Design of coating thickness gauge based on pulse eddy current testing technology

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Abstract

Coating technology has been widely used in aerospace, nuclear industry, ship manufacturing, petrochemical, metallurgical machinery and other fields, which can significantly improve the performance of materials, and is a key equipment and components that can work for a complicated, harsh environment. Guarantee. However, the thickness of the coating and the degree of coating will directly affect the reliability and life of the coating and the substrate, and thus quantify the thickness of the coating is a key means of improving the quality of the equipment and parts. In many coating thickness detection techniques, eddy current non-destructive testing technology is favored by its advantages such as cost, accuracy, measurement speed, operational difficulty, but has been limited in terms of conductive coatings. In this paper, according to the basic principle of edible detection of eddy current, the pulse scroll flow method detects the signal output law of the conductive coating thickness, and formulates the measurement scheme, and finally uses a pulsed vortex non-destructive detection technology to design a non-conductive coating on the metal substrate or The coating thickness gauge measured by the electrical conductivity is less than the single layer of electrically conductive coating of the substrate.

Keywords

Pulsed eddy current; non-destructive testing; single layer conductive coating; coating thickness.

1. Introduction

With the rapid development of science and technology, people have made further exploration towards unknown and difficult fields in all aspects. At the same time, the performance requirements of products are becoming higher and higher. Single materials often cannot meet the use needs of products in production and life. The surface coating technology can effectively make up for the lack of material performance and improve the quality of products. It is an "iron cloth shirt" for materials and parts to adapt to harsh working conditions. Surface coating technology plays an important role in improving the wear resistance, corrosion resistance and heat resistance of products. Its application in the manufacturing field is in the ascendant and has a very broad development prospect. At present, surface coating technology has been widely used in instrument manufacturing, petrochemical industry, medical equipment, aerospace, shipbuilding, nuclear industry, power electronics and other fields, such as coating tool surface coating by vapor deposition, internal protective coating of oil transportation pipeline, thermal barrier coating of aircraft engine surface, corrosion-resistant coating of ship surface, conductive coating of Multilayer PCB board, etc[1].

Coating thickness gauge based on eddy current testing technology has an indispensable position in industrial production. For a long time, it has been the focus of research at home and abroad. At present, the research on coating thickness measurement at home and abroad has achieved fruitful results, and many types of eddy current coating thickness gauges have been put into production. As a new branch of eddy current testing, pulse eddy current has more advantages than the traditional sine wave eddy current. It is mainly used in defect detection, defect identification, defect imaging, residual stress detection and coating thickness detection in practical engineering applications. This technology has gradually become a research hotspot of scholars at home and abroad[2].

The objective of this design is to design a quantitative measuring instrument for coating thickness. Its function is to measure the thickness of some single-layer conductive coatings on the basis of the non-conductive coating on the metal substrate. The research route is to establish a mathematical model according to the principle of eddy current testing, analyze the main factors that affect the output of the coating thickness signal of pulse eddy current testing, explore the relationship between them and design the inversion method of coating thickness measurement, and verify it through the physical design and simulation model. For the measurement of the conductive coating on the metal substrate, eddy currents will be generated in the conductive coating and the conductive substrate, and the size of eddy currents is mainly affected by the metal conductivity. In extreme cases, the conductivity of the coating and the substrate is equal, which can be divided into two cases: the coating conductivity is higher than the metal substrate and the coating conductivity is lower than the metal substrate. In this design, aluminum is used as the metal substrate for research, The conductivity of the coating is lower than that of the metal substrate[3].

Measurement object: quantitative detection of non-conductive coating on non-magnetic metal substrate or single-layer conductive coating with coating conductivity less than that of metal substrate (the metal substrate used in this paper is aluminum);

Range: (0-500) μm.

2. Theoretical Foundation

The pulse eddy current detection uses periodic square wave excitation, as shown in Figure 2.1. Given a square wave eddy current signal, the period of the signal is t, the frequency is f, and the width of the square wave signal is. All the periodic signals can be expressed by Fourier series as the superposition of sinusoidal signals, as shown in formula 2-1. Therefore, the pulse eddy current detection is equivalent to the simultaneous action of infinite sinusoidal excitation, and its measurement principle is the same as that of the eddy current detection.

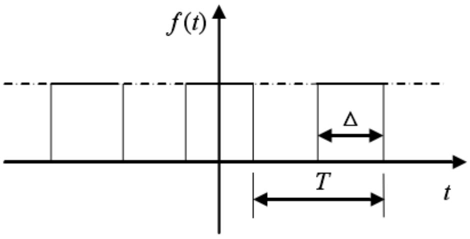

Figure 2.1 Schematic diagram of pulse square wave signal

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \sin(n\omega_1 t + \varphi), n = 1,3,5,7.... \quad (2\text{-}1)$$

In formula 2-1, A_0 is the DC component, A_n is the amplitude, ω_1 is the fundamental wave angular frequency, and φ is the phase spectrum[4].

