Development of integrated hardware-in-the-loop (hil) test bench anti-lock brake system (abs) instrument

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Abstract. Carrying out an Antilock Brake System (ABS) testing performance for ECU-ABS software development validation in real-time by an on-road test drive is challenging. Besides, it requires more time, cost, and effort. This research aims to develop a test bench device for ABS testing performance based on hardware in the loop (HIL). HIL-based ECU-ABS testing performance offers an approach that improves the validation process, and at the same time providing potential cost, time, and energy savings. To achieve this goal, this device is created through experimental development methods and a prototype is built consisting of input/output devices that can be set out and manipulated due to the desired real braking conditions. The result of the study is an ABS test performance device equipped with a data acquisition system (DAQ) hence the parameters which are working during the test can be read, harvested, and further analyzed for the development and improvement of the ABS. The design and prototyping process employ several software (i.e. MatLab, Proteus, Ansys, C++ Compiler, and Visual Basic), hardware (asynchrony motor, speed sensors, hydraulic actuator, PCI-Card LabView, PC, LCD monitor, keyboard, printer), frame structure and flywheel, calibration utility and test space that meets NASVA standards.

1. Introduction
Since the late 1950s, various microprocessor-based testing methods have been developed to enhance the capabilities of automotive control systems [Peijang Chen, 2015]. One of the concerns in this method is hardware-in-the-loop (HIL) simulation, which is used along with increasing high-tech applications in the automotive field. HIL testing method originally came from the aviation industry where it was often impossible to test on actual systems. HIL testing is a technique in which the real signal of the controller is connected to a testing system that simulates the real conditions in which the vehicle components work, manipulating the controller so that the test conditions are similar to the real working conditions. With the use of input and output interface (I/O interface) simulators, it can simulate the real conditions and obstacles of vehicle systems.

This method provides comprehensive test results without having to use the final product. By utilizing the control system on the test tool, we can do the testing quickly and as much as possible to get data relevant to the validation needs [W.Chaaban1, et al, 2011]. However, the
method has one disadvantage where under certain conditions must be equipped with some large equipment and the appropriate test area [Dezhong Huang & Jibao Shen, 2010]. These technology developers such as Jae and Myung successfully developed a HIL simulator that is able to provide data on vehicle and wheel speed, brake oil pressure, and slip ratio. But it is intended for four-wheeled vehicles that make the system more complex [Jae-Cheon Lee & Myung-Won Suh, 2016]. Similarly, a HIL simulator developed by Suh in early 2000 can also provide data on all three elements [Suh, M.W., et al, 2014]. The problem statement is that an analysis of the vehicle braking instrumentation model takes into account the deviation value and modeling of the braking system that is measured and corrected simultaneously, thus it is able to obtain improvements to the braking phase instrumentation model.

The purpose of the research is to develop a HIL-based test bench instrumentation model or simulator for ABS test performance to analyze the operation of the ECU-based ABS control.

1.1. ABS Modelling

For our proposed device model, it is designed with assuming that a car moves on the road where the tires contact the road surface. Subsequently, an optimum braking is performed to stop the car without any wheel slip. Thus the brake force is formulated as follows.

\[ F_b = \frac{\mu \cdot m \cdot g}{4} = a \cdot m \]  

(1)

The brake torque on the wheel is

\[ T_w = F_b \cdot R_w = \frac{\mu \cdot m \cdot g \cdot R_w}{4} \]  

(2)

Where \( \mu \) is a function of slip \( \lambda \), it can be expressed that

\[ \mu_\lambda = \frac{R_{k(\lambda)}}{m} \]  

(3)

And the tire dynamics model employs the Magic Formula given by Pacejka formula, which is

\[ R(\lambda) = d \cdot \sin[c \cdot \arctan[b \cdot (1 - e)\lambda + e \cdot \arctan(b \cdot \lambda)] \]  

(4)

The linear speed \( V_b \) of the vehicle body can be formulated as

\[ V_b = \int a \, dt = \frac{1}{4} \int \mu \cdot g \cdot dt \]  

(5)

The linear speed can be transformed into an angular speed, thus Eq. (5) is reformulated as

\[ \omega_b = \frac{1}{4 \cdot R_w} \int \mu \cdot g \cdot dt \]  

(6)

Then the braking torque is formed by the drum or rotor disc
\[ T_b = K_f \cdot \text{sigm} \{ \text{error}(\lambda) \} \cdot \frac{100}{(TB \cdot S^2 + S)} \]  

