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Bicycle Anti-Lock Braking System Prototype Development

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Abstract: The passive and also the active safety systems of the vehicles evolved in the last decades. Beside the safety system of cars and trucks the smaller vehicles like the motorbikes, scooters, e-bikes and bicycle's systems evolved as well. The aim of the project was to create and develop a prototype bicycle that uses a hydraulic type anti-lock braking system.

The paper presents shortly the dynamics of the bicycle and steps of development of the prototype and the developed control algorithm with experimental results.

Keywords: vehicle safety, vehicle dynamics, bicycles, motion control, modeling, simulation

1. Introduction

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

The most of the new cars are equipped with active safety-systems like anti-lock braking system (ABS), electronic stability program (ESP) [1]. For motorbikes there are also active protective systems such as anti-lock braking system, rear wheel lift off protection etc.

Bicycle is a much simpler construction there is no need to have a driving license to use one thus it is reachable easily as means of traffic. In the last years more and more people choose to use bicycle and high number of accidents caused by bicyclists and suffered by bicyclists [2, 3]. A lot of people use it without the minimum protection, for example helmet, knee- or elbow-protector [4]. A simple fall can cause serious injuries. One solution to protect the rider is to have the safety function on the bicycle itself. This is the reason why a new project was started for examining the bicycle dynamics and developing hydraulic ABS for a bicycle.

The aim of the research was to create and develop a prototype bicycle that uses hydraulic type anti-lock braking system, and make a proof-of-concept development and test to prove, it is possible to develop an efficient dynamics based anti-lock braking system algorithm for bicycles. Also to get information what main difficulties can occur during development of a new, optimized bicycle anti-lock braking system.

2. Existing methods

Results of the research survey in the bicycle ABS field shows that there is no widespread active safety product for bicycles nowadays [5]. For electric motor aided or hybrid bicycles are already present, 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 more complex methods such as brake force distribution or balancing. Scanning the literature [5] a few proof of concepts could be found but any ready to buy product that uses some kind of intelligence does not exist. 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 can be seen that many attempts have been initiated to solve the problem; but none of them use 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 has been started.

3. The Bicycle model

Some vehicle and bicycle dynamics based model was examined [6, 7, 8, 9] and a longitudinal dynamics based model was created to test the ABS control methods (*Fig. 1*). The main equations of the model can be seen below. The symbols of the equations can be found in (I).

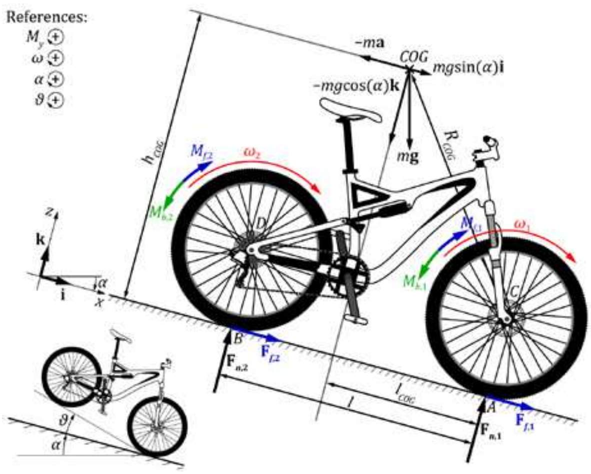

Figure 1: The forces, moments, references and geometry.

$$\sum F_x = ma_x = m\frac{dv_x}{dt} = F_{f,1} + F_{f,2} + mg\sin(\alpha) \quad (1)$$

$$\sum F_z = ma_z = m\frac{dv_z}{dt} = F_{n,1} + F_{n,2} - mg\cos(\alpha) \quad (2)$$

Table 1: Applied symbols for the bicycle model

Symbol	Description
M	the overall mass of the bicycle
a_x, v_x	the longitudinal acceleration and velocity of center of gravity (CoG)
$F_{f,1}$, $F_{f,2}$	the friction forces acting on front and rear wheels, respectively
a_z, v_z	the vertical acceleration and velocity of CoG
$F_{n,1}$, $F_{n,2}$	the normal forces acting on front and rear wheels, respectively
$\Theta_y^{(C)}$	the moment of inertia of overall bicycle about point C (the front wheel axle)
A	the slope angle of the road surface (considered as constant)magnetization
βy, ωy, ϑ	the pitch angular acceleration, velocity and pitch angle
L	the wheelbase of the bicycle
l_d, h_d	the lever arms
Θ_w	the moment of inertia of the wheels
B_1, β_2	the angular accelerations of the wheels
R	the radius of the wheels
$M_{b,1}$, $M_{b,2}$	the brake torques applied on front and rear wheels, respectively
Ω_1, ω_2	the angular speeds of the wheels
μ_1, μ_2	the friction coefficients of front and rear wheels, respectively
s_1, s_2	the relative slips of front and rear wheels, respectively

