Progress In Electromagnetics Research M, Vol. 31, 117–127, 2013

IMPROVED IMMUNITY MEASUREMENT OF A MICROCONTROLLER TO CONDUCTED CONTINUOUS WAVE INTERFERENCE

Fayu Wan[1, 2, *], Junxiang Ge[1, 2], Yong Zhou[1, 2], and Bing Yu[1, 2]

[1]College of Electronics and Information Engineering, Nanjing University of Information Science and Technology, Nanjing, China

[2]Jiangsu Key Laboratory of Meteorological Observation and Information Processing, Nanjing University of Information Science and Technology, Nanjing, China

Abstract—This paper discusses an improved in-situ immunity measurement test bench of a microcontroller — PIC18F458 to conducted continuous wave interference (CWI). The updated measurement algorithm gives more accurate measurement result. Compared with normal failure criterion, the DC shift failure criterion is adopted because it gives better description of the immunity behavior of the microcontroller. Finally, the susceptibility results are explained in detail.

1. INTRODUCTION

Millions of microcontrollers have been used in the automotive, aeronautics and aerospace industries as well as in household appliances. In the presence of electromagnetic interference (EMI), the microcontroller could be disturbed, and also, the microcontroller based system can be influenced. The unintended acceleration of Toyota may give us a warning on the safety control system.

Nowadays, microcontrollers contain both digital circuit components and analog circuit components. Digital circuits have a noise margin which can help to avoid small continuous wave interference (CWI); transient interference may be the main problem. Analogue circuits which are memory-less can recover from the transient interference. Analogue circuits do not have a noise margin, and even small

Received 19 April 2013, Accepted 22 May 2013, Scheduled 3 June 2013

* Corresponding author: Fayu Wan (fayu.wan@nuist.edu.cn).

CWI cannot be ignored. The focus on the analogue to digital converter (ADC), which is inside the microcontroller as the research target, is because it will be primarily affected in the electromagnetic environment (EME). The ADC is an important component in a control system and is often used to sample the feedback signal. If the ADC is disturbed, it will give a fault signal which cannot represent the true parameters, causing the instability of a control system. In order to know the behavior of ADC in the presence of CWI, the immunity measurement is necessary.

The previous works on immunity measurement benches, such as direct power injection (DPI) [1], buck current injection (BCI) and near field scan injection (NFSI), have been developed. Chahine et al. [2, 3] not only utilized DPI test bench but also improved the injection circuit to realize an accurate measurement. Boyer et al. [4] presented NFSI and extended the DPI measurement frequency range up to 4 GHz. Alaeldine et al. [5] dealt with the modeling of DPI test bench. Paez et al. researched about the uncertainty in the immunity measurement [6]. All the works are necessary and help us to understand the immunity result of the component. But these works have not focused on low frequency interference because of the limit of the bias tee circuit. Their measurements are from 1 MHz, even 10 MHz, to 1 GHz. The low frequency components are sensitive in low frequency. The measurement bandwidth of this work contains all the interesting frequency band of the ADC. Furthermore, few of them have discussed the algorithm of the measurement and researched the failure criterion of the measurement. The measurement result is only compared with the simulation result of a model to verify the correctness of the model. If the immunity measurement algorithm and failure criterion is not well designed, the measurement result cannot reflect the actual behavior of ADC, then the measurement result based models will not work very well.

The behavior of the component in the presence of EMI is another main task in this work. The previous work [7] on the nonlinear effects of interference on operational amplifier prompted us to raise further questions. Considering that the interference could have nonlinear effects on amplifier, is it possible to cause the same problem on ADC? Do nonlinear effects degrade the performance of ADC? In addition, since immunity result represents the behavior of the component under the pressure of interference in measurement bandwidth, can we use the nonlinear effects as the failure criterion in the measurement?

