Design and Implementation of Ultrasonic Transducer Detection System Based on STM32

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Abstract. In order to quickly and accurately detect the performance of ultrasonic transducers used for reversing radar. An ultrasonic transducer detection system was designed by using the embedded real-time operating system μC/OS-III and graphical user interface software emWin, based on STM32 microcontroller. According to the characteristics of collected data, a filtering algorithm based on mean filtering is proposed to reduce the influence of noise interference on result. Based on the waveform similarity detection, a method for judging the stability of the waveform is proposed, which solves the problem of judging the state of the ultrasonic transducer. Finally, the function of the ultrasonic transducer detection system was verified through experiments. Experiments have shown that the system is simple, stable, reliable, and highly practical.

Keywords: Ultrasonic transducer, reversing radar, mean filtering, waveform similarity, STM32, μC/OS-III.

1. Introduction

Since the reform and opening up, China's economy has developed rapidly, and car ownership has increased year by year. Parking spaces for cars are also becoming more and more tense. Ultrasonic reversing radar is an auxiliary parking device that helps drivers park their vehicles safer and easier. As an important part of the ultrasonic reversing radar, the performance of the ultrasonic transducer directly affects the accuracy of detecting obstacles. The transducers delivered by the transducer manufacturer are required to pass the failure rate of no more than 1ppm (one millionth). The ultrasonic transducer must pass rigorous testing and sorting through multiple indicators including static capacitance (SC), resonant frequency (RF), residual vibration time (RVT) and sensitivity(S). Then it can be installed on the vehicle. At present, oscilloscope, impedance analyzer, capacitance tester and other instruments are mainly used to detect the transducer. In particular, the detection of waveform morphology requires manual observation of the oscilloscope waveform, which is greatly influenced by subjective factors. It often requires multiple processes and phased detection to sort out qualified transducers [1]. There are some researches on ultrasonic transducer detection devices [2-5]. However, most of them are targeting ultrasonic transducers in the field of underwater acoustic or non-destructive testing. The parameter indicators concerned are very different from the transducer used for ultrasonic reversing radar.

In this paper, based on the ARM core-based STM32 microcontroller and 7-inch LCD touch screen, the ultrasonic transducer detection system for the car reversing radar is designed. It is possible to judge whether it is qualified by automatically scanning the frequency and capacitance values and comparing them according to preset values. At the same time, the ultrasonic waveform signal can be intelligently analyzed to obtain the results of the residual vibration time and sensitivity.

2. Testing Principle of Ultrasonic Transducer

The detection of the ultrasonic probe mainly includes four parts: static capacitance, resonance frequency, residual vibration time and sensitivity. The ultrasonic probe can be equivalent to an RLC series-parallel circuit [6], as shown in Fig. 1:

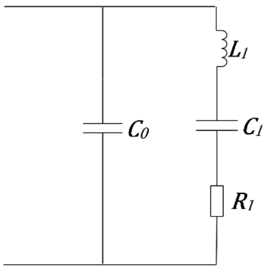


Fig. 1 Equivalent circuit of ultrasonic transducer

Where C_0 is the static capacitance, L_1 is the equivalent inductance, C_1 is the equivalent capacitance, and R_1 is the equivalent resistance.

2.1 Testing of Static Capacitance C_0

The shunt capacitance of the equivalent circuit of the oscillator can be measured with an appropriate capacitance bridge [7]. The measurement circuit is shown in Fig. 2:

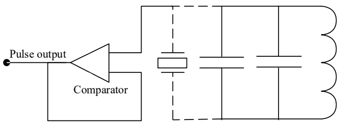


Fig. 2 Static capacitance measurement circuit

During measurement, an operational amplifier and LC circuit is used to form a resonant circuit. When there is no transducer, the resonant frequency of the circuit is:

$$f=\frac{1}{2\pi\sqrt{LC}}\#\tag{1}$$

f is the frequency of the signal (Hz); L is inductance (H); C is capacitance (F).

