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Research Report

Development of a Multiple Synthesizer System for Electronic Music

Ichiro TSUJI

Abstract

This paper describes the design and signal paths of a synthesizer system that produces rich sound effects by performing sound synthesis of a sine wave and a pulse width modulation (PWM) signal using Wien bridge oscillators, a multiplier, and a biquad circuit. Three Wien bridge oscillators were used in this system. Although the output signal of a conventional Wien bridge oscillator is a sine wave, the first Wien bridge oscillator in the proposed system opens the conventional feedback loop of the Wien bridge oscillator and inserts a novel feedback circuit that introduces pulse-width modulation into the signal path. Furthermore, the gain, frequency, and feedback signal of the Wien bridge oscillator are controlled by a PWM signal. Thereby, the Wien bridge oscillator outputs the signal modulated intricately. The second Wien bridge oscillator includes an analog photocoupler whose resistance can be changed by using a control signal to implement frequency modulation. The third Wien bridge oscillator performs frequency modulation using a variable resistor. Next, the output signal of the first Wien bridge oscillator is fed into a biquad circuit. The biquad circuit creates an output signal by adding the output signal of the bandpass filter of the biquad circuit and the output signal of an analog switch. The input signal of the biquad circuit drive this analog switch. By controlling the resistance and analog switch status of the biquad circuit using two control signals, the biquad circuit can be changed to a band elimination filter, an all-pass filter, and two bandpass filters with different sensitivities, thereby changing the timbre. Furthermore, multiplication is carried out using the output signals of the Wien bridge oscillators. Two multipliers are used. The first multiplier performs the multiplication of the output signals of the second and the third Wien bridge oscillators. The second multiplier performs the multiplication of the output signals of the first and the third Wien bridge oscillators. Finally, by inputting three control signals into a voltage control circuit, the output signal of the biquad circuit and the output signals of two multipliers are controlled, and sound synthesis is conducted. The control signals used for the biquad circuit, second Wien bridge oscillator, and voltage control circuit are all derived from the output signal of a Universal Serial Bus (USB) device. This system can then be used to create sound effects by analyzing its input and output signals. To evaluate the performance of this system, the design was tested, and its timbre was evaluated.

1. Introduction

The Wavestation A/D synthesizer, designed by Korg Inc., includes a wave sequence function that performs sound synthesis by utilizing a digital waveform to control the timbre. (Jungleib and Phillips 1991). Four kinds of wave sequences can be simultaneously generated to produce one sound, and complicated timbres can be produced. Furthermore, an envelope, low-frequency oscillator (LFO) modulation, and special effects such as reverberation, time delays, or flanging can be applied to the wave sequence. The newest iWAVESTATION is an application that can run on the iOS operating system; moreover, it is convenient and miniaturized. This system is simple compared with the wave sequence of Wavestation A/D. However, analog signal processing is necessary to produce different timbres with digital signal processing. The possibility of controlling the timbre by connecting an analog waveform has been considered. Furthermore, amplitude modulation by a multiplier and frequency modulation by a Wien bridge oscillator have been employed to create a rich timbre.

2. Basic Structure of Multiple Synthesizer System

The basic structure of our proposed system is shown in Figure 1. A computer and a USB device are connected with a USB interface (I/F) to form a computer synthesizer (Tsuji 2015). A computer synthesizer generates a PWM signal and a control signal that are output from a USB device. The USB-FSIO30 from Km2net was used for the USB device (Komatsu 2011). A PWM signal is input into the Wien bridge oscillator 1 and the control circuit 1. A control signal is input into control circuit 2. The signal output from control circuit 1 controls the frequency, the gain, and the feedback signal of Wien bridge oscillator 1. The signal output from control circuit 2 controls the analog switch, the resistance of the biquad circuit, the center frequency (or phase shift) of the biquad circuit, the frequency of the Wien bridge oscillator 2, and a voltage control circuit. The multiplication of the output signals of Wien bridge oscillator 2 and Wien bridge oscillator 3 is carried out using multiplier 1. The multiplication of the output signals of Wien bridge oscillator 1 and Wien bridge oscillator 3 is carried out using multiplier 2. The output

