Design of an experimental platform to investigate the effects of audible sounds on plant growth

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Abstract: An experimental platform was developed to investigate the effects of audible sound (20 Hz to 20 MHz) on plant growth promotion, which included a microcontroller-based embedded system for audible sound adjustment and analysis. The direct digital frequency synthesis (DDFS) method was used to generate various waveforms of sound in the platform. Soundproof glass and mufflers were used to reduce background noise. The developed system was tested on various plants, including hydroponic tomatoes, celery and mung bean. The testing results showed that the developed platform could produce pure tone and mixing audible sound with high stability and accuracy, make octave analysis of the sound under experimental environments, and the background noise in the testing chamber of the platform was lower than 55 dB(A) when the compression engine was working. The developed experimental platform has a great potential on facilitating scientific research on acoustic biology effects on plants and collecting real-time experimental data.

Keywords: plant growth, background noise, acoustic biology effect, direct digital frequency synthesis, sound sensor
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1 Introduction

Modern agriculture heavily relies on applications of fertilizers to promote plant growth and crop yield. However, long-term fertilizer applications have brought severer environmental pollution. Reduction of chemical uses in crop production has been one of the major tasks for agricultural engineers. Recent studies have revealed that as a clean solution, audible sound stimulation has a great potential to improve plant growth and the quality of products. In recent years, many researchers have been investigating the effects of various kinds of sound on the growth of plants or animals, including human beings. Ultrasound and infrasound can have effects on biological tissues through thermal or mechanical process[1-4]. The germination period of plant seeds (Vigna radiate, Okra and Zucchini) were reduced after audible sound treatments[5,6]. Sound stimulation could decrease requirements of chemical fertilizers and biocides[7-9]. Sound stimulation can speed up the protoplasmic movement in the cells by vibrating plant leaves[10-12]. Some results showed that the appropriate acoustic wave could accelerate plant growth. Some commercial

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growers have started to apply various sounds to increase plant growth rate[9,13]. Hou et al.[14-16] applied music tones to improve yield of tomato plants and investigated the effect of sound technology on the plant meridian system to improve the yield and quality of plants.

Although many results showed the impacts of sound on improving growth rate and quality of plants, there was no solid theoretical proof or mathematical models which could be used to establish appropriate plant-specific sound systems. Most of research was based on trial-and-error due to lack of precise devices to facilitate plant growth studies in the acoustic biology. Intelligence artificial climate chambers are commonly used for plant experiments. They are not suitable to conduct experiments of audible sound effects on plants because they often have high background that makes high noise (usually higher than 65 dB(A)) during operation.

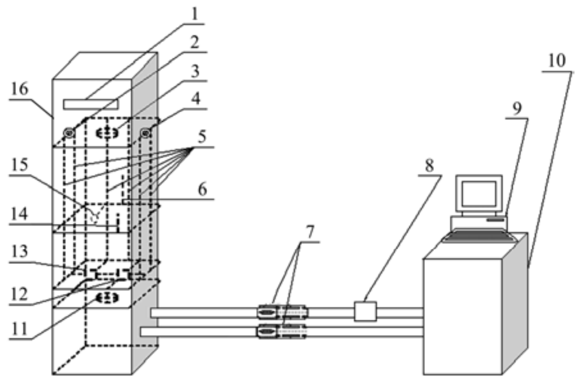
Direct digital frequency synthesis (DDFS) devices are used to generate analog arbitrary signals[17] which consist of ARM microprocessor, digital signal processing (DSP) unit, and field programmable gate array (FPGA) unit. The devices can provide faster switching between output frequencies, better frequency resolution, and broader frequency ranges than traditional signal generation approaches. They are often included in complex system development, algorithm verification, prototype trial-manufacture and prototype evaluation such as multimedia processing system, digital communication system, high performance instrument prototype development, however, they have not been used for audio signal generation systems.

The main objective of this research was to design and develop a new scientific research platform with lower working noise and higher stability to assist the study on how audible sounds affect plant growth.

2 Principle and methods

2.1 Composition of the designed experimental platform

Figure 1 shows the developed experimental platform, including a control circuit board for environment parameter adjustment, two infrared cameras, two speakers, a daylight source, a humidity sensor, ducts mufflers, a circulation fan, a PC for data entry, collection, and storage, a box for heating tube and refrigeration compressor, load cells, a temperature sensor, an illumination sensor and a plant cultivation chamber.



