VIRTUAL TESTING OF ACTIVE SAFETY CONTROL FOR TWO-WHEELED VEHICLES AT BRAKING MODE

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ABSTRACT

The paper discusses a design expertise for active safety systems with reference to the two-wheeled vehicles. The special emphasis is placed on various approaches to the anti-lock braking systems.

Taking into account the specificity of motorcycles, scooters and other two-wheeled vehicles, the variants of single and double-channel braking control are examined.

Approbation of developed control strategy has been performed through simulation with AMESim software. This allowed to consider the very important factors like hysteresis losses in brake gears and response time of brake drive. In accordance with results of virtual testing, the paper proposes an evaluation of pre-extreme algorithms for motorcycle anti-lock braking systems.

INTRODUCTION

The speedy upgrowth of fleet of two-wheeled mobile machines poses the question to enhance essentially the safety for this kind of vehicles. The appropriate methods for handling a problem lie in two main areas:

- Gain in passive safety level during special rider's equipment
- Increase in active safety level using vehicle dynamics control systems.

The second issue is a subject of inquiry under discussion.

One of the first effective engineering solutions for motorcycle active safety was the first generation of anti-lock braking systems (ABS) entered in 1988 for BMW K100. This system gained the further development in models of ABS II (1993) and ABS III (2000) for family of BMW motorcycles [1].

The ABS evolution shows that it is essential to investigate on various aspects of wheel rolling with reference to dynamics of two-wheeled vehicles. For example, there is the tyre side slip and wheel inclination, which take place permanently by motorcycle braking. This can result in short-term wheel locking, with a consequent turnover (by front wheel locking) or skidding (by rear wheel locking). The more detailed description of these and other dangerous aspects can be found in [2-4]. The question of installation of advanced active safety systems on the light-weight two-wheeled vehicles (scooters, choppers) is also acute. This can cause in considerable cost increase and in the machine complication.

It is appropriate to evaluate merits and demerits for various active safety systems at designing stage on basis of previous simulation results. The presented investigation gives a comparative analysis performed in AMESim software [5] for some ABS variants.

SUBJECTS OF INVESTIGATION

In relation to the independent front and rear brake gears, the variants of single-channel ABS and double-channels ABS are possible for motorcycles. The single-channel ABS is more simple and cheap construction, and it controls only front wheel (see Figure 1). The double-channel ABS controls braking process on both wheels (see Figure 2).

As has been mentioned, the discussed investigation is based on application of AMESim because this software allows creating the vehicle model structures with reliable adequacy. Creating the two-wheeled vehicle model, the following sub-models can be used.

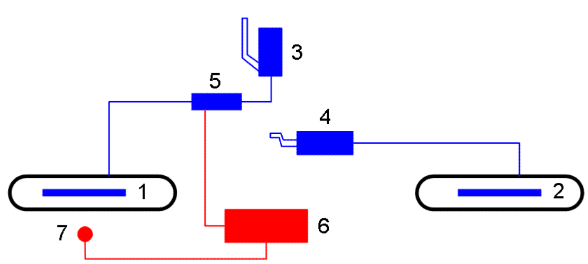


Figure 1. Single-channel ABS: 1, 2 – brake gears; 3 – front brake lever; 4 – rear brake pedal; 5 – hydraulic control unit; 6 – electronic control unit; 7 – wheel speed sensor.

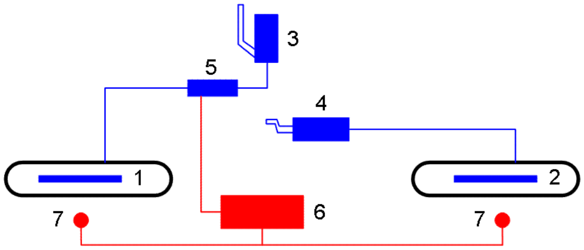


Figure 2. Double-channel ABS: 1, 2 – brake gears; 3 – front brake lever; 4 – rear brake pedal; 5 – hydraulic control unit; 6 – electronic control unit; 7 – wheel speed sensor.

1) Power train (see Figure 3). In that case the geometry parameters of continuously variable transmission (CVT) are input data. The CVT application in the developed model complies with the real unit for scooters and ensures the required moment ratio between power unit and driving wheel (wheels).