After paralleling the transducer, the frequency of the oscillating circuit can be expressed as:

$$f^{'}=\frac{1}{2\pi\sqrt{L(C+C_0)}}\#\tag{2}$$

Thus：

$$C_0=\left(\left(\frac{f^{'}}{f}\right)^2-1\right)C\#\tag{3}$$

2.2 Testing of Resonant Frequency

The resonant frequency is measured by three-voltage method [8]. The principle is shown in Fig. 3

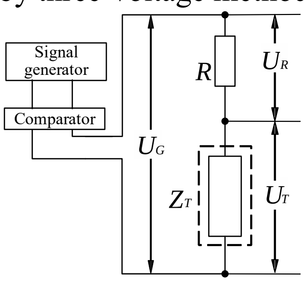


Fig. 3 Three-voltage method

A voltage U_G is applied to the series circuit composed of the transducer to be tested and a pure res istor R, and voltages U_T and U_R are respectively generated at both ends of the transducer and across the resistor. Let the current in the series circuit be I, then the impedance of the transducer is

$$|Z|=\frac{U_T}{I}=\frac{U_T}{U_R}R\#\tag{4}$$

When resonance is reached, the impedance is lowest and U_T is highest. Therefore, the amplitude-frequency response curve can be obtained by measuring the change of U_T.

2.3 Testing of Waveform

As shown in Fig. 4. The length of the residual vibration time determines the range of the blind zone of the ultrasonic transducer, and the sensitivity determines the detection distance of the ultrasonic transducer. A driver board is used to drive the ultrasonic transducer to periodically send an ultrasonic signal, and the echo waveform is collected and analyzed to judge whether the transducer is qualified.

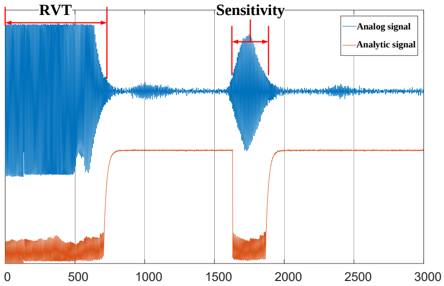


Fig. 4 Ultrasonic waveform

3. System Hardware Design

The hardware of the system consists of STM32F407 microcontroller, static capacitance detection circuit (SCDC), resonant frequency detection circuit (RFDC), wireless transmission module and other modules. In order to complete the detection of multiple indicators at one time, relays are used to switch the detection circuit. The system hardware structure is shown in Fig. 5.

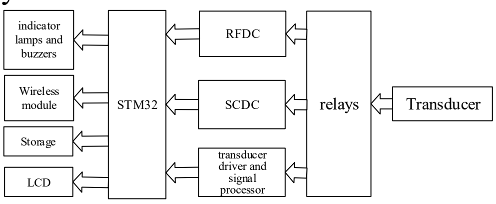


Fig. 5 System hardware block diagram

3.1 Microcontroller

The STM32 microcontroller is the core of the detection system, which is used to control a variety of peripherals, collect and process test data. This system uses the STM32F407IGT6 chip with ARM Cortex-M4 core, with the up to 168MHz master frequency, supports 3 ADCs, 17 built-in timers, and 15 built-in communication interfaces[9]. The chip can meet the design requirements of this system.

3.2 Static Capacitance Detection Circuit (SCDC)

The comparator LM393DG plus the LC oscillating circuit is used to measure the capacitance [7]. Using the open-circuit characteristics of the LM393, its voltage is set to 12V and its logic level is set to 3.3V. When the circuit is designed, the level of the input comparator in the LC oscillator circuit is obtained by a 12V voltage division, and the output of the back end is 3.3V, so the 3-pin input of the comparator after the voltage division should not exceed 3V. The final output of the capacitance measurement is a pulse signal, and the MCU gets the frequency by counting the number of pulses, then deriving the capacitance value.

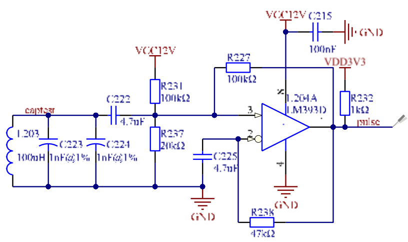


Fig. 6 Static capacitance detection circuit

3.3 Resonant Frequency Detection Circuit (RFDC)

The resonant frequency is measured by the three-voltage method[8]. The PLL source is generated by AD9833[10] during the measurement process, which is used to drive the transducer through an op amp. The op amp is implemented using the OPA1612. The output voltage of the AD9833 is around 600mV, amplified to about 10V by an op amp, and loaded into a series circuit, formed by an ultrasonic transducer and a 10kΩ pure resistor. The resonant frequency detection circuit is shown in Fig. 7.

