Structural damage detection system based on FPGA and EMI method

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Abstract. This paper designs a miniaturized structure health detection system based on the electro-mechanical impedance (EMI) method. The system uses two orthogonal signals of the same frequency as the excitation source, which effectively solves the problem of determining the phase difference in phase detection. According to the characteristics of the piezoelectric sensor, the FPGA is used as the main control chip, the measurement frequency range is adjustable by the user, and transmitted through the wireless serial port. The admittance curve of the piezoelectric sensor is displayed on the host computer, and real-time calculation of the RMSD value and relative RMSD value of the admittance curve. Compared with the current impedance analyzer on the market, it has the characteristics of wide measurement frequency range, small size and low cost.

1. Introduction
The small damage of the structure may be extended to become a major accident that endangers public safety. In response to this phenomenon, research on structural damage detection technology uses various methods to detect the structure, which is used for damage assessment, prediction of remaining service life, and reduction of safety accidents. The incidence rate is extremely important [1]. The damage identification method based on the principle of piezoelectric impedance is very sensitive to changes in the local state of the structure, is not easy to be disturbed by the external environment, does not rely on model analysis, is suitable for complex engineering structure detection, and is also suitable for online monitoring. It is a simple and reliable structure damage identification Method [2]. However, the existing commonly used precision impedance analyzers such as Agilent 4294A have the disadvantages of high price, large size, and heavy weight. In the actual measurement, not all the functions of the device are used, and the measurement range and measurement accuracy far exceed the measurement demand. The micro impedance analyzer based on the AD5933 chip can measure less than 100KHz, which is limited to the principle circuit designed by it, with few sampling points and difficult to adjust the frequency range [3]. In order to overcome the shortcomings of the existing piezoelectric impedance measurement devices, this paper proposes a small piezoelectric impedance measurement device with the functions of real-time acquisition, storage and wireless transmission of impedance and temperature signals. It can meet the long-distance, real-time online impedance measurement in the laboratory or engineering field.

Structural damage detection system uses FPGA software to program to control external devices and complete data algorithm processing. The system software mainly includes: DDS frequency sweep signal generation module program, three-way AD data acquisition and storage module program, data
processing module program, wireless serial communication module program, and adjustable gain
generation module program. The data processing module is the basic and core module of the system.

2. Sensor principle
Piezoelectric sensors are widely used because of their unique piezoelectric effect. The essence is the
conversion between electrical energy and mechanical energy. The physical picture of the piezoelectric
sensor is shown in Figure 1.

![Figure 1. Piezo sensors.](image)

When a piezoelectric sensor is strained by external excitation, the sensor will cause electrodelation
and generate a certain amount of charge. The amount of charge is proportional to the force. The
polarity of the charge is related to the direction of the force. Thereby, mechanical energy is converted
into electrical energy, and this phenomenon is a positive piezoelectric effect. Piezoelectric sensors
undergo polarization under the action of an electric field, strain occurs on the fulcrum of the material,
and the strain value is proportional to the electric field strength. The direction is related to the direction
of the electric field, thereby converting electrical energy into mechanical energy. This imagination is
reverse piezoelectric effect. Therefore, according to the positive and negative piezoelectric effect,
piezoelectric materials are used as receivers and excitation sources with electromechanical
conversion[4]. The piezoelectric equation takes the electric field strength E and stress σ as independent
variables, and the electrical displacement D and strain ε as dependent variables. The piezoelectric
equation expression is:

\[
E_i = C_{ij}^E \sigma_{ij} + d_{ij}^P E_j \quad \text{and} \quad D_i = d_{ij}^P \sigma_{ij} + \varepsilon_{ij}^P E_j
\]

Where: \(C_{ij}^E\) is the compliance coefficient of complex elasticity; \(d_{ij}^P\) is the pressure strain constant;
\(d_{ij}^P\) is the piezoelectric strain constant; \(\varepsilon_{ij}^P\) is the complex permittivity when the pressure is zero or
constant.