$$\sum M_y^{(C)} = \Theta_y^{(C)} \beta_y = \Theta_y^{(C)} \frac{d\omega_y}{dt} = \Theta_y^{(C)} \frac{d^2 \vartheta}{dt^2} = \\ mg\sin(\alpha)h_d - mg\cos(\alpha)l_d - ma_x h_d - ma_y l_d + F_{n,2} l \tag{3}$$

Lever arms l_d, and h_d depend on pitch angle ϑ:

$$l_d = l_{COG}\cos(\vartheta) - (h_{COG} - R_{CoG})\sin(\vartheta) \tag{4}$$

$$h_d = l_{COG}\sin(\vartheta) + (h_{COG} - R_{CoG})\cos(\vartheta) \tag{5}$$

The equations below show the dynamics of the wheels:

$$\Theta_w \beta_1 = \Theta_w (d\omega_1 / dt) = F_{f,1} R + M_{b,1} \\ \Theta_w \beta_2 = \Theta_w (d\omega_2 / dt) = F_{f,2} R + M_{b,2} \tag{6}$$

The relations between the friction forces and normal forces are calculated based on (7).

$$F_{f,1} = \mu_1(s_1) F_{n,1} \\ F_{f,2} = \mu_2(s_2) F_{n,2} \tag{7}$$

Definitions of tire slips:

$$s_1 = (R\omega_1 - v_x)/v_x \\ s_2 = (R\omega_2 - v_x)/v_x \tag{8}$$

The torques produced by front and rear brake systems are denoted with M_1 and M_2. These are the available maximum torques, not the actually applied brake torques. These torques ($M_{b,1}$ and $M_{b,2}$) can only decelerate the front and rear wheels, their sign is always the opposite of the corresponding wheel speeds. The brake torques can block the braked wheels. Therefore if on the front wheel ω1 (on the rear wheel ω_2) is not zero, then:

$$M_{b,1} = -\text{sgn}(\omega_1) M_1 \\ M_{b,2} = -\text{sgn}(\omega_2) M_2 \tag{9}$$

If the wheel speed is zero, then the amplitude of the applied brake torque is equal to the minimum of M_i and the absolute value of the torque produced by the tire friction force, and acts against the torque produced by the tire friction force:

$$M_{b,1} = -\text{sgn}(F_{f,1} R)\min(M_1, |F_{f,1} R|) \\ M_{b,2} = -\text{sgn}(F_{f,2} R)\min(M_2, |F_{f,2} R|) \tag{10}$$

The longitudinal acceleration and speed are defined by (11) and (12). The pitch angular velocity are given by (13) and (14):

$$a_x = F_{f,1} + F_{f,2} + mg\sin(\alpha)/m \tag{11}$$

$$v_x = \int_0^t a_x d\tau + v_0 \tag{12}$$

$$\omega_y = \left(\int_0^t \sum M_y^{(C)} d\tau + \omega_0 \right) / \Theta_y^{(C)} \tag{13}$$

$$\vartheta = \int_0^t \omega_y d\tau + \vartheta_0 \tag{14}$$

The vertical acceleration and the relation between the normal forces are the following:

$$a_z = \beta R_{CoG} \cos(\vartheta + \vartheta_{CoG}) - \omega^2 R_{CoG} \sin(\vartheta + \vartheta_{CoG}) \tag{15}$$

$$F_{n,1} = ma_z + mg\cos(\alpha) - F_{n,2} \tag{16}$$

The torque caused by gravitational and inertial forces about point C is given by (17).

$$M_y = mg\sin(\alpha)h_d - mg\cos(\alpha)l_d - ma_x h_d - ma_z l_d \tag{17}$$

Normal force $F_{n,2}$ is non-negative. If the pitch angle ϑ is zero, than pitch angular acceleration cannot be negative. Therefore, if ϑ is zero and M_y is negative, then:

$$F_{n,2} l = mg\sin(\alpha)h_d - mg\cos(\alpha)l_d - ma_x h_d - ma_z l_d \tag{18}$$

Otherwise it results:

$$\Theta_y^{(C)} \beta_y = M_y = mg\sin(\alpha)h_d - mg\cos(\alpha)l_d - ma_x h_d - ma_z l_d \tag{19}$$

The model was implemented in Matlab/Simulink (*Fig. 2*) and was tested with our ABS control algorithm. On the *Fig. 3* there is the result of an emergency braking maneuver from 18 km/h. During these maneuver only the rear wheel speed is shown to be comparable with the implemented version of the algorithm.

