An Intelligent Auxiliary Vacuum Brake System

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Abstract — **The purpose of this paper focuses on designing an intelligent, compact, reliable, and robust auxiliary vacuum brake system (VBS) with Kalman filter and self-diagnosis scheme. All of the circuit elements in the designed system are integrated into one programmable system-on-chip (PSoC) with entire computational algorithms implemented by software. In this system, three main goals are achieved: (a) Kalman filter and hysteresis controller algorithms are employed within PSoC chip by software to surpass the noises and disturbances from hostile surrounding in a vehicle. (b) Self-diagnosis scheme is employed to identify any breakdown element of the auxiliary vacuum brake system. (c) Power MOSFET is utilized to implement PWM pump control and compared with relay control. More accurate vacuum pressure control has been accomplished as well as power energy saving. In the end, a prototype has been built and tested to confirm all of the performances claimed above.**

Key Words:, Intelligent system, Auxiliary Vacuum Brake System (VBS), Kalman Filter, Self-diagnosis, Programmable System-on-chip (PSoC), Dynamic Reconfiguration .

I. INTRODUCTION AND PROBLEM FORMULATION

The brake system is one of the most important systems in a vehicle. In general, a hydraulic brake system of vehicle consists of six major parts: a brake pedal, a power brake booster, a master cylinder, hydraulic lines, wheel cylinders, disc brakes and/or drum brakes [1][2][3]. The power brake booster is the key component. It utilizes the pressure difference between the vacuum chamber and working chamber providing pneumatic boosting to enhance the force from the brake pedal. This force then pushes disc brakes and/or drum brakes to generate an adequate braking torque for the vehicle. The vacuum source of vacuum chamber mainly comes from inlet manifolds of engine. An auxiliary vacuum pump is provided to ensure the vacuum power. Normally, the auxiliary vacuum pump is occasionally activated when the pressure of vacuum is reaching run-out. An auxiliary vacuum brake system (VBS) gives some benefits including providing brake function when the engine is not operating or the engine is under heavy loads. However, the noisy surroundings in the vehicle and bulky controller circuits impose difficulties upon design. Our team came out a neat solution by using programmable system-on-chip (PSoC) [4], shown in Figure 1. Problems have been solved.

Another problem has been raised. The auxiliary VBS is infrequently over-vacuumed due to relay damage. The transit from on to off with heavy pump current can induce serious electric arc. This undesired electric arcing could damage relay by welding contactors together. As a result, vacuum system is over-vacuumed due to pump malfunction. Demands of self-diagnosis system and PWM pump control have been raised to secure the reliability of VBS system. Therefore, in this paper three main goals have been formulated: (a) Kalman filter and hysteresis controller algorithms are employed within PSoC chip by software to surpass the noises and disturbances from hostile surrounding in a vehicle. (b) Self-diagnosis scheme is employed to identify any breakdown element of the auxiliary vacuum brake system. (c) Power MOSFET is utilized to implement PWM pump control and compared with relay control. More accurate vacuum pressure control has been accomplished as well as power energy saving.
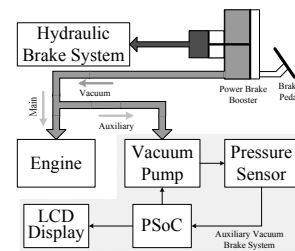

Figure 1. Structure of Auxiliary Vacuum Brake System (VBS)

II. METHEDOLOGY

In this paper, Kalman filter is utilized to fight noise and disturbance from hostile environment in a vehicle. This control application is neither set-point nor tracking control. Its purpose is to regulate pressure within a specific range, between -300 mm-Hg and -450 mm-Hg. Switching backward and forward is one common problem encountered. Hysteresis controller is then employed to overcome the switching back and forth during control change. The Kalman filter along with hysteresis controller can uplift the noise immunity for the VBS system. Also, PWM control is utilized to lessen the compressor current and pressure overshoot. In order to accomplish an intelligent VBS system, a programmable system-on-chip (PSoC) IC is chosen. All the hardware circuits and all the software algorithms are integrated and implemented in one single chip. The PSoC chip with dynamic re-configuration feature, as well as intelligent self-diagnosis scheme are explained. Therefore, discrete Kalman filter algorithm, hysteresis control algorithm, and PWM control are introduced at first, followed by PSoC with dynamic re-configuration and intelligent self-diagnosis scheme.

