TEKA Kom. Mot. Energ. Roln., 2005, 5, 217–225

AN ANALYSIS OF HYDRAULIC BRAKING SYSTEM RELIABILITY

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Summary. For the purpose of improving driving safety, vehicles are equipped with the electronic anti-lock braking system – a part of the braking system responsible for vehicle safety during driving. Therefore, its high reliability is required. All ABS elements are two-state elements which are characterized by two states: the state of ability (reliability state in which an object can perform tasks in the way consistent with the requirements) and the state of inability (reliability state in which an object cannot perform tasks in the way consistent with the requirements). The reliability structure of a chosen ABS electronic system as well as the results of system reliability calculations will be presented in the paper.

Key words: braking system, driving safety, ABS electronic system

INTRODUCTION

The operation of the ABS lies in controlling the lengthwise wheel spin (by means of regulating the pressure in the braking system) so that the spin can remain within the limits of the optimum interval, i.e. such an interval in which values of adhesive force are close to maximum.

Six systems can be distinguished among ABS units. They differ in braking system division, the number of pressure control channels and the number of wheel speed sensors. Considering braking system division, those solutions are divided into:

– diagonal
– front/rear.

Considering the number of pressure control channels, the following systems are distinguished:

1) the so-called two-channel ones, i.e. those with two channels of pressure control,
2) the so-called three-channel ones, i.e. those with three channels of pressure control,
3) the so-called four-channel ones, i.e. those with four channels of pressure control.

Considering the number of wheel speed sensors, the following systems are distinguished:

– those with two sensors of wheel speed,
– those with three sensors of wheel speed,
– those with four sensors of wheel speed.

There are different kinds of ABS units with different numbers of elements mentioned above. The systems differ not only in the number of elements but also in braking characteristics. The systems which are most often used now are those with three or four sensors as they ensure the most efficient functioning of the braking system in the event of ABS operation.

Reliability is defined as an object property characterizing its ability to perform particular functions, in particular conditions and in a particular time interval. As the ABS is a part of the braking system, the main system responsible for driving safety, high reliability of its functioning is required. All elements of the ABS are two-state objects which are characterized by two states: the state of ability (reliability state in which an object can perform tasks in the way consistent with the requirements) and the state of inability (reliability state in which an object cannot perform tasks in the way consistent with the requirements).

Particular elements, which form the ABS due to the fact that they cooperate, must also be characterized by adequately high stability, i.e. the power to retain the state of ability in particular conditions up to the end of maintenance so that the reliability of the system is high. That is particularly important for such elements as wheel speed sensors which are subject to mechanical damage and impurities etc. during the car maintenance. In order to have high stability, they should be characterized by high resistance to failure, i.e. the power to retain the state of ability during the whole task performance. Besides, the ABS elements are not dependant elements, i.e. the failure of one element results in no changes in reliability and stability of other elements, e.g. master cylinder failure (e.g. its leakage) is not followed by changes in stability and reliability of the hydraulic modulator. That is very important because, apart from a higher reliability of the whole system, in the event of a particular element failure (e.g. wheel speed sensor),/ the braking system remains efficient enabling further braking and, additionally, repair costs are lower.

Another factor leading to the increase of system reliability is irreparability of its main elements, i.e. such elements as hydraulic modulator or wheel speed sensor cannot be fixed. In case of failure, those elements are replaced by new ones; consequently, the system is characterized by greater stability and reliability. Besides, there are also reparable elements in the anti-lock braking system. Hydraulic elements of the braking system such as master cylinder or brake calipers belong to this group. In the event of those elements failure, and transition from the state of ability to the state of inability, restoring the state of ability and further functioning is achieved by exchanging accessible spare parts. However, it cannot be expected that an element after the repair will be characterized by the same stability as a new one. Consequently, the system reliability decreases. Besides, if an element has been repaired a few times, it reaches a limiting state, i.e. such a physical state in which further maintenance of an object is not advisable or even impossible. Then, it is necessary to replace an element with a new one.

Besides, anti-lock braking systems are designed with a definite service life (overhaul life), i.e. random variable determining the number of kilometers covered from the beginning of maintenance up to the moment the limiting state is reached. This aims at ensuring that all ABS elements are characterized by high reliability. Moreover, this makes it possible to forecast the time of failure and to establish periods between surveys.