As for the factors affecting eddy current thickness measurement, in the 1990s, scholars C.V.Dodd and W.E.Deeds reached the conclusion that the change of coil impedance was determined by many factors by establishing a theoretical model, and obtained the analytical solution of coil voltage when the air core coil was placed above the metal plate. This conclusion made a breakthrough in the research of pulse eddy current technology, And it lays a foundation for the calculation method of the pulse eddy current testing technology[5][6]. The impedance model proposed by scholars C.V.Dodd and W.E.Deeds is shown in Figure 2.2.

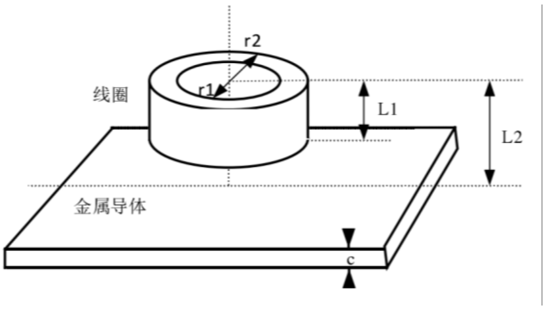

Figure 2.2 Single coil impedance model

The mathematical expression of impedance change is as follows:

$$Z = Kj\omega\int_0^{\infty}\frac{P^2(r_1,r_2)}{\alpha^5}\left\{2(L2-L1)+\frac{1}{\alpha}\left[2\exp\left[-\alpha(L2-L1)\right]-2+A(\alpha)\phi(\alpha)\right]\right\}d\alpha \tag{2-2}$$

$$K = \frac{\pi\mu_0 N^2}{(L_2-L_1)^2(r_2-r_1)^2} \tag{2-3}$$

$$P(r_1,r_2) = \int_{\alpha r_1}^{\alpha r_2} xJ_1(x)dx \tag{2-4}$$

$$A(\alpha) = \left[\exp(-\alpha L_1)-\exp(-\alpha L_2)\right]^2 \tag{2-5}$$

$$\phi(\alpha) = \left[\frac{(\alpha+\alpha_1)(\alpha_1-\alpha_2)+(\alpha-\alpha_1)(\alpha_1+\alpha_2)\exp(2\alpha_1 c)}{(\alpha-\alpha_1)(\alpha_1-\alpha_2)+(\alpha+\alpha_1)(\alpha_1+\alpha_2)\exp(2\alpha_1 c)}\right] \tag{2-6}$$

$$\alpha_{1,2} = \sqrt{\alpha^2 + j\omega\mu_0\sigma_{1,2}} \tag{2-7}$$

3. Design

This chapter mainly designs the hardware circuit and software system of the coating thickness gauge based on the characteristics of pulse eddy current testing and the measurement methods of conductive coating and non-conductive coating on the metal substrate. The system block diagram of the coating thickness gauge based on pulse eddy current testing technology is shown in Figure 3.1.

As shown in the block diagram of Figure 3.1, under the action of the excitation voltage, the eddy current sensor measures the coating thickness of the tested part, converts the coating thickness information into the change of the output voltage, and the signal conditioning circuit processes the voltage containing the coating thickness information, which is more conducive to data collection. The AD conversion circuit converts the analog signal into a digital signal, which is read by the microcontroller, and the microcontroller digitally filters the read data, Then display and store the measurement signal. The whole measurement process can be controlled by the key system.