A. Discrete Kalman Filter Algorithm

The Kalman filter is an efficient recursive filter that estimates the state of a linear dynamic system from a series of

noisy measurements, referred to Figure 2. The Kalman filter estimates a process by using a form of feedback control: the filter estimates the process state at some time and then obtains feedback in the form of noisy measurements. As such, the equations for the Kalman filter fall into two distinct phases: time update equations (predictor) and measurement update equations (corrector). The time update equations are responsible for projecting forward (in time) the current state and error covariance estimates to obtain the *a priori* estimates for the next time step. The measurement update equations are responsible for the feedback—i.e. for incorporating a new measurement into the *a priori* estimate to obtain an improved the *a posteriori* estimate.
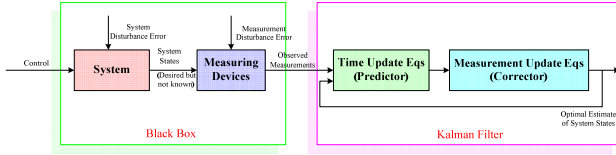

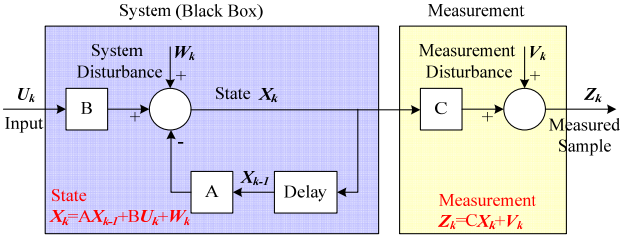Figure 2.   Process of Kalman Filter Algorithm

Figure 3.   Discrete-time Dynamic System Block Diagram for Kalman Filter

The probabilistic filtering problem in the Kalman sense can be formulated in this manner [5]. Consider the state-space model of a linear discrete-time dynamical system according to:

System: States $x_k = Ax_{k-1} + Bu_{k-1} + w_{k-1}$ (1)

Output $y_k = Cx_k$ (2)

Measurement $z_k = Cx_k + v_k$ (3)

where x_k is the state vector, u_{k-1} is the input vector, y_k is the output vector, w_{k-1} is the process noise vector, z_k is the measurement vector and v_k is the measurement noise vector. Illustrate in Figure 3. The probability of process noise w_k is *P(w)* with process noise covariance *Q*. The probability of measurement noise v_k is *P(v)* with measurement noise covariance *R*. The *a priori* estimate error and *a posteriori* estimate error are defined as follow:

A priori estimate error $\hat{e}_k^- = x_k - \hat{x}_k^-$ (4)

A posteriori estimate error $e_k = x_k - \hat{x}_k$ (5)

where $\hat{x}_k^-$ and $\hat{x}_k$ are the *a priori* state estimate and *a posteriori* state estimate respectively. The *a priori* estimate error covariance P_k^- is then formulated as:

$$P_k^- = E\{\hat{e}_k^- \cdot \hat{e}_k^{-T}\} = AP_{k-1}A^T + Q \quad (6)$$

and the *a posteriori* estimate error covariance P_k is developed

$$P_k = E\{e_k \cdot e_k^T\}$$

$$= E\{[x_k - \hat{x}_k^- + K(z_k - C\hat{x}_k^-)]\cdot[x_k - \hat{x}_k^- + K(z_k - C\hat{x}_k^-)]^T\}$$

$$= (I - KC)P_k^- \quad (7)$$

In deriving the algorithm for the Kalman filter, one should begin with the goal of finding an equation that computes an *a posteriori* state estimate as a linear combination of an *a priori* estimate and a feedback from error between an actual measurement and a measurement prediction with a weighted gain *K* as shown below

A posteriori estimate $\hat{x}_k = \hat{x}_k^- + K(z_k - C\hat{x}_k^-)$ (8)

In order to find a suitable gain *K* that minimizes the *a posteriori* error covariance in (7). This minimization can be accomplished by first substituting (8) into the above definition for e_k, substituting that into (7), performing the indicated expectations, taking the derivative of the trace of the result with respect to *K*, setting that result equal to zero for finding minimum, and then solving for *K*. One form of the resulting *K* that minimizes (7) is given by

Kalman gain $K = P_k^- C^T (CP_k^- C^T + R)^{-1}$ (9)

This gain, known as the optimal Kalman gain, is the one that yields minimal MSE (mean square error) estimates when used. For this reason, the Kalman filter is known as an optimal estimator to evaluate the internal state of a dynamic system under certain patterns of process and/or measurement disturbances presented in the physical world.