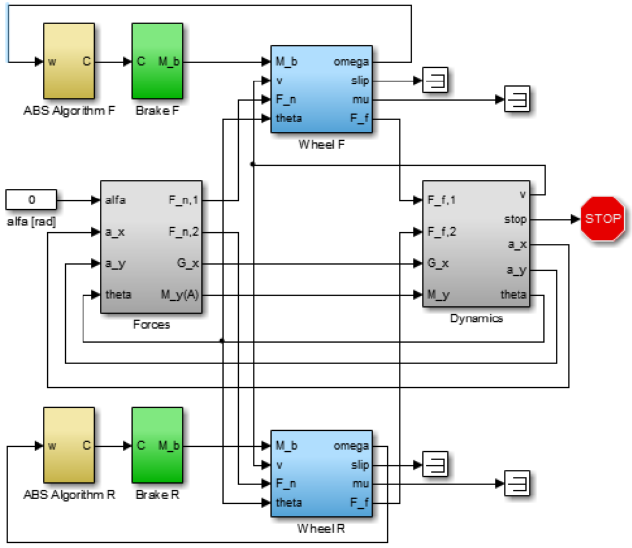

Figure 2: The Matlab/Simulink implementation of the vehicle dynamics based model.

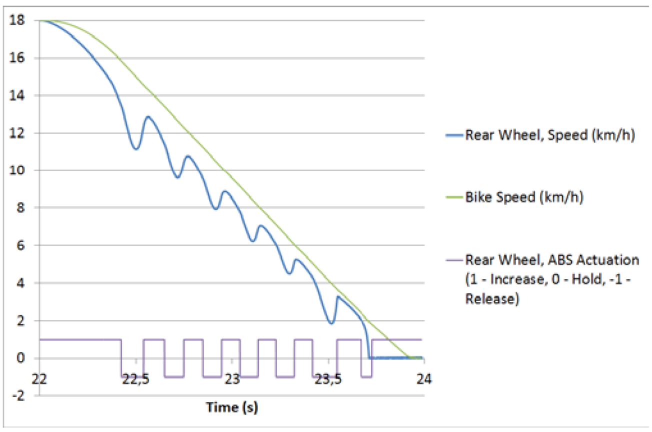

Figure 3: The result of a simulation (emergency braking with the rear wheel from 18 km/h, on dry asphalt).

4. The implemented control algorithm

The results of the simulations were in concordance with the expectations; it is possible to implement the model for an electronic control unit (ECU) of an ABS. Based on the experiences and knowledge from vehicle dynamics based model an ABS control algorithm was implemented in parallel in Matlab/Simulink and NI LabVIEW. The algorithm based on the comparison of the wheel speed and a calculated reference speed (the algorithm is the same for rear and front wheel, only the parameters are different).

A. Signal filtering

The incoming wheel speed is smoothed by a filter to decrease the noise in the signal (5):

$$v_{\text{filtered}}(n) = \left(\sum_{i=n-K_{\text{filter}}}^{n} v_{\text{unfiltered}}(i) \right) / (K_{\text{filter}} + 1) \tag{20}$$

where v_{filtered} is the filtered wheel speed, the $v_{\text{unfiltered}}$ is the unfiltered wheel speed and the K_{filter} is the filtering level which can be changed dynamically.

B. Road surface determination

The task of this part is to select the road surface from a look-up table according to the behavior of the wheels and the anti-lock braking system. The current algorithm chooses the road surface (and a friction coefficient value) from a look-up table, but a new method is under development which estimates this value by approximation methods.