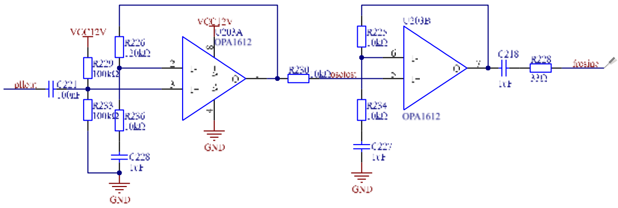


Fig. 7 Resonant frequency detection circuit

3.4 Transducer Drive and Signal Process Module

This module is used to detect the ultrasonic waveform morphology. By which the ultrasonic transducer is driven to emit ultrasonic waves, and the reflected ultrasonic signals are received and processed for subsequent analysis by the MCU. Chip E524.09 is chosen for drive transducer and process ultrasonic wave signal received from transducer. For often, this module is the same as it is used on master board of reversing radar. If an external master board is connected to the system via I/O interface of MCU, it is also possible to switch between E524.09 and the external module.

3.5 Wireless Communication Module

Wi-Fi module USR-215 is used for the wireless communication. This module is an ultra-low power serial to WIFI module, supporting WiFi@2.4 GHz 802.11b/g/n wireless standard and TCP/IP protocol [11]. The module has the transparent transmission function from the serial data to the network data, so the MCU can realizes the wireless network communication between the device and the upper computer through the serial port transmission and reception.

4. System Software Design

The functions to be implemented by the software are divided into three aspects: 1. Real-time displ ay and dynamic switching of detection results; 2. Data transmission and reception of communication modules; 3. Control and scheduling of various microcontrollers and external peripherals to collect an d process detection data.

4.1 Software Framework

In this system, the touch events of the display screen, the sending and receiving information of the communication module, the drawing of graphics and other events have different degrees of real-time requirements, and different events must work in coordination with each other. µ/COS-III is an highly tailorable and scalable open source embedded real-time operating system with excellent real-time performance[12], suitable for small embedded system devices with limited resources. Therefore, µ/COS-III is used as the software foundation to realize various functions.

According to the priority of tasks, it can be divided into human-computer interaction task, data acquisition and processing task and wireless communication task. The software frame diagram is shown in Fig. 8.

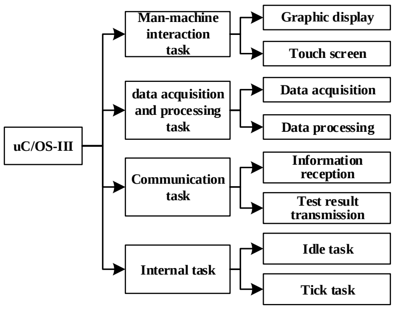


Fig. 8 Software framework

4.2 Software Flow

Each time a transducer is connected, the data acquisition and processing task will complete the detection of each indicator according to the priority. If any one of the tests fails, the transducer is deemed unqualified.

1) Static capacitance test

The I/O port of the STM32F407 is multiplexed into the built-in timer channel of the chip, and the timer is set to work in the input capture mode to capture the number of pulses of 10 milliseconds, which is used to derive the frequency of the oscillation circuit and calculate the capacitance of the transducer.

2) Resonant frequency test

The transducer is connected to the resonant frequency detecting circuit through a relay, and the MCU controls the waveform generator to produce sine sweep output. A/D converter is used to collect a sufficiently long sinusoidal signal of each frequency. The peak values of the response voltage values is preserved to plots the amplitude-frequency response curve, and obtains the resonant frequency.

3) Waveform test

The transducer driver is programmed to drive the ultrasonic transducer to emit a pulsed ultrasonic signal every 40 milliseconds. Imitate the edge triggering principle of the oscilloscope and set a trigger level. When the sampled value of the A/D converter crosses this trigger level, MCU starts collecting a fixed-length signal, then recognizes the transmit and echo waveforms, and judges the residual vibration time and sensitivity of the transducer.

