Study on the wireless transmission method of cosmic ray detector in NPPs

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Abstract. The data detected by the cosmic-ray imaging detector used to imaging the distribution of nuclear fuel cannot be transmitted outside the vessel. An ultrasonic through-wall communication system is designed to support the true-wireless monitoring in NPPs. This system could transmit data through the Steel Lining or the concrete wall of the containment wirelessly without cables and penetration, which could protect the leakproofness and integrity of the containment and enhance the safety of NPPs. With 40 kHz ultrasonic carrier waves, this system could communicate at 4.8kbits/s baud rate through over 10cm concrete wall, over 10cm steel liner and 10cm lead + 5cm steel combination wall. An application test has been finished on the 20:1 experiment containment to AP1000 in the Beijing Key Laboratory of Passive Safety Technology for Nuclear Energy, this system could operate steadily with 0 error rate.

1. Introduction

The cosmic-ray imaging technique is sensitive to high atomic number materials with high penetration, which has been demonstrated to be applicable for monitoring of nuclear materials [1]. In order to reduce the error caused by the scattering interaction when muons pass through the wall of containment (usually constituted with concrete or metal), the detector was ideal to deployed around the pressure vessel. But there are some problem limiting the application of cosmic-ray detector in the containment and the realization of true-wireless monitoring in NPPs (no data cable, no control cable and no power cable). One of these problems is the electromagnetic shielding of wireless signals by the wall of containment (usually constituted with concrete or metal). Typically, the cables and containment penetration are still necessary to get the information from the inside of the containment [2-5], which would cause new problem and cost to protect the leakproofness and integrity of the containment.

To solve the problem of communication through the containment wall, we have developed an ultrasonic communication system. We try to change the information carrier from electromagnetic wave to ultrasonic wave (to be accurately, its mechanical vibration), which would be transmitted more stably through the concrete or metal wall of sealed containers.
2. Design requirement analysis
The ultrasonic communication has been used in industrial control field and through-wall communication of metal container has been proved feasible by some research result recently [5]. The technology bottleneck of using ultrasonic communication through the containment wall is limitation of the baud rate and transmitting distance in the metal wall. Such as in the AP1000 nuclear power plant, the thickness of the containment steel liner is 44.45mm [5]. If we want to realize the true-wireless transmission of the data collected by muon detector in the containment of AP1000, we need to develop an ultrasonic communication system with at least 4kbits/s baud rate and more than 5cm transmitting distance in the steel material.

3. System Design
The ultrasonic communication system is constituted by modulation unit, transmitting unit, receive unit and demodulation unit. The modulation unit could receive the data from muon detector and modulate the data with 40 kHz carrier waves (5 cycles wave for binary “1” and direct current for binary “0”), then send the modulating waves to the transmitting unit [6-7].

The transmitting unit is constituted by one piece of 40 kHz piezoelectric ceramic and a low-power drive circuit (<25mW) to provide 20V excitation to the piezoelectric ceramic. Then, the modulated ultrasonic waves are generated and transmitted into the steel liner. The receiving unit is constituted by one piece of 40 kHz piezoelectric ceramic and a three stage filter circuit to get the 40 kHz carrier wave from the steel liner and reduce the interference of noise signals. Then, the clean modulated ultrasonic waves would be transmitted to the demodulation unit. Details of the transmitting and receiving units are given below.

3.1. Transmitting circuit design
The transmitting unit is mainly composed of a carrier generating circuit, a modulating circuit and a driving circuit. The carrier generation circuit adopts NE5SD. The NE555D chip is a widely used base unit integrated circuit with a threshold value, Vth1=2Vcc/3 and a trigger level, Vth2=2Vcc/3. Figure 1 shows the multiharmonic oscillation circuit whose duty cycle and period could be adjusted. With the design of circuit, Rv1 is used to adjust the resonant period and Rv2 is used to adjust the resonant duty cycle (Rv2 does not affect the resonant period). After generating a 40 kHz carrier, the signal needs to be loaded onto the carrier. In this study, the 741L900 and the non-gate chip are developed to realize the modulation process after which the positive and negative signals are output to the next stage of the drive circuit. The modulation circuit is shown in Figure 2.

![Figure 1. The design of multiharmonic oscillation circuit.](image1)

![Figure 2. The design of modulation circuit.](image2)
As shown in Figure 3, the drive circuit provide a differential voltage of up to 20V for the ultrasonic transmitter by using the chip MAX232 in the case of 5V power supply of the transmitting circuit. The 1μF capacitors, marked with C5 and C7, provide a charge pump for the two-way transmission of the chip MAX232. With the high low-level of TTL, the output of T1OUT and T2OUT are ±10V, corresponding to T1IN an T2IN. Therefore, this circuit can provide a driving voltage of 20 V for the ultrasonic transmitter.