1. Control unit for environment parameter adjustment 2,4. Infrared cameras, 3,11. Speakers 5. Daylight source 6. Humidity sensor 7. Ducts mufflers 8. Circulation fan 9. PC for data entry and record 10. Heating tube and refrigeration compressor 12,13. Load cells 14. Temperature sensor 15. Illumination sensor 16. Plant cultivation cabinet

Figure 1 Structure of experimental platform for studying audible sound effects on plant growth

To study plant growth, the inside climate of the plant cultivation chamber needs maintained at specific levels of temperature, humidity, carbon dioxide and light, respectively.

The control circuit board was designed for creating plant growth environments and the sound analysis and adjustment part was also designed combined with the circuit board for produce reliable arbitrary waveforms sound. In order to reduce the background noise in the plant cultivation cabinet, the refrigeration compressor was separated from the cabinet and installed in another box and two mufflers were set in the circulation fan ducts, moreover, soundproof glass was used in the cabinet walls. Two infrared cameras mounted on adjustable pulleys and load cells along with the PC were used to monitor the growth of plant. The levels of temperature, humidity, carbon dioxide and light were controlled in a conventional way as the Intelligence artificial climate chamber produced by experimental instrument factory of Ningbo Haishu SAIFE (Type: PRX-600C-C02), whose temperature control ranging from 15°C to 50°C (adjusting precision ±0.8°C), humidity control ranging 30%-90%RH (adjusting precision ±7%RH), carbon dioxide control ranging 280-5000 μL/L and light control ranging 0-22 000 lx.

As the characteristics of sound loaded in plant growth conditions is a main factor in studies of audible sound effects on plant growth, generating high quality sound and enabling sound analysis and adjustment are the most important task that should be considered in the design.

When the plant growth chamber works, the speakers will generate various waveforms according to input signals from the PC, the two infrared cameras and load cells are used to record the states of plant growth continuously, and the temperature and humidity sensors are used to measure the real-time environment parameter of the plant growth chamber.

2.2 Basic principle of arbitrary waveforms generator

The direct digital frequency synthesis (DDFS) method was used to generate various waveforms. It consists of a phase accumulator, phase-to-amplitude converter, a digital-to-analog converter (DAC), and a filter (Figure 2).

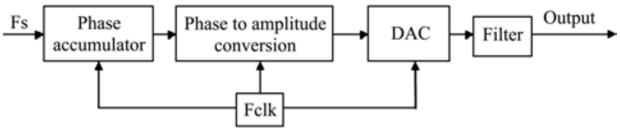


Figure 2 Block diagram of direct digital frequency synthesis (DDFS) device

The frequency of the generated signal depends on three variables: a reference-clock frequency (F_{clk}), the length of accumulator (k), and a binary number (f_s) programmed into the phase register. When a sine signal is recorded, the phase accumulator computes a phase address for the waveform memory, which outputs the digital value of amplitude to the DAC. The DAC, in turn, converts the number to a corresponding value of analog voltage or current. To generate a fixed-frequency sine wave, the phase increment was determined by the binary number f_s added to the phase accumulator every clock cycle, and the phase accumulator was used to generate phase data for the system. When the phase increment is small, the phase accumulator will take many more steps, thus generating a slower waveform. When the phase increment is large, the phase accumulator will step quickly through the sine record in the waveform memory and then generate a high frequency sine wave.

The frequency of the output sine wave can be described as follows (also known as the tuning equation of DDFS):

$$F_{out} = \frac{f_s \times F_{clk}}{2^k} \quad 2^{k-1} > f_s \geq 1 \tag{1}$$

where, F_{out} is the output frequency of DDFS; f_s is the frequency setting word; k (in bits) is the length of the phase accumulator; F_{clk} is the system clock frequency.

According to Equation (1), any changes on the value of f_s result in immediate changes in the output frequency. In a DDFS, no loop settling time is incurred as in the case of a phase locked loop (PLL). As the output frequency is increased, the number of samples per cycle decreases. According to sampling theory, at least two samples per cycle are required to reconstruct the output waveform. The maximum fundamental output frequency of a DDFS is $F_{\mathrm{clk}}/2$. But the output frequency is limited to less than that for practical applications, improving the quality of the reconstructed waveform and permitting filtering on the output. When generating a constant frequency, the output of the phase accumulator increases linearly. Therefore, the analog waveform it generates is inherently a ramp.