3. EMI detection technology
EMI method is also known as the electromechanical coupling impedance method based on
piezoelectric materials. This method attaches a piezoelectric sensor to the structure under test, and
measures the change in electrical impedance and admittance through the relationship between the
coupling impedance and the state of the structure, and to determine the existence and size of damage
in the structure[5].

This article builds a EMI detection technology circuit based on the piezoelectric impedance method.
The circuit diagram is shown in Figure 2. The DA digital-to-analog conversion module uses ADI's
AD9767 to generate dual in-phase positive frequency conversion signals, one of which is buffered by
the voltage follower module (AD817) and sent to the band-side structure and the true RMS detection
module. The other channel is sent to the phase detector as a reference signal; the signal returned from
the structure is divided into two channels after passing through the current-voltage conversion module
(TLC2201). The true RMS detection module detects the actual true RMS value of the return signal;
the phase detector uses ADI's AD8302, which converts the phase difference obtained by comparing
the two voltage signals into a voltage value; the RMS detection module uses ADI's AD637, which
converts the actual true RMS measured from two channels into voltage values, so as to obtain the
calibration voltage and the reflected voltage value of the sensor.
4. System software overall design

The software scheme design of the structural damage detection system is shown in Figure 3. The system software is mainly designed according to the system hardware, and the software of the FPGA is used to program to control external devices and complete data algorithm processing.

The operating flow of the system software is shown in Figure 4. After the program starts to run, each module will be initialized first; then wait for the start instruction of the host computer and the measurement frequency adjustment instruction. After the FPGA main controller obtains the control word instruction, it will match the measurement frequency range and control the DDS frequency sweep signal. The generator outputs a swept signal in the frequency range as the excitation signal of the piezoelectric sensor; the excitation signal is subdivided into 1000 incremental frequency points, and the swept frequency range is divided by 1000 as the frequency interval of each point. After starting the excitation sensor with the starting frequency as the starting point, control the three AD acquisition modules to sample the excitation source voltage value, sensor output voltage value and phase difference from the excitation source at this frequency point and store them separately in three RAM data temporarily. Save the module, and then add the frequency point to the frequency interval to switch the frequency point, and then sample and store it. Repeat this process until 1000 frequency sweep frequency points are completed, and then send the RAM data temporary storage module to a total of 6000 8bit data to the data The processing module performs data calculation processing and FIR filtering to calculate the admittance curve. In addition, the system is also equipped with a temperature sensor, which can measure the temperature environment of the structure in real time.

5. FPGA-based software design

According to the overall scheme design and analysis of the system requirements, it can be seen that the most important part of the software design is the filter algorithm module and the DDS sweep signal generation module.
5.1. Program Design of DDS Sweep Signal Generation Module
This design uses DA conversion module chip model is AD9767 produced by ADI, its resolution is 14 bits, and the highest frequency of signal output is 125Msps. The AD9767 uses the host to give the control clock and WRT signal to perform DA digital signal to analog signal output. After the rising edge of the control clock, the WRT signal performs a rising edge. The AD9757 converts a 14-bit data into an analog voltage output. The timing diagram is shown in Figure 5.

![Figure 5. AD9767 timing diagram.](image)

Figure 5. AD9767 timing diagram.

Figure 6 is an RTL view of a DDS frequency sweep signal generating module, which mainly includes a data phase accumulation module for an accumulator, a ROM table lookup module, and a positive and negative sign conversion module. The DDS_datapath module is used as an accumulator module. The basic structure is shown in Figure 7. It is mainly composed of a synchronization register and an accumulation register. The output data is used as the sampling address of the waveform memory. The rom module is used as a sine waveform data addressing module to complete the conversion from address to phase amplitude. The DDS_signed_shift module is a positive and negative sign conversion module. Because the AD9767 chip is designed with two-stage voltage op amps, the first stage is current-to-voltage and the second stage is voltage amplification, but the second stage voltage amplification will cause voltage polarity and original polarity. The opposite is true, so the sign of the DA output data needs to be converted.

