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Original Research Article

Development of a bicycle anti-lock braking system prototype

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Abstract

In order to satisfy the increasing need for security and comfort the active safety systems of the smaller vehicles like the motorbikes, scooters, e-bikes and bicycles have an intensively studied research topic over the last decade. This paper describes the development of a hydraulic type anti-lock braking system (ABS) prototype for bicycle applications. Based on vehicle dynamics of bicycles, a mechanical model has been built and a novel ABS control algorithm was designed. This algorithm is based on a newly developed reference speed calculation method which uses the angular acceleration values of the wheels. The proper operation of the algorithm is proved through simulations and based on the results a prototype was built. In the prototype system the algorithm was implemented on an external controller module which involves a Continental-developed motorbike hydraulic electronic control unit. The functionality of the prototype system has been verified on a test track in several real road surface conditions such as dry and wet asphalt, grassy ground and dirt road.

Keywords: safety systems, vehicle dynamics, bicycle, anti-lock braking system

Nomenclature

a_x	Longitudinal acceleration of center of gravity (CoG)
g	Gravitational acceleration
h_{CoG}	Height of center of gravity above ground
m	Overall mass of the bicycle
p_0	Available maximum brake pressure
p_b	Brake pressure at the brake pistons
t_D	Time delay of the brake system
$v_{filtered}$	Filtered speed
v_{init}	Initial speed
v_{ref}	ABS reference speed value
v_x	Longitudinal velocity of center of gravity (CoG)
A_b	Area of brake pistons
L	Wheelbase
L_f	Center of gravity to the front axle
M_f	Braking torque
M_b	Driving torque
N	Elapsed time from the measurement of the initial speed
S	Speed slope
R	Tire radius
R	Brake piston radius
α	Slope angle
β	Angular accelerations of the wheels
μ	Friction coefficient
μ_b	Friction coefficient of brake pistons
ω	Wheel angular velocity
γ	Desired pressure gradient
τ_b	Time constant of the first order brake model
Θ	Inertia of the rotating parts of the wheel

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1. Introduction

Nowadays more and more efforts are made to make the road traffic safer. Not even for the cars and trucks, but also for the motorbikes and bicycles there are extra safety products to avoid or at least to reduce the harms and injuries.

The most new cars are equipped with active safety-systems such as anti-lock braking system (ABS) and electronic stability program (ESP) [1, 2]. There are also active safety systems for motorbikes such as anti-lock braking system, rear wheel lift-off protection, etc. A bicycle is a much simpler construction than the motorized vehicles. There is no need to have a driving license to use one, thus it is reachable easily as means of transport. In the last years more and more people choose to use bicycles and high number of accidents were caused and suffered by cyclists [3, 4]. A lot of people ride without essential protection, for example helmet, knee- or elbow-protector [5] so a simple fall can cause serious injuries. One solution to protect the rider is to have the safety function on the bicycle itself. This research project was started to develop hydraulic ABS prototype for bicycles through examining the bicycle dynamics.

2. The existing methods for the bicycle ABS

Results of the research survey in the bicycle ABS topic shows that there is no widespread active safety product for bicycles currently [6 – 10]. For electric motor aided or hybrid bicycles there are some active safety systems available, but regular bicycles are still not supported. There are some simple solutions by modifying the brake-pad shape, using springs in the brake wires and also exist a few more complex methods such as brake force distribution or balancing. Scanning the literature [6] a couple of proof of concepts can be found but no out-of-box product exists that uses some kind of intelligence. The idea to apply some intelligent decision aiding mechanism is relatively new. In the list below a few of them can be seen:

- mechanical brake force distribution;
- pneumatic aided ABS;
- ABS realization with electronic stepper motor.

From the list it can be seen that many attempts have been initiated to solve the problem but none of them uses a hydraulic anti-lock braking system on both wheels. To elaborate the full wheel anti-lock braking system the development of a bicycle dynamic model was started.

3. The vehicle dynamics based model

The basis of the algorithm is a longitudinal two-wheel model [11 – 14] appropriate to describe the behavior of the bicycle which is performing an emergency braking maneuver on plain or sloping surfaces. In this model the longitudinal dynamics are dominant and therefore the lateral dynamics are unconsidered. The longitudinal dynamics are governed by Equation (1).

$$\sum F_x = ma_x = F_{xf} + F_{xr} + mg\sin(\alpha) \quad (1)$$

where m is the overall mass of the bicycle and the cyclist, a_x is the longitudinal acceleration, g is the gravitational acceleration, α is the slope angle of the road surface.