2.3 Hardware component for sound analysis and adjustment

As shown in Figure 3, the hardware for sound analysis and adjustment system consisted of a C6-Integra DSP+ARM Processor OMAP-L137 (Texas Instruments), a Xilinx Spartan™-3A FPGA Platform--XC3S50A (Xilinx), a D/A converter CS4341 (Cirrus Logic, Inc.), an A/D converter AK5350 (Asahi Kasei Microsystems), sound sensor and a personal computer (PC).

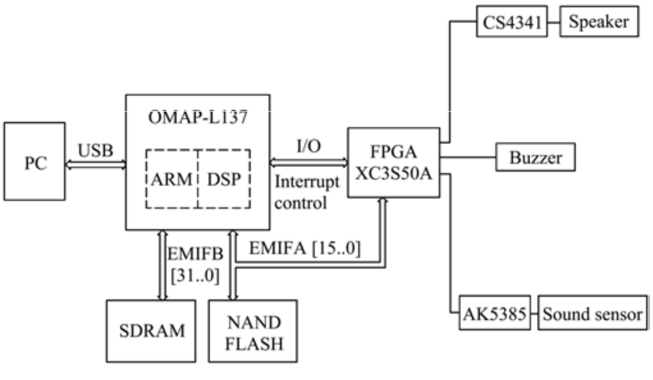


Figure 3 Schematic diagram of hardware component for sound analysis, adjustment and storage

The OMAP-L137 is a low-power processor based on an ARM926EJ-S and a C674x DSP core. It had features of robust operating system support, rich user interfaces, and high processing performance through the maximum flexibility of fully integrated mixed processor solutions. The ARM926EJ-S is a 32-bit RISC processor core that performs 32-bit or 16-bit instructions and processes 32-bit, 16-bit or 8-bit data, and the core uses pipelining so that all parts of the processor and memory system can operate continuously. The C674x DSP core uses a two-level cache-based architecture: the Level 1 program cache (L1P) is a 32 kB direct mapped cache and the Level 1 data cache (L1D) is a 32 kB 2-way set-associative cache; the Level 2 program cache (L2P) consists of a 256 kB memory space that is shared between program and data space. L2 memory can be configured as mapped memory, cache, or combinations of the two. Although the DSP L2 is accessible by ARM and other hosts in the system, an additional 128 kB RAM shared memory is available for use by other hosts without affecting DSP performance. The Spartan-3A FPGA XC3S50A is one of programmable chips with 1.4 M system gates, and 502 I/Os, with density migration. The phase accumulator and phase to amplitude conversion of DDFS were realized through programming in the FPGA which was also used for data communications and external state control. The CS4341 is a complete stereo digital-to-analog system including digital interpolation, fourth-order Delta-Sigma digital-to-analog conversion, digital de-emphasis and switched capacitor analog filtering. The advantages of this architecture include: ideal differential linearity, no distortion mechanisms due to resistor matching errors, no linearity drift over time and temperature and a high tolerance to clock jitter. The CS4341 can accept data at audio sample rates from 4 kHz to 100 kHz. There is a filter in the inner of CS4341. So it is not necessary for us to design additional filter for the DDFS module. The AK5385A is a 24-bit, 192 kHz sampling rate, and 2-channel A/D converter for high-end audio system. The modulator in the AK5385A uses the Enhanced Dual Bit architecture and the AK5385A realizes high accuracy and low cost. The AK5385A performs 114 dB dynamic range, which can meet the dynamic range from 0 dB to 110 dB of our design requirement. The feedback analysis network was accomplished through using a sound pressure sensor, the A/D converter and programming in the OMAP-L137 (the sound analysis are mainly made by the C674x DSP core), which can improve sound the sound output accuracy.

In the design, the functions such as user interface, frequency setting control for the DDFS system, feedback analysis for output sound waves are mainly conducted on the OMAP-L137 processor, which is one of the cores in the design of audible sound analysis and adjustment.

The PC was used to send or receive control or sound signal information from the OMAP-L137 processor through user-friendly software. The audible sound signals detected by the sound pressure sensors were recorded in the PC.

2.4 Verification test of the designed experimental platform

The main functionalities and advantages of the designed experimental platform, including producing various waveforms, having lower background noise, making octave analysis of the sound frequency components in the plant cultivation cabinet, and the output accuracy before and after the closed control loop works were tested, respectively.

