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Research Report

Development of the Controlled Analog Filter Using an Input Signal

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Abstract

This paper describes the signal of a rich sound effect obtained by controlling the timbre and volume of three kinds of analog filters using an input signal. The designed analog filter mainly consists of a low-pass filter, bandpass filter, band-elimination filter, bypass circuit, voltage-control circuit, and digital circuit. The low-pass filter, bandpass filter, and band-elimination filter are designed by a multi-feedback low-pass filter (Jung 2004), Deliyannis–Friend circuit (Deliyannis 1968), and Bainter circuit (Bainter 1975), respectively. A voltage-control circuit carries out the voltage control of two signals using two control signals. A control signal, which is generated in a digital circuit from an applied input signal, is subsequently fed into each filter and voltage-control circuit. This analog filter carries out the voltage control of an output signal of a low-pass filter, an output signal of a bandpass filter, an output signal of a band-elimination filter, and a bypass signal using control signals. Furthermore, the cutoff frequency of the low-pass filter and the center frequency of the bandpass filter are controlled. An analog photocoupler is used as a resistance that controls the cutoff and center frequencies. This resistance, the photo register of a cadmium sulfide cell, can be changed by inputting a control signal into the light-emitting diode of an analog photocoupler and the cutoff and center frequencies can be controlled (Tsuji 2016). Finally, this filter creates a rich sound effect by the signal analysis of the input and output signals of this filter by adding the output signal of a voltage-control circuit, which inputs a bypass signal and output signal of a band-elimination filter; the output signal of a voltage-control circuit, which inputs the output signal of a low-pass filter; and the output signal of a bandpass filter. Moreover, as an example of application, a pulse-width-modulated (PWM) signal output from a Universal Serial Bus (USB) device carries out control by a computer and attempts to construct a synthesizer system by inputting PWM signals into analog filters. In addition to this filter, a biquad circuit, Sallen–Key circuit, and all-pass filter were used for an analog filter.

1. Introduction

Using an input signal as a control signal, the typical effector, which can control the voltage of an input signal, uses BOSS SG-1 Slow Gear (Roland Corp. 1979) of Roland Corp. Similarly, using an input signal as a control signal, the typical effector, which can control a center frequency of a bandpass filter, uses Doctor Q (Kyoritsu Corp.) of Electro-Harmonics (Otsuka 2011). In this study, the developed analog filter carries out voltage control of the output signal of a low-pass filter, output signal of a bandpass filter, output signal of a band-elimination filter, and a bypass signal, using an input signal as a control signal. Furthermore, the cutoff frequency of a low-pass filter and the center frequency of a bandpass filter are controlled. A control signal is used for a signal that divides the frequency of an input signal by a binary counter (Micro Communications 1981) and a signal that carries out a logical product by the output signals of a binary counter (Tsuji 2018). Two control signals that control a low-pass filter and bandpass filter carry out four pattern preparations, and enabled them to be changed by a computer. Thus, although the scale of the hardware becomes large compared with the conventional products, the voltage control of a signal, the control of a cutoff frequency, and the control of a center frequency are achieved simultaneously. Furthermore, a rich timbre can be created because the control signal is complicated.

2. Design of analog filter

The basic structure of the designed analog filter is shown in Figure 1. The circuit structure carries out a cascade connection of a circuit of block A and block B. Block A has a parallel connection of a band-elimination filter and bypass circuit. Block B has a parallel connection of a low-pass filter, bandpass filter, and bypass circuit. A bypass signal and output signal of a band-elimination filter of block A carry out the voltage control in a voltage-control circuit. The voltage-control circuit is shown in Figure 2. Because an analog photocoupler is used as a voltage-control circuit, the output signal of the voltage-control circuit can be reduced gradually (Tsuji 2016). Similarly, for block B, the output signals of the low-pass filter and bandpass filter carry out the voltage control in a voltage-control circuit. Furthermore, an analog photocoupler is used for a resistance that controls the cutoff frequency of the low-pass filter and the center frequency of the bandpass filter. The voltage control, cutoff frequency, and center frequency can be controlled by inputting a control signal into the voltage-control circuit, low-pass filter, and bandpass fil-