B.   Hysteresis Controller for Vacuum Pump

In order to regulate the vacuum chamber pressure within desired range and further eliminate false output changes due to noise, hysteresis controller algorithm is chosen and carried out next to Kalman filter. Equation (10) and Figure 4 describe this noise immunity scheme. Noise of any type can cause the output to switch rapidly back and forth in the vicinity of either P_{TL} (low threshold point) or P_{TH} (high-threshold point). Hysteresis controller algorithm assures that the input pressure signal (P_r) near any one of the threshold point can induce only one output switch, after which it have to move beyond the other threshold point to cause another switch. There are three benefits: (a) Keep vacuum camber pressure within desired range. (b) Increase noise immunity (c) Avoid the driving devices (relay or power MOSFET) and vacuum pump from damage.

$$\begin{cases} P_r < P_{TL}, Control ="Off" \\ P_{TL} < P_r < P_{TH} \ \& \ P_r \uparrow, Control ="Off" \\ P_{TL} < P_r < P_{TH} \ \& \ P_r \downarrow, Control ="On" \\ P_r > P_{TH}, Control ="On" \end{cases} \quad (10)$$
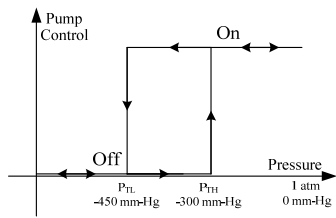
Figure 4.   Scheme of Hysteresis Controller

C.   Pulse Width Modulation Control of Pump Current

Air pressure is one of the swiftly changing parameter. Normally, pressure regulation with relay is commonly used to control vacuum pump and therefore regulate the vacuum pressure. It is a simple, effective and inexpensive way though. However, there are three main drawbacks with this control scheme: (a) Considerable time-delay is expected and causes the high pressure overshoot. (b) The transit from on to off with heavy pump current can induce serious electric arc. This undesired electric arcing could damage relay by welding contactors together. As a result, vacuum system is over-vacuumed due to pump malfunction. (c) High starting current and operating current are expected with on-off control by relay.

In order to smoothly manipulate pump current, power MOSFET and PWM method with proportional negative feedback are utilized. Two IRF1010 MOSFET devices are parallel-connected to make up a 160-Amp current driving capability. This pressure control scheme has overcome some of the drawbacks stated above: (a) Pressure overshoot has reduced. (b) Starting and operating current has diminished. (c) The possibility of arcing damage is lessened by a snubber circuit.

D.   Programmable System-on-Chip (PSoC) and Dynamic Re-configuration

In order to implement the peripheral devices and execute the intelligent self-diagnosis scheme with Kalman filter algorithm and hysteresis controller of digital signal processing in one chip, the CY8C29466 Programmable System-on-Chip (PSoC) from Cypress is selected [6]. This chip is one of the best choices in the market. PSoC is a mixed-signal array with on-chip MCU. This device is designed to replace multiple traditional MCU-based system components with one, low cost single-chip programmable components.   It includes 12 configurable blocks of analog and 16 blocks of digital hardware components as well as programmable pin-out and interconnection to create a unique customized peripheral configuration that matches the requirements of each individual application. One CY8C29466 PSoC chip can provide all the hardware components needed for this design application, such as instrumentation amplifier, programmable gain amplifier, filter, ADC, DAC, counter, timer, LCD driver, and digital I/O pins. Almost no external component is employed; therefore, no circuit board debug is needed. High-level integration, immunity to noise, and insensitivity to component variations can all be achieved.

