Acoustic Frequency Division Based on Active Metamaterial: An Experimental Demonstration of Acoustic Frequency Halving

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Abstract. In this paper, an acoustic filter with low frequency bandstop and a broadband (0.3–3 kHz) bandstop filter are presented. In this paper, control algorithm and related equipment are integrated with piezoelectric ceramic thin film, ADC and FPGA to study a system which can mix acoustically in the process of acoustic transmission and only allow one-way transmission of sound waves.

Keywords: Piezoelectric · Mix acoustically

1 Introduction

Metamaterials have offered an entirely new route to understand and control the properties of broad kinds of materials [1]. Controlling acoustic transport at will has been pursued for many years in modern physics and applications [2]. Active acoustic metamaterial (AAMM) with tunable properties brings new potentials into acoustics [3]. For example, an acoustic second harmonic generator has been achieved with a highly nonlinear AAMM [4]. By further investigating the behavior of the signal processing system in [4], we propose an AAMM scheme for acoustic frequency division.

2 Active Control of Acoustic Transmission

By connecting the change of sound pressure with the change of electrical quantity in piezoelectric materials, part of the response function of the material to sound waves will be replaced by the response function of the circuit. The response of acoustic metamaterials to sound waves determines their equivalent acoustic parameters, so the equivalent acoustic parameters of active acoustic metamaterials are a quantity controlled by a circuit.

Consider a cavity with a piezoelectric ceramic film at one end (as shown in Fig. 1). At this point, the formula can be rewritten in the Laplace transform domain [5]

$$\begin{bmatrix} \Delta V_{\mathrm{O}} l_p \\ q \end{bmatrix} = \begin{bmatrix} C_d & d_A \\ d_A & 1/Z_p s \end{bmatrix} \begin{bmatrix} \Delta p_p \\ V_P \end{bmatrix} \tag{1}$$

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Where, $\Delta V_{\mathrm{O}}l_p$ is the volume change of the piezoelectric ceramic film, q is the accumulated charge on the surface, Δp_p is the pressure difference on both sides of the piezoelectric ceramic film, V_P is the voltage on the piezoelectric ceramic, C_d is the flexibility coefficient of the film, d_A is the effective piezoelectric coefficient, Z_p is the impedance of the piezoelectric ceramics and its subsidiary circuit.

For mechanical vibration, there is also a similarity with the circuit components. For example, the behavior of the material's compliance coefficient is similar to that of the capacitor. The quality of the material has the effect similar to that of the inductor. Thus, the system shown in Fig. 1 can be fully represented as a circuit form. As shown in Fig. 2, the final circuit form is the acoustic domain, and the mechanical vibration domain and the electrical domain together form a structure. Through this equivalent circuit, we can directly control the behavior of the piezoelectric ceramic (mainly its voltage) by solving its transfer function, and then control the sound pressure change to obtain the required acoustic parameters.

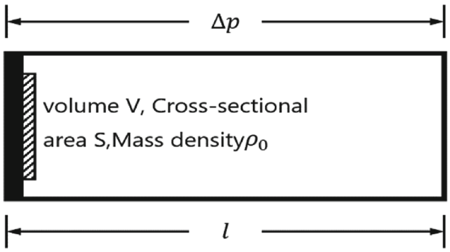

Fig. 1. Piezoelectricity

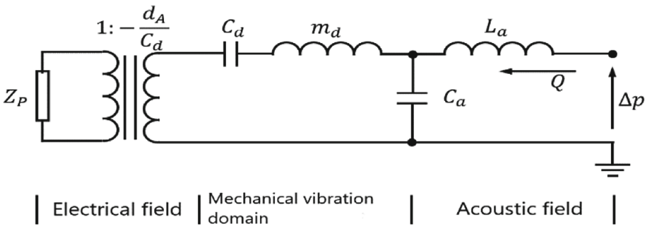

Fig. 2. Equivalent circuit of a thin film cavity of piezoelectric ceramics

3 One-Way Active Acoustic Mixer Based on Metamaterial

The above investigation shows that the desired acoustic parameters can be obtained by introducing piezoelectric materials and reasonable control of electrical quantity. Further, if the desired filtering function is achieved directly by the circuit connected with the piezoelectric material, the range of functions of the acoustic metamaterial can be greatly extended. Cummer et al. proposed a method that can realize the transformation of incident sound wave into its second-order harmonic, and this material has directional selectivity. Only the sound wave incident from the "positive direction" can be converted and amplified, so it is a one-way nonlinear acoustic metamaterial [6].