An in-situ component immunity test bench [8] is introduced in this paper; it receives the output data by USART which is a normal module inside the microcontroller. The method could be used in the automotive field when the oscilloscope is not convenient to detect the output data of the microcontroller. A broadband bias tee extends the measurement bandwidth from 15 kHz to 1 GHz. We improve the accuracy of the immunity result through a measurement algorithm which can avoid non-uniform comparison between the sampling data and the reference signal. Two failure criteria which can identify the linear and nonlinear distortion of ADC are introduced in this paper.

This paper is organized as follows. A test bench setup is introduced in Section 2, while the susceptibility measurement is presented in Section 3. In Section 3, an improved test bench is briefly introduced. In Section 3, first, the interference in input port of ADC is introduced, then measurement algorithm is described shortly. Moreover, the failure criteria are developed, and the interference in Vcc port is discussed. After that, the susceptibility measurement is analyzed in detail. Lastly, several methods to increase the immunity of the microcontroller are presented.

2. TEST BENCH SET UP

2.1. Test Bench

Our test bench is shown in Figure 1. It consists of a R&S signal generator, a bias tee circuit, a microcontroller (PIC18F458) [8] board and a computer.

The signal generator serves as an interference source. The bias tee circuit merges the RF signal with the DC signal (2.5 V), which

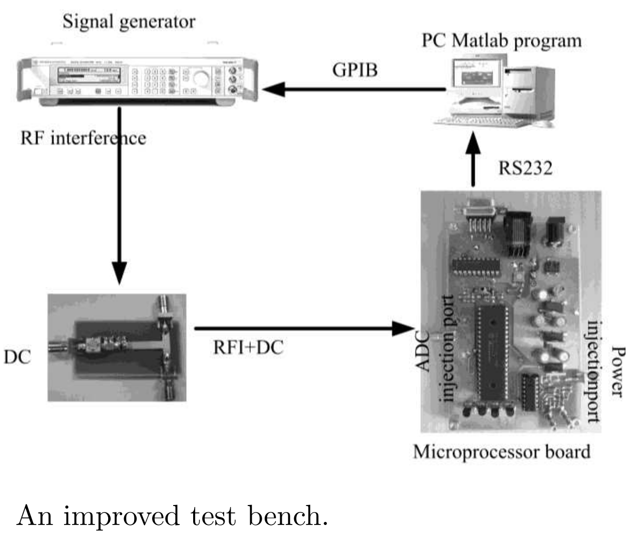

Figure 1. An improved test bench.

works as the victim of RF disturbance. The microcontroller board samples the perturbation signal, converts it into a digital signal, and sends it to a computer. The test setup is controlled automatically by a Matlab program. The program sends instruction commands to the signal generator by GPIB and receives data from the microcontroller by RS232.

Compared with DPI or other immunity test methods, the biggest difference of this test bench is the way we obtain the output data from the microcontroller. Other methods use oscilloscopes to receive output data from microcontroller. In this case, as we only care about the conversion result of ADC, the scope is not necessary, and we rely on the microcontroller itself to detect the status of the microcontroller. We utilize the RS232 to realize the communication between micro controller and computer, and a C language program is used to convert the analogue signal (DC voltage and perturbation signal) into a digital signal, and send it to the computer by RS232. Another Matlab program which receives the result of the ADC is designed in the computer. This method replaces the oscilloscope on DPI or other immunity test methods, giving us the opportunity to receive output signal of the microcontroller in the automotive field.

3. MEASUREMENTS

The output of an ADC conversion result equals $\frac{V_{in}}{V_{ref}} \times 2^{10}$. The input signal ($V_{in}$) and the conversion reference voltage (V_{ref}) will influence the conversion result of the ADC. Therefore, the research of injections on the input of the ADC and VCC (V_{ref}) is necessary.