In this design application, dynamic re-configuration is employed in order to achieve hardware deploy of self-diagnosis [7][8]. Every programmable semiconductor device, has limited resources. Dynamic reconfiguration is a powerful and unique feature of PSoC. It allows PSoC devices to easily reuse analog and digital resources to achieve a greater level of functionality in firmware code. This feature is accomplished by switching between multiple hardware configurations. One way to do dynamic reconfiguration is superimposing different layers for specific functionalities. There is a fundamental layer called "Base", any other secondary configurations superimposed on the "Base" are called "Overlays". Thus, one system-on-chip can perform a variety of functions without increasing any hardware costs. But only one function may be active at any point in time. This is the most amazing feature of PSoC, and self-diagnosis scheme makes use of this feature in this design.

E.   Intelligent Self-diagnosis Scheme

The structure of auxiliary VBS is composed of four main components: compressor (pump), pressure sensor, current sensor, and compressor driver (relay or MOSFET) with PSoC as the controller, shown in Figure 5. This intelligent self-diagnosis scheme can rule out six types of failure without any additional circuit or component. With the mighty feature of dynamic re-configuration, the self-diagnosis scheme is achieved by system start-up self-diagnosis test and on-line self-diagnosis test. Explanations are given as follow:
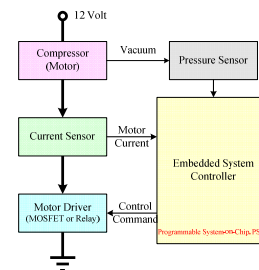

Figure 5.   Main Elements & Functions of Auxiliary Vacuum Brake System

1)   System Start-up Self-diagnosis Test

The pressure sensor is made of Wheatstone bridge. One way to check the bridge network is by mean of inspecting if the bridge is balanced when no pressure is applied. Thus, the bridge network is measured during system start-up by two 12-bit AD converters connecting to both arms. The readings of both ADCs must be a half of the excitation voltage with omittable difference between two arms. There is no spare analogue module to setup two more amplifiers and two AD converters. As a consequence, dynamic re-configuration is evoked to accomplish this task prior to normal operation, shown in Figure 6.   Also, compressor is checked by connecting to battery via a high-impedance resistor. Voltage can be taken into for analysis through pre-amp and ADC. Either motor coil shorted or open can be easily identified. Total of two types of failure (pressure sensor failure or compressor failure, or both) can be recognized during system start-up diagnosis.
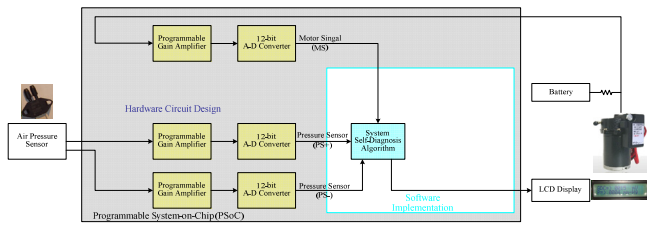
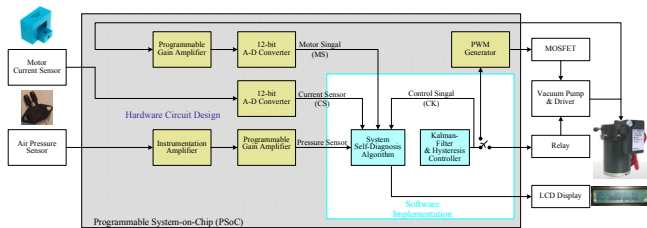Figure 6.   Block Diagram of System Start-up Self-diagnosis

Figure 7.   Block Diagram of VBS with Kalman Filter and Self-Diagnosis

TABLE I.   TABLE OF SELF-DIAGONSIS SCHEME

Control Input	Motor	Current Sensor	Problem Diagnosis
0	0	0	Normal
0	0	1	Current Sensor Failure
0	1	0	Motor & Current Sensor Failure
0	1	1	MOSFET or Relay Shorted
1	0	0	MOSFET or Relay Not Responding
1	0	1	Motor & Current Sensor Failure
1	1	0	Current Sensor Failure
1	1	1	Normal

Note: (a) Control Input: Status of Relay or MOSFET, "0"➔"OFF","1"➔"ON".
(b) Motor: Status of Motor, "0" ➔ "OFF", "1" ➔ "ON".
(c) Current Sensor: Current Detected, "0" ➔ "NO", "1" ➔ "YES".