In order to maintain high reliability of the system, periodical surveys should be carried out so that the object is in the state of ability. The following tasks should be done:
– testing the condition of flexible brake pipes,
– testing the contents of water in brake fluid,
– testing the condition of conductors and connections,
– testing the level of brake fluid in the reservoir,
– testing the system for leakage,
– testing the condition of frictional elements.

CHARACTERISTICS OF BOSCH 2B ANTI-LOCK BRAKING SYSTEM

The Bosch 2B anti-lock braking system is one of the basic constructional solutions. It is a so-called two-channel system. Fig. 1 presents the block diagram of the system. The main elements of the system are the following: the electronic control unit ECU and the hydraulic modulator, brake calipers and sensors. The electronic control unit ECU is susceptible to high temperature; therefore it is mounted possibly far away from hot engine elements or inside the vehicle.

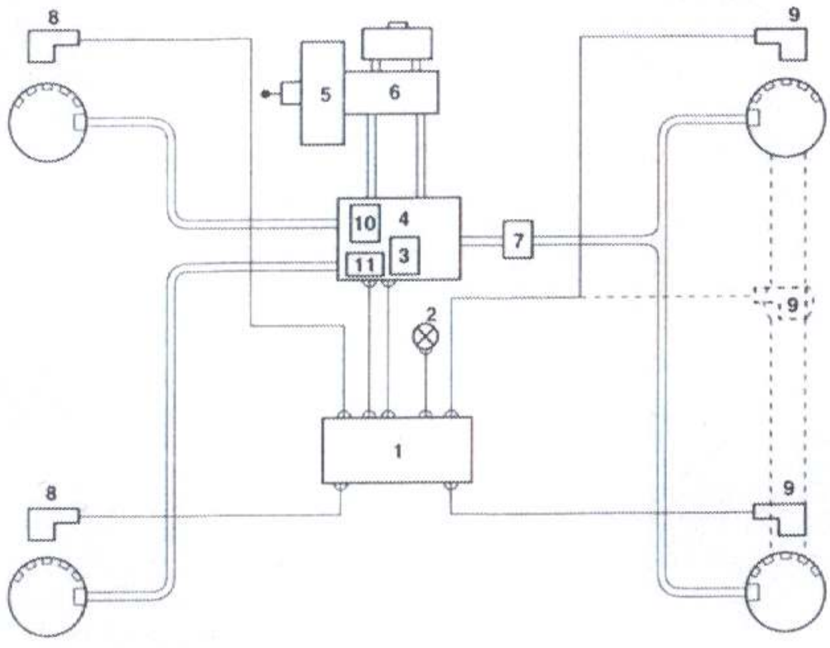

Fig. 1. Diagram of Bosch 2B system [Łazowski 2004]: 1 – electronic control unit ECU, 2 – warning lamp –ABS, 3 – pump motor, 4 – hydraulic modulator, 5 – servo, 6 – master cylinder, 7 – pressure limiting/proportioning valve, 8 – front wheel speed sensors, 9 – rear wheel speed sensors, 10 – solenoid valves, 11 – relay

By monitoring the signals from the wheel speed sensors during braking the electronic control unit ECU determines which wheel is about to lock. To prevent wheel lock the electronic control unit ECU controls the relevant solenoid valve in the hydraulic modulator regulating the pressure of brake fluid within the brake circuit.

Solenoid valves can operate in three stages which enable: pressure increase, maintaining constant pressure and pressure decrease. In the stage of pressure increase, the hydraulic system operates without any restrictions and the pressure generated in the master cylinder has an effect directly on brake calipers as a result of pressing the brake pedal. In such a position of the solenoid valve the free flow of brake fluid from the master cylinder to the brake caliper is possible. The position of the solenoid valve in this stage is presented in Fig. 2.

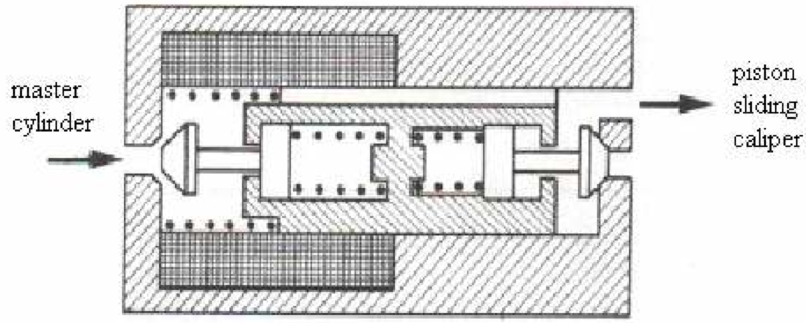

Fig. 2. Position of the solenoid valve piston in the stage of pressure increase [Łazowski 2004]

In the case of the system's failure, the solenoid valve remains in the position enabling the braking system to function in a conventional way. In the stage of maintaining constant pressure, the solenoid valve is controlled by 2,5 A current. As a result of magnetic field influence, the piston covers half of its stroke and cuts off the inflow of brake fluid to the brake caliper. This makes later increase of pressure value impossible, irrespective of the force of depressing the brake pedal. The position of the piston in this stage is presented in Fig. 3.