3.1. Injection on Input Port

In the presence of conducted CWI, the ADC begins to fluctuate. In normal operation, with no disturbance, the output signal is captured on the computer and surrounded by a tolerance frame. This becomes a reference signal that is defined according to a criterion defined by the user [9]. It is usually set to 30% or 40% of the output voltage level when the target component is a digital circuit, because the digital signal has very high noise margin. But for an analogue circuit and analogue signal, for example, the immunity failure criterion of the ADC is normally set to several least significant bit (LSB). LSB is easy to be compared to the output conversion result of the ADC.

If the output signal is below the criterion, the disturbance can be tolerated by the microcontroller. However, if the output signal is beyond this limit, the signal can be wrongly interpreted by the microcontroller, and the microcontroller may generate a wrong control signal. Determining how to avoid this problem and detecting the perturbation level are the main purpose of this measurement.

3.2. Algorithm

A conducted CWI is coupled with a DC signal, and then injected in the input of the ADC. For each frequency, the amplitude of CWI is increased until the failure criterion or the maximum amplitude is reached, and the last frequency and amplitude of CWI when the microcontroller is at an acceptable level are saved. This is a normal immunity measurement algorithm [10]. In the normal susceptibility measurement, we just take one value of the output signal and judge if the microcontroller fails; but under pressure of CWI, the output signal is similar to a periodic sinusoidal waveform. If the program just takes one value which we cannot be sure if it is the maximum value or the minimum value of the output signal under the pressure of the perturbation and the difference value between the maximum and the minimum value could reach dozens of mV, then the immunity curve cannot represent the true immunity level of the microcontroller.

The normal immunity measurement algorithm is modified to save the output conversion result of ADC and for each perturbation points. To establish such a data library, for each perturbation point, 100 output data points will be saved. The modified algorithm is shown in Figure 2.

The maximum power used in this measurement is 18 dBm, which is the highest power that our signal generator can provide.

3.3. Failure Criterion [11]

Because of the non-ideal power reference voltage (4.9 V) of the SAR ADC and the reference DC signal (2.46 V), the reference output conversion result is 514 ($\frac{2.46}{4.9} \times 2^{10}$). The sampling rate of the ADC is limited to about 30 kHz (by ADC conversion time). If the input interference is below 15 kHz, the conversion result and input signal can be considered as a linear relationship. We consider a weakly nonlinear relationship between the output signal V_o and the input signal V_i when the input signal frequency is higher than 15 kHz. As shown in Equations (1) and (2).

$$\begin{aligned} V_o &= a_1 \times Vi + a_2 \times Vi^2 + a_3 \times Vi^3 + \ldots \\ V_i &= b \times \sin(\omega t) \end{aligned} \tag{1}$$

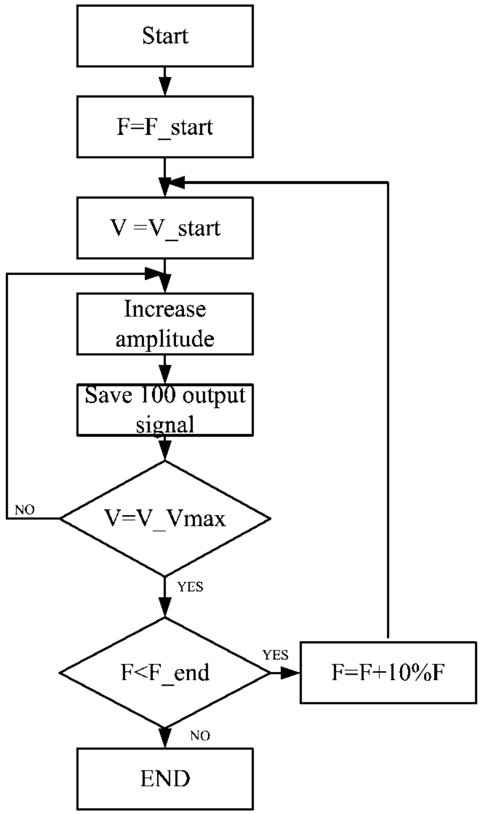

Figure 2. Developed algorithm for measurement.