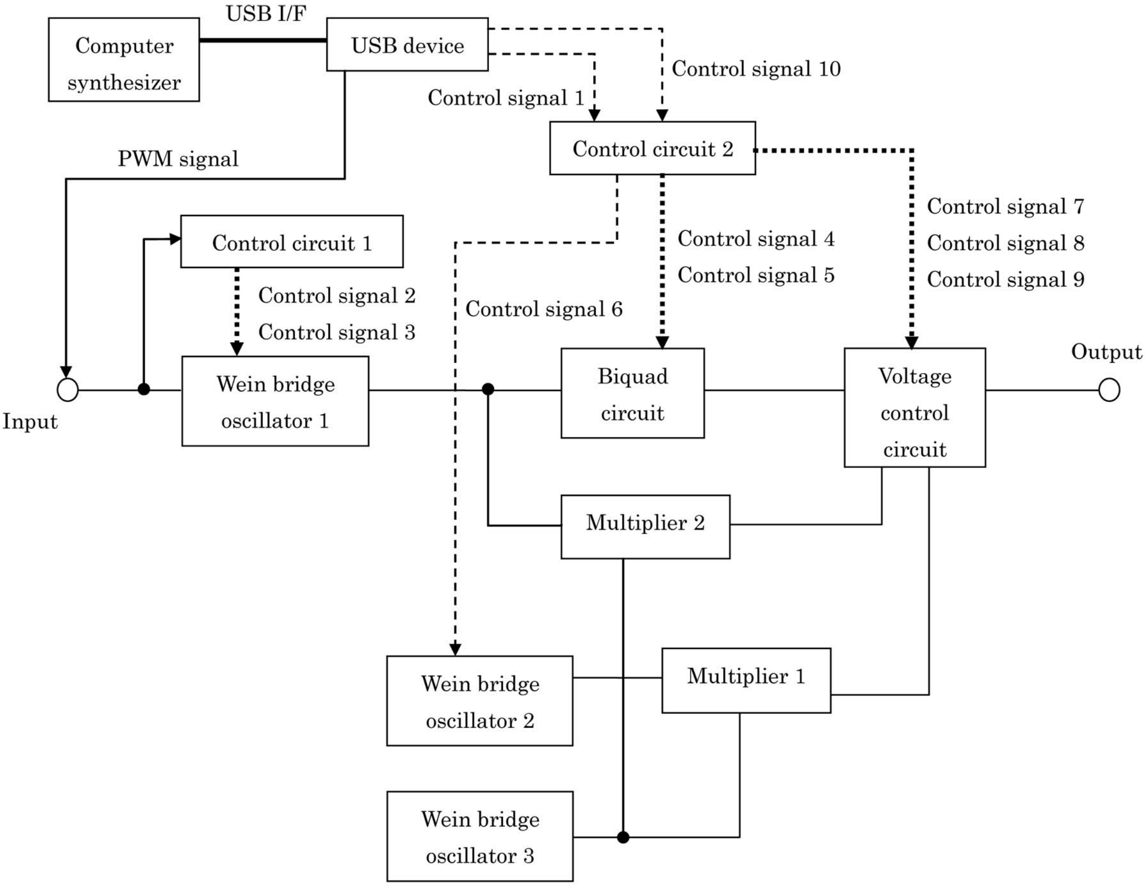


Figure 1. Basic structure of the system

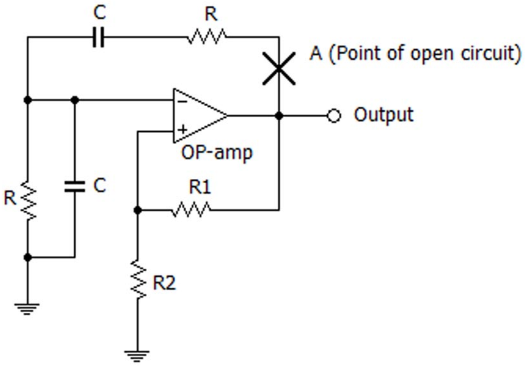


Figure 2. Conventional Wien bridge oscillator

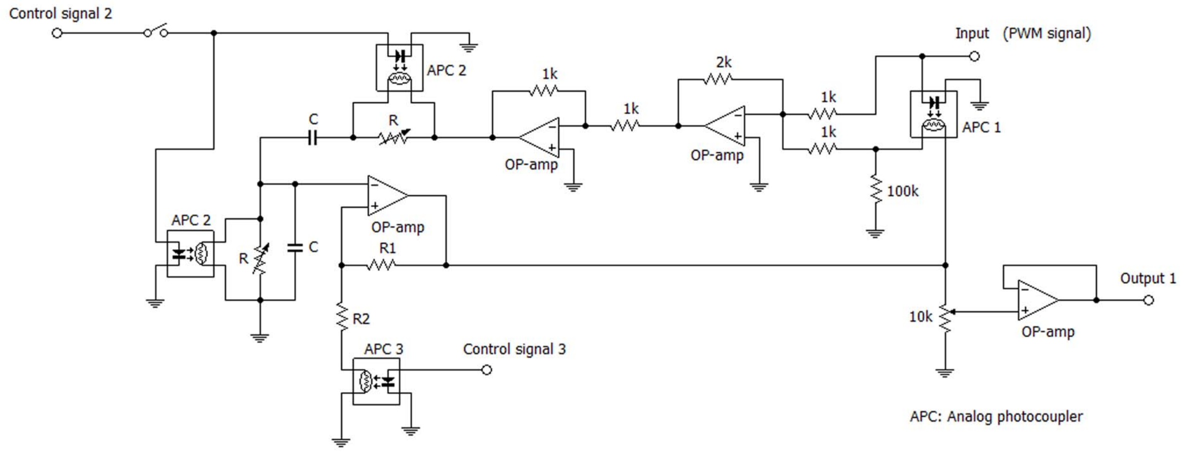


Figure 3. Wien bridge oscillator 1

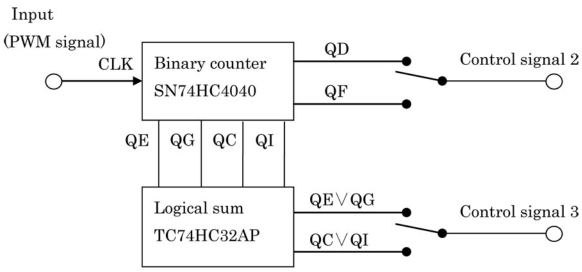


Figure 4. Basic structure of control circuit 1

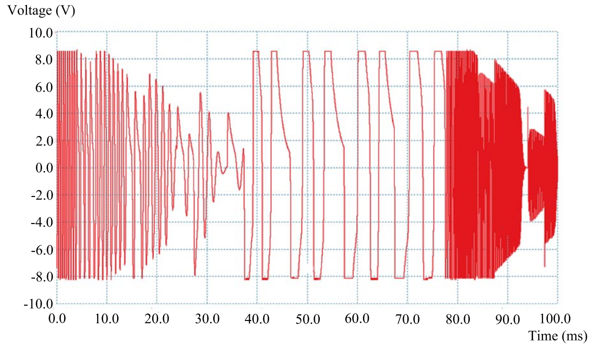


Figure 5. Example of the output signal of Wien bridge oscillator 1

signals of the biquad circuit, multiplier 1, and multiplier 2 are controlled by a voltage control circuit. In addition, Figure 10 shows that current is supplied to each control signal as required by using a current control circuit (CCC). The design of the CCC is based on a transistorized analog circuit and a buffer circuit.

3. Design of Wien Bridge Oscillator 1

A conventional Wien bridge oscillator is shown in Figure 2 (Van Valkenburg 1982). The conditions for achieving oscillation in this circuit are specified by the characteristic equation. The characteristic equation is given by Eq.(1), where LG is the open-loop gain.

$$\begin{aligned} 1 - LG &= \frac{s^2 + (3-K)\dfrac{1}{RC}s + (\dfrac{1}{RC})^2}{s^2 + \dfrac{3}{RC}s + (\dfrac{1}{RC})^2} \\ K &= 1 + \frac{R1}{R2} \end{aligned} \tag{1}$$

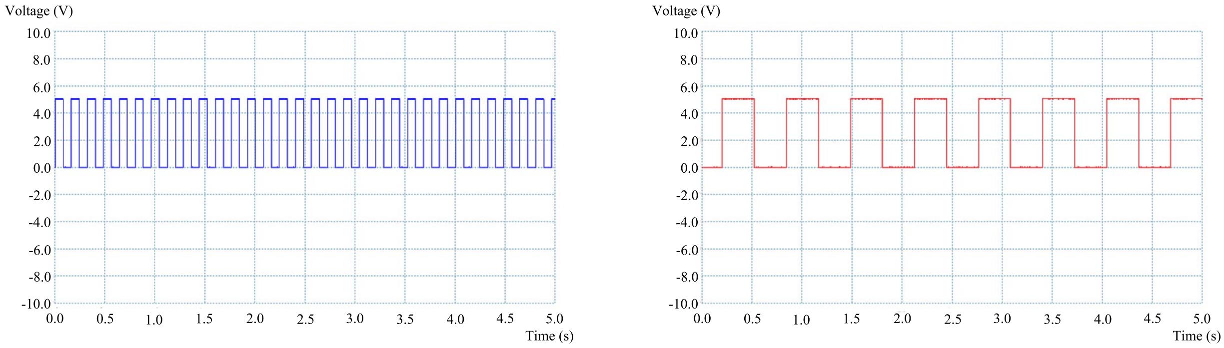
The characteristic equation and the value of K needed to sustain oscillation are expressed in Eq.(2), where D represents the denominator of Eq.(1). To fulfill the conditions of Eq.(2), the value of K is 3, but in practice, the circuit might not oscillate reliably unless K is greater than three.

$$\begin{aligned} 1 - LG &= \frac{1}{D}(s^2 + (\frac{1}{RC})^2) \\ K &\geq 3 \end{aligned} \tag{2}$$

The oscillation frequency ω of this circuit is expressed by Eq.(3).