The structure of the material is two back-to-back Helmholtz resonators, which use a piezoelectric ceramic film as the common surface. Figure 3 is a schematic diagram of the piezoelectric ceramic film. It has three electrodes: ground, main and a sensing electrode. As shown in Fig. 4, the two Helmholtz resonators in this material have similar structures. They are all cylindrical cavities with only one opening, and the structural parameters are the same except for the different diameter of the opening.

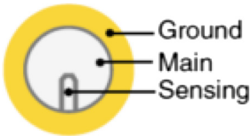

Fig. 3. Schematic diagram of piezoelectric ceramic film

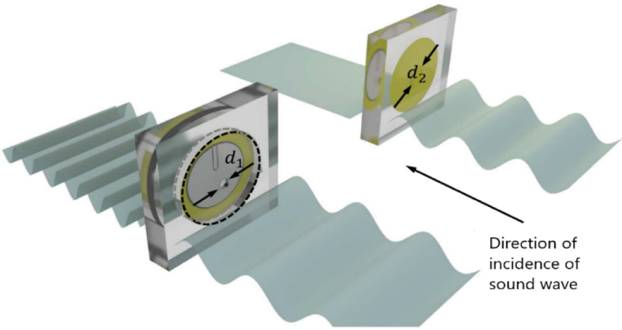

Fig. 4. Functional diagram of unidirectional acoustic frequency multiplier material [6]

This design has some disadvantages in practical use. For example, in circuit design, the isolation of electrical signals between the measuring electrode and the main electrode must be considered, which requires that the resonant frequencies of the two Helmholtz resonators are far apart from each other. Since the method to produce second order harmonic is to use a full wave rectifier, it can only produce an even number of times frequency signal, and the higher the intensity of the signal is lower, which makes the material has poor universality.

With the acoustics of the corresponding part of the process in the operation process analog circuit alternative ideas are similar, we can realize the corresponding function in the digital domain, and through the AD/DA converter (AD/DA) implementation between analog signal and digital signal conversion, is shown in Fig. 5 the analog signal processing to replace as shown in Fig. 5 the digital signal processing. The adoption of digital signal processing not only achieves good isolation between input and output signals through the conversion process of AD/DA, but also allows us to not stick to the full-wave rectifier, but to use more general frequency conversion strategies.

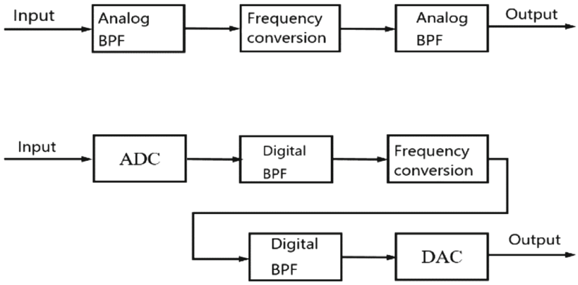

Fig. 5. Analog and digital implementation of active acoustic metamaterial control circuits

Since there are two bandpass filters before and after the frequency change module to filter out the frequency components beyond the required frequency, the input signal can be multiplied by the sine wave of a certain frequency and then the signal can be passed through the bandpass filter with the required frequency as the center frequency. As shown in Fig. 6, A signal with a center frequency of f_c is superimposed with a sine wave with a frequency of f_0 in the time domain, so the change in the frequency domain is that the signal will be shifted by f_0 in the positive and negative directions of the frequency domain, that is, the superposition of two signals with center frequency of $|f_c - f_0|$ and $f_c + f_0$ is obtained. In this way, after obtaining the frequency of the input signal, only the sine wave of the appropriate frequency needs to be generated and the input signal can be processed as described above to transform the input signal to any frequency point.