$$\begin{aligned} V_o \;=\; & \left(\frac{a_2 \times b^2}{2} + \frac{3a_4 \times b^4}{8} + \dots\right) \\ & + \left(a_1 \times b + \frac{3a_3 \times b^3}{4} + \dots\right) \times \sin(\omega t) \\ & - \left(\frac{a_2 \times b^2}{2} + \frac{a_4 \times b^4}{2} + \dots\right) \times \cos(2\omega t) - \dots \end{aligned} \tag{2}$$

The input signal is the mixed signal of a DC signal and a sinusoidal signal. In this case, the DC signal is always in bandwidth of the ADC, so the sinusoidal signal is the only consideration. The nonlinear distortion is a harmonic distortion which is particularly harmful because of DC shift, and DC shift is generated by the accumulation of an asymmetrically rectified signal, which is caused by the voltage clamp diode in this case [12]. The DC shift depends on the even-order nonlinear behavior (shown in Equation (2)), and DC shift is a DC effect which is very difficult to remove. As shown in Figure 3(a), with 1 MHz and 6 dBm interference, the output signal has about 2–3 LSB DC shift compared to the reference signal. As the interference frequency increases, even small amplitude interferences can cause large DC shifts, as shown in Figure 3(b). With 3 MHz, 3 dBm interference signal, the output signal has about 12 to 13 LSB DC shift. The parameters in Equation (1) are frequency dependent. Of some frequency points, the output signal can have the positive DC shift, and the Volterra series can be used to represent the relationship between the input signal and the output signal of the ADC.

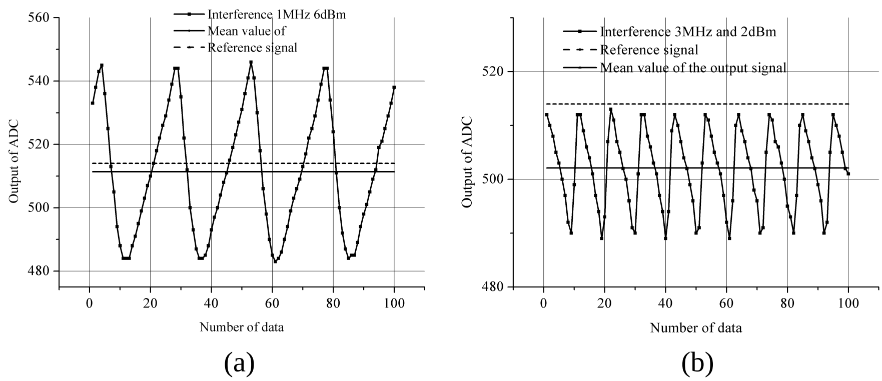

Figure 3. Output signal of ADC in the presence of interference.

3.4. Vpp Failure Criterion [11–14]

As shown in Figure 3, the output signal is a periodic signal, like sinusoidal waveform. In normal immunity measurement, the peak to peak amplitude of the output signal is compared with the reference signal to judge if the failure criterion is exceeded. The interference in Figure 3(a) is much more serious than in Figure 3(b) with the consideration of Vpp failure criterion. In fact, the linear distortion of Figure 3(a) could be easily filtered out by an average digital filter, but the DC shift in Figure 3(b) is not easy to be compensated. The Vpp failure criterion contains both linear and nonlinear distortions of ADC. The nonlinear distortion is the concern in the measurement, and the immunity result with the Vpp failure criterion cannot reflect the actual threshold of the ADC. The immunity result with failure criterion is shown in Figure 4. In low frequency, ADC is very sensitive, even

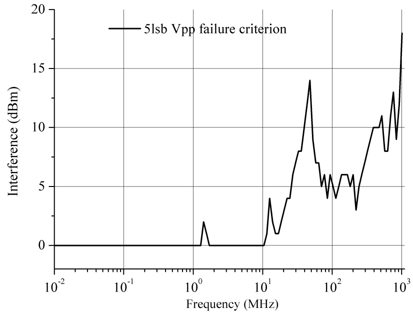

Figure 4. Susceptibility result of the microcontroller with the Vpp failure criterion.