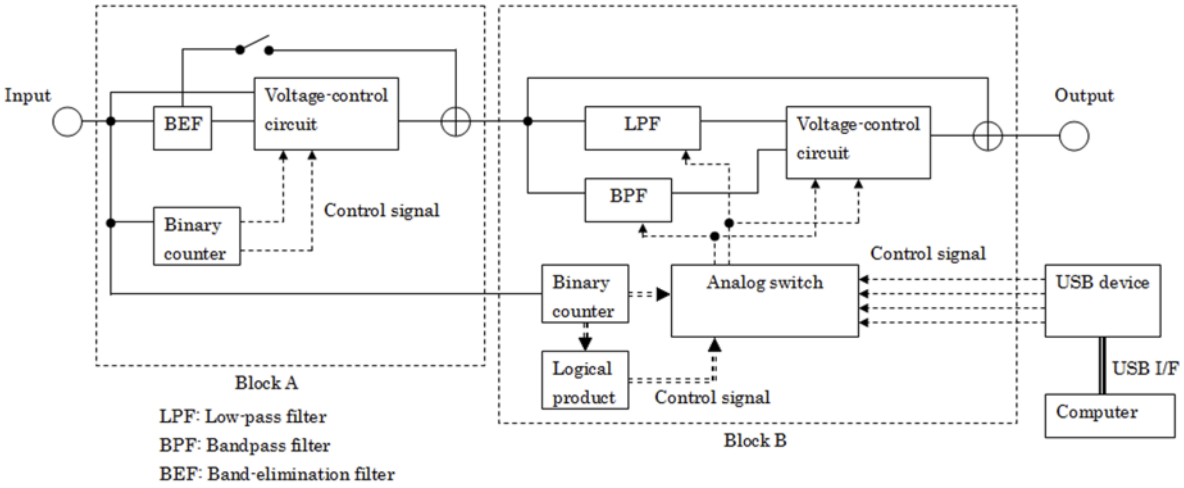


Figure 1. Basic structure of an analog filter

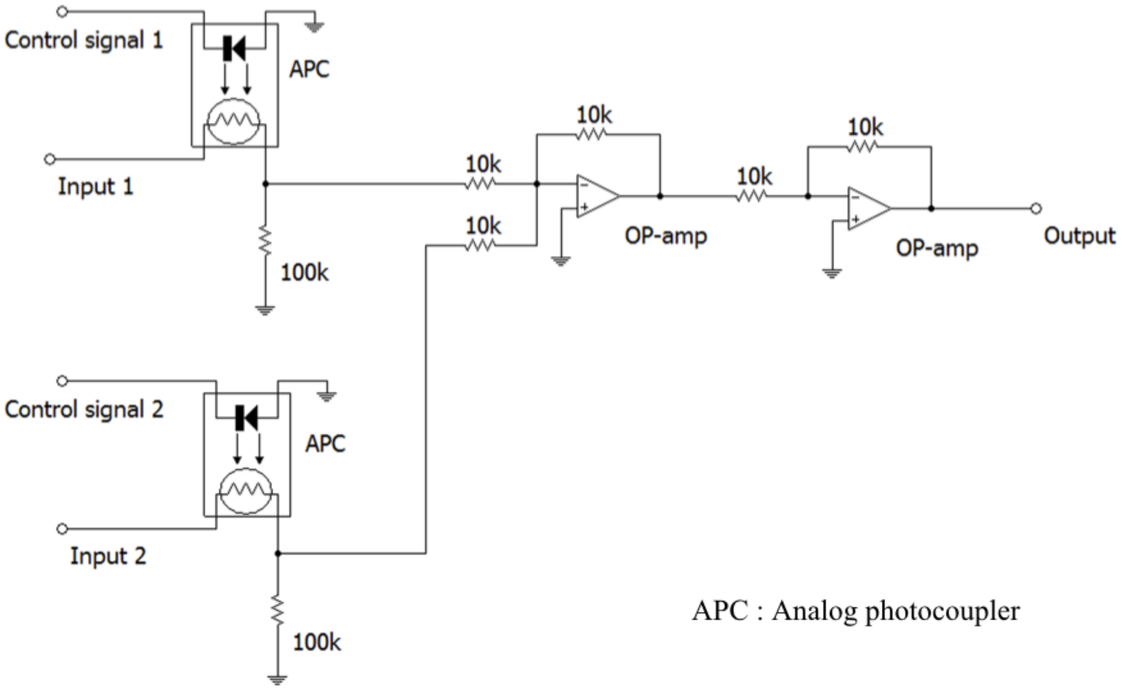


Figure 2. Voltage-control circuit

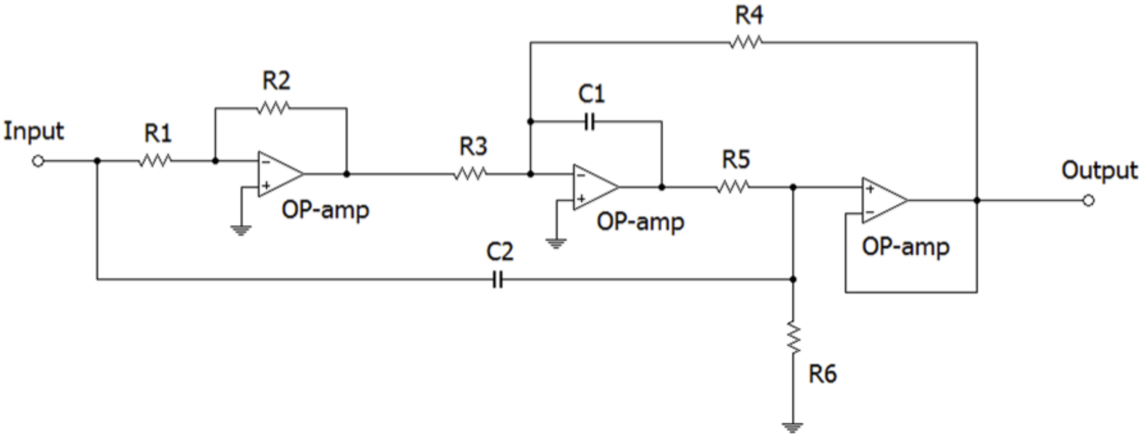


Figure 3. Conventional Bainter circuit

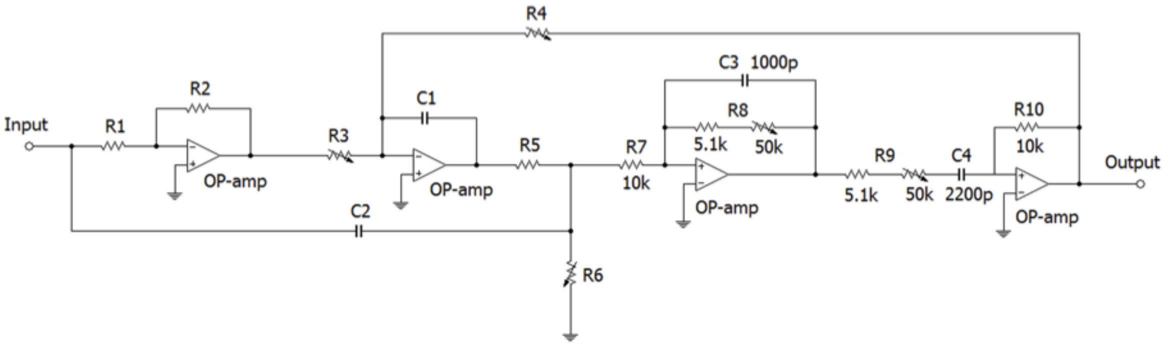


Figure 4. Designed Bainter circuit

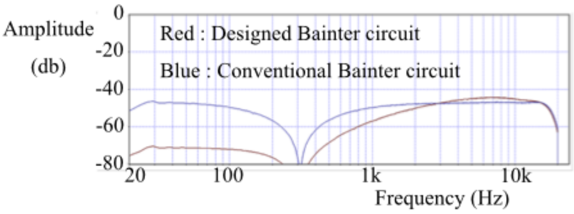


Figure 5. Frequency characteristics of Bainter circuit

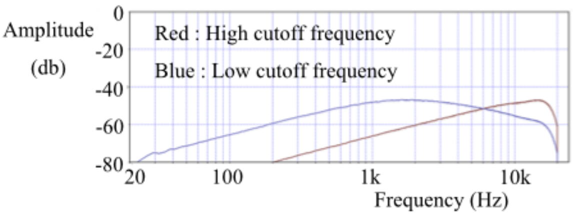


Figure 6. Cascade connection of first-order low-pass filter and first-order high-pass filter

ter. Finally, an output signal of block A (a bypass signal of block B) and an output signal of a voltage-control circuit of block B are added. The following sections describe the structure and characteristics of the band-elimination filter, low-pass filter, and bandpass filter. The frequency characteristic was measured using WaveGene and WaveSpectra software by efu (efu).