2)   On-line Self-diagnosis Test

Current sensor, relay (or MOSFET), and compressor are inspected on-line to rule out system malfunction during normal operation. The statuses of three major components are closely monitored and four types of failure can be recognized via on-line self-diagnosis. Figure 7 shows the block diagram of auxiliary VBS with Kalman filter and on-line self-diagnosis. Table I lists the scheme for on-line problem shooter. Note that pump current can not vary instantly. No conclusion can be drawn unless five consecutive sets of sampled data are analyzed although the scheme listed in Table I seems to be quiet straightforward.

The pump starting current could go as high as 120 Amp and incurs the relay (or MOSFET) malfunctioning. As a result, either no action or over-vacuum could damage the vehicle. On-line self-diagnosis can set alerts for further actions, therefore system liability is increased.

III.   AN INTELLIGENT AUXILIARY VACUUM SYSTEM IMPLEMENTED BY PSoC AND TEST RESULTS

To implement this auxiliary vacuum pump system, one CY8C29466 PSoC chip is utilized to carry out all of signal conditioning and control block diagrams in Figure 6 and Figure 7. The VBS system is made of a pressure sensor, a vacuum pump with its driver (relay or MOSFET), a current sensor, one PSoC chip, a LCD display. All the circuits, except power supplies for PSoC and sensors, are integrated into PSoC chip, shown in Figure 15 (Right). All the circuits in the gray area of block diagrams, Figure 6 and Figure 7, are carried out by interconnecting the configurable analogue and digital hardware blocks in PSoC.   Also, intelligent self-diagnosis scheme, Kalman filter, and hysteresis controller (in light blue area of block diagram) are implemented by C code in PSoC. There are a lot of benefits. Cut a lot of development time and save a lot of hardware expenses. Immunity to both noise and component variations as well as circuit reliability can all be improved. Design is described in the following sections:

A.   Hardware Implementation (Dynamic Re-configuration)

The base-configuration called "pressure_sensor_test1" and overlay-configuration call "Test_1" are composed to form the system start-up self-diagnosis, shown in Figure 8 and Figure 9 accordingly. Both arms of Wheatstone bridge are taken into PSoC by two different preamps in "Test_1" overlay, referred to Figure 9. Then, signals from pressure sensor are converted into digital data by ADCs in base-configuration, referred to Figure 8. Pressure sensor and compressor are checked in system start-up self diagnosis. Note that these two failure checkups are not included in Table I. Test results then display on a LCD screen, shown in Figure 11 (a)~(d). If any problem should occur, program would terminate VBS with warning displayed on LCD.

After passing system start-up check, PSoC performs dynamic re-configuration, i.e. switches overlay configuration "Test_1" to another overlay configuration "Kalman", shown in Figure 10.   Overlay configuration "Kalman" together with base configuration in Figure 8 comes up with the hardware for normal operation as well as on-line self-diagnosis.   Two preamps are replaced by an instrumentation amp to pick up signal from pressure sensor. Then, signals from pressure sensor and current sensor, as well as motor are converted into digital data by ADCs for further analysis. Also, a 9-bit DAC output is provided for observation from Kalman filter output.
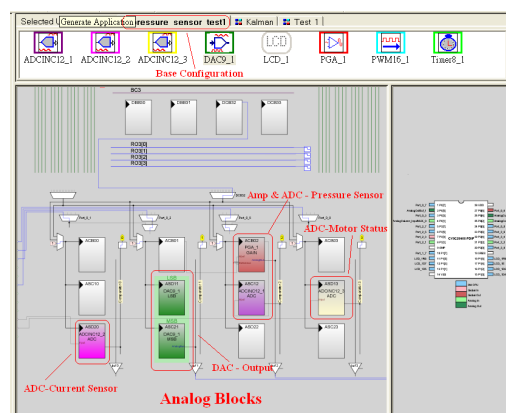