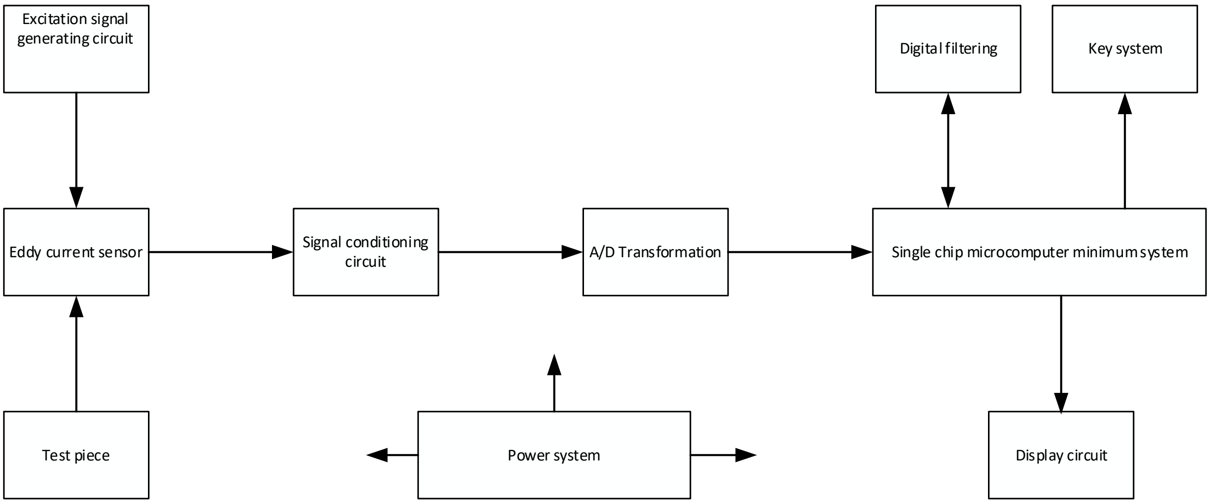

Figure 3.1 System block diagram of coating thickness gauge

3.1. Hardware design and analysis of thickness gauge

3.1.1. Design of eddy current probe

For thickness measurement of non-conductive coating on aluminum substrate and conductive coating with lower conductivity than the substrate, in order to improve the detection sensitivity and ensure the correctness of the simulation conclusion, the detection points of eddy current probe shall be consistent with the simulation model. According to the principle that the change of magnetic flux in the coil will generate induced electromotive force in the coil, the detection coil is used to detect the change rate of magnetic flux in the excitation coil. In the physical design, in order to better reflect the output change of the detection coil caused by eddy current, the probe is designed as a differential type. The designed eddy current probe is shown in Figure 3.2.

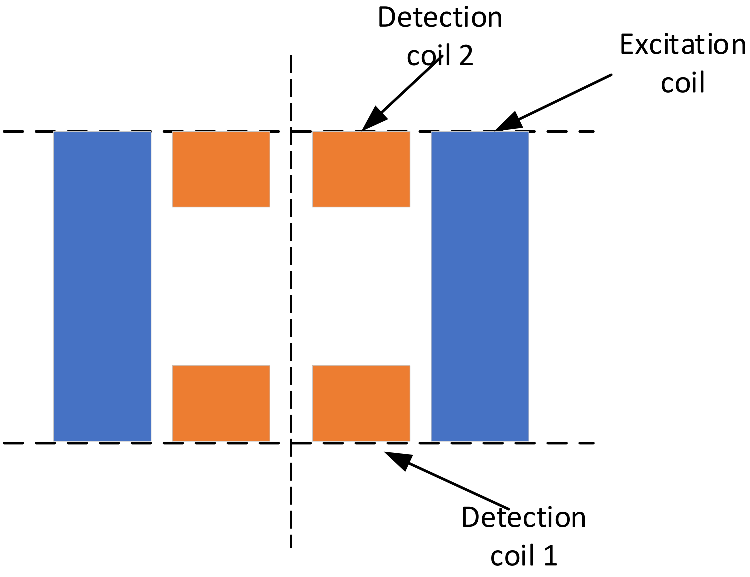

Figure 3.2 Cross section of eddy current probe

As shown in Figure 3.2, the probe is composed of one excitation coil and two detection coils. The two detection coils are located inside the excitation coil. The probe structure is symmetrical from top to bottom. When the excitation signal is applied to the excitation coil, the excitation magnetic field generated by the excitation coil has the same effect on the detection coil 1 and the detection coil 2. Due to the differential structure, the output is 0 at this time; When the probe is used for detection, the induced magnetic field generated by the eddy current in the measured conductor has different effects on the detection coil 1 and the detection coil 2, forming a differential output. A certain distance is maintained between the two detection coils to reduce the influence of the induced magnetic field on the coil 2. The differential structure design also has a certain temperature compensation function and can eliminate the influence of air gap. The physical diagram of the probe is shown in Figure 3.3,Figure 3.4.