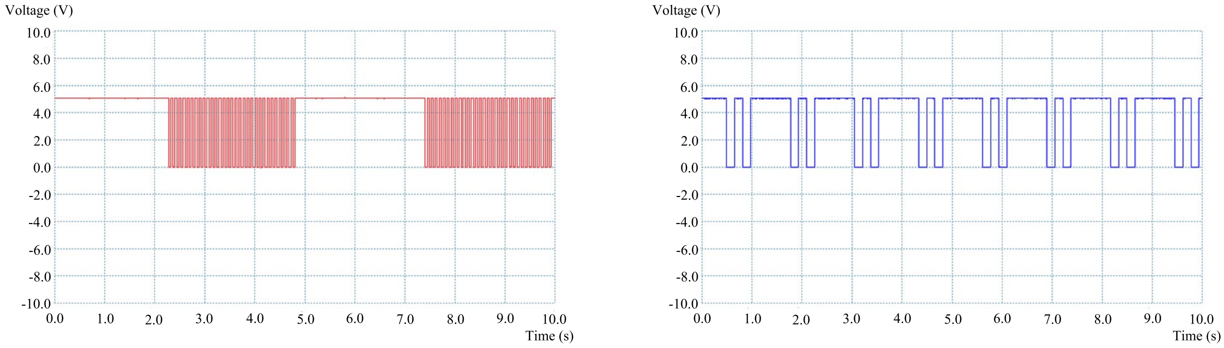
$$\omega = \frac{1}{RC} \tag{3}$$

The transfer function T_0 when A of Figure 2 is open-circuited and a general form T_{BP} of the second-order response characteristic are expressed in Eq.(4), where ω_0



(a) QD (b) QF

Figure 6. Examples of control signal 2



(a) $QC{\vee}QI$ (b) $QE{\vee}QG$

Figure 7. Examples of control signal 3

represents the center frequency and Q represents the sensitivity.

$$\begin{aligned} T_0 &= \frac{\frac{K}{RC}s}{s^2+\frac{3}{RC}s+(\frac{1}{RC})^2} \\ T_{BP} &= \frac{\frac{\omega_0}{Q}s}{s^2+\frac{\omega_0}{Q}s+\omega_0^2} \end{aligned} \tag{4}$$

From Eq.(4), the Wien bridge oscillator circuit uses the output of a bandpass filter for feedback purposes. Therefore, the current study examined the effects of inputting a PWM signal at point A of Figure 2, using an adder and inverting amplifier. Wien bridge oscillator 1 is shown in Figure 3. From Figure 3, a PWM signal is applied to analog photocoupler (APC) 1 to control the feedback signal of the Wien bridge oscillator. To achieve frequency modulation, control signal 2 drives APC 2. To control the gain of the non-inverting amplifier, control signal 3 drives APC 3. Because Wien bridge oscillator 1 is connected to a biquad circuit and to multiplier 2, the output of the Wien bridge oscillator must be connected using a buffer. The basic structure of control circuit 1 is shown in Figure 4. Control signals are applied to the binary counter that divides the frequency of the PWM signal and to the logic gate that performs the logical summation of the output signals of the binary counter (Tsuji 2018a). The SN74HC4040 chip from Texas Instruments was used for the binary counter (Texas Instruments 2003). A PWM signal is fed into the input terminal CLK of the binary counter. The TC74HC32AP chip from Toshiba Corp. was used to calculate the logical sum of the output signals of the binary counter (Toshiba Corp. 2014a). The output signal QD or QF of the binary counter is used as control signal 2. Control signal 3 is either the signal $QC{\vee}QI$ that is the logical sum of the output signals QC and QI of the binary counter, or the signal $QE{\vee}QG$ that is the logical sum of the output signals QE and QG of the binary counter. Each signal is selected by a switch. An example of the output signal of Wien bridge oscillator 1 is shown in Figure 5. Examples of control signals 2 and 3 are shown in Figures 6 and 7, respectively. The input signal in Figure 3 and 4 that drives the binary counter is a PWM signal with a frequency of ∼101 Hz and a duty ratio of ∼33.3%. Figure 5 shows that the output signal of the Wien bridge

