of one million samples and exploitation in real life conditions and concludes that threshold of optimal performance for any of the braking units meets exceeds the safety margin of 180 [bar].

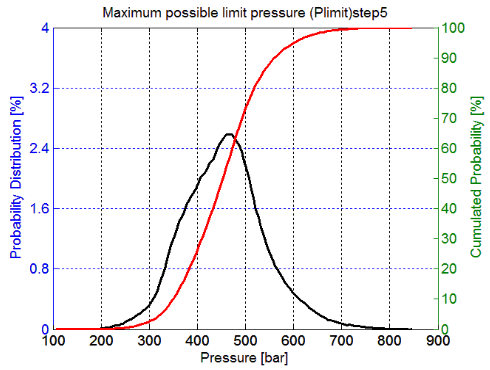

Figure 21. Monte Carlo simulation result case scenario VI

The aim of Monte Carlo simulation case VI is to identify the behavior of a worst case braking system unit throughout lifetime exploitation. By setting the components tolerances to a fixed value, it means that each iteration represents the simulation of the same braking unit. Only the environmental parameters will be varied. This concludes that one million iterations will mean one million brakes apply on the same braking system. The result of this simulation is presented in figure 22 shows that 0.03% from the total of 1 million brake applies are below threshold of 200[bar] and only 0.01% under the threshold of 180[bar]. This simulation concludes that for a worst case unit throughout its lifetime for 100 brake events ABS valve switch event is not guaranteed.

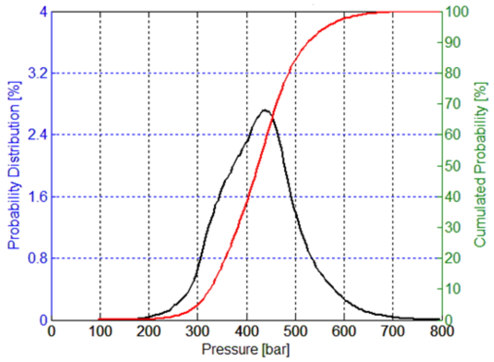

Figure 22. Monte Carlo simulation result case scenario VII

To better visualize and compare the results an overlay figure presents the results obtained with Monte Carlo simulation in Figure 23.

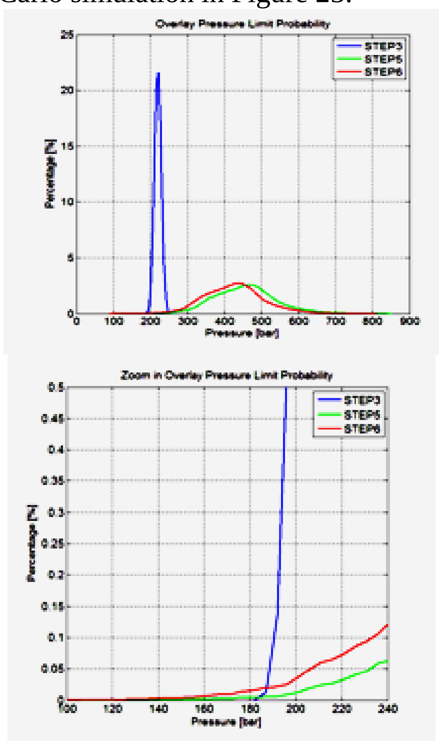

Figure 23. Overlay Monte Carlo simulation result case scenario V to VII

12. CONCLUSIONS

The study over the effect of system components tolerances and external environmental conditions under real life exploitation is required for fully guarantee system robustness during operation.

In mass production each component of a mechatronic system has a certain amount of deviation from its nominal design values. Because of this unavoidable effect of manufacturing variation and in the scope of emphasize the influence of tolerances over the system performance, a detailed analysis has been carried out in this work.

In the first part of the article the architecture of mechatronic braking system and its ABS function are explained. Components which are subject to tolerances are identified and probabilistic distributions of the values are set. The model of the braking system is developed and simulation type chosen for the evaluation is Monte Carlo.

The statistical method used here to evaluate the impact of manufacturing variations and external perturbations over the braking system performance shows results for different case scenarios and also calculates the probability of a possible fault that may occurs during exploitation

13. REFERENCES

[1] T.K. Bera, K. Bhattacharya, A.K. Samantaray, *Evaluation of antilock braking system with an integrated model of full vehicle system dynamics.*

[2] Stephan Philippi, *Analysis of fault tolerance and reliability in distributed real-time system architectures.*

[3] H. Straky*, M. Kochem, J. Schmitt, R. Isermann, *Influences of braking system faults on vehicle dynamics.*

[4] Ahmed Jawad Qureshi a, Jean-Yves Dantana, Vahid Sabri a, Paul Beaucaire d, Nicolas Gaytond, *A statistical tolerance analysis approach for over-constrained mechanism based on optimization and Monte Carlo simulation.*

[5] Fangcai Wua, Jean-Yves Dantan b, Alain Etienne, Ali Siadat, Patrick Martin, *Improved algorithm for tolerance allocation based on Monte Carlo simulation and discrete optimization.*

[6] P. Beaucairea*, N. Gaytona, E. Duca, J.-Y. Dantanb *Statistical tolerance analysis of a mechanism with gaps based on system reliability methods.*

[7] Paul Beaucaire, Nicolas Gayton, Emmanuel Duc, Maurice Lemaire, Jean-Yves Dantan, *Statistical tolerance analysis of a hyperstatic mechanism, using system reliability methods.*