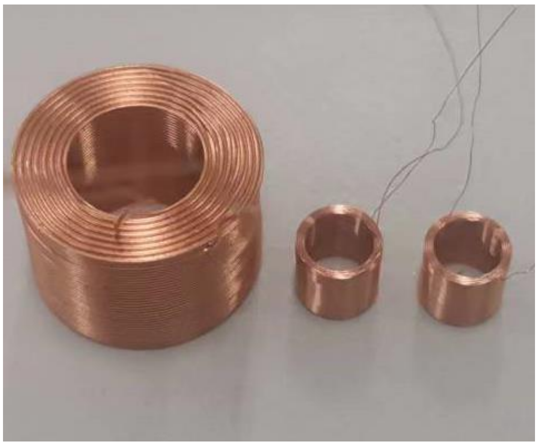

Figure 3.3 Coil for probe

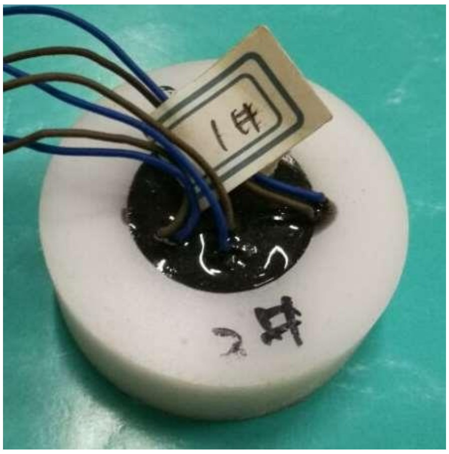

Figure 3.4 Physical diagram of probe

3.1.2. Excitation signal generating circuit

It can be seen from the above that the output signal of the eddy current sensor is mainly related to the coating thickness (the distance between the probe and the metal substrate), the conductivity and permeability of the coating and the metal substrate, and the excitation frequency of the probe. When the tested part is determined, the conductivity and permeability remain unchanged. As long as the excitation frequency of the probe is controlled to a certain value, the relationship between the coating thickness and the output signal can be reflected. Therefore, providing a stable excitation frequency is the key to the design of the coating thickness gauge. In addition, when the thickness gauge is debugged, it also needs to meet the problem of switching between two frequencies during the measurement of single-layer conductive coating. Therefore, the DDS circuit that can be programmed is selected as the excitation signal generation circuit.

Direct digital synthesizer is a frequency synthesis technology that directly converts the generated digital signal into the desired waveform from the phase concept. A direct digital frequency synthesizer consists of a phase accumulator, an adder, a waveform storage ROM, a D / A converter and a low-pass filter.

At present, DDS circuit has quite mature technology. This design will use AD9832 produced by adeno semiconductor company to design the circuit. Since the DDS output signal has a small amount of common mode interference and the effective value of the output voltage of AD9832 is relatively low, it is necessary to design an amplifier circuit with high common mode rejection ratio to filter the common mode interference. OPA2277 produced by Texas Instruments is used as the operational amplifier circuit. The design of the whole signal generation circuit is shown in Figure 3.5.

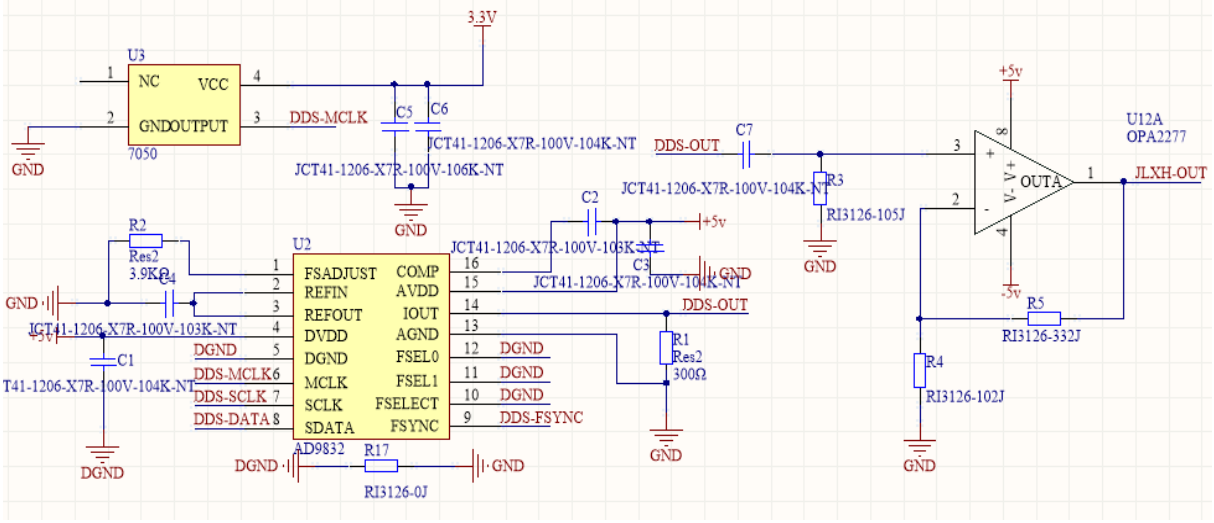

Figure 3.5 Excitation signal generation circuit

3.1.3. Signal conditioning circuit

It can be seen from the detection circuit that after passing through the signal detection circuit, the output is two AC signals with the same frequency and phase. According to the above analysis, the difference between the two signals is the effective signal for measuring the coating thickness. The signal difference can be realized by the differential amplification circuit with high common mode rejection ratio, and the zero drift and common mode signal existing in the system can be effectively suppressed, and the signal can be amplified to the range of a / D conversion. Due to the influence of the detection environment and other factors, the mixing of the detection signal and the external interference is easy to generate high-frequency interference. Therefore, the second-order low-pass filter is used after the amplification circuit to process the collected signal. The cutoff frequency of the second-order low-pass filter is set to 45khz. Then the RMS detection circuit is used to convert the signal into DC analog voltage output. The direct use of effective value conversion circuit can avoid the complex signal demodulation process, not only save the hardware cost, but also effectively reduce the introduction of noise and interference. Finally, the signal is converted into digital signal by a / D conversion chip to complete the whole signal conditioning process. The flow diagram of signal conditioning circuit is shown in Figure 3.6.