2) Wheel unit (see Figure 4). These components allow simulating the wheel rolling together with reduced vehicle mass as well as tribological situation in brake gear.

3) Brake gear (see Figure 5). Brake gear sub-model is created using basic mechanical and hydraulic elements. These components shape the brake cylinder and all moving parts within brake gear.

4) ABS components. There are two variants of ABS circuits considered for the motorcycle model under discussion: with one 3-position relay valve (see Figure 6a) and two 2-position relay valves (see Figure 6b).

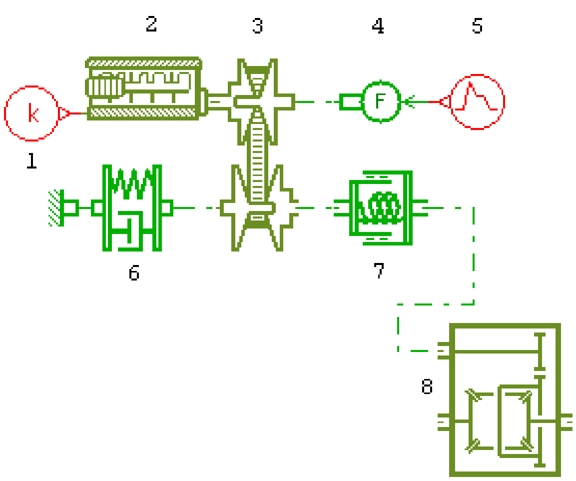
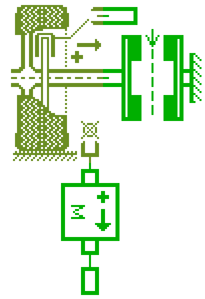


Figure 3. Power train sub-model: 1 – constant signal on engine port, 2 – engine, 3 – CVT, 4 – conversion of signal input into a force, 5 – CVT control signal, 6 – ideal spring damper system, 7 – rotary spring and damper, 8 – gearbox.



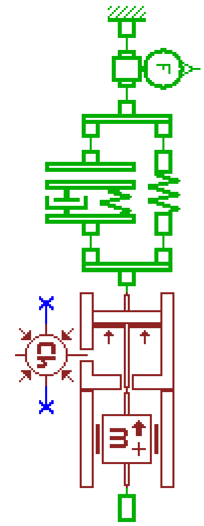
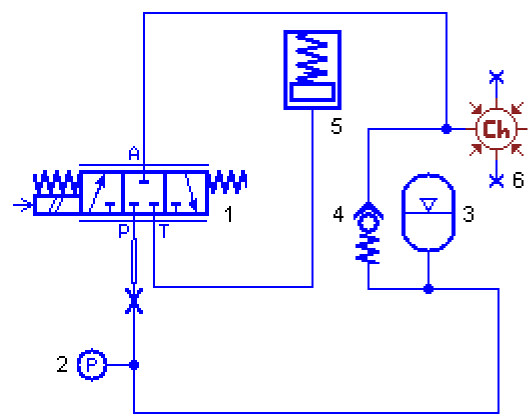
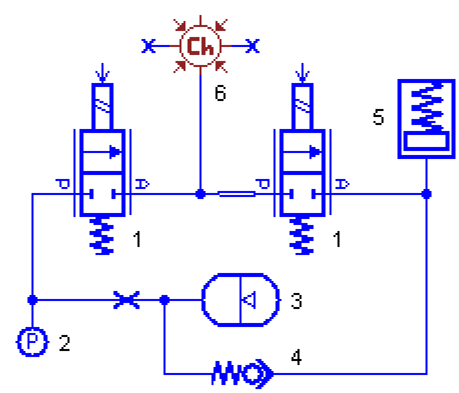


Figure 4. Wheel unit sub-model.

Figure 5. Brake gear sub-model.



a)



b)

Figure 6. ABS sub-models: 1 – relay valves, 2 – pressure source, 3 – damping chamber, 4 – relief valve, 5 – hydraulic accumulator, 6 – hydraulic volume.

The combinations of above mentioned sub-models allow creation of the following ABS variants for two-wheeled vehicle models:

- Single-channel ABS with one 3-position relay valve
- Single-channel ABS with two 2-position relay valves
- Double-channel ABS with one 3-position relay valve
- Double-channel ABS with two 2-position relay valves.