The longitudinal friction forces (F_x) are equal to the products of the friction coefficients (μ) and normal tire forces (F_z) (Equation (2)):

$$\begin{aligned} F_{xf} &= \mu_f F_{zf} \\ F_{xr} &= \mu_r F_{zr} \end{aligned} \quad (2)$$

The normal tire forces are the solutions of the following equation systems (Equation (3) and Equation (4))

$$\sum F_z = 0 = F_{zf} + F_{zr} - mg\cos(\alpha) \quad (3)$$

$$\begin{aligned} &\sum M_y^{(C)} = 0 = (mg\sin(\alpha) - ma_x) \\ &(h_{CoG} - R_f) - mg\cos(\alpha)L_f + F_{zr}L \end{aligned} \quad (4)$$

where h_{CoG} is the height of center of gravity above ground, R is the tire radius, L_f Center of gravity to the front axle and L is the wheelbase.

Equation (1) was rearranged into ordinary differential equation form using the solution of Equation (2) – (4) for F_{xf} and F_{xr} (Equation (5)):

$$a_x = \frac{dv_x}{dt} = g\cos(\alpha)\frac{\mu_f L + (\mu_r - \mu_f)L_f}{L - (\mu_r - \mu_f)h_{CoG}} + g\sin(\alpha) \tag{5}$$

The rotational motions of the wheels are governed by the following torque equations (Equation (6)):

$$\begin{aligned} \Theta_{wf}\beta_f &= F_{xf}R_f + M_{bf} \\ \Theta_{wr}\beta_r &= F_{xr}R_r + M_{br} + M_{fr} \end{aligned} \tag{6}$$

Equation (6) was rearranged into ordinary differential equation form using the solution of Equation (2) – (4) for F_{xf} and F_{xr} (Equation (7)):

$$\begin{aligned} \beta_f &= \frac{d\omega_f}{dt} = \frac{1}{\Theta_{wf}^{(C)}}\left[-\mu_f mg\cos(\alpha)\frac{L - L_f - \mu_r h_{CoG}}{L - (\mu_r - \mu_f)h_{CoG}}R_f - \operatorname{sgn}(\omega_f)M_{bf}\right] \\ \beta_r &= \frac{d\omega_r}{dt} = \frac{1}{\Theta_{wr}^{(D)}}\left[-\mu_r mg\cos(\alpha)\frac{L_f + \mu_f h_{CoG}}{L - (\mu_r - \mu_f)h_{CoG}}R_r - \operatorname{sgn}(\omega_r)M_{br} + M_{fr}\right] \end{aligned} \tag{7}$$

In the equations above the M_f is the driving torque, M_b is the brake torque. In the subscript f and r denote front and rear, respectively. The geometrical parameters should be considered as constant values and can be seen on the Figure 1.

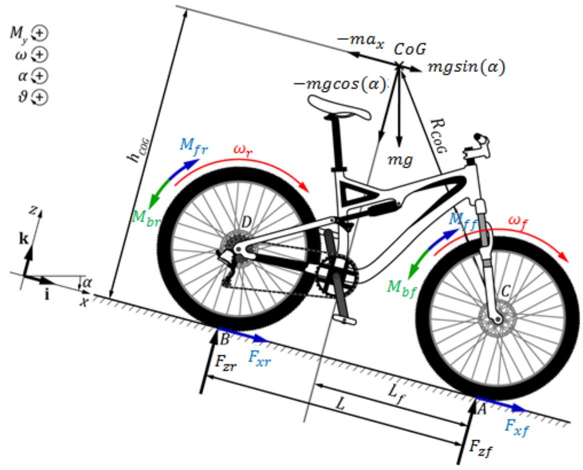

Figure 1. The main parameters of the bicycle model

The driving torque is produced by the driver and it should be introduced as an input of the model. The braking torques depend on the brake pressures (Equation (8)).

$$\begin{aligned} M_{bf} &= p_{bf}2A_{bf}\mu_{bf}R_{bf} \\ M_{br} &= p_{br}2A_{br}\mu_{br}R_{br} \end{aligned} \tag{8}$$

The other parameters of the braking system which have impact on the braking torques can be considered as constant values. The brake torques are the maximum torques available, not the actually applied. It is very important because these torques can only decelerate the front and rear wheels, and their sign is always the opposite of the corresponding wheel speeds. The brake torques can lock the braked wheels.