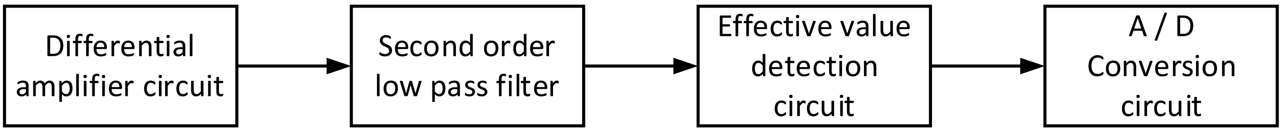

Figure 3.6 Signal conditioning flow chart

Low power precision instrument amplifier INA129 is selected as the high common mode rejection ratio amplification circuit, and LTC1968 is selected as the effective value conversion chip. Among them, LTC1968 is a real RMS to DC converter, which uses an innovative ΔΣ Calculation method: compared with the traditional logarithmic inverse RMS to DC converter, the advantages of LTC1968 proprietary architecture are higher linearity and accuracy, amplitude independent bandwidth, and improved temperature characteristics. When the absolute error of frequency is less than 1% (independent of the amplitude stability of the circuit), it can measure signals up to 500KHz and bandwidth up to 15MHz. The signal conditioning circuit is shown in Figure 3.7.

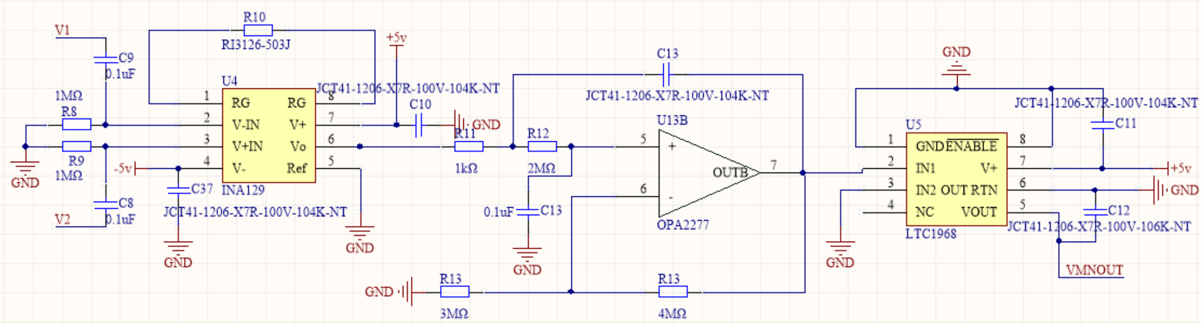

Figure 3.7 Signal conditioning circuit

3.1.4. Analog to digital conversion circuit

After the signal processing by the differential amplification circuit and the effective value conversion circuit, the complex and tiny measurement signal has been conditioned into a convenient DC analog signal. Next, the conversion from analog signal to digital signal needs to be completed.

The signal conditioning circuit has been designed in the previous stage circuit. This section mainly shows the design of a / D drive circuit, reference voltage source and ADC circuit. In order to ensure the sampling accuracy, we also need to design an ADC driver circuit. For an ADC driving circuit, it is necessary to meet the two points that the driving capacity of the operational amplifier is strong enough and the setup time and slew rate of the operational amplifier are much greater than the sampling interval time of the ADC. According to these two requirements, the operational amplifier chip AD8655 produced by Adi company can be selected. AD8655 is a precision CMOS amplifier with the lowest noise in the industry. It uses ADI's digitrim ® Technology to obtain high dc accuracy. The analog-to-digital conversion circuit is shown in Figure 3.8.