Sine waves with frequency of 1.1 kHz, 2.2 kHz, 3.3 kHz, 1.1 kHz+2.2 kHz, 2.2 kHz+3.3 kHz, and 1.1 kHz+3.3 kHz were generated, and output signals of the platform were collected and compared with the original signals.

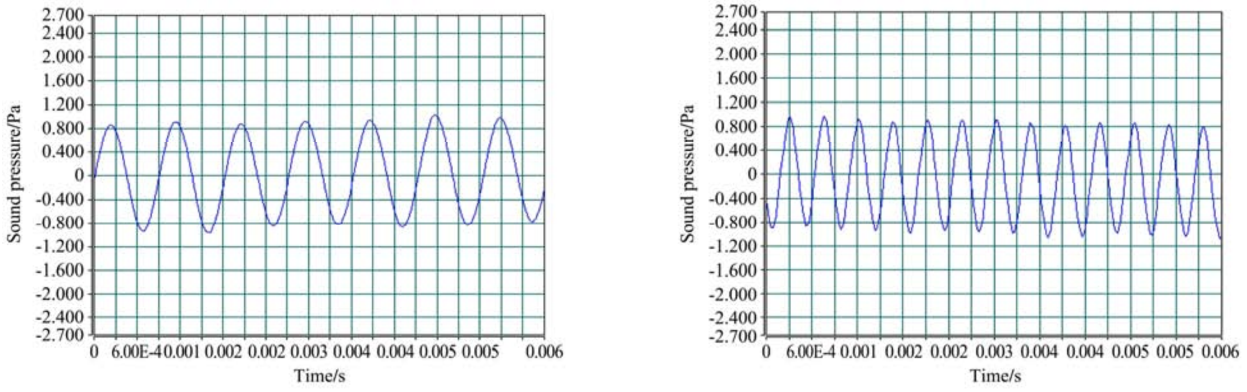
In order to compare the levels of background noise from the developed platform and the traditional intelligence artificial climate chamber, the total background noises were collected and compared.

Although sound level sensors have been used as a conventional way to measure sound, they could not obtain frequency information. It is difficult to compare different sound effects when they were used to study audible sound effects on plant growth[18,19]. Octave analysis filtered the signal and measured the energy at the output to provide useful frequency information. With fractional-octave analysis, a frequency resolution could be selected that was well adapted to the signal of interest. Hence, octave analysis was a valuable tool for visual inspection and comparison during our researches. The developed experimental platform offers octave analysis of output sound both for the output regulation and frequency information. Octave analysis was made in the plant cultivation cabinet when the test work was conducted. The octave analysis of background noise, Mozart music, and insects'/ birds' sounds were input to the platform to test whether the platform could offer important scientific evidences (such as frequency components of the sound in the plant growth environment) for experiment of sound effects on plant growth.

The accuracy of closed-loop control for audible sound output was tested using a section of music sound.