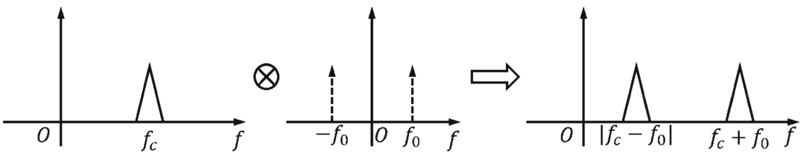

Fig. 6. Schematic diagram of general spectrum

4 Manufacturing, Implementation and Testing of Active Acoustic Mixer

The design of active acoustic metamaterials needs to consider both the material and the circuit at the same time. Therefore, the preparation of the materials, the design and implementation of the circuit system and the construction of the test system should be considered comprehensively when testing the corresponding materials.

4.1 Material Preparation

The same piezoelectric ceramic thin film in [6] is used here (as shown in Fig. 7). It is manufactured by Murata, and its corresponding model is 7bb-35-3cl0.

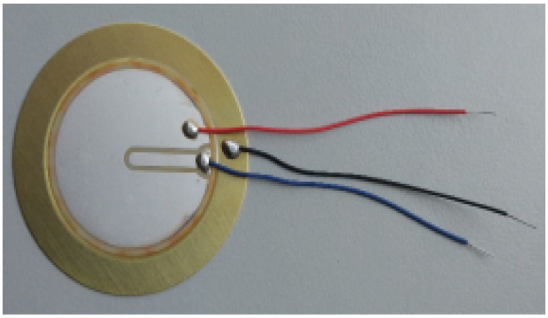

Fig. 7. Physical picture of piezoelectric ceramic film

The dimensions of two back-to-back cylindrical Helmholtz resonators are: the cavity body diameter is 33 mm, the height is 1.5 mm, the opening depth is 1.5 mm, and the opening diameter is 3 mm and 9 mm, respectively. The material used is acrylic. Through simulation of the two sized Helmholtz resonators in Sect. 2, the absorption coefficient curve shown in Fig. 8 can be obtained. It can be seen that their corresponding resonant frequencies are about 1350 Hz and 2700 Hz respectively.

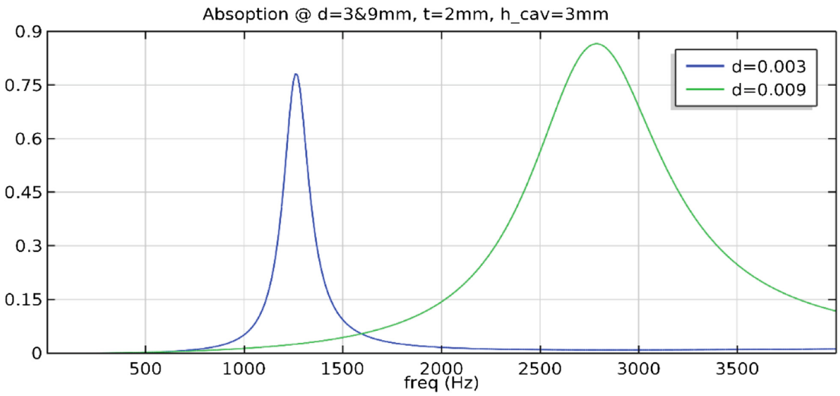

Fig. 8. The absorption coefficient curve of Helmholtz resonator

The specific manufacturing method is to carve the required cavity or hole on the 1.5 mm thick acrylic board, and then bind the acrylic board and the piezoelectric ceramic film together. In order to control the simplicity of piezoelectric ceramic thin films, two piezoelectric ceramic thin films are used, one specially for measuring incident acoustic signals and the other specially for producing output acoustic signals. The final material is shown in Fig. 9.