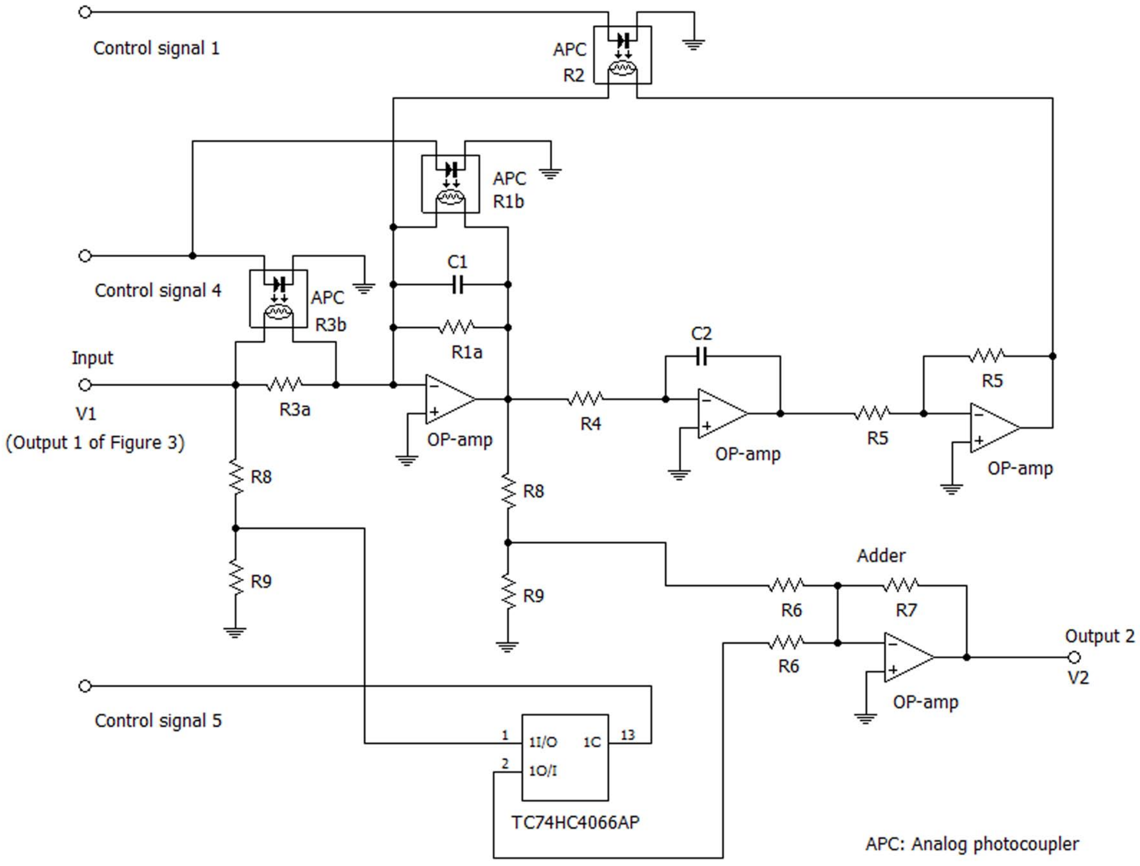


Figure 8. Design of the biquad circuit

oscillator 1 is being modulated.

4. Design of the Biquad Circuit

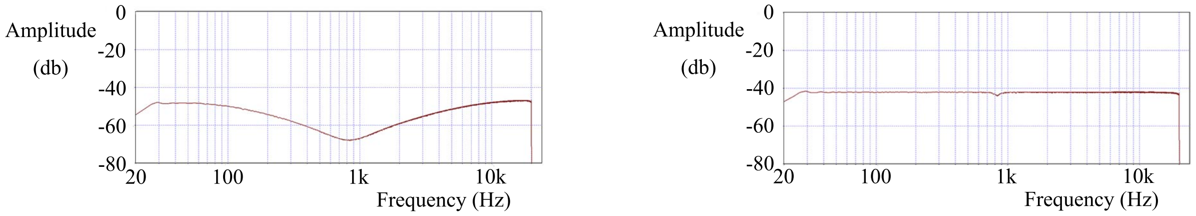
The biquad circuit designed in this project is shown in Figure 8 (Tow 1968). Eq.(5) shows how $R1$ is related to the resistance $R1a$ and the impedance of APC $R1b$; and $R3$ is a function of the resistance $R3a$ and the impedance of APC $R3b$.

$$\begin{aligned} R1 &= \frac{R1a \times R1b}{R1a + R1b} \\ R3 &= \frac{R3a \times R3b}{R3a + R3b} \end{aligned} \qquad (5)$$

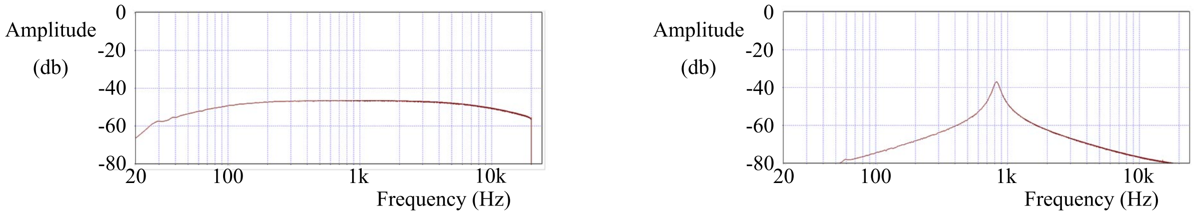
When control signal 4 is high (~5 V), the impedance of APC is small; in this situation, $R1$ is approximately equal to $R1b$, and $R3$ is approximately equal to $R3b$. When the control signal 4 is low (~0 V), the impedance of APC is large; in this case, $R1$ is approximately equal to $R1a$, and $R3$ is approximately equal to $R3a$. In other words, the values of $R1$ and $R3$ fulfill the conditions of Eq.(6).

$$\begin{aligned} R1 &\approx R3\ (Control\ signal\ 4 = High) \\ \frac{R1}{2} &\approx R3\ (Control\ signal\ 4 = Low) \end{aligned} \qquad (6)$$

From Figure 8, when control signal 5 is high, the analog switch transmits a signal from Output 1 of Figure 3 to the input of the adder; but when control signal 5 is low, the analog switch blocks this signal. The output signal of the biquad circuit (Output 2 of Figure 8) adds together the output signal of the analog switch and the output signal of the bandpass filter of the biquad circuit, and then amplifies the sum (Zumbahlen 2012). In addition, the input voltage of the biquad circuit is reduced to ~1/10 of its original value before being input into an analog switch so that the input voltage rating of the analog switch is not exceeded. Similarly, the output voltage of the bandpass filter of the biquad circuit is also reduced to ~1/10 of its original value, added to the output signal of the analog switch, and then amplified. The TC74HC4066AP chip from Toshiba Corp. was used for the analog switch (Toshiba Corp. 2017). When control signal 4 and control signal 5 are both high, the



(a) Band elimination filter (b) All-pass filter



(c) Bandpass filter with low sensitivity (d) Bandpass filter with high sensitivity

Figure 9. Frequency characteristics of each filter

biquad circuit functions as a second-order band elimination filter. The transfer function T_1 of the second-order band elimination filter, the general form T_{BE} of a second-order response characteristic, and the desired relationship between $R1$ and $R3$ are all shown in Eq.(7), where ω_0 represents the notch frequency and Q represents the sensitivity.

$$
\begin{aligned}
T_1 &= \frac{V2}{V1} \\
&= -\frac{s^2 + (\frac{1}{R1C1} - \frac{1}{R3C1})s + \frac{1}{R2R4C1C2}}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
&= -\frac{s^2 + \frac{1}{R2R4C1C2}}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
T_{BE} &= \frac{s^2 + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \\
R1 &\approx R3 \qquad (7)
\end{aligned}
$$

When control signal 4 is low and control signal 5 is high, the biquad circuit behaves like a second-order all-pass filter. The transfer function T_2 of the second-order all-pass filter, the general form T_{AP} of the second-order response characteristic, and the necessary relationship between $R1$ and $R3$ are all shown in Eq.(8), where ω_0 represents the angular frequency corresponding to a phase shift of 360° and Q represents the sensitivity.