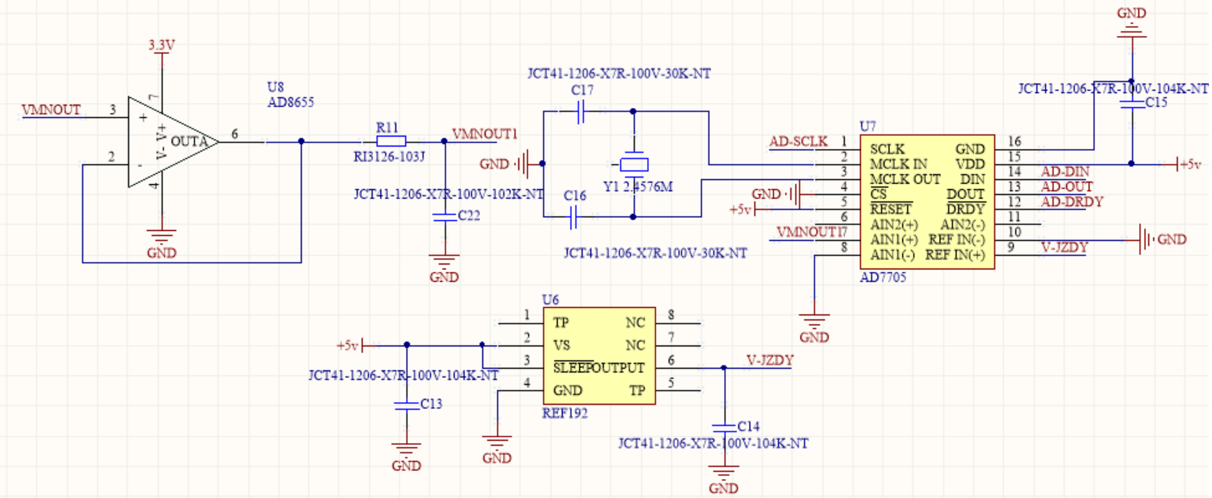

Figure 3.8 A / D conversion circuit

As shown in Fig. 3.8, the first-order low-pass filter composed of R11 and C18 at the output end of ad drive can filter out high-frequency noise and provide sufficient charge for the sampling capacitor in ADC to avoid voltage collapse during sampling.

3.1.5. PCB drawing and physical welding of circuit

Through the previous circuit design, the hardware system of the coating thickness gauge is basically completed. Next, the physical production of the hardware circuit board needs to be completed. First, according to the idea of hardware design and the selected devices, use Altium designer 15 to gradually complete the drawing of hardware circuit schematic diagram. After the schematic diagram is compiled correctly, draw the PCB diagram. Finally, weld the circuit board according to the PCB. The PCB diagram and the physical diagram are shown in Figure 3.9, Figure 3.10.

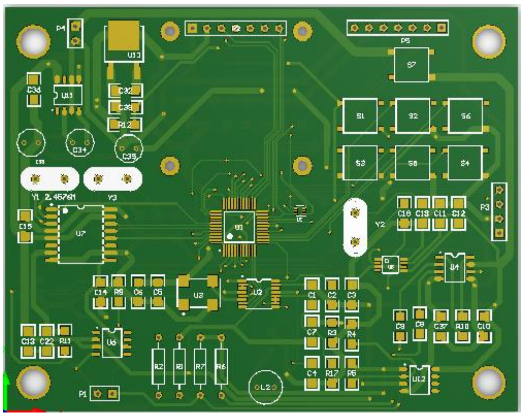

Figure 3.9 PCB view

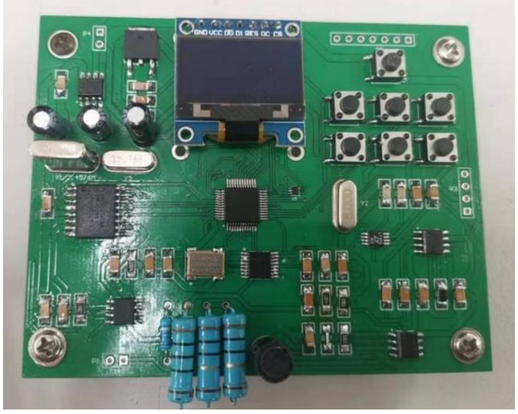

Figure 3.10 Front view

3.2. Software system design of thickness gauge

The previous sections completed the hardware circuit design of the whole system. Through multiple processing such as amplification and shaping of the measurement signal of the eddy current sensor, the output signal is more accurate and easier to be received and recognized. For the whole system, in order to fully realize its functions, in addition to reasonable hardware circuits, supporting software systems are also required. The design of the software part is mainly to realize the drive and control of the DDS circuit, the signal acquisition and conversion of the A / D acquisition circuit, the digital filtering, the drive and display of the display circuit, etc.

The software system designed this time is mainly divided into three modules from the use function, which are DDS pulse signal generation module, ADC data acquisition module and OLED display module. Among them, the peripheral devices that need to be driven by the software system include DDS circuit, ADC circuit, display circuit, serial port circuit, key interrupt and flash. In addition to driving the peripheral devices, the digital filtering and data conversion of the collected signals need to be completed through software programming. The design flow chart of the software system is shown in Figure 3.11.

As shown in the above figure, after the thickness gauge system is started, the I / O port, timer, DDS circuit, ADC circuit, OLED display and other modules are initialized in sequence. Then, the frequency of the excitation signal is selected by pressing the key. After the selection is completed, the single chip microcomputer drives ad9832 chip to generate the pulse signal of the corresponding frequency. When the eddy current probe detects the measured part, press the measurement button. At this time, the analog signal containing the coating thickness information will be transmitted to the ADC circuit. The MCU drives the ADC circuit to convert and collect the measured data. At the same time, the digital signal collected by AD7705 is also read through the interface, and then the data is filtered and converted in the MCU, Finally, the data is sent to the display module connected with the MCU through I / O to display the measurement data.