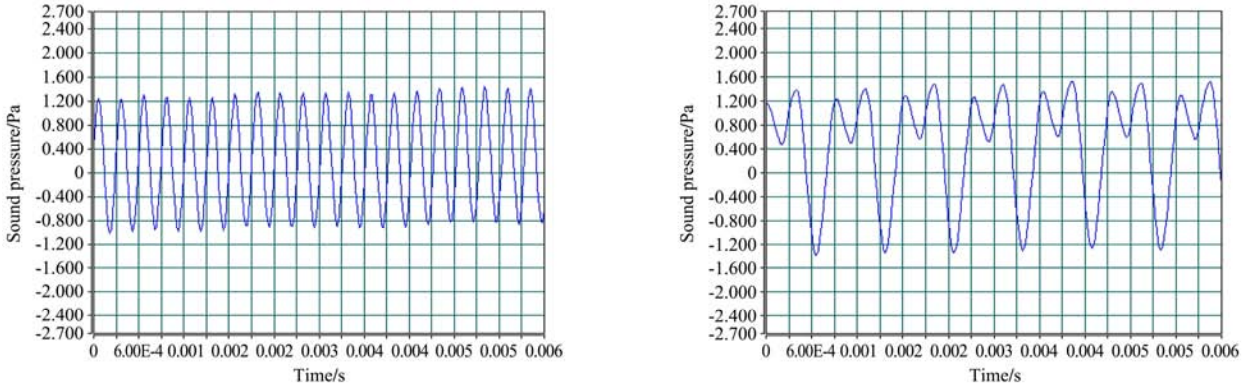
3 Results and discussion

Figure 4 shows the time domain signal graph of sound waves collected at the output of the developed platform when a sine wave with frequencies of 1.1 kHz, 2.2 kHz, and 3.3 kHz was input respectively and a sine wave with combined frequencies of 1.1 kHz+2.2 kHz, 1.1 kHz+ 3.3 kHz, and 2.2 kHz+3.3 kHz was input respectively. The results showed that the platform could output sound within a frequency range of 20 Hz to 20 kHz and combined sound wave in the plant growth chamber with high output accuracy.



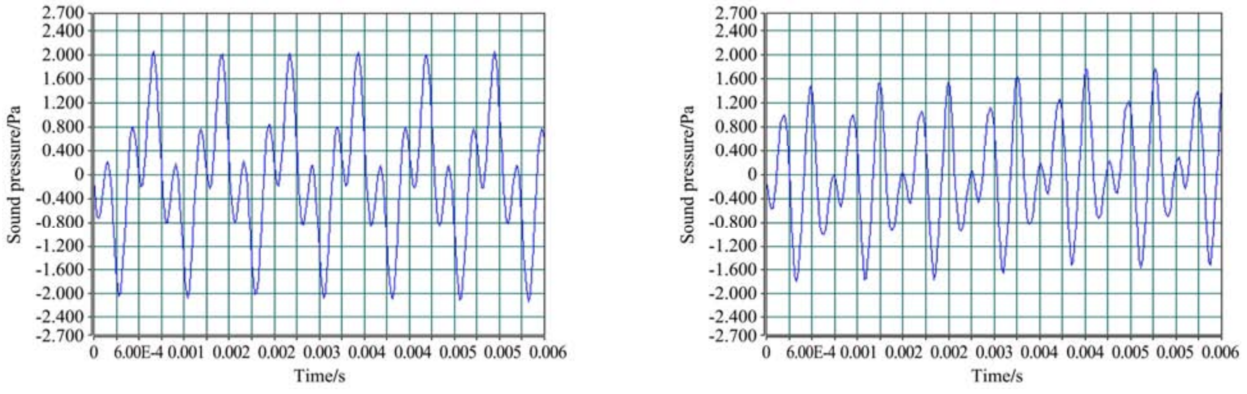
a. 1.1 kHz

b. 2.2 kHz



c. 3.3 kHz

d. 1.1 kHz+2.2 kHz



e. 2.2 kHz+3.3 kHz

f. 1.1 kHz+3.3 kHz

Figure 4 Output signals collected from developed platform with different input signals

Figure 5 shows the octave analysis graph of background noise in the plant cultivation cabinet of the platform. The background noise was also a factor in the research on propagation growth. So it will give us deeper understanding on the grow environment and help to explore growth promotion secrets to analysis background noise. Moreover, it can be found that the total noise is less than 55 dB(A) in the plant cultivation cabinet, which offers a better experimental environment than intelligence artificial climate boxes (usually, the background noise in the boxes are more than 65 dB(A)) available in present markets).

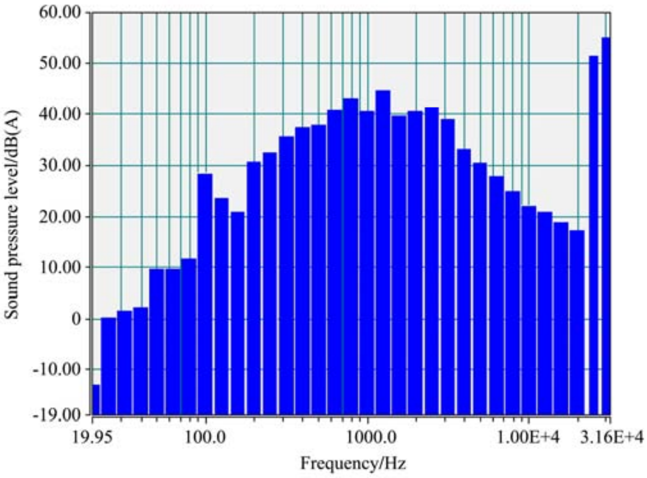


Figure 5 Octave analysis graph of background noise

Figure 6 is the octave analysis graph of a slice of Mozart music. Through the octave analysis on Mozart music, it can be found that frequencies around 1.5 kHz are main frequency components in the Mozart music. This offers us a scientific way in study of sound signal frequency component.