4.2 System Block Diagram and Module Realization

Figure 10 is the FPGA implementation block diagram of the test system and control circuit. Both the test and metamaterial control circuits are on the FPGA, which can be

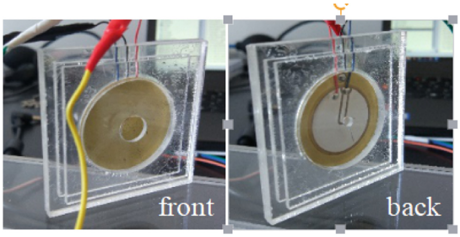

Fig. 9. The resulting active acoustic metamaterials

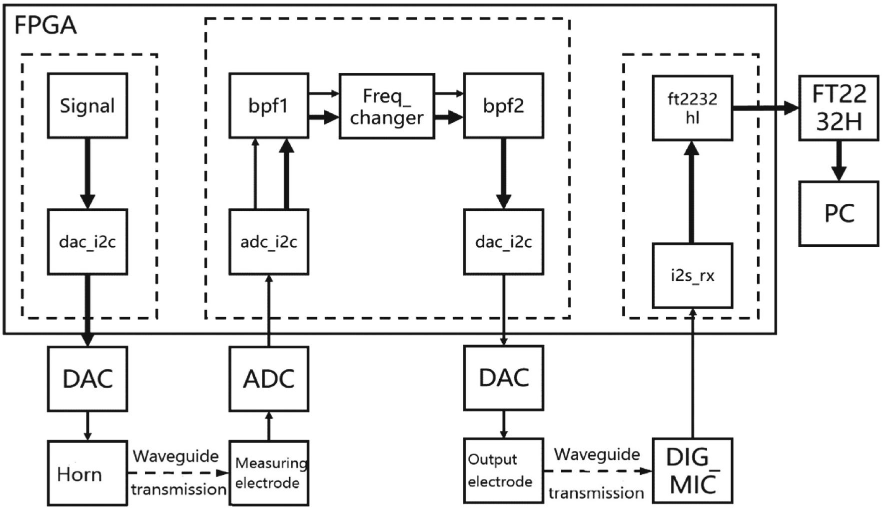

Fig. 10. FPGA realization block diagram of measurement and control system

roughly divided into three modules by function. In the left box is the test signal generator circuit, the DAC will convert the signal into analog signal output to the horn. On the right is a signal measurement module based on the digital microphone based on I2S bus, which will measure the acoustic wave transmitted from the material. The intermediate block diagram is the control circuit of acoustic metamaterial, which obtains the corresponding input sound wave signal through ADC, and then transmits the output sound wave signal to the piezoelectric ceramic film through DAC. Figure 11 is the physical picture of the whole system

4.3 Module Implementation

ADC/DAC Control Module. The ADC and DAC functions are implemented via Philips semiconductor's PCF8591 chip, which integrates AD/DA functions on a single chip. The PCF8591 chip provides an I2C bus interface for communication with the outside world, and its sampling frequency is up to 11 kHz with 8-bit digits. Two DAC and one ADC are required for the entire test system.

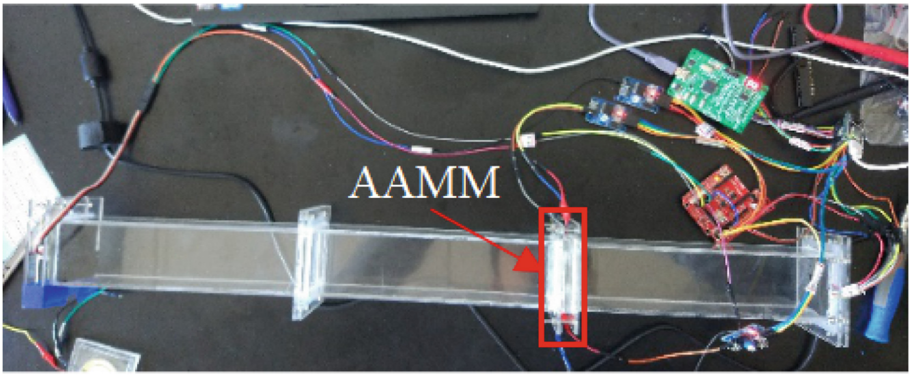

Fig. 11. Test system physical map

Digital Microphone Module. The system USES digital microphone as signal collector when collecting the final result. The digital microphone circuit module made by Adafruit is used here. Its core chip is the MEMS digital microphone made by Knowles, sph0645lm4h-b. The chip is based on the I2S audio bus, which has a sampling precision of 18 bits signed number. Its sampling frequency is adjusted by setting the frequency of the clock that controls microphone operation. The sampling frequency adopted in this paper is 46.875 kHz.