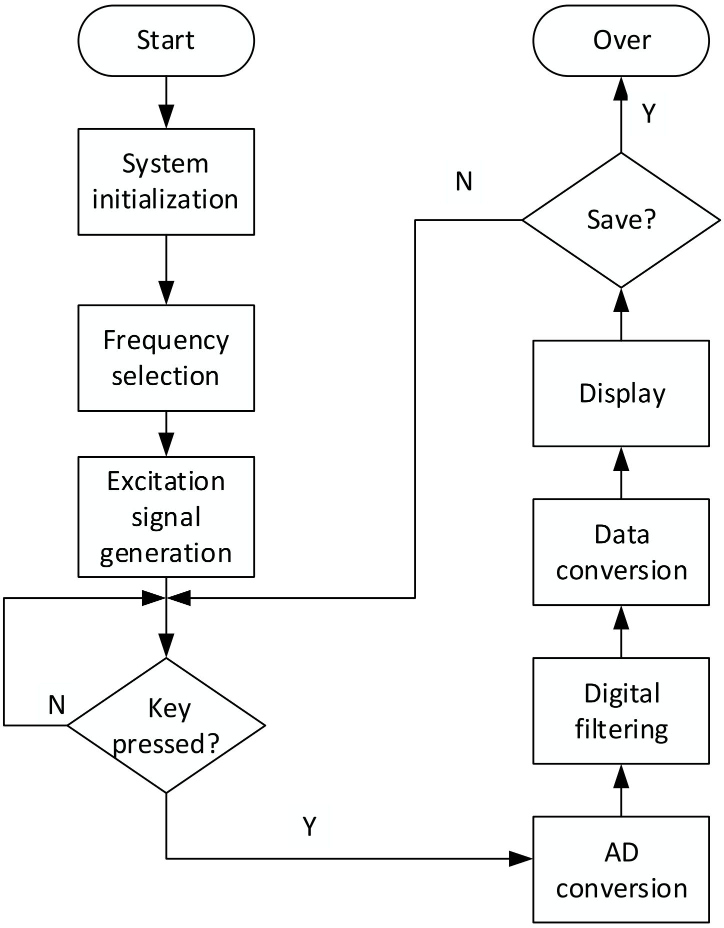

Figure 3.11 Software flow diagram

4. Prototype test experiment and result analysis

According to the principle of eddy current thickness measurement, the hardware system and software system of the whole system have been designed, and the circuit board has been drawn and welded, and the system joint debugging has been carried out. This chapter mainly completes the calibration and verification of the completed thickness gauge. By building the system experimental platform, the overall performance of the conductive coating and the non-conductive coating measured by the measuring system is tested, and the recording of the experimental process, the processing and analysis of the measurement data are completed. Finally, the error analysis of the coating thickness gauge is completed.

4.1. Prototype test and result analysis

After determining the measurement frequency of the parts to be tested and the conductive coating and the non-conductive coating, it is necessary to calibrate and measure the accuracy of the conductive coating and the non-conductive coating.

4.1.1. Model fitting for thickness measurement of nonconductive coating

For the measurement of the non-conductive coating, it is consistent with the simulation. The excitation frequency is selected as 30kHz, and the output voltage of the measuring coil corresponding to the coating thickness is measured. Since there are only 7 standard thickness measuring pieces and aluminum based zero plates in this experiment, and the number of test pieces is not large, in order to avoid the situation that the accidental error caused by the small number of measurements has too great impact on the results, the existing coating thickness test pieces are superimposed and combined to generate a new coating thickness. The non-conductive coating probe is used to measure the coating thickness video. The corresponding output voltage value of the coating thickness is shown in table 4.1.

Table 4.1 measurement experimental data

Frequency	Coating thickness: (μm)	Measuring voltage (mV)	Frequency	Coating thickness: (μm)	Measuring voltage (mV)
1	0	42	9	233	318
2	11	58	10	281	337
3	17	63	11	331	345
4	50	141	12	359	368
5	98	227	13	383	379
6	149	241	14	416	394
7	183	268	15	464	403
8	200	289	16	500	418

4.1.2. Model fitting for thickness measurement of conductive coating

Since the measuring range of the coating thickness measuring system designed this time is (0-500) μ m. The metal material sheets of various standard thicknesses can be stacked on the aluminum based Zero plate from 0 to 5 in order to achieve a thickness of (0-500) μ m. At 100 μ M is the coating thickness change of the interval. In addition, during the experiment, it is necessary to ensure that the metal sheet and the metal sheet and the substrate are closely bonded, so that the upper and lower metal sheets can be exchanged at the same time, and the measured output voltage value remains unchanged. Stainless steel, beryllium copper, phosphor copper and brass were selected as calibration materials. The excitation signal is set at 40KHz, and the conductive coating made of stainless steel, beryllium copper, phosphor copper and brass is measured with the conductive coating measuring probe for several times to take the average value. The measurement results are shown in table 4.2.