Figure 7 gives examples of one of the complete models. For simulation purposes, such models have been connected with ABS algorithm model created in MATLAB / Simulink (Figures 7 does not show co-simulation interface). This co-simulation allows to take into account weight redistribution between wheels during braking, response time of ABS valves, hysteresis losses in brake gears and drive.

The initial data for simulation procedure, which are given in Table 1, have been chosen or calculated for motorcycle prototype MMVZ 3.115 (manufactured by Minsk motorcycle and bicycle plant).

Table 1.
Initial data for simulated two-wheeled vehicle.

Parameter	Value
Maximal engine torque by 90 km/h	12,45 Nm
Transmission ratio	7,3425
Full mass of vehicle	203 kg
Front wheel loading	95,4 kg
Rear wheel loading	107,6 kg
Moment of wheel's inertia	0,84 kg·m^2
Effective tyre radius	0,295 m
Piston stroke in brake gear	0,5 mm
Brake support stiffness	10^8 Nm
Hydraulic storage pressure	5 MPa
Tube diameter	5 mm
Maximal pressure in brake drive	10 MPa
Brake fluid	DOT 4

ABS ALGORITHM DESCRIPTION

The subsequent discussion considers two-wheeled vehicles with anti-lock braking systems based on the pre-extreme control algorithms [6, 7].