$$
\begin{aligned}
T_2 &= \frac{V2}{V1} \\
&= -\frac{s^2 + (\frac{1}{R1C1} - \frac{1}{R3C1})s + \frac{1}{R2R4C1C2}}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
&= -\frac{s^2 - \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
T_{AP} &= \frac{s^2 - \frac{\omega_0}{Q}s + \omega_0^2}{s^2 + \frac{\omega_0}{Q}s + \omega_0^2} \\
\frac{R1}{2} &\approx R3 \qquad (8)
\end{aligned}
$$

When control signal 4 is high and control signal 5 is low, the biquad circuit behaves like a second-order bandpass filter with low sensitivity. The transfer function T_3 of the second-order bandpass filter and the desired relationship between $R1$ and $R3$ are shown in Eq.(9).

$$
\begin{aligned}
T_3 &= \frac{V2}{V1} = \frac{\frac{1}{R3C1}s}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
R1 &\approx R3 \qquad (9)
\end{aligned}
$$

When control signal 4 and control signal 5 are both low, the biquad circuit functions as a second-order bandpass filter with high sensitivity. The transfer function T_4 of the second-order bandpass filter and the desired relationship between $R1$ and $R3$ are shown in Eq.(10).

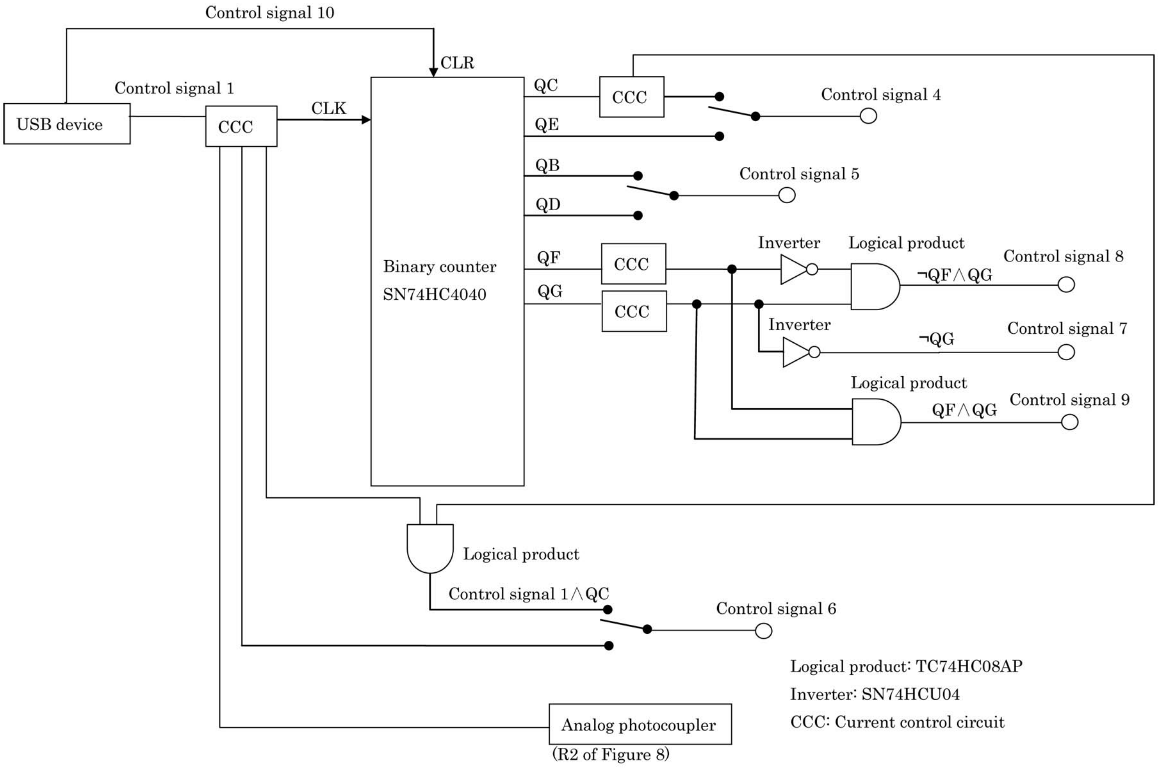


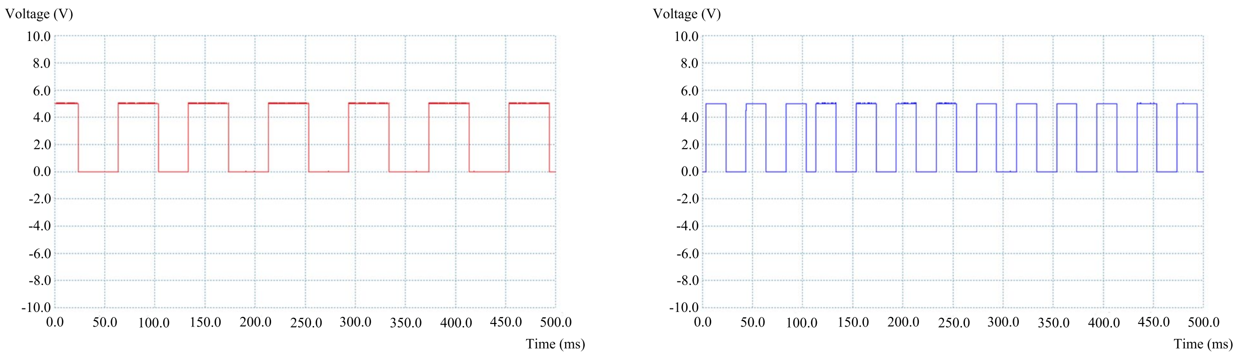
Figure 10. Basic structure of control circuit 2

$$
\begin{aligned}
T_4 &= \frac{V2}{V1} = \frac{\frac{1}{R3C1}s}{s^2 + \frac{1}{R1C1}s + \frac{1}{R2R4C1C2}} \\
\frac{R1}{2} &\approx R3 \qquad (10)
\end{aligned}
$$

Examples of the frequency characteristics of each type of filter are shown in Figure 9. In order to perform the frequency measurements, APC $R2$ of Figure 8 was temporarily replaced by a variable resistor. The frequency characteristic was measured using WaveGene and WaveSpectra software from efu (efu 2017). The basic structure of control circuit 2 is shown in Figure 10. From Figure 10, control signals 4 and 5 are derived from the frequency-divided outputs of the binary counter, which–in turn–is fed by control signal 1 that comes from the USB device. Control signal 1 drives the CLK input terminal of the binary counter. Moreover, to control the center frequency (or phase shift) of the biquad circuit, control signal 1 drives APC $R2$ (Tsuji 2016). The output signal QC or QE of the binary counter is used as control signal 4, and the output signal QB or QD of the binary counter is used as control signal 5. Each signal is changed with a switch. The waveforms of control signal 4 driven by QC and that of control signal 5 driven by QB are shown in Figure 11. At the time these waveforms were measured, control signal 1 had a frequency of ∼101 Hz and a duty ratio of ∼33.3%.