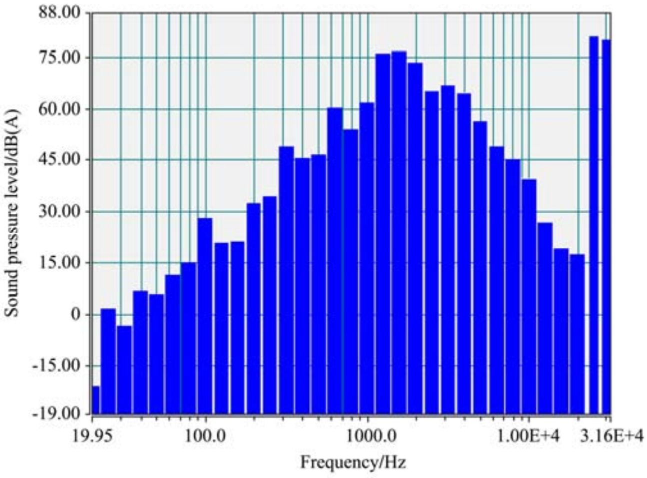


Figure 6 Octave analysis graph of a slice of Mozart music

Natural sound such as thrush sound may have an effect on propagation growth according to many studies[6,20]. The experimental platform can simulate the cricket or other insects' or birds' sound for the studies and the sound frequency can also be analyzed by the platform.

Figure 7 shows the octave analysis graph of thrush sound. Through the octave analysis on thrush sound, it can be found that frequencies around 2.0 kHz are main frequency components in thrush sound. This offers us a scientific way in study of birds' sound effect on the growth of plant.

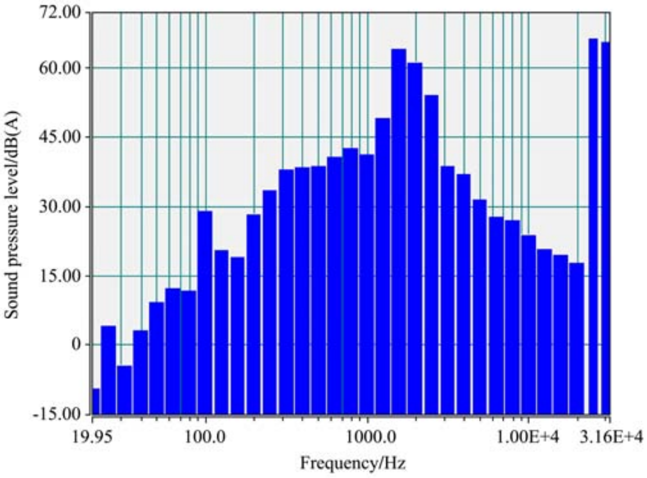


Figure 7 Octave analysis graph of thrush sound

Figure 8 is the octave analysis graph of cricket sound. Through the octave analysis on cricket sound, we can find that frequencies around 4.0 kHz are main frequency components in cricket sound. This offers us a scientific way in study of insects' sound effect on plant growth.