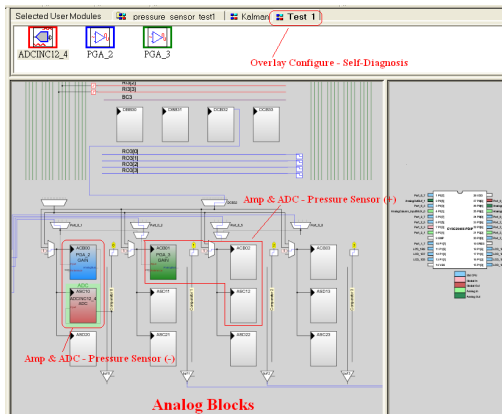
Figure 8.   Base Configuration of VBS

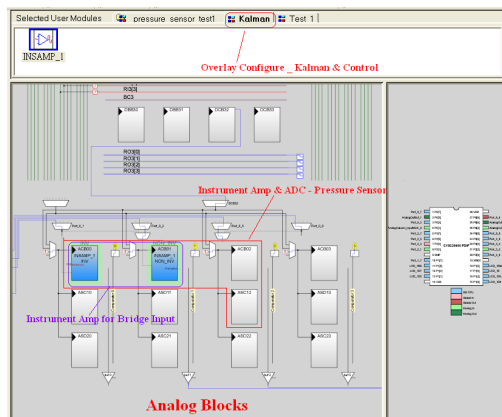Figure 9.   Overlay Configuration 1 of VBS (System Start-up Self-diagnosis)

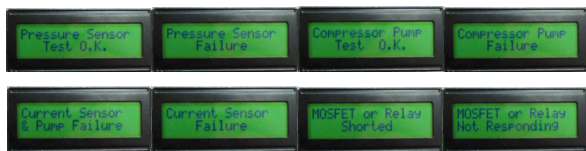Figure 10. Overlay Configuration 2 of VBS (Normal Operation and On-line Self-diagnosis)

Figure 11. Warning Display of Intelligent Self-Diagnsis (a)~(d), from left to right, up to down

B.   Software Implementation (Kalman Filter, Hysteresis Controller and Intelligent Self-Diagnosis)

After the pressure signal is processed and converted into digital sequence, the Kalman filter and hysteresis controller algorithms are implemented in C code to suppress noises, referred to Section III A and B. Figure 12 (Left) illustrates the vacuum chamber pressure before and after Kalman filter within the operational pressure range (-300 mm-Hg to -450 mm-Hg). Obviously, noises and disturbance are repressed as expected.

Besides, testing signal of 1 Hz sinusoid wave is employed to test the performance of Kalman filter with hysteresis controller. The output is satisfying although there are some unexpected disturbances in the input, shown in Figure 12 (Right).
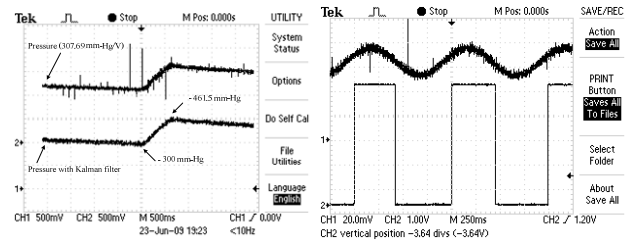

Figure 12. Pressure Signal w/wo Kalman Filter (Left), 1 *Hz* Sinusoid Test Signal with Disturbance, Output of Kalman Filter with Hysteresis Controller

Intelligent self-diagnosis is also carried out by C code, referred to Section III E. There are two types of checkup, system start-up diagnosis and on-line diagnosis. Pressure sensor and compressor are checked in system start-up diagnosis, shown in Figure 11 (a)~(d). Current sensor, relay or MOSFET, and compressor are routinely checked on-line according to Table I during normal operation. Total of six types of failure can be identified. If any problem should occur, program would terminate VBS with corresponding warning displayed on LCD, shown in Figure 11 (e)~(h).

C.   Test Results

In a vehicle, the vacuum sources of vacuum chamber may come from inlet manifolds of engine or vacuum pump driven by either engine or electricity. In this test, vacuum chamber is controlled solely by VBS without inlet manifolds of engine. Some air leakage is induced on purpose to perform pressure regulation. Two types of test are performed. First one is pressure control starting from 0 mm-Hg to -450 mm-Hg, shown in Figure 13 (Left and Right). Another is pressure regulation between -300 mm-Hg and -450 mm-Hg, shown in Figure 14 (Left and Right). The sampling frequency for VBS is 40 Hz. The vacuum chamber pressure and motor current are recorded by TDS-1012 digital oscilloscope from Tektronics. Pressure reading is taken from 9-bit DAC after processed by Kalman filter and current reading is taken directly from current sensor output.