5. Design of the Multiplication Circuit using a Wien bridge oscillator and a Multiplier

The circuit using Wien bridge oscillator 2, Wien bridge oscillator 3, multiplier 1, and multiplier 2 is shown in Figure 12. The same design procedure used for Wien bridge oscillator 1 was also used for 2 and 3. Wien bridge oscillator 2 uses an APC and a variable resistor for the resistance, which allows its frequency to be modulated. The variable resistor is used to establish the lower frequency limit. The frequency of Wien bridge oscillator 3 can be varied by using the variable resistor. From Figure 10, control signal 6 is the signal that drives APCs of Wien bridge oscillator 2. This control signal 6 can be switched between control signal 1 and $control\ signal\ 1 \wedge QC$. The latter is the logical product of control signal 1 and signal QC, which–in turn–is one of the frequency-divided outputs of the binary counter. The TC74HC08AP chip from Toshiba Corp. was used to generate the logical products (Toshiba Corp. 2014b). An example of the control signal 6 waveform is shown in Figure 13. At this time this waveform was measured, control signal 1 had a frequency of ∼101 Hz and a duty ratio of ∼33.3%. From Figure 13, because



(a) Control signal 4, when connected to QC

(b) Control signal 5, when connected to QB

Figure 11. Examples of control signal 4 and control signal 5

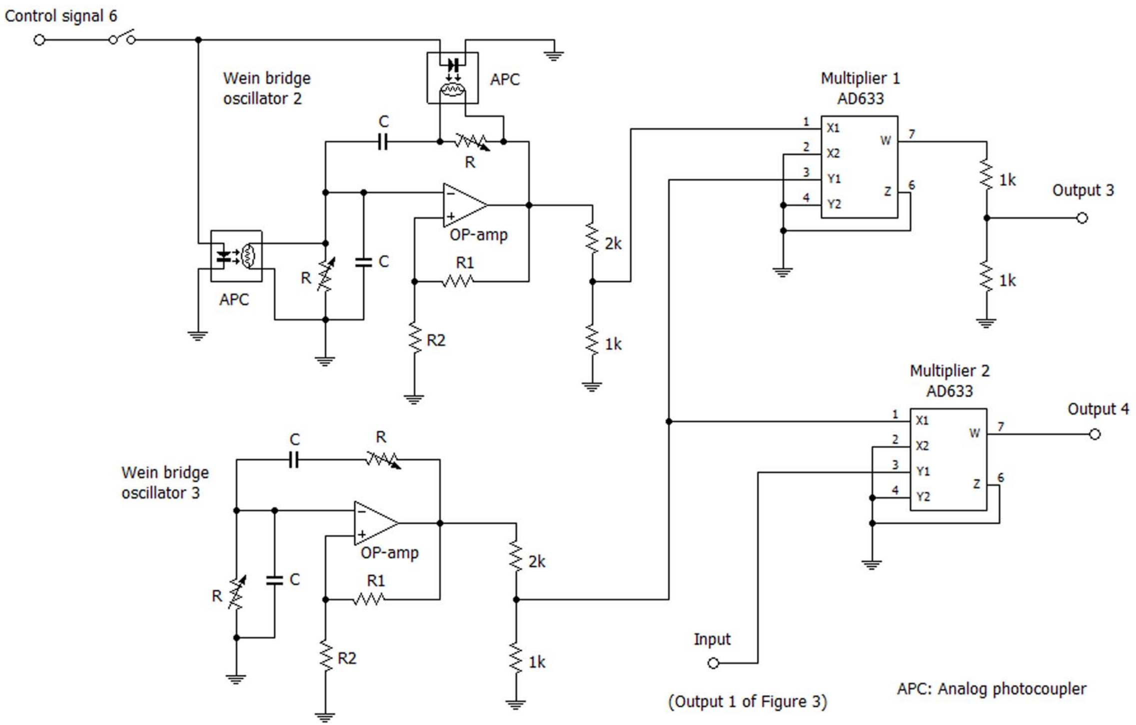


Figure 12. Multiplication circuit using Wien bridge oscillators and multipliers

control signal 1 is connected to the APC of Figure 12, the voltage is maintained at $\sim$1.9 V because of the effect of the light-emitting diode in APC. From Figure 12, the output signals from Wien bridge oscillator 2 and Wien bridge oscillator 3 are fed into multiplier 1; while the output signals of Wien bridge oscillator 1 and Wien bridge oscillator 3 are fed into multiplier 2. An AD633 chip from Analog Devices, Inc. was used for the multiplier (Analog Devices, Inc. 2015).

6. Design of the Voltage Control Circuit

The voltage control circuit is shown in Figure 14 (Tsuji 2018a). The output signals from the biquad circuit, multiplier 1, and multiplier 2 are input to the voltage control circuit. A different control signal is fed into each of three APCs, and each input signal is thereby subjected to voltage control. From Figure 10, control signal 7 that controls the output of the biquad circuit (Output 2 of Figure 8) is the signal $\neg QG$, which is the inverse of signal QG; where QG is one of the frequency-divided outputs of the binary counter. Control signal 8 that controls the

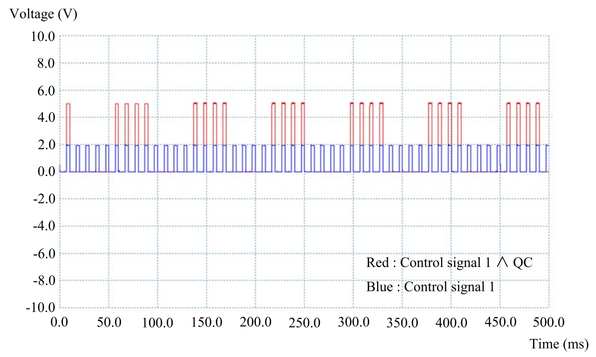


Figure 13. Example of control signal 6

output of multiplier 1 (Output 3 of Figure 12) is the signal $\neg QF \wedge QG$, which is the logical product of QG and the inverse of QF; where QF and QG are two of the outputs of the binary counter. Control signal 9 that controls the output of multiplier 2 (Output 4 of Figure 12) is the signal $QF \wedge QG$, which is the logical product of QF and QG. The SN74HCU04 chip from Texas Instruments Inc. was used for the inverter (Texas Instruments Inc. 2004). By using these control signals, three kind of analog signals can be connected to form the wave sequence. When a PWM signal is not being output from the USB device, the control signal 10 output from the USB device is set to high and drives the CLR terminal of the binary counter. Therefore, all the outputs of the binary counter, as well as control signals 8 and 9, are set to low and the signals from the multipliers are not output by the voltage control circuit. Examples of the waveforms of control signals 7, 8, and 9 are shown in Figure 15, along with signal QF. Because the signal QF is connected to the SN74HCU04 and TC74HC08AP, the voltage is maintained at ~3.1 V. At the time these waveforms were measured, control signal 1 had a frequency of ~101 Hz and a duty ratio of ~33.3%. Each control signal was measured in conjunction with QF. Thereby, the changes in each of the control signals in Figure 15 have an effect on the wave sequence.