The overall process is shown in Fig. 9:

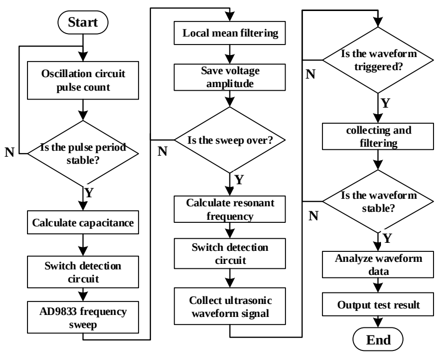


Fig. 9 Data acquisition process flow

4.3 Amplitude-Frequency Response Local Mean Filtering Algorithm

When measuring the resonant frequency, the waveform generated by the AD9833 is amplified by the operational amplifier, and there is clutter interference, which makes the calculation of the amplitude have errors. The drawn amplitude-frequency response curve is not smooth, and the resonant frequency calculation is not accurate.

To solve this problem, an improved filtering algorithm based on mean filtering[13] is adopted: at each sweep frequency point, the largest twenty points of the waveform are acquired, the two largest points and the two minimum points are deleted, the average is taken as the amplitude frequency response value. The specific implementation is as follows: the data collected by the ADC is stored in a minimum heap. If the number of elements in the heap has reached 20, the newly acquired data is compared with the top element of the heap. If it is larger than the top element of the heap, the top of the heap is removed and insert new element. If it is smaller, it will not be processed. Finally, the 16 points in the middle are taken out and averaged as the amplitude-frequency response value under the frequency. Therefore, data with relatively large errors is filtered out. The algorithm flow chart is shown in Fig. 10.

The test results are shown in Fig. 11.It can be seen that the algorithm can fix the problem that the amplitude-frequency response waveform is not smooth, which helps to determine the frequency of the transducer resonance frequency more accurately.

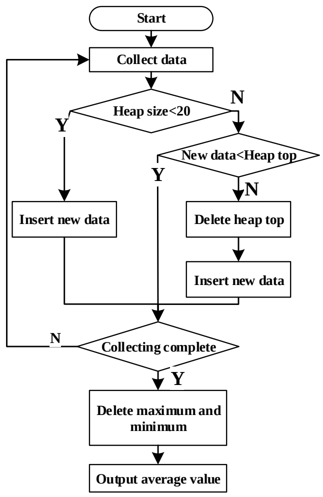
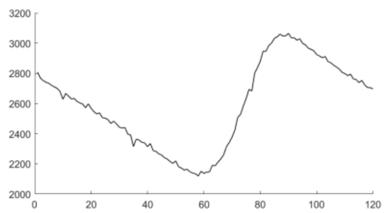
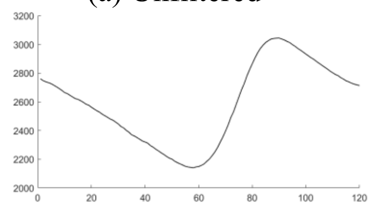


Fig. 10 Improved local mean filtering algorithm



(a) Unfiltered



(b) Filtered

Fig. 11 Amplitude frequency response curve

4.4 Waveform Stability Judgment Algorithm

When collecting the ultrasonic shape signal, it must be ensured that the ultrasonic transducer is in an anechoic chamber, and the transducer is in a stable state, that is, the transducer is firmly connected to the detection device, and placed on the clamp of the test platform. A method is needed to determine if the ultrasonic transducer is properly placed. If the transducer has not been stably placed in the anechoic chamber, the complex indoor environment, various mechanical vibration and the multipath effect of the ultrasonic wave itself will lead to a large number of random noises in the signal received by the ultrasonic transducer.