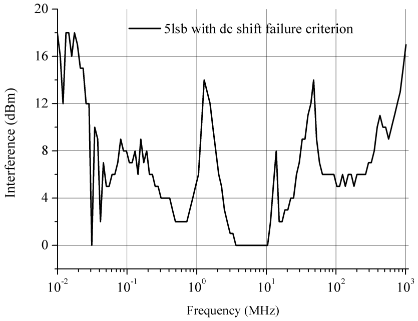

Figure 5. Susceptibility result of the microcontroller with the DC shift failure criterion.

0 dBm interference can disturb it, but we do not know whether it is caused by linear distortion or nonlinear distortion.

3.5. DC Shift Failure Criterion

The DC shift caused by the disturbance can be used to compare with the reference signal to achieve the actual immunity measurement result. Then the output signal $V = \frac{\sum_{k=1}^{n} Vk}{n}$ or $V = \frac{V_{\max}+V_{\min}}{2}$ can be used to compare with the reference signal to obtain the immunity result. Both equations reflect the DC shift behavior of the output signal. The DC shift failure criterion produces an accurate immunity level of the ADC and sensitive frequency bandwidth which is highly important because with the DC shift, filter will not work well within that bandwidth. The interference is harmless to the ADC if it can be filtered easily. It does not need to be concerned, even though the Vpp of the output signal is very large. The immunity result with DC shift failure criterion is shown in Figure 5. The result shows some bandwidths which should be concerned.

3.6. Injection on VCC

For an ADC inside of a microcontroller, the power supply of the microcontroller is always chosen as the conversion reference voltage of the ADC, and the independent reference voltage is expensive. The interference injected in power supply of microcontroller not only disturbs the ADC, but also influences other parts of the microcontroller. The injection method is shown in Figure 6.

With the same measurement algorithm of injection on the input port, the immunity result is shown in Figure 7. 2 LSB Vpp and DC shift failure criteria are taken because the decoupling capacitor stops the CWI entering the Vcc; the Vcc cannot be disturbed easily. The frequency range between 30 to 60 MHz is sensitive in both failure criteria; the nonlinear distortion is the main contribution. In low frequency, though the decoupling capacitor does not work very well, the linear distortion is the main factor in Vpp failure criterion. In high frequency the decoupling capacitor works well, even the highest disturbance cannot exceed both failure criteria.

Many factors can influence the susceptibility result, not only the input power supply impedance and decoupling capacitor, but also some

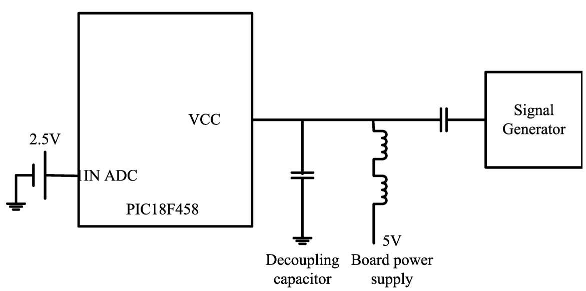

Figure 6. Path of injection on VCC.

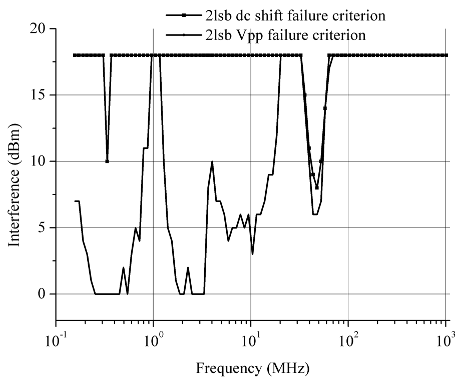

Figure 7. Susceptibility result of the microcontroller with injection on VCC.

digital parts, such as serial communication, because it shares the same power part with ADC.