Perform functional simulation on this module, input frequency control word and phase control word, and output 50 ~ 1000KHz, phase swept signal with 0°. The simulation result is shown in Figure 8.

![Figure 6. RTL view of the DDS swept signal generation module.](image)

![Figure 7. Basic structure of DDS.](image)

Figure 6. RTL view of the DDS swept signal generation module.

Figure 7. Basic structure of DDS.

Figure 8. Simulation results of the DDS sweep signal generation module.

5.2. Filter algorithm programming
This section introduces the program design of the filter algorithm, which mainly consists of the limiting filter algorithm and the FIR filter algorithm. The limiting filter algorithm module is mainly composed of limiting comparison and mean calculation. The schematic diagram is shown in Figure 9. Figure 11 is the RTL view of the filter algorithm module. The limit_filter module compares the difference between two adjacent input data. If the difference is within the limited amplitude range, the
mean value is output. Otherwise, the original data is output. The Average_value module calculates the average of the first 8 input data.

The FIR filter algorithm is designed as a FIR low-pass filter, and its system function is formula 2.

\[
H(z) = \sum_{n=0}^{N-1} h(n)z^{-n} = h(0) + h(1)z^{-1} + \cdots + h(N-1)z^{-(N-1)}
\]  

(2)

In order to improve the operating speed of the filter designed by FPGA, the FIR filter adopts a parallel structure and adds specific symmetric coefficients at the same time to improve the operation speed. Therefore, the system clock frequency is consistent with the data output clock frequency. The specific parameters of the filter are kaiser windows, the sampling frequency is 5000Hz, the cutoff frequency is 600Hz, the filter order is 16, and the quantization number of filter coefficients is 14bit. The frequency response curve is shown in Figure 10. The fir_low_kais module in Figure 11 is a FIR filter module.

6. System measurement and result analysis

After the complete structural damage detection system is set up, the pressure sensor is placed in a constant temperature to run the system, and the calculated admittance curve is output and displayed. The test sensor displays the change of the admittance curve under continuous operation for 3 days, and calculates the RMSD value and the relative RMSD value on the admittance curve on the host computer. Figure 13 shows the change of the room temperature admittance curve under three days of
continuous operation. The results show that the test environment is 23.2 °C, the RMSD value is 2.77%, and the relative RMSD value is 0.37%, which meets the design requirements.

![Figure 13: Variation of room temperature admittance curve for three days of continuous operation.](image1)

![Figure 14: Change of admittance curve during the sensor's decrease from pressure 5N to no pressure.](image2)

The structural damage detection system is subjected to a simulated pressure damage test. In this paper, multiple repeated pressure tests were performed on the detection system, and each measurement data obtained was basically the same, thereby verifying the stability of the system designed in this paper.

In order to analyze the difference between the admittance curves of different pressures and sensors, a pressure gauge is used to apply different pressures to the sensors, and the pressure is maintained at the expected pressure for another 5 minutes. The sensor pressure is attenuated and the pressure value of the pressure gauge is recorded. For the admittance curves of 5N, 2N and 1N, and take the second peak of the admittance curve to enlarge. Figure. 14 is a graph showing a change in an admittance curve during a process in which a sensor decreases from a pressure value of 5N to no pressure.

7. Summary
The design of structural damage detection system based on FPGA meets the design requirements of damage detection. The DDS frequency sweep signal generation module generates a 50-1000KHz in-phase sinusoidal frequency conversion signal to excite the pressure sensor; then it can effectively collect the signal reflected by the sensor and send it to the FPGA controller for data calculation processing. First, the system performs filtering algorithms on the sampled signal to reduce external interference and improve measurement accuracy. Secondly, it converts the collected phase difference, calibration voltage value and reflected voltage value into an admittance curve. The test results show that the structural damage detection system designed in this paper measures a frequency range of 50 ~ 1000KHz, an impedance measurement range of 50 ~ 100KΩ, a root-mean-square offset error of less than 3%, a phase difference measurement range of -90 ° ~ 90 °, and a relative root-mean-square offset error of less than 2 %.

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