Data Transmission Module. The digital signal measured by the digital microphone is first sent by the FPGA to the FT2232H chip, which then transmits the data to the computer through the USB port. On the computer, the C program written by the corresponding driver needs to read the measurement results from the USB port. FT2232H is a USB serial port chip made by FTDI. FPGA can send data to the USB port in bytes or read data from the USB port. After obtaining the measurement results of digital microphone, FPGA needs to send the data to FT2232H chip through the data transmission module ft2232hl.

Design of Bandpass Filter. The bandpass filter module is one of the bandpass filters with central frequency of 1350 Hz and 2700 Hz respectively. Their amplitude spectrum and phase spectrum are shown in Figs. 12 and 13. According to the different functions of octave or half frequency, the positions of them will be interchanged before and after the frequency conversion module. Half frequency is just the opposite. The filter coefficient is quantified by the number of eight symbols.

Frequency Conversion Module. The frequency conversion module is a module taking the absolute value in frequency multiplication. For the number of symbols represented by binary complement, we can carry out different processing according to the different symbol bits. This paper adopts a unified approach, namely: the use of any a binary number of which is “1” exclusive or invert, and the characteristics of “0” or stay the same, the complement says first every bit binary number and its exclusive or the sign bit, and then will get the results of the exclusive or plus the sign bit, and the final result is obtained.

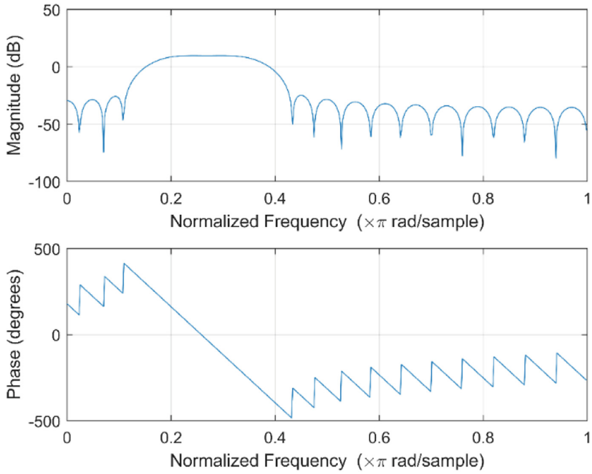

Fig. 12. The amplitude and phase spectrum of a bandpass filter with a central frequency of 1.35 kHz

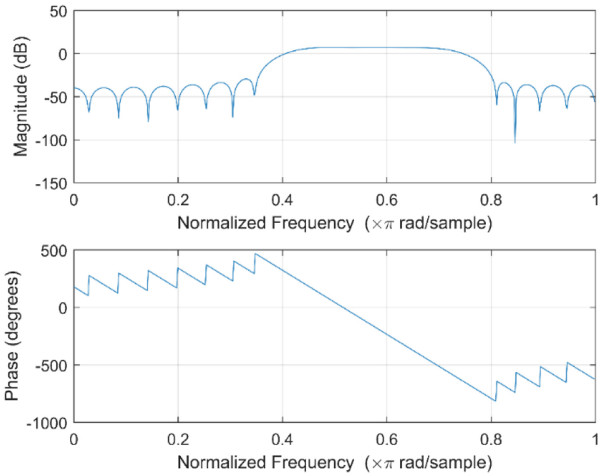

Fig. 13. The amplitude and phase spectrum of a bandpass filter with a central frequency of 2.7 kHz

In half-frequency conversion, the frequency conversion module includes a peak position control square wave generator and a multiplier. The peak position is determined by whether the current signal is larger than the previous signal and the latter signal at the same time. If the detection determines the peak position, a flag will be flipped. So, the flag signal is a pseudo-square wave. Because multiplication and square wave multiplication is actually and, so the actual implement the operation of the time and take the absolute value of similar methods: will take the sign bit of absolute value operation substitute flag bit can achieve the desired effect, and also is the data of each flag and exclusive or, then add flag will be the final result. Therefore, the square wave generator and multiplier mentioned here are corresponding to their actual effects, and the actual circuit will not actually realize a square wave generator and multiplier.