The front and rear braking systems can be modeled as independent first order systems. The output of the brake model is the brake pressure at the brake pistons (p_b). The input parameter is the available maximum brake pressure (p_0) which can be modulated by the ABS and can be obtained by the integration of the desired pressure gradient (γ) (Equation (9)).

In the Equation (9) the τ_b is the time constant of the first order brake model, t_D is the time delay of the brake system.

$$\tau_{bf}\frac{dp_{bf}}{dt}+p_{bf}=p_{0f}=\int_0^t \gamma_{bf}(\tau-t_{Df})d\tau$$
$$\tau_{br}\frac{dp_{br}}{dt}+p_{br}=p_{0r}=\int_0^t \gamma_{br}(\tau-t_{Dr})d\tau \quad (9)$$

Based on the Equations (1) – (5) a MATLAB/Simulink model was created to simulate the longitudinal behavior of the bicycle. The model was tested with the following parameters:

Table 1. The model parameters

Parameter	**Value**
m	85 kg
h_{COG}	1 m
L_f	0.95 m
L	1.165 m
A_{bf}, A_{br}	0.75E-4 m^2
R_{bf}, R_{br}	0.08 m
μ_{bf}, μ_{br}	1
R_f, R_r	0.3302 m
I_f, I_r	0.1344 kgm^2

The results can be seen on the Figure 2. The behavior of model during an emergency braking maneuver, meets the requirements.

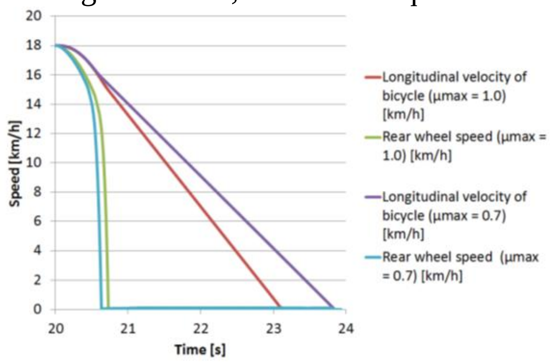

Figure 2. The simulation results of emergency braking maneuvers on different surfaces without ABS

4. The implemented control algorithm of the ABS prototype

The results of the simulations were in concordance with the expectations; the ABS control algorithm was implemented in MATLAB/Simulink development environment based on the experiences and knowledge from vehicle dynamics based model introduced in Section 3. The algorithm compares the wheel speed and a calculated reference speed in five steps (the algorithm is the same for rear and front wheel, only the parameters are different):

1. Signal Filtering: The input wheel speed is smoothed by a filter to decrease the noise in the signal and to clear off the roughness of the sensor ring.
2. Road Surface Determination: The task of this part is to select the road surface parameters from a look-up table according to the behavior of the wheels and the anti-lock braking system.

Reference Speed Calculation: The calculation of the reference speed is based on a linear function defined by a speed slope value and the initial speed (v_{init}) value similarly to Equation (10)

$$v_{\mathrm{ref}}(n)=S(n)N(n)+v_{\mathrm{init}}(n) \quad (10)$$

where v_{ref} is the reference speed value, S is the speed slope, N is the elapsed time from the measurement of the initial speed (the last valid speed value before the actuation). The defined speed slope is dynamically altered during the braking due to the changing of the road surface. The initial speed value is calculated in every loop of the algorithm, based on Equation (11).

$$v_{init}(n)=\begin{cases} v_{filtered}(n) & \text{if} \quad v_{ref}(n)\le v_{filtered}(n) \\ v_{init}(n) & \text{if} \quad v_{ref}(n)>v_{filtered}(n) \end{cases} \quad (11)$$

1. ABS State Selection: The choice between the different states is based on the comparison of speed and the calculated reference speed (the states will be specified in details at the description of the prototype). The default state of the ABS is the increase state, if the ratio of the reference and the measured speed is higher than a predefined value the ABS will be switched into hold state. If this ratio continues to increase the state will be modified to release.
2. State Override: After the state selection there is a state override part. This is a safety function to prevent the actuation if some errors are detected or

to prevent the overheating of the ABS hydraulic and electronic control unit (HECU).

The algorithm was embedded into the vehicle dynamics based model. The Figure 3 and 4 show the results of an emergency braking maneuver with initial speed 18 km/h on different surfaces. During these maneuvers only the rear wheel speed is shown to be comparable with the result of the measured data from the prototype tests. It can be seen when the wheels started to block the ABS was actuated and the brake pressure was decreased and the algorithm switched successfully between the ABS states.