2.1. Structure and characteristics of band-elimination filter

The conventional Bainter circuit, which is a second-order band-elimination filter, is shown in Figure 3. Because the timbre created by a Bainter circuit is unique in terms of the frequency components, the buffer circuit of Figure 3 was replaced with a cascade connected first-order low-pass filter and first-order high-pass filter. The designed Bainter circuit is shown in Figure 4. The influence of the first-order low-pass filter and first-order high-pass filter is ignored, and if these transfer functions are set to 1, its filter is used for the second-order band-elimination filter. The transfer function is expressed by formula 1. T_{BE} represents a general form of the secondary form-response characteristic. T_1 represents the transfer function of the designed filter. T_a represents the transfer function of the first-order low-pass filter. T_b represents the transfer function of the first-order high-pass filter. ω_1 and ω_z represent the notch frequencies and Q_1 represents the sensitivity. When ω_1 is greater than ω_z, the frequency characteristic is a high-pass notch characteristic. When ω_1 is equal to ω_z, the frequency characteristic is a regular notch characteristic. When ω_1 is less than ω_z, the frequency characteristic is a low-pass notch characteristic. An example of the frequency characteristics of the conventional Bainter circuit and the designed Bainter circuit is shown in Figure 5. However, at this point, the conventional Bainter circuit replaces the first-order low-pass filter and first-order high-pass filter of the designed Bainter circuit with two inverting amplifiers. The characteristics in red represent the frequency characteristics of the designed Bainter circuit, whereas those in blue represent the frequency characteristics of the conventional Bainter circuit. From Figure 5, the low-frequency component is decreasing in the designed Bainter circuit compared with the conventional Bainter circuit. This is considered to be influenced by the first-order low-pass filter and first-order high-pass filter. The frequency characteristic of the circuit is shown in Figure 6, in which a cascade connection was carried out of the first-order low-pass filter and first-order high-pass filter. The characteristics in red represent the frequency characteristics when the cutoff frequency of the first-order low-pass filter is ˜31206.9 Hz and the cutoff frequency of the first-order high-pass filter is ˜14184.9 Hz, whereas those in blue represent the frequency characteristics when the cutoff frequency of the first-order low-pass filter is ˜2888.5 Hz and the cutoff frequency of the first-order high-pass filter is ˜1312.9 Hz. Moreover, the timbre is not expected to change owing to ω_z. To introduce a change in the timbre due to ω_z, it is necessary to short-circuit the capacitor $C4$ shown in Figure 4. Thereafter, the sensitivity of the converted filter increases, and the timbre is different than that of the designed Bainter circuit shown in Figure 4.

$$
\begin{aligned}
T_{BE} &= \frac{s^2+\omega_z^2}{s^2+\frac{\omega_1}{Q_1}s+\omega_1^2} \\
T_1 &= \frac{(s^2+\frac{R2}{C1C2R1R3R5})T_aT_b}{s^2+\frac{1}{C2}(\frac{1}{R5}+\frac{1}{R6}+\frac{1}{R7})s+\frac{1}{C1C2R4R5}T_aT_b} \\
T_a &= \frac{-\frac{1}{C3R7}}{s+\frac{1}{C3R8}} \\
T_b &= \frac{-\frac{R10}{R9}s}{s+\frac{1}{C4R9}} \\
\omega_1 &= \sqrt{\frac{1}{C1C2R4R5}} \\
\omega_z &= \sqrt{\frac{R2}{C1C2R1R3R5}} \\
Q_1 &= \frac{R5R6R7}{R6R7+R5R7+R5R6}\sqrt{\frac{C2}{C1R4R5}} \qquad (1)
\end{aligned}
$$

2.2. Structure and characteristic of low-pass filter

The multi-feedback low-pass filter of a second-order low pass filter is shown in Figure 7. The transfer function is expressed by formula 2. T_{LP} represents a general form of the secondary form-response characteristic. T_2 represents the transfer function of the multi-feedback low-pass filter, ω_2 represents the cutoff frequency, Q_2 represents the sensitivity, and K_2 represents the gain. An example frequency characteristic is shown in Figure 8. The designed low-pass filter is shown in Figure 9. The resistance $R2$ of Figure 7 is replaced with an analog photocoupler. From Figure 9, an analog photocoupler carries out parallel connection to resistance $R4$, which adds a limit to the cutoff frequency of the lower bound of the designed low-pass filter. This particular filter obtains a constant pass band to the input signal. Using an input signal as a control signal, the control signal is input into an analog photocoupler and the cutoff frequency of the designed low-pass filter is controlled. Moreover, an example frequency characteristic that carried out a cascade connection of the designed Bainter circuit and multi-feedback low-pass filter is shown in Figure 10. From Figure 10, because it is found that a signal decreases by carrying out a cascade connection of the filter, it is necessary to amplify the output signal of the multi-feedback low-pass filter. However, because the bypass signal of block A is used as input to the multi-feedback low-pass filter, the frequency characteristic of this filter, shown by Figure 8, may sometimes change or overlap with the frequency characteristic of Figure 10. The frequency characteristic of each filter was obtained without the voltage-control circuit.

$$\begin{aligned}
T_{LP} &= \frac{\omega_2^2}{s^2 + \frac{\omega_2}{Q_2}s + \omega_2^2} \\
T_2 &= \frac{-\frac{R3}{R1}\frac{1}{C1C2R2R3}}{s^2 + \frac{1}{C1}(\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3})s + \frac{1}{C1C2R2R3}} \\
\omega_2 &= \sqrt{\frac{1}{C1C2R2R3}} \\
Q_2 &= \frac{R1R2R3}{R2R3 + R1R3 + R1R2}\sqrt{\frac{C1}{C2R2R3}} \\
K_2 &= \frac{R3}{R1} \qquad (2)
\end{aligned}$$

2.3. Structure and characteristic of bandpass filter

A Deliyannis–Friend circuit of a second-order bandpass filter is shown in Figure 11. The transfer function