System Operation Flow Chart. The flow diagram of the whole system is shown in Fig. 14. Since active control, including test signal generation, result measurement and metamaterials, is performed on the FPGA, there are three independent processes on the FPGA after it starts and initializes the ADC/DAC module, data transfer module and several shift registers.

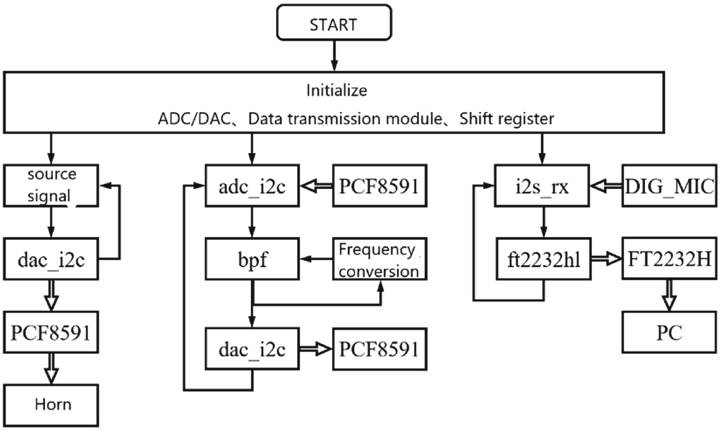

Fig. 14. System operation flow chart

Firstly, the source signal generation module and dac_i2c module cooperate to continuously convert the source signal into DAC and drive the horn to generate the initial sound wave required for testing. Secondly, the i2s_rx module and ft2232hl module cooperate to continuously read the final results from the digital microphone and send them to the upper computer through the USB chip. Thirdly, the adc_i2c module continuously reads the response of the piezoelectric ceramic film under the action of acoustic wave, and then drives the piezoelectric ceramic film to generate the corresponding target sound wave after being processed by bandpass filter - frequency conversion - bandpass filter.

5 Test Results

The half-frequency function is tested. The signal output to the horn is the sound wave input signal with center frequency of 2700 Hz. After the acoustic wave passes through the material in the forward direction, the time-domain waveform and spectrum of the signal measured at the digital microphone are shown in Fig. 15. When the sound wave enters the material from the opposite direction, the time-domain waveform and spectrum of the signal measured at the digital microphone are shown in Fig. 16. It can be seen from Figs. 15 and 16 that the unidirectional half-frequency material has a good effect in frequency conversion and a unidirectional inhibition rate of 44.8 dB is achieved.

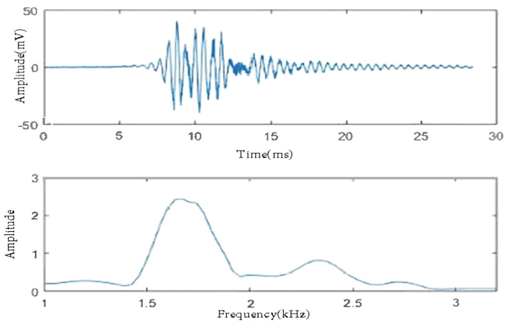

Fig. 15. The time domain waveform and spectrum of transmission signal of half frequency material in positive direction

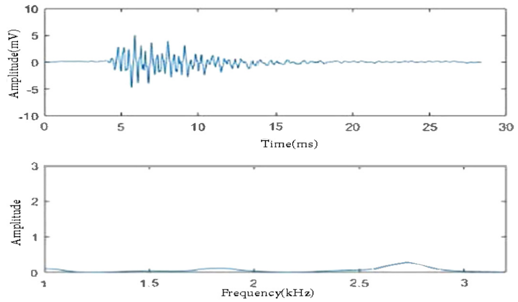

Fig. 16. The time domain waveform and spectrum of the transmission signal of the frequency multiplier material in the opposite direction

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