4. CONCLUSION

In this paper, an improved test bench that makes the immunity measurement of the microcontroller more convenient is presented. The developed measurement algorithm could improve the accuracy of the measurement. The DC shift is a DC effect which is easy to be removed. It is the nonlinear behavior which needs to be concerned, and the DC shift was chosen as the failure criterion which reflects the truth behavior of the ADC. Through analyzing the possible weakness of the ADC, both input port and power supply of ADC were chosen as the research target. Finally, the immunity result is analyzed in detail.

REFERENCES

1. IEC EMC Task Force, "Direct RF power injection to measure the immunity against conducted RF-disturbances of integrated circuits up to 1 GHz," IEC Draft Tech. Rep., IEC 62132-3, Aug. 2001.
2. Chahine, I., M. Kadi, E. Gaboriaud, A. Louis, and B. Mazari, "Characterization and modeling of the susceptibility on integrated circuits to conducted electromagnetic disturbance up to 1 GHz," *IEEE Trans. Electromagn. Compat.*, Vol. 50, No. 2, 285–293, May 2008.
3. Chahine, I., M. Kadi, E. Gaboriaud, X. Gallenne, A. Louis, and B. Mazari, "Enhancement of accuracy for measuring the susceptibility of integrated circuits to conducted electromagnetic disturbances," *IET Sci. Meas. Technol.*, Vol. 1, No. 5, 240–244, Sep. 2007.
4. Boyer, A., E. Sicard, and S. Bendhia, "Characterization of electromagnetic susceptibility of integrated circuits using near-field scan," *IET Electron. Lett.*, Vol. 43, No. 1, 15–16, Jan. 2007.
5. Alaeldine, A., R. Perdriau, M. Ramdani, J. Levant, and M. Drissi, "A direct power injection model for immunity prediction in integrated circuits," *IEEE Trans. Electromagn. Compat.*, Vol. 50, No. 2, 52–62, Feb. 2008.
6. Paez, E., C. Tremola, and M. A. Azpurua, "A proposed method for quantifying uncertainty in RF immunity testing due to EUT presence," *Progress In Electromagnetics Research B*, Vol. 29, 175–190, 2011.

7. Fiori, F. and P. S. Crovetti, "Nonlinear effects of radio-frequency interference in operational amplifier," *IEEE Trans. on Circuits Syst. I*, Vol. 49, No. 3, 367–372, Mar. 2002.
8. Wan, F., F. Duval, X. Savatier, A. Louis, and B. Mazari, "Study of susceptibility of an MCU control system in the automotive field," *Asia-Pacific Int. Symp. on EMC*, 610–613, Beijing, China, Apr. 2010.
9. Sketoe, J. G., *Integrated Circuit Electromagnetic Immunity Handbook,* National Aeronautics and Space Administration, Marshall Space Flight Center, 2000.
10. Boyer, A., S. Bendhia, and E. Sicard, "Modeling of a mixed signal processor susceptibility to near-field aggression," *IEEE Symp. on EMC*, 1–5, Honolulu, USA, Jul. 2007.
11. Gros, J.-B., G. Duchamp, A. Meresse, and J.-L. Levant, "Electromagnetic immunity model of an ADC for microcontroller's reliability improvement," *Micro. Rel.*, Vol. 49, Nos. 9–11, 963–966, Sep. 2009.
12. Wan, F., F. Duval, X. Savatier, A. Louis, and B. Mazari, "Effects of conducted electromagnetic interference on an analog-to-digital converter," *IET Electron. Lett.*, Vol. 47, No. 1, 23–25, Jan. 23–25, 2011.
13. Redouté, J. and M. Steyaert, *EMC of Analog Integrated Circuits*, Springer, Berlin, 2009.
14. Bendhia, S., M. Ramdani, and E. Sicard, *Electromagnetic Compatibility of Integrated Circuits, Techniques for Low Emission and Susceptibility*, Springer-Verlag, Berlin, Germany, 2006.