C. 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 value (21):

$$v_{\text{ref}}(n) = S(n)N(n) + v_{\text{init}}(n) \tag{21}$$

where v_{ref} is the reference speed value defined by linear function, S is the speed slope, N is the elapsed time from measurement of the initial speed and v_{init} is the initial speed (the last valid speed value, before the actuation). The defined speed slope is dynamically changing during the braking by the changing of the road surface and the algorithm the v_{init} value is calculated in every loop based on (22):

$$v_{init}(n) = \begin{cases} v_{filtered}(n) & \text{if} \quad v_{ref}(n) \le v_{filtered}(n) \\ v_{init}(n) & \text{if} \quad v_{ref}(n) > v_{filtered}(n) \end{cases} \tag{22}$$

D. 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 brake pressure at the wheel be reduced if

$$v_{\text{ref}}(n) / v_{\text{filtered}}(n) \ge K_{\text{release}}(n) \text{ and } v_{\text{ref}}(n) > v_{\text{limit}}(n). \tag{23}$$

The brake pressure will be hold if

$$\begin{aligned} &v_{\text{ref}}(n) / v_{\text{filtered}}(n) \ge K_{\text{hold}}(n) \text{ and} \\ &v_{\text{ref}}(n) / v_{\text{filtered}}(n) < K_{\text{release}}(n) \text{ and } v_{\text{ref}}(n) > v_{\text{limit}}(n) \end{aligned} \tag{24}$$

else the brake pressure will be increased.

In the equations K_{release} is the limit for the release state K_{hold} is the limit for the hold state and v_{limit} is the speed limit for ABS actuation.

E. 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).

5. The prototype

To test and validate the new ABS control algorithms a prototype bicycle was developed. The prototype is based on a professional mountain bicycle, equipped with high quality hydraulic brake system. The bike was not modified only the hydraulic brake pipes were cut (*Fig. 4*).

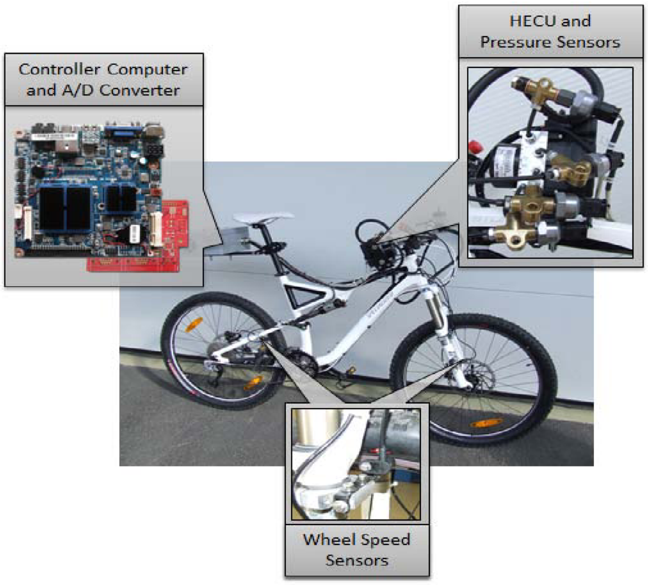

Figure 4: The hardware architecture of prototype.

A. ABS HECU block

The ABS HECU (Hydraulic and Electronic Control Unit) 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 flow can be modulated from the brake-lever to the brake-pad, this is the inflowing part into the HCU, and also in the other direction that is the effluent part. The control unit currently works without a control algorithm and operates only as an actuator, the control algorithm function is disabled and an external controller has to send the control messages and states to the ECU. The active ABS has three different pressure modulation phases, and can actuate valves independently for the front and rear brake circuits: increase, hold, release.

The pressure on the brake pads that is modulated by the system is gained from the applied squeezing force on the hand-lever by the bicycle rider.

In the increase phase the pressure is let applied by the rider, not modulated by the HCU.

In the hold phase the oil flow is stopped from the inflowing (hand-lever) and the effluent (brake-pad) side also. Thus the pressure that is present on the brake-pads is hold.

In the release phase the pressure is stopped 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 to the pressure on the brake-pads.

To create the connection of 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.

B. The wheel speed sensors

On the bicycle there are four different active wheel speed Hall-sensors to test which one is the most suitable in different conditions. Two sensors are mounted for each wheel. One of the sensors measures the polarity of magnetic tape slices which are stuck on the rim of the wheels with changing polarity. The other sensor is mounted to sense the holes on the brake disc.

The bicycle is equipped with pressure sensors as well. 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 can measure the pressure to the brake-pads.

C. The external controller computer

The external computer is a nano ITX sized SBC (Single Board Computer). It is small PC with, standard interfaces and Windows Embedded Standard 2009 operating system. This computer runs the control algorithm and collects the data from the ECU.