7. Signal Analysis

Frequency analysis was performed on the input signal and output signal of this system. A PWM signal from the computer synthesizer with random modulation and LFO modulation was used as the input signal. The frequency analysis of an input signal and the corresponding output signal is shown in Figure 16. The input signal and output signal were digitized at a sampling frequency of 44.1 kHz, and the linear quantization was 16 bits. The power spectrum for the frequency analysis was calculated by using Burg's method; the auto regression coefficient of Burg's method is the 48th order (Ehara 1991). One frame carries out a frequency analysis on the audio data with a duration of 100 ms (4410 samples). Next, the sample numbers of one frame are shifted by 20 ms (882 samples), and 20 ms of new audio data is input. This operation is repeated, and the frequency analysis continues for 10 s. The number of samples of audio data x(n) is set to N, the frame number is set to e, and the number of shifts is set to s; where x(n) is expressed by Eq.(11). The frequency spectra are normalized, and the input and output signals are compared (Tsuji 2018b). In Figure 16, because the frequency components of the input signal and the output signal are different, one can infer that the timbre of the input signal and that of the output signal are also very different.

$$x(n)\ (n = e \cdot s, e \cdot s + 1, e \cdot s + 2, ..., e \cdot s + (N-1),$$
$$e = 0, 1, 2, ..., 495, s = 882, N = 4410) \quad (11)$$

8. Actual Performance

This system, after being connected to an amplifier and a speaker, is shown in Figure 17. An actual photograph is shown in Figure 18. A PWM signal, control signal 1, and control signal 10 are output from the USB device. The performance of the computer synthesizer was demonstrated using random modulation and/or LFO modulation of a PWM signal. Actual performance has confirmed that a PWM signal and a sine wave were modulated by this system, and the timbre was changed. Furthermore, referring to Figure 3 and Figure 12, it has been experimentally confirmed that amplitude modulation was implemented by isolating control signal 2 and control signal 6 with a switch and changing the variable resistors of Wien bridge oscillators 2 and 3.

9. Conclusion

The Wien bridge oscillator accepts a PWM signal as its input and creates a novel signal by using the PWM signal to control the frequency, gain, and feedback. By controlling a resistance and an analog switch with a control signal, a biquad circuit can be changed into a band elimination filter, an all-pass filter, and two bandpass filters with different sensitivities. Moreover, the multiplication of the output signal of the Wien bridge oscillator and voltage control of the output signal of two multipliers and a biquad circuit were carried out; and an attempt was made to perform sound syntheses such as wave sequencing. In an actual test, a PWM signal and a sine wave were modulated by the system, and it was confirmed by the timbre of the modulated signal that this sound synthesis method was effective. In the future, I intend to develop a synthesizer system using digitally controlled analog signal processing.

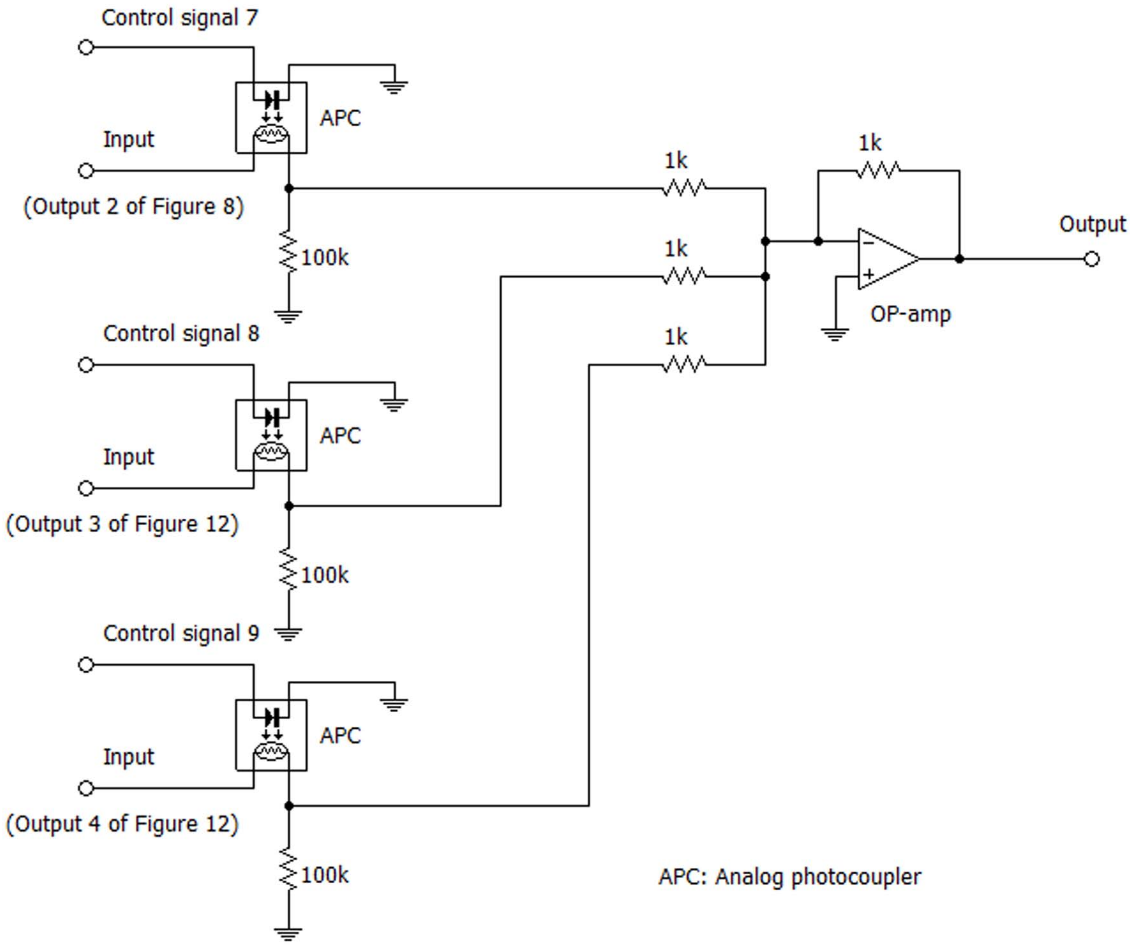
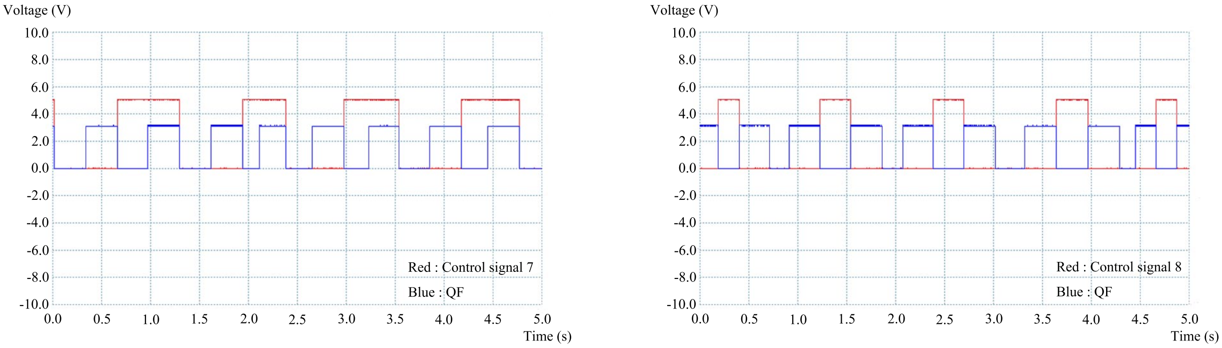
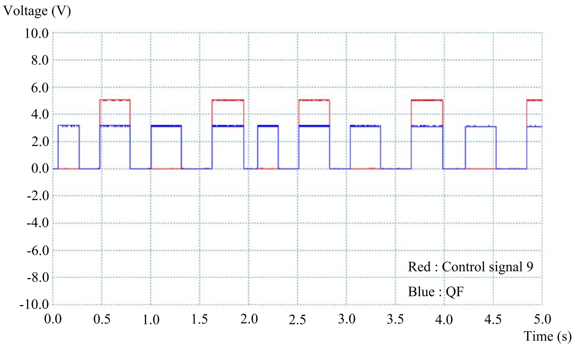