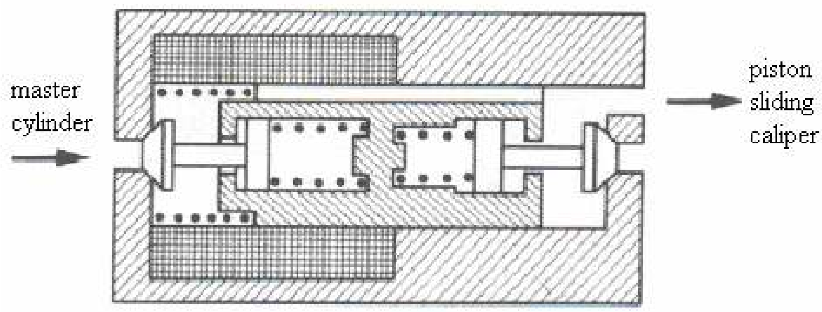

Fig. 3. Position of the piston in the stage of maintaining constant pressure [Łazowski 2004]

In the stage of pressure decrease, the solenoid valve is controlled by 5 A current. The piston influenced by the magnetic field of higher intensity is shifted and that results in closing the inlet pipe and connecting the brake caliper circuit with the electric pump. At the same time the electronic control unit ECU switches on the electric pump through an adequate relay and the pump reduces the pressure of fluid in the brake caliper circuit pumping it towards the master cylinder. The position of the piston in this operation stage is presented in Fig. 4.

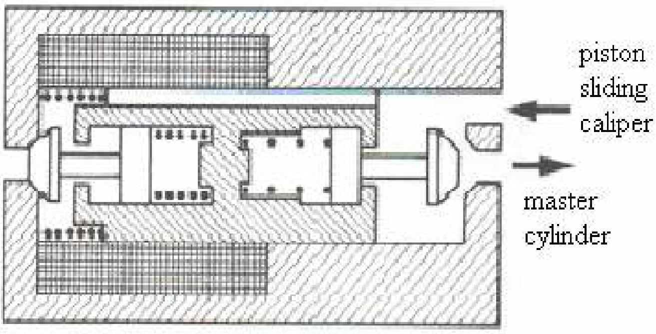

Fig. 4. Position of the piston in the stage of pressure decrease [Łazowski 2004]

The regulation of brake fluid pressure occurs several times per second and results in vibration through the brake pedal which is felt by the driver.

The electronic control unit ECU incorporates self-diagnosis function making it possible to register and gather information about incorrect operation within the system. Such information is available as fault codes. If a fault happens to occur, the electronic control unit ECU switches off the ABS and alerts the driver by illuminating a warning lamp. The electronic control unit ECU switches off the ABS at road speed below 5 km/h. The electronic control unit ECU is presented in Fig. 5.

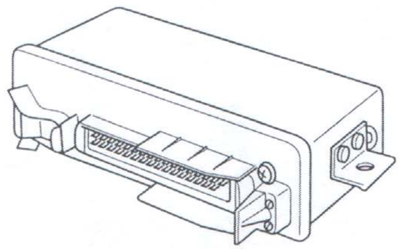

Fig. 5. Electronic control unit ECU in Bosch 2B system [Łazowski 2004]

The hydraulic modulator is controlled by the electronic control unit ECU and regulates hydraulic pressure in each of the brake circuits separately. It is located between the master cylinder and the brake caliper. The modulator contains solenoid valves separate for each brake circuit and an electrically operated hydraulic pump with a pressure accumulator. The hydraulic modulator is presented in Fig. 6.

Wheel speed sensors process wheel speed courses into electric signals which are sent to the electronic control unit ECU. Front wheels have separate wheel speed sensors;

however, the number and location of sensors installed on the rear axle vary for different car makes.