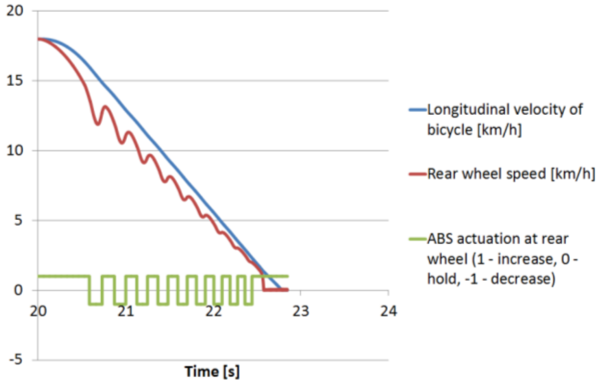

Figure 3. The simulation results of emergency braking maneuvers on dry asphalt (μ_{max} = 1.0) with active ABS

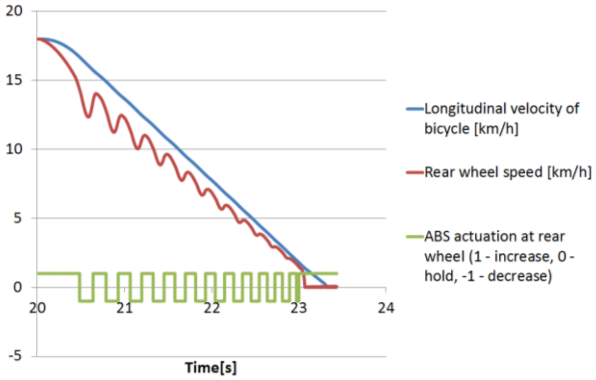

Figure 4. The simulation results of emergency braking maneuvers on wet asphalt (μ_{max} = 0.7) with active ABS

5. The implemented bicycle ABS prototype

After the simulations the creation of a prototype system was necessary to test and validate the new ABS control algorithm and the model. The prototype is based on a professional mountain bike (Specialized Stumpjumper FSR Comp 29), equipped with a high quality hydraulic brake system. The bike has not been modified, only the hydraulic brake pipes were disconnected and the HECU was inserted (Figure 5). To create the connection between the hydraulic system of the motorbike ABS and the brake system of the bicycle was difficult, because these parts were designed for different pressure intervals and filling methods.

The main hardware component is the ABS HECU (Hydraulic and Electronic Control Unit) which is a modified motorbike HECU. It consists of two main parts; one is the ECU (Electronic Control Unit) that is the electronic control part for the HCU (Hydraulic Control Unit) that modulates the flow of the brake fluid. The control unit currently works without a control algorithm and operates only as an actuator. Therefore an external controller module (Texas Instruments Tiva TM4C123GH6PM based board) has to run the control algorithm and send the control messages to the ECU on CAN bus.

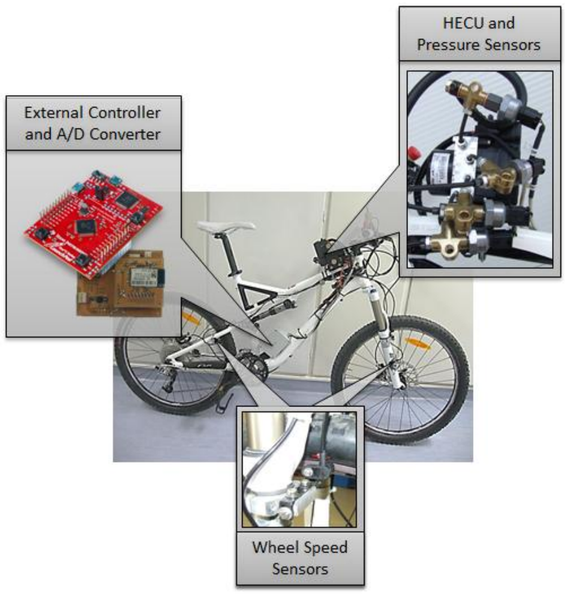

Figure 5. The hardware structure of the prototype

The pressure on the brake pads modulated by the system is gained from the applied squeezing force on the hand-lever by the bicycle rider. The active ABS can be switched into three different pressure modulation phases (increase, hold, release) via CAN messages, independently in the front and rear brake circuits:

- In the increase phase the pressure is applied by the rider, not modulated by the HCU.
- In the hold phase the oil flow is obstructed from the inflowing (hand-lever) and the effluent (brake-pad) side, as well. Thus the pressure that is present on the brake-pads is hold.
- In the release phase the pressure is obstructed from the inflowing part, and the effluent part is open, so the pressure will be decreased on the brake-pads. In this state the rider’s squeeze-force does not matter, it has no effect on the pressure at the brake-pads.