Subsequently, the torque resultant on the wheel from Eq. (7) is

\[ T_{\text{res}} = T_w - T_b \]  

At this moment, an angular speed rises on the wheel can be formulated as

\[ \omega_w = \frac{1}{I} \int (T_w - T_b) \cdot dt \]  

Thus the wheel slip can be obtained by calculating the difference between wheel and body speed compared to the body speed, which is formulated as

\[ \lambda = \frac{\omega_b - \omega_w}{\omega_b} \]  

The delta error of slip is defined as follows.

\[ \text{error}_\lambda = \lambda - 0.2 \]  

Eq. (2) can be reformulated as

\[ T_w = \mu \cdot m \cdot g \cdot R_w \cdot \frac{a \cdot I}{4} \]  

While the inertia \( I \) is

\[ I = m \cdot R_w^2 \]  

Where

- \( I \) = Inertia wheel
- \( T_w \) = Wheel torque
- \( T_b \) = Torsi rem ABS
- \( W_b \) = Body rotation speed
- \( W_w \) = Wheel spin speed
- \( \lambda \) = Factor slip
- \( \mu \) = Tire-roller friction coefficient
- \( m \) = Roller mass

\( b, c, d \) and \( e \) represent fitting constants and \( R \) (magic formula) is a force or moment resulting from a slip parameter \( \lambda \).

The mathematical theory/model of the ABS-HIL test tool is modelled and simulated in the MATLAB® Simulink to results in a braking response. However, the layout of the proposed device model is shown in Fig. 1.
2. Method
The technical procedure to develop the proposed device is divided into 3 phase as shown in Fig. 3. It can be explained as follows.

1) The 1st phase is the mechanical design of the test bench as well as the analysis of the function of the required components. All the requirements and the needs are defined. Following by designing the components of the device using CAD, material procurement and manufacturing process for all the components. In overall, it needs approximately 3 months.

2) The 2nd phase is the parts and components integration and functionality test. Each component is assembled into complete structure, and continued with analyzing the functions of each component. Meanwhile the algorithm of the DAQ interface card is developed, generated and loaded into the DAQ module. The initial calibration (pre-calibration) of data reading of the device is carried out, followed by parameter tuning. This phase requires longer period of the entire program, which is about 7 months.
However, some activities can be done simultaneously with stage 1 particularly when one the component has been completely made.

3) The 3\textsuperscript{rd} phase is the study and validation of overall system performance of the device, including test bench reliability researches. At this stage, the whole components and systems of the HIL-based simulator test bench function are validated until the robustness and reliability of the device is guaranteed and the device is completely ready to use. The total time requires in this stage is approximately 4 months, including the preparation of the project report.

![Diagram of Test Bench of ABS Braking Test Performance Technology Research and Development]

Figure 2: The Phase of Test Bench of ABS Braking Test Performance Tech. R & D

3. Result and discussion

3.1. HIL-based Models in MATLAB\textsuperscript{®} Simulink

Figure 3 shows the MATLAB\textsuperscript{®} Simulink model of the HIL-based ECU-ABS braking test performance. It is developed from the mathematical model which is employed in a car with ABS in its braking system.
Figure 3: Mathematical model of ABS for HIL-based device in MATLAB® Simulink

The HIL-based ABS braking test performance model requires an electric motor to drive the wheel including the flywheel and the roller until the initial braking speed is reached. Subsequently, the motor power is cut off and a maximum braking is performed. Therefore, it is necessary to formulate the characteristics of the fly wheel as follows.

\[ T_w = \frac{R_w}{R_{rot}} \cdot T_{rot} \quad \text{While} \quad T_{rot} = a_{rot} \cdot I_{rot} = \frac{\partial \omega_{rot}}{\partial t} \cdot I_{rot} \]  \quad (14)

\[ T_w = \frac{R_w}{R_{rot}} \cdot I_{rot} \cdot \frac{\partial \omega_{rot}}{\partial t} = \mu \cdot N \cdot R_w \]  \quad (15)

Thus the speed of the angular roller can be expressed as follows.

\[ \omega_{rot} = \int \left( \frac{\mu \cdot N \cdot R_{rot}}{I_{rot}} \right) \cdot dt \]  \quad (16)

The stopping distance (S) can be derived from Eq. (16), thus yields

\[ S = R_{rot} \int \left( \frac{\mu \cdot N \cdot R_{rot}}{I_{rot}} \right) dt \cdot dt \]  \quad (17)
These mathematical modelling of the device is designed in the MATLAB® Simulink block and run, thus resulting a braking response. The block diagram and the result of the braking response are shown in Fig. 4 below.