The system determines whether the transducer state is stable by continuously collecting multiple signals and judging the waveform similarity between several groups of data. The methods of judging waveform similarity include the Cosine method, feature interval vector method, Hausdroff distance method, average absolute difference method, etc.[14]. the Cosine method is not sensitive to the change of waveform amplitude. The Hausdroff distance method is relatively complex and insensitive to noise. Average absolute difference method is simple to calculate and sensitive to the amplitude difference between waveforms. In this paper, average absolute difference method is used to determine waveform similarity. The specific steps are as follows:

Step 1: extract the envelope of the waveform through peak holding, U is the sequence of waveform data collected, L is the number of points maintained by the peak, take L as 7, then the sequence X after peak holding is:

$$X_n = \max_{0 \le i \le L} (U_{n*L+i}) \# \quad (5)$$

Step 2: Calculate the absolute difference between the data frames. N is the sequence length after peak hold, then the average absolute difference D between data frames is:

$$D = \frac{1}{N} \sum_{k=0}^{N} \left| X_k - X_k^{'} \right| \# \quad (6)$$

Step 3: Insert the difference calculated in the previous step into the FIFO. M is the FIFO length, which is set to 5, then the sum S of all the differences in the FIFO is:

$$S = \sum_{k=0}^{M} D_k \# \quad (7)$$

S is compared with the preset threshold T. If S<T, the waveform is stable, the waveform data is analyzed and processed, and the result is output; otherwise, the waveform is unstable, and step 1 is repeated.

4.5 GUI Design

The human-computer interaction interface is based on the 800×480 resolution TCTLCD, which can display the echo waveform, amplitude-frequency response curve and test results of various indicators in real time. As shown in Fig. 12.

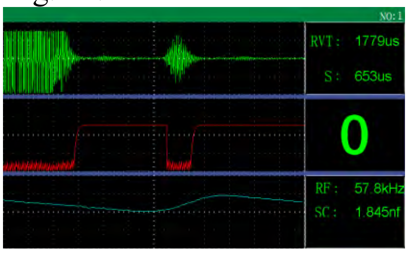


Fig. 12 Human-computer interaction interface

5. Experiment

5.1 Experiment Platform

In order to verify the function of the ultrasonic transducer detection system, based on the system hardware and software design, a prototype of the transducer detection system was built, as shown in Fig. 13. Four indicators and a buzzer are installed on the prototype to alert the operator to the results. The ultrasonic transducer driving motherboard is STK58K reversing radar motherboard.

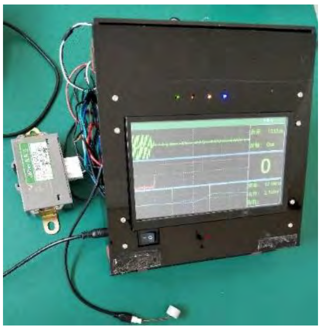


Fig. 13 Ultrasonic transducer detection device

5.2 Experiment Result

1000 numbered HC58-14TRAJ-T1 transducers is selected on the ultrasonic transducer production line of an electronics company in Chengdu. Firstly, Test this batch of transducers according to the factory's test procedure, includes three processes, namely, process 1: testing static capacitance (ST), process 2: testing resonant frequency (RF), and process 3: testing residual vibration time (RVT) and sensitivity (S). record the test result of each transducer, and then recheck the transducers with the transducer detection system. Finally, the results of the two tests are compared. The whole test procedure was carried out in an anechoic chamber built with sound-absorbing cotton at room temperature of 24.8°C. The experimental results are shown in Tables 1 and 2.

Table 1 Test results of traditional process

Test process	Number of transducers passed each test				Time cost
	SC	RF	RVT	S	
Process 1	971	--	--	--	23min19sec
Process 2	--	964	--	--	22min40sec
Process 3	--	--	959	961	54min33sec
Sum	971	964	959	961	100min32sec

Table 2 Test results of transducer detection system

Test process	Number of transducers passed each test				Time cost
	SC	RF	RVT	S	
All-in-one	971	964	951	958	73min05sec

Experimental results show that the detection results of static capacitance and resonant frequency of the transducer detection system are consistent with those of the factory test procedure. Due to the quantification of the residual vibration and sensitivity detection indicators, compared with the method of manually observing the oscilloscope, the subjective factors of the echo waveform judgment are avoided, so the judgment is more accurate. The detection process is simplified, and the detection result is obtained after an average of 1 to 2 seconds after the transducer is connected to the system, so the overall detection time of the system is relatively less.

6. Summary

In this paper, the software and hardware of the ultrasonic transducer detection system is designed with the STM32F407 microcontroller as the core. The system can mainly realize automatic detection of ultrasonic transducers and improve the production efficiency of the transducer production line. E xperiments have shown that the system is simple, stable, reliable, and highly practical.

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