To operate the control algorithm it is necessary to measure the wheel speeds. On a standard bicycle there are no high-precision wheel speed sensors. To solve this problem the prototype was equipped with four different active Hall-sensors to test which one is the most suitable in different conditions. Two sensors were mounted for each wheel. One of the sensors measures the polarity of magnetic tape pieces which are stuck on the rim of the wheels with changing polarity. The other sensor senses the holes on the brake disc.

The bicycle is also equipped with pressure sensors to log the pressure data for further investigations. These sensors are connected to the hydraulic block with an adapter block. In the brake system there are four pressure sensors, two for each brake circuit. The test system can measure the pressure applied by the rider from the levers, and also able to measure the pressure to the brake-pads.

It is possible to monitor the behavior of the ABS, the bicycle (wheel speeds) and the CAN communications, as well. To facilitate these options the external controller module was extended with a Bluetooth and standard IEEE802.11b/g wireless LAN module. Each of these modules opens a duplex communication interface, therefore the monitoring of the parameters and signals can be realized with an Android, iOS or Windows Phone based smart phone or a conventional notebook or PC (Figure 6.).

6. The measurement results

The prototype control algorithm was tested on a test track with different surfaces, such as grassy ground, dry and wet asphalt. The first tests had some efficiency problems but applying the fine-tuned parameters in the simulation and also in the control algorithm the results were in concordance with the expectations. The proper operation of the algorithm is proved on wet and dry surfaces and also on slopes. Figure 7 shows the results of an emergency braking maneuver with initial speed 18 km/h on flat and dry asphalt. During the maneuver only the rear brake pressure was modulated because of driver safety issues (on lower speeds the two wheel test were also successfully). It can be seen when the wheels started to block the ABS was actuated and the brake pressure was decreased.

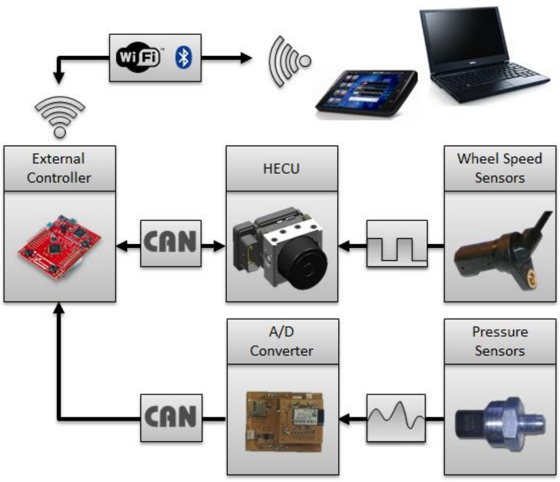

Figure 6. The communication structure of the prototype

7. Conclusion

A longitudinal two-wheel model was introduced which can be exploited to serve as the basis of an ABS algorithm. After the examination of the model in

MATLAB/Simulink environment an ABS prototype was constructed. The behavior of the ABS algorithm and the prototype was validated on a test track in several different conditions.

During the measurements a lot of experiences were gained about the potential hardware problems. The currently used brake system is not capable to support the too often occurred changes in big pressure range that are common for motorbikes. For a bicycle braking system this leads to an early wearing of the parts. Thus both the bicycle brake pistons and gaskets should be strengthened or an ABS system should be developed that uses analogue valves and applies less pressure “jumps”. For this prototype the bridging solution was the application of hydraulic choke valves and less actuations.

Different types of wheel speed sensors were also tested with different placements and the conclusion was that the usage of the magnetic sensors with higher resolution is not necessary in conventional cases.

Based on the experiences, the “downsizing” of the ABS hydraulic control unit was started and the troubleshooting of the above presented problems are in progress.

In many countries around the world a lot of people use bicycle not only for free time activity but also as a part of their everyday life to commute to their workplace. During these times accidents can happen to anybody, so it is important to prevent the bicycle riders from injuries. With this prototype the aim of the project team is to show that the ABS technology is also a solution (for bicycles) to make cycling safer. After the test rides further improvements of the software should be realized that can help the riders in dangerous situations to mitigate collision or just to stop in a safe way.

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