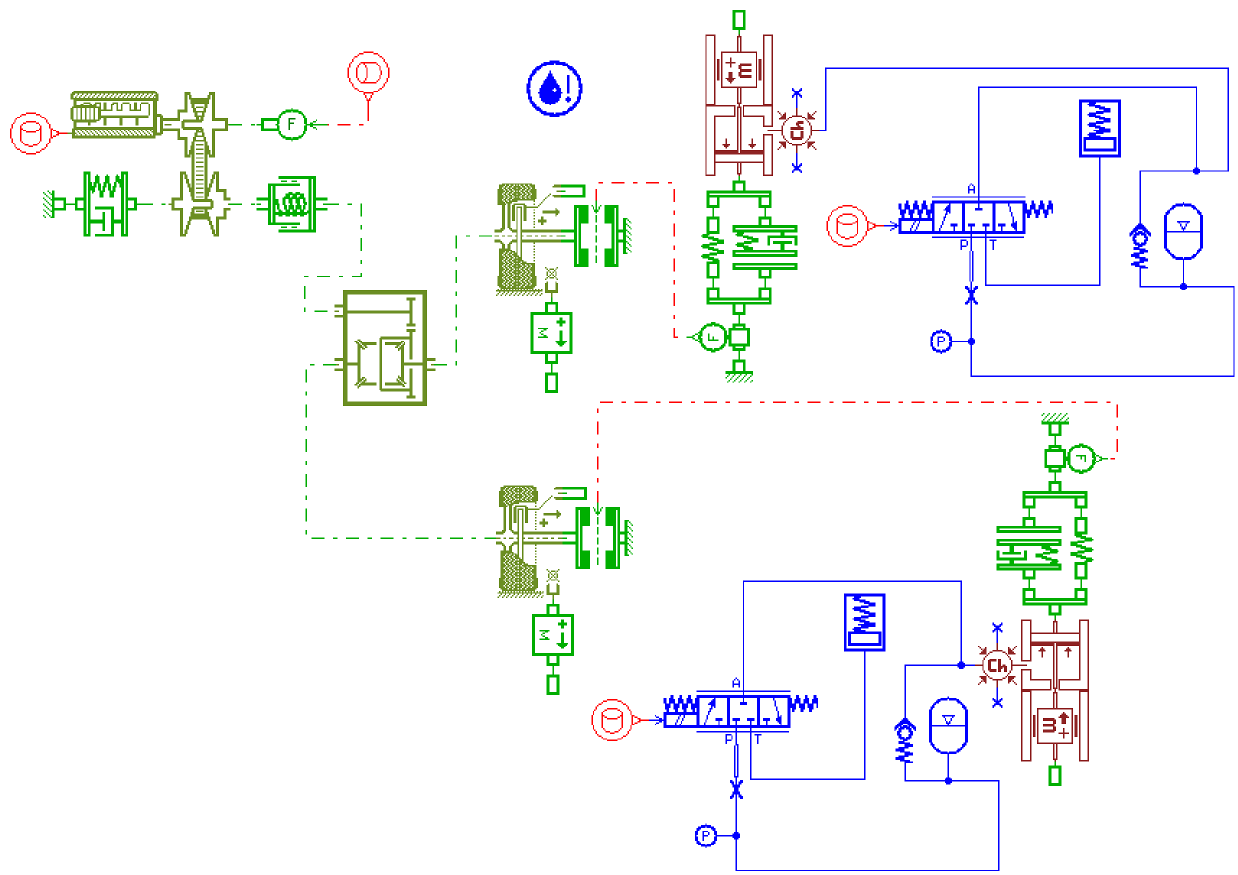


Figure 7. A simplified model example for two-wheeled vehicle: double-channel ABS with 3-position relay valve.

The investigated variant of algorithm applies a gradient control principle based on information about the change of $dF_{\mu x}/ds$-sign, where $F_{\mu x}$ is the longitudinal force within tire-road contact; s is the wheel slip (see Figure 8).

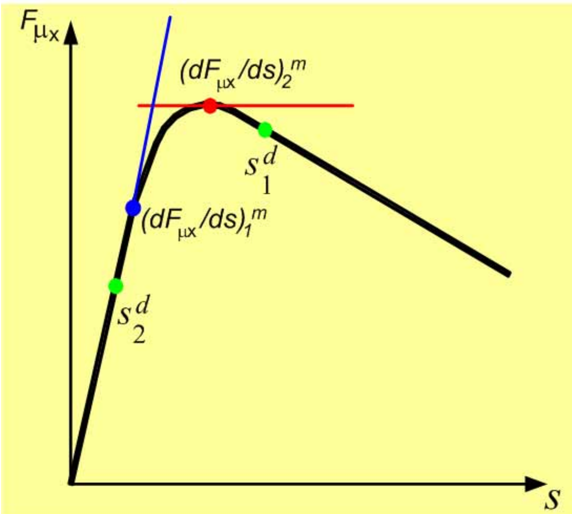


Figure 8. Dependence between longitudinal force within tire-road contact $F_{\mu x}$ and wheel slip s.

The corresponding pre-extreme algorithm can be described for braking mode at follows. The system applies signal for the pressure release when the following criteria take place

$$dF_{\mu x} / ds > 0 \quad (1),$$

$$\left| \left(\frac{dF_{\mu x}}{ds} \right)_i - \left(\frac{dF\mu x}{ds} \right)_{i-1} \right| \le \chi_1 \quad (2),$$

where χ_1 is a control deviation for the pressure release. The attainment of value χ_1 is evidence for the completion of linear section of $F\mu_X(s)$-curve and for the tendency to the approach of an extremum. During pressure reduction the system monitors the fulfillment of relations

$$dF_{\mu x} / ds < 0 \quad (3),$$

$$\left| \left(\frac{dF_{\mu x}}{ds} \right)_i - \left(\frac{dF_{\mu x}}{ds} \right)_{i-1} \right| \le \chi_2 \quad (4),$$

where χ_2 is a control deviation for the pressure build-up. These deviations indicate that the rating value for displacement from extremum takes place. If the main informational channels [$(dF_{\mu x}/ds)_1{}^{m}$ and $(dF_{\mu x}/ds)_2{}^{m}$] cannot process the situation with assurance or fall out, so the parallel double channels [s_1^d and s_1^d] come into effect.

A hardware-based estimation of $F_{\mu x}$ force can be carried out according to equation

$$F_{\mu x} = \frac{1}{V_s}\left(mV\frac{dV}{dt} - \omega\left(k_p \cdot p - J\frac{d\omega}{dt} \right) \right) \quad (5),$$

where V_s is wheel slip velocity, m – vehicle mass reduced to the wheel, V – vehicle velocity, ω – rotational velocity of a wheel, p – brake pressure, k_p – transfer ratio "brake moment – brake pressure", J – moment of wheel's inertia. To use Equation (5) by simulation, the brake pressure and wheel's velocity are transmitted to MATLAB/Simulink from AMESim; the tire model computes the wheel slip velocity. The generalized structure of Simulink-model is described in [6].