3.2. Complete Model of the Proposed Device
The HIL-based ECU-ABS braking performance test simulator consists of two main parts: hardware and software. A roller (13) is placed on the mainframe and is supported by two bearings. A portable flywheel (10) that is removable and can be adjusted to the calculation of the weight of the vehicle, mounted in-line with rollers to obtain the appropriate large inertia. A set of wheels/tires (7) complete with rims mounted on the top and resting on rollers so that the surface of the wheel and roller can be connected. It is also supported by the addition of a joint point (16) so that the wheel will always rest on the roller. A motor (6) is attached to the upper wheel shaft to drive the wheel. ABS brake devices are also paired, ranging from the master cylinder (1), hydrolysis control unit (2), electronic control unit/ABS ECU (3), caliper and rotor disc (5). There are 3 sensors, namely 2 round sensors (8 & 12) and a pressure sensor (4).
sensor (8) leads to an encoder attached there is a wheel shaft to calculate the round angle of the wheel ($\omega_W$) and the sensor (12) leads to the encoder attached to the roller shaft for use calculating the round angle of the roller ($\omega_R$).

Furthermore, the pressure sensor (4) detects the hydraulic pressure of the brake oil. The signal of each sensor is connected to a data-grabbing device (DAQ) provided as a bridge between the computer and the sensor. It has three main components: a signal processing circuit, an analog to digital converter (ADC), and a computer bus. This device primarily functions to convert analog signals to digital to facilitate compilation to the next electronic device. The DAQ interface card uses a micro control unit (MCU) board to read signals from encoders and pressure sensors and send those signals to the Virtual Instrument (VI) program on the computer. VI is a program or subprogram in LabView™ which is used to display the response of an analog or digital signal of DAQ.

![Figure 5: HILL-based ABS Braking Test Performance Laboratory](image)

HIL-based ECU-ABS testing offers an approach that is possible to improve the validation process while effectively reducing potential cost, time, and energy. This HIL-based ECU ABS test tool is able to emulate on the road braking test. This device allows us to use ECU-ABS from various manufacturer brands or principles, thus experimental testing with virtualization, and real-time vehicle emulation that using computing software will be easy, efficient and effective for industry 4.0 today. The ABS test equipment development is a need for the automotive market mainly used in the test hall type ministry of transportation, research and development of vehicle factories, research and development of universities majoring in mechanical engineering, and transportation as well as official of vehicle maintenance workshops.
Figure 6: HIL-based ABS Braking Test Real-Time Testing Display

It is also equipped with a data acquisition (DAQ) system so that the parameters that work during testing can be read and obtained and can be further analyzed for the development and improvement of abs systems. The design and prototyping process involves software (MATLAB® Simulink, Proteus, Ansys, C++ Compiler, and Visual Basic), hardware (asynchrony motor, speed sensors, hydraulic actuator, PCI-Card LabView, PC, LCD monitor, keyboard, printer), mechanical steel frame and flywheel, calibration facility and test space that complies with NASVA standards.
Figure 6 shows the display panel consisting of a communication port, wheel and car body speed, brake fluid pressure, and longitudinal wheel slip graphs. Whenever the display panel is turned on and the port number is selected, the device is ready to measure. Once when the wheel is accelerated, the real-time speed of the wheel and car body is monitored and shown on the panel display as well as the brake fluid pressure, and the longitudinal slip. Whenever the braking is begun, a particular brake fluid pressure is displayed on the panel.

All those data are then saved which can be further analyzed. Figure 7 shows the response of those variables during braking. Each wheel and car body speed, brake fluid pressure, and longitudinal wheel slip data during the braking can be perfectly obtained.

4. Conclusion
The study and development of the HILL-based ABS braking test performance have been carried out. This test bench is a device that is equipped with a data acquisition system (DAQ) hence the parameters that performing during the test can be read, harvested, and further analyzed for the development and improvement of the ABS. The design and prototyping process involves software (MATLAB® Simulink, Proteus, Ansys, C++ Compiler, and Visual basic), hardware (electric motor, speed sensors, hydraulic pressure sensors and actuators, PCI-Card LabView, PC, LCD monitor, keyboard, and printer), mechanical steel frame and flywheel, calibration utility, and test area which satisfies NASVA standards.

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