![Figure 3. The design of drive circuit.](image)

3.2. Receiving circuit design
A three stage amplification filter circuit is designed in front of the detection circuit to provide a better waveform for the detection circuit. Figure 4 shows the design of amplifying circuit. Firstly, the circuit performs preliminary amplification on the original signal. Secondly, it filters out the non-40 kHz frequency signal component in the original signal and finally it amplifies the appropriate post-wave signal to a detection circuit. The filtered and amplified signal becomes a fluctuating DC signal through the precision detector circuit, as shown in Figure 5. Figure 6 gives the design of fitter and comparison circuit after which we acquire the digital signals.

![Figure 4. The design of amplifying circuit.](image)

![Figure 5. The design of detector circuit.](image)
4. System debugging and testing

The bit error rate is an important indicator to evaluate the performance of a wireless communication system. In order to understand the signal transmission performance of the system, some experimental studies have been carried out. Firstly, the test target used in the experiment is a geometric model of the containment, which constructed according to the ratio of 20:1 with the containment of AP1000 nuclear power plant. The shape can be approximated as a four-column steel closed container with a wall thickness of about 2 mm. After a long period of trials, the ultrasonic communication system designed has a transmission error rate of less than 10^{-6}. This test proves that the ultrasonic communication system can achieve accurate data transmission under the condition of large-area steel container.

In addition, the penetration plate communication test was carried out under the condition that the bit error rate was lower than 10^{-6}. With the frequency of 40 kHz and the baud rate of 2400 Bd, the device could penetrate 36.5 cm steel plate with a bit error rate of 0. As a result, the accurate transmission of data can be achieved in the case of thicker steel containers.

In order to understand the ability of the device to penetrate the steel plate under the condition of BER of less than 10^{-6}, a comparative experiment was conducted with different baud rates. The input condition of the experiment were that the bit error rate is lower than 10^{-6} and the singles were sent at 1000 ms periodically. The measurements were made on 2400, 4 800, 9 600, and 14 400 Bd and the results are shown in Table 1. According to the result, the thickness of the steel plate penetrated by different baud rate devices is significantly different.

| baud rates/Bd | 2400 | 4800 | 9600 | 14400 |
|--------------|------|------|------|-------|
| Thickness/cm | 36.5 | 10   | 7    | 2     |

5. Conclusion

In the research reported here, we designed a wireless communication system that uses ultrasonic communication technology which could be applied in NPPs. The ultrasound communication system is designed for a frequency of 40 kHz and a baud rate of 2400 Bd. The system was tested using the AP1000 containment analog simulation bench. As a result, the system can stably realize wireless communication inside and outside the reactor containment under the condition that the bit error rate is lower than 10^{-6}. The system was used to carry out the maximum penetration thickness test under the condition of near zero bit error rate communication and the comparison test of the thickness of the steel plate which can be penetrated by different baud rates. The results show that the penetrable steel plate has the thickest thickness of 36.5 cm at a baud rate of 2 400 Bd. However, this wireless communication system needs to be verified and improved in operation: the communication rate is not high enough. Due to the particularity of the reactor structure function, the interference of various rays to the wireless signal, and the influence of the wireless communication signal on the reactor are not given consider.

Acknowledgments

This work was financially supported by the National Laboratory Foundation (Grant NO.6142004180203).
References

[1] Liu Y Y, Zheng P, Heng-Guan Y I, et al. Muon Reconstruction Algorithm for Reactor Core Monitoring in Severe Accident[J]. Atomic Energy Science & Technology, 2016, 50(5).

[2] Lv R , Shen L , Hu J . Design and Implementation of a Wireless Sensor Network Gateway Supporting Multi-Mode Wide Area Access and Video Monitoring[C]// International Conference on Information Science & Engineering. IEEE, 2009.

[3] Chen W, Yu Q , Cheng X L, et al. Ultrasonic Wireless Communication Technology in Reactor Containment[J]. Nuclear Electronics & Detection Technology, 2016.

[4] Xiao C. Laser Ultrasonic Measurement System Based on Wireless Communication Technology[J]. Acta Optica Sinica, 2009, 29(1):203-207.

[5] Zhang Y P, Qiu S Z, Su G H, et al. Analysis of safety margin of in-vessel retention for AP1000[J]. Nuclear Engineering & Design, 2010, 240(8):2023-2033.

[6] Xiao C, Yan F. Wireless ultrasonic data transmission based on CC2430 chip[C]// International Conference on Test & Measurement. 2010.

[7] Sales G, Pye D. Ultrasonic Communication by Animals[J]. 1974.