In the case of tire side slip, which requires taking into account the lateral force within tire-road contact $F_{\mu y}$, the function of the sum force is used:

$$F_{\mu} = \sqrt{F_{\mu x}^2 + F_{\mu y}^2} \quad (6).$$

To improve the reliability of the gradient algorithm, ABS model includes a parallel controller with dependence between the force $F_{\mu x}$ and the brake control effort F_c as operating characteristic. The $F_{\mu x}(F_c)$-curve is of extreme shape and allows to form the control thresholds through value of $(dF_{\mu x}/dt)/(dF_c/dt)$ (see Figure 9). The logical element Σ analyses this ratio based on signals from the differentiator units *D1* and *D2*. The output of logical element produces signal for ABS actuator.

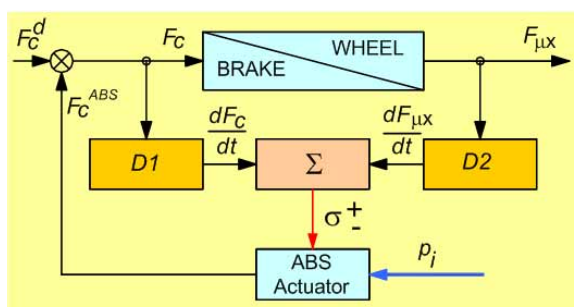


Figure 9. Parallel ABS controller for gradient algorithm: F_c^d – brake gear control effort required by driver, F_c^{ABS} – brake gear control effort adjusted by ABS.

SIMULATION RESULTS AND ANALYSIS

Investigations on Hydraulic Functions of ABS Components

Because the preliminary stage of investigations resulted in synthesis of several ABS variants for two-wheeled vehicles, the primary task is to evaluate the properties of the ABS circuits each in respect to their hydraulic functionality. The reason is that such parameters like response time and hysteresis losses of the brake drive influence vastly on efficiency of ABS.

For these purposes, the functions of the following main parameters have been monitored during simulation procedure in AMESim:

- Wheel slip
- Brake pressure
- Brake forces on wheels
- Average frequency at braking
- Maximal work frequency
- Operating time for brake system.

Figure 10 gives examples of some obtained dependencies, and the most important evaluation parameters are included in Table 2.

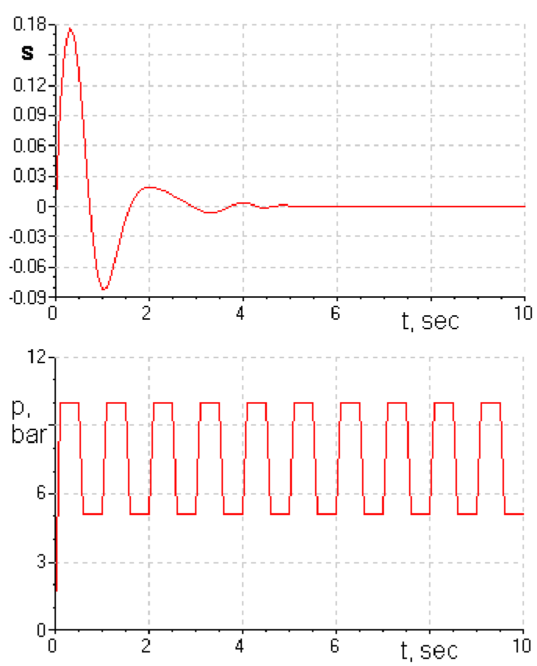


Figure 10. Examples of time dependencies for wheel slip *s* and brake pressure *p* (work smoothness testing for single-channel ABS with two 2-position relay valves).

The operating time is determined by the volumetric capacity of brake system. The average ABS frequency at braking is required to optimize the construction parameters on the designing stage. The maximal work frequency gives functional limitations to the ABS control algorithm.

Table 2.
Evaluation parameters for ABS functions at AMESim testing.

Parameter	Value
ABS with 3-position relay valve	
Operating time	0,5 sec
Average frequency at braking	3,5 Hz
Maximal work frequency	18 Hz
ABS with 2-position relay valves	
Operating time	0,48 sec
Average frequency at braking	4 Hz
Maximal work frequency	21 Hz

From the results obtained the following conclusions may be deduced.

1) The value of wheel slip does not exceed the level in 0.18 at ABS braking for the tire-road friction coefficient corresponding to the dry surface. The *s*-value at braking without ABS can reach 0.5, it can be dangerous for the motorcycles under discussion.

2) The system with 2-position relay valves works more softly as against the ABS with 3-position relay valve. This is connected with the smoothness of brake pressure buildup.