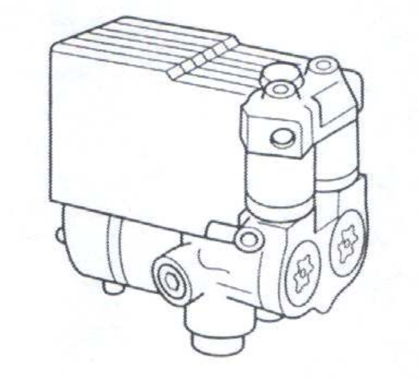

Fig. 6. Hydraulic modulator in Bosch 2B system [Łazowski 2004]

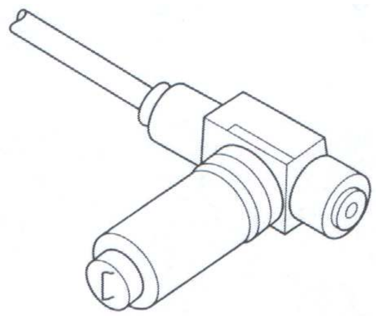

Fig. 7. Wheel speed sensor in Bosch 2B system [Łazowski 2004]

For example, some cars with conventional drives might have one wheel speed sensor placed close to the differential gear. The wheel speed sensor is presented in Fig. 7.

Estate cars have a pressure limiting/proportioning valve to restrict the value of brake fluid pressure to the rear brake circuit. Alternatively, a load sensing valve can be fitted to the rear suspension of the vehicle to restrict brake fluid pressure to the rear brake circuit dependant upon vehicle load.

The brake pedal position switch the BPP signals to the electronic control unit ECU when the brake pedal is depressed, indicating the beginning of braking and ensures that the ABS is only functional during brake application.

CALCULATING RELIABILITY STRUCTURE OF ABS ELECTRONIC SYSTEM

In order to assess a given element reliability, results of testing a large number of elements in a specified time t should be collected. If after time *t n(t)* elements will be left free from failure and *m(t)* elements – with failures, the number described by the formula:

$$R(t) = \frac{n(t)}{n} \tag{1}$$

is the probability of the lack of failure or failure-free operation.

The probability of failure will be described by the following formula:

$$P(t) = \frac{m(t)}{n} \tag{2}$$

Because of the fact that probabilities of failure and the lack of failure are mutually exclusive events, their sum will equal:

$$\frac{n(t)}{n} + \frac{m(t)}{n} = R(t) + P(t) = 1 \tag{3}$$

The characteristic feature of function $R(t)$ is that for $t = 0$, $R(t) = 1$ and for $t = \infty$, $R(t) = 0$, i.e. it assumes values from 0 to 1, respectively.

In the event of hydraulic brake circuit failure, the driver has no chance of braking. Therefore, the hydraulic system has been divided into two circuits to increase the braking system's reliability. If there is a failure in one circuit, the second one is fully functional and braking is possible. Thus, the system can be presented as a parallel serial structure, i.e. such a structure which functions correctly when at least one of its circuits is fully functional. Fig. 8 presents an example of a parallel serial structure of the ABS hydraulic system on the basis of Bosch 2B anti-lock braking system.

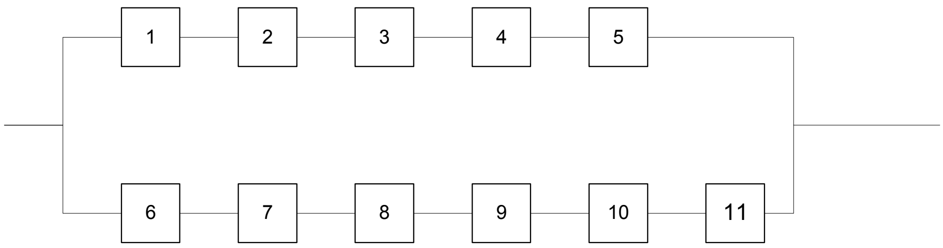

Fig. 8. Parallel serial structure of Bosch 2B hydraulic system: 1 – section 1 of master cylinder, 2 – pipes delivering brake fluid, 3 – front wheel solenoid valves, 4 – brake caliper of left front wheel, 5 – brake caliper of right front wheel, 6 – section 2 of master cylinder, 7 – pipes delivering brake fluid, 8 – rear wheel solenoid valves, 9 – pressure limiting/proportioning valve, 10 – brake caliper of left rear wheel, 11 – brake caliper of right rear wheel

On the basis of the system's data, it can be assumed that in the considered time period there were no failures in such ABS elements as the hydraulic modulator and the pressure limiting/proportioning valve, according to formula (1) their reliability equals 1. Because of that, the reliability structure is simplified and is presented in Fig. 9 as:

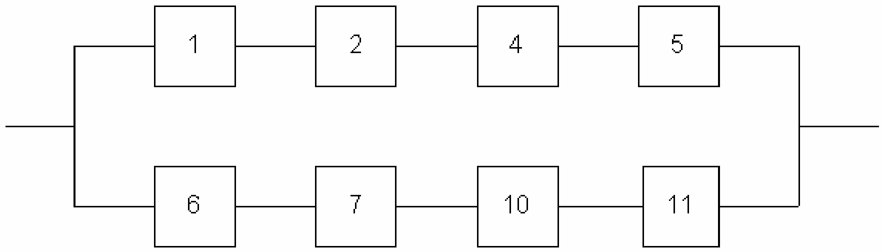

Fig. 9. A simplified parallel serial structure of Bosch 2B hydraulic system

1). section 1 of master cylinder – $R_1 = 0.997$
2). pipes delivering brake fluid – $R_2 = 0.995$
4) brake caliper of left front wheel – $R_4 = 0.997$
5). brake caliper of right front wheel – $R_5 = 0.997$
6). section 2 of master cylinder – $R_6 = 0.997$
7). pipes delivering brake fluid – $R_7 = 0.995$
10). brake caliper of left rear wheel – $R_{10} = 0.997$
11). brake caliper of right rear wheel – $R_{11} = 0.997$.

The reliability of a parallel serial object R_{rs}, composed of n units with serially connected elements can be calculated with the use of the following formula:

$$R_{rs} = 1 - \prod_{j=1}^{n}(1 - R_{sj}) = 1 - \prod_{j=1}^{n}(1 - \prod_{i=1}^{m} R_{ij}) \tag{4}$$

where: R_{ij} – reliability of the i element from the j unit.

After substitution it is the following:

$$R_{rs} = 1 - [(1 - R_{1\div5}) \cdot (1 - R_{6\div11})] \tag{5}$$

$$R_{1\div5} = R_1 \cdot R_2 \cdot R_4 \cdot R_5 \tag{6}$$

$$R_{6\div11} = R_6 \cdot R_7 \cdot R_{10} \cdot R_{11} \tag{7}$$

where: $R_{1\div5}$ – reliability of section 1 of hydraulic circuit,
$R_{6\div11}$ – reliability of section 2 of hydraulic circuit.

$$R_{1\div5} = 0{,}997 \cdot 0{,}995 \cdot 0{,}997 \cdot 0{,}997 = 0{,}9861$$

$$R_{6\div11} = 0{,}997 \cdot 0{,}995 \cdot 0{,}997 \cdot 0{,}997 = 0{,}9861$$

$$R_{rs} = 1 - [(1 - 0{,}9861) \cdot (1 - 0{,}9861)] = 0{,}9998.$$

On the grounds of the above calculations, it can be stated that the hydraulic system reliability is higher than the electronic system reliability.

For particular elements assumed data, the reliability analysis is the following:
1) section 1 of master cylinder – $R_1 = 0.98$
2) pipes delivering brake fluid – $R_2 = 0.97$
4) brake caliper of left front wheel – $R_4 = 0.98$
5) brake caliper of right front wheel – $R_5 = 0.98$
6) section 2 of master cylinder – $R_6 = 0.98$
7) pipes delivering brake fluid – $R_7 = 0.97$
10) brake caliper of left rear wheel – $R_{10} = 0.98$
11) brake caliper of right rear wheel – $R_{11} = 0.98$.

The reliability of a parallel serial object R , composed of n units with serially connected elements can be calculated with the use of the following formula (4).

After substitution it is the following:

$$R_{1\div5} = 0{,}98 \cdot 0{,}97 \cdot 0{,}98 \cdot 0{,}98 = 0{,}913$$

$$R_{6\div11} = 0{,}98 \cdot 0{,}97 \cdot 0{,}98 \cdot 0{,}98 = 0{,}913$$

$$R_{rs} = 1 - [(1 - 0{,}913) \cdot (1 - 0{,}913)] = 0{,}993.$$

The reliability of the whole system for the assumed values is high.

CONCLUSIONS

1. The carried out calculations of the ABS hydraulic system prove its high reliability.
2. The comparison of electronic system and ABS hydraulic system reliabilities proves the role of the basic braking system.
3. Further investigation into ABS reliability should be concentrated on the analysis of maintenance elements wear and the course of braking process.

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