D. Internal and external communication

The controller computer is extended with a high speed CAN interface to communicate with the ECU and the A/D converter of the pressure sensors (*Fig. 5*).

The external communication is implemented as a standard IEEE802.11b/g wireless LAN. For monitoring the behavior of the system and the algorithm, a standard remote desktop connection or a special own, server-client architecture software can be used. With the special software it is possible to monitor the whole CAN communication and data can be displayed and logged in different file formats.

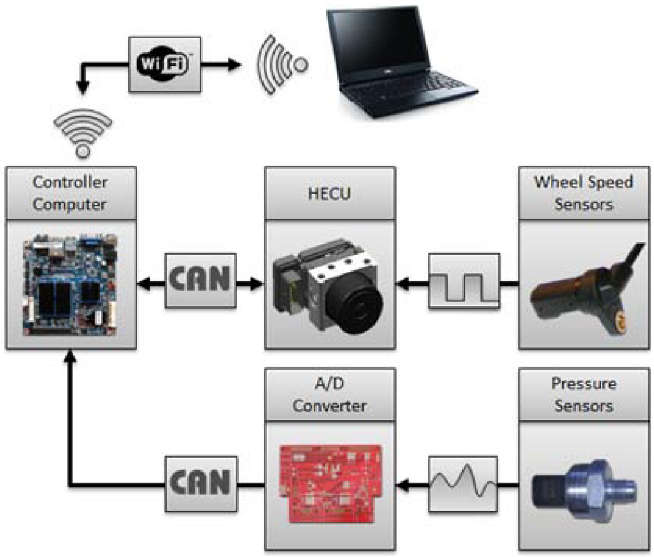

Figure 5: The communication architecture of prototype.

6. The results

The prototype control algorithm was tested on a test track on different surfaces, like asphalt, grassy ground, etc. On the first tests were some efficiency problems but after some fine-tuning of the parameters of the control algorithm (the limits) the results were in concordance with the expectations (*Fig. 6*).

7. The experiences

The current brake system is not capable to support the too often and big pressure changes that are common for motorbikes. For a bicycle brake system this leads to an early wearing of the parts. Thus either the bicycle brake pistons have to be strengthened or an ABS system should be developed that uses analogue valves and applies less pressure "jumps". As the aim is to keep the original brake system on the bicycle as much as possible the second option is reasonable

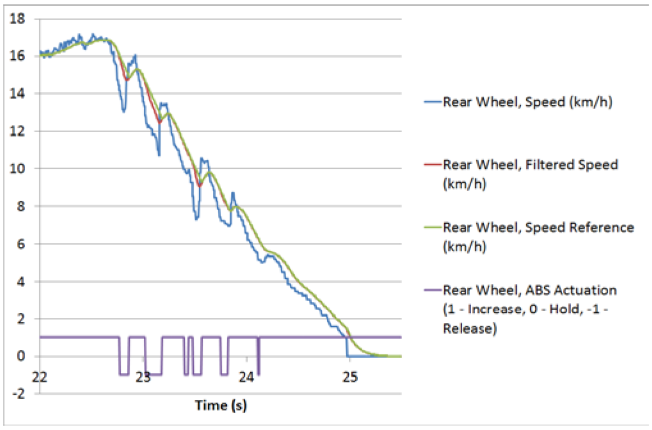

Figure 6: The result of a test (emergency braking with the rear wheel from 18 km/h, on dry asphalt).

8. Conclusion

In many countries in the world a lot of people use bicycle not just for free time activity but also as 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. After testing and 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.

The introduction of ABS in car industry at the beginning has some skepticism and now it is a compulsory supplement in every car produced in Europe and America also. The theory of anti-lock braking system is the same for cars and bicycles the circumstances are really different. The point of later development shall be to keep the focus on the helping the rider to run in a safe way. In the future if the development of the bicycle brake assist system evolves as the brake systems for the car, in some-ten years the ABS for high-end bicycles or mopeds will be compulsory also.

The first concept of electrical and hydraulic components are mounted on the bicycle, the control model can be tuned now. In automotive industry the ABS system tuning for a vehicle is a long process based on the experience of the drivers and engineers. For the bicycle it is even more specific because there is no previous test result.

In a later development phase beside ABS other safety and comfort control functions can be added to the system (e.g.: lift-off protection, hold-and-go function, brake-by-wire) and the development of a smaller more efficient ABS HECU, specialized for bicycles (with new hydraulic, sensor and control unit) was started.

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