1) Kalman filter can get rid of noises and big disturbances as shown in Figure 12 (Left). Experiment proves that along with hysteresis, vacuum pressure regulation can be assured, shown in Figure 12 (Right). Besides, there is no switching back and forth during control change as expected, shown in Figure 13 and Figure 14. Noise immunity has been assured. As a consequence, relay contactor could be also prolonged as well as the VBS liability.

2) PWM control provides two advantages over relay control: (a) Low starting current and operating current. The starting current has been diminished from 107.8 Amp to 76.4 Amp for pressure originating from 0 mm-Hg to -450 mm-Hg, shown in Figure 13. Also, the starting current has been cut from 90.1 Amp to 69.6 Amp during normal operation, shown in Figure 14. The operating current has been confined to 43.7 Amp for both cases. Although the duration of operation with PWM control is longer than that of relay control, it is not a problem at all as long as the chamber pressure is within the desired range, between -300 mm-Hg and -450 mm-Hg. The

brake booster can function perfectly for the hydraulic brake system. However, battery life can be extended as well. (b) Low overshoot. The overshoot is obviously reduced from -492.3 mm-Hg to -461.5 mm-Hg.

3) Intelligent self-diagnosis scheme can identify different types of errors caused by different elements such as: (a) pressure sensor open, short, or unbalance. (b) compressor open or short. (c) current sensor failure. (d) relay or MOSFET open or short.

4) A prototype has been designed and made with one PSoC chip, VBS system shown in Figure 15. All of the signal conditioning circuits, algorithms, and self-diagnosis scheme are integrated and implemented inside the system-on-chip IC.
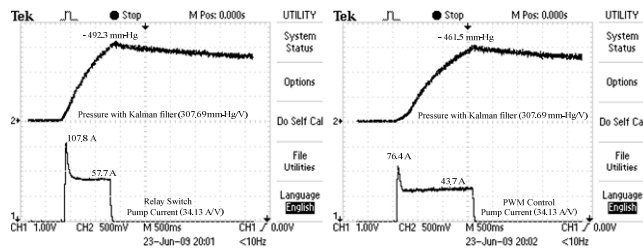

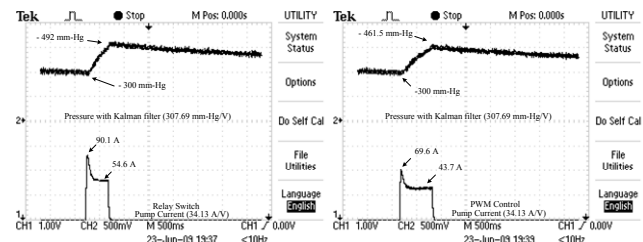Figure 13. Compressor Starting with Relay Control (Left), with PWM Control using MOSFET (Right)

Figure 14. Pressure Regulation with Relay Control (Left), with PWM Control using MOSFET (Right)
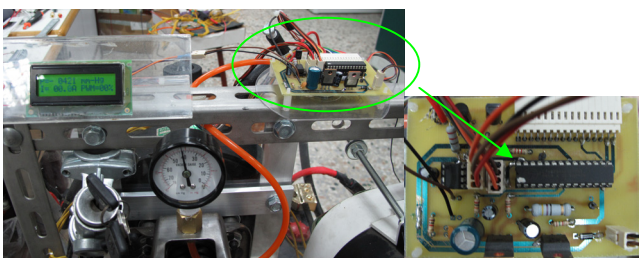

Figure 15. Intelligent VBS Implemented in One PSoC Chip

IV. CONCLUSION

In this paper, three main goals are achieved: (a) Kalman filter and hysteresis controller algorithms are employed within PSoC chip by software to surpass the noises and disturbances from hostile surrounding in a vehicle. (b) Self-diagnosis scheme is employed to identify any breakdown element of the auxiliary vacuum brake system. (c) Power MOSFET is utilized to implement PWM pump control and compared with relay control. More accurate vacuum pressure control has been accomplished as well as power energy saving. In the near future, this system can be applied to electric vehicles as the primary brake system with some minor modifications.

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