Figure 14. Voltage control circuit



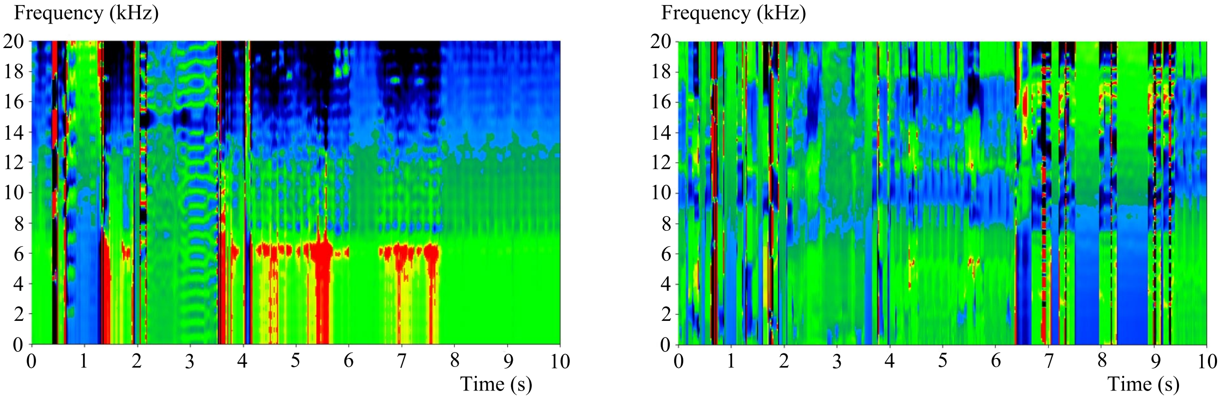
(a) Control signal 7

(b) Control signal 8



(c) Control signal 9

Figure 15. Examples of control signals 7, 8, and 9, compared to QF



(a) Input signal

(b) Output signal

Figure 16. Frequency analyses of the input signal and the output signal

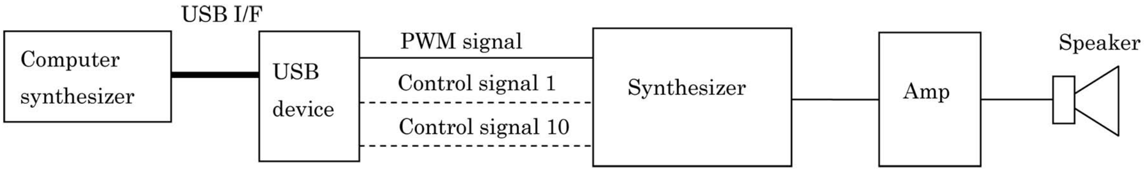


Figure 17. Block diagram of the system connected to an amplifier and speaker

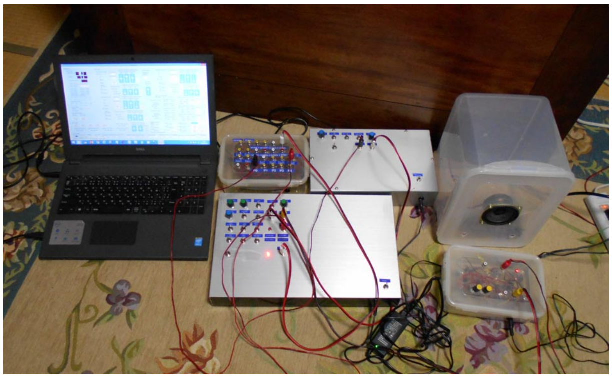


Figure 18. Actual photograph of the system

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10. Author's Profile

Ichiro TSUJI

Ichiro Tsuji was born in 1966 and graduated from the Department of Electrical Engineering Faculty of Technology of Kokushikan University in 1991. He joined NEC Home Electronics Corp. the same year. At the Development Research Laboratory, he engaged in research of a three-dimensional playback system for a two-channel speaker. He then moved to NEC Corp. and engaged in the research and development of a multimedia-related project. He retired in 1998. He is currently a regular member of the Acoustical Society of Japan.

As for his musical activities, in Tokyo in 1986, he started working on noise/industrial music for his band named "Dissecting Table." He returned to his hometown of Hiroshima in 1998, and has been pursuing musical activities ever since. His records and compact disks have been released under the independent label of the UPD organization, and under labels in Europe and the United States. Since 2011, the works have been produced by controlling PWM signals output from a USB device on a computer.