Table 4.2 measured voltage values of different conductive coatings (MV)

Material / Thickness	Stainless steel	Beryllium copper	Phosphorous copper	Brass
0μm	93	93	93	93
100μm	117	115	109	105
200μm	147	127	124	120

300μm	164	144	147	139
400μm	198	165	162	156
500μm	212	191	185	167

4.2. Error analysis

Error of experimental device: since the coating thickness gauge is a high-precision lift off displacement measuring tool, the weak influence invisible to the eyes may also cause changes in the results early. For example, there are unclean dirt on the sensor probe during measurement, or the standard test piece used for calibration has been used for too many times, resulting in certain wear and dirt, resulting in inaccurate measurement data. In addition, in the design process, due to the limited experimental equipment, there are few standard test pieces used for the thickness measurement of non-conductive coating, and the thickness span of the test pieces is too large and the thickness value distribution is uneven, which is easy to cause the low linearity of the final fitting line and increase the measurement error. In the calibration process of conductive coating, there are also a few samples of metal coating. Since there are no experimental conditions for preparing conductive coating, the metal sheet stacking method is used to simulate the change of coating thickness, and the thickness of the metal sheet may not be uniform. In addition, it is difficult to ensure that there is no air gap between them during the stacking process, which also has a great impact on the final experimental results.

Environmental error: in the design process of the thickness gauge system, although many filter circuits have been added to the hardware circuit to filter out the interference, and the median value average filter method has also been used in the software design to ensure the accuracy and reliability of the measurement results, it is difficult to completely shield the interference, and there will always be some interference, which will have a certain impact on the measurement circuit. In addition, in the actual use process, there will definitely be nonlinear interference of sensors, air pressure and electromagnetic signals in the system, as well as external environmental interference, such as humidity, temperature, air pressure and electromagnetic signals.

Personnel error: no professional instruments are used during the measurement, and manual measurement is prone to human factors. For example, the probe is not perpendicular to the test piece, and the pressure applied by the hands before and after several times is inconsistent, which will have a certain impact on the measurement results.

5. Summary and outlook

5.1. Summary

Eddy current nondestructive testing technology has significant advantages in coating thickness measurement. However, due to its detection characteristics, it has been limited in the detection of conductive coatings, which leads to the use of destructive detection methods to detect the thickness of conductive coatings in production. It is an urgent problem to be solved to use eddy current nondestructive testing technology to realize the thickness detection of conductive coatings. In this paper, the pulse eddy current nondestructive testing technology is deeply studied, and the measurement methods of the thickness of the non-conductive coating on the metal substrate and the single-layer conductive coating with lower conductivity than the substrate are explored. The coating thickness measurement scheme based on the pulse eddy current nondestructive testing technology is developed and the coating thickness gauge is designed for physical verification, which proves the correctness of the thickness measurement methods of the conductive coating and the non-conductive coating.

5.2. Outlook

In the hardware design process of measuring coating thickness, many differential amplification circuits are used. Although most of the spatial noise can be reduced, the introduction of more operational amplifiers may lead to the error of the measurement system itself in the measurement results. In order to reduce this error, further optimization of the hardware circuit is required. Secondly, there is no iron core inside the measuring probe designed this time, which leads to Pinardi's measurement sensitivity. In the later stage, we can consider redesigning the probe, winding the coil and adding a magnetic core inside the probe to improve the sensitivity of the detection signal.

The measurement of the single-layer conductive coating in this measurement system only considers the case where the conductivity of the coating is lower than that of the substrate, and does not explore the case where the conductivity is higher than that of the substrate. However, according to the measurement results of the single-layer conductive coating with lower conductivity than the substrate, when the coating thickness is the same, the output voltage is related to the conductivity of the coating. The larger the coating conductivity is, the smaller the output voltage is. Therefore, it can be boldly inferred that when the coating conductivity is greater than the substrate, the output voltage and the coating thickness have a linear relationship with a slope less than zero, and the larger the coating conductivity is, the smaller the slope of the fitting line is;

This measurement system only discusses the thickness measurement of single-layer coating, and the application of multi-layer conductive coating is very wide. Although the measurement principle of multi-layer conductive coating is given in the paper, this system has not been tried. Theoretically, on the basis of the measurement of single-layer conductive coating, it can be extended to the thickness measurement of multi-layer conductive coating;

The coating thickness gauge designed in this paper can only measure the aluminum substrate, and the range of measurement is relatively simple. In the future, the universality of the measurement system for coating measurement can be increased through algorithm research.

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