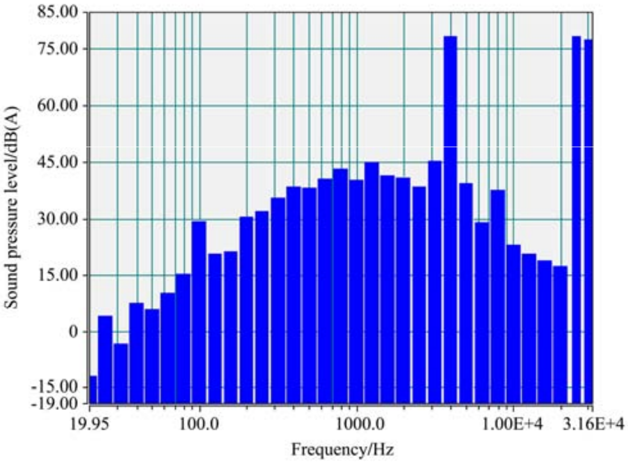
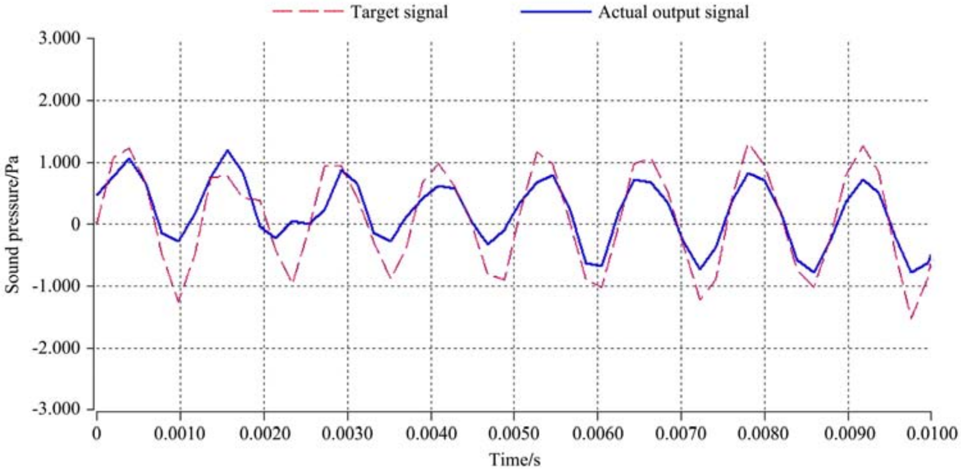
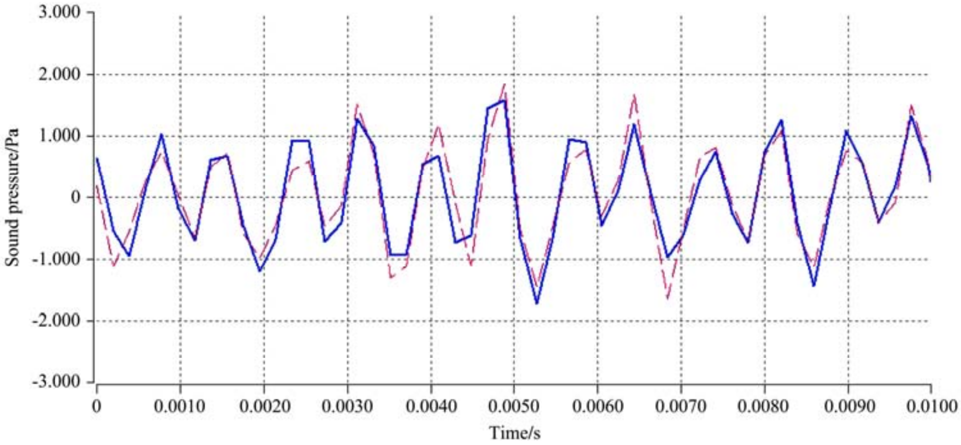


Figure 8 Octave analysis graph of cricket sound

Figure 9 is the time domain diagram of target music and the measured actual output audio signals before and after calibration. From the comparison of the actual output audio signals, we can find that the audible sound output is more accurate when the sound sensor is used for feedback and calibration (closed loop) than the output before the feedback sound sensor of analysis network works (open loop).



a. Results of open loop control for audible sound generating



b. Result of closed loop control for audible sound generating

Figure 9 Time domain diagram of target music and measured actual output audio signals

In summary, the experimental platform developed in the study could meet the requirements for generating various audible sound waveforms, monitoring the output of sound waves, and analyzing the characteristics of sound waves. The background noise of the plant cultivation cabinet in the developed platform was lower than those of most of the current available plant growth chambers. It could be a useful tool for researchers to study acoustic biology effects on plants.

4 Conclusions

An experimental platform was designed and developed for studying sound signal frequency component and facilitating the study of sound effects on plant growth. The platform could generate various sound waveforms required for the studies, and analyze sound characteristics based on octave analysis function in the plant growth chamber.

Compared with most of traditional temperature controllable experimental devices of plant growth such as artificial climate boxes, the background noise of the plant cultivation cabinet in the developed platform was lower than 55 dB(A) when the compression engine was working. The sound sensing and analysis function developed was based on a new embedded development system with microprocessors (ARM, DSP, and FPGA cores), multiple sensors (sound level sensor, Temperature sensor and so on), and the DDFS technology, which enable us to make feedback analysis networks for the output sound and generate arbitrary waveforms in the novel plant growth chamber.

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