3) The maximal work frequency of ABS lies in limits up to 20…25 Hz, which are enough for the pre-extreme algorithms, especially taking into account the small moment of wheel's inertia for motorcycles and scooters.

4) All investigated variants of ABS have the comparable operating time, which falls within requirements to the brake performance.

It should be pointed out that the circuits with two 2-position relay valves appropriate most of all for the light-weight motorcycles.

Investigations on ABS Algorithm

To evaluate the functional properties of an anti-lock braking system, the models of double-channel system with 2- and 3-position relay valves have been chosen. The Simulink/AMESim co-simulation of two-wheeled vehicle dynamics at emergency braking was developed for $F_{\mu x}(s)$-curves complying with the dry and wet road surface. The database of road properties was created for these curves. The braking with the side slip on front wheel was also investigated.

The following characteristics of ABS braking have been chosen as the evaluation parameters:

- Average work frequency, ν
- Brake distance changing as compared to braking without ABS, ΔS_{br}
- Maximal value of slip, s_{max}.

Some results are summarized in Table 3. Their analysis allows to make a number of conclusions.

Table 3.
Evaluation parameters for testing ABS properties.

Parameter	ABS with 2-position valves	ABS with 3-position valve
Braking from 90 km/h on dry road, side slip angle 0°		
ΔS_{br}, %	-0,55	-0,63
ν, Hz	0,8	0,5
s_{max}	0,14	0,3
Braking from 120 km/h on dry road, side slip angle 0°		
ΔS_{br}, %	-0,85	-0,75
ν, Hz	0,68	0,5
s_{max}	0,19	0,27
Braking from 90 km/h on dry road, side slip angle 6°		
ΔS_{br}, %	+0,36	-0,16
ν, Hz	1,32	0,67
s_{max}	0,136	0,46
Braking from 120 km/h on dry road, side slip angle 6°		
ΔS_{br}, %	+0,66	-0,09
ν, Hz	1,52	0,43
s_{max}	0,133	0,44
Braking from 90 km/h on wet road, side slip angle 0°		
ΔS_{br}, %	-24,36	-16,0
ν, Hz	0,69	0,32
s_{max}	0,395	0,67
Braking from 120 km/h on wet road, side slip angle 0°		
ΔS_{br}, %	-27,45	-18,80
ν, Hz	0,55	0,31
s_{max}	0,33	0,65
Braking from 90 km/h on wet road, side slip angle 6°		
ΔS_{br}, %	+3,45	-2,59
ν, Hz	2,11	0,4
s_{max}	0,155	0,36
Braking from 120 km/h on wet road, side slip angle 6°		
ΔS_{br}, %	+3,48	-2,99
ν, Hz	1,82	0,32
s_{max}	0,155	0,36

1) Both of ABS variants with the developed pre-extreme algorithm achieve in the most of cases the small deviation of brake distance from values obtained at braking without ABS. The exceptions take place for the emergency braking on wet surface without side slip. In this case the system achieved the considerable reduction of brake distance in the range from 16 % to 27.5 %.

2) The work frequency of ABS does not exceed 2.11 Hz. This is evidence of fact that proposed algorithms can guarantee the sparing consumption of actuating fluid and the high ergonomic features.

3) The anti-lock braking system with 2-position relay valves operates in the more close-cut slip area resulting in the sufficient support of vehicle stability. At the same time, both of ABS circuits did not allow the momentary wheel's locking for all investigated braking processes.

Hence the developed structural and algorithmic solutions, which are applied to the ABS for two-wheeled vehicles, have the required preliminary approbation and can be considered for the further investigations, including the constructive realization and actual testing.

CONCLUSIONS

The use of anti-lock braking systems on two-wheeled mobile machines allows enhancing the active safety level for this kind of vehicles. But the choice of the principle circuits for ABS must take into account also the cost factors and the field of vehicle application.

It can be supposed on basis of the results obtained that the double-channel anti-lock braking systems can provide the higher safety level because of the stability and steerability keeping practically at any braking process.

The results of virtual testing displayed that the systems with 2-position valves are more preferable in the view of hydraulic assembling and vehicle stability. It should be marked that such ABS configuration fits with rising of active safety potential thanks to the integration of advanced systems like the traction and stability control systems on the two-wheeled vehicles. Authors plan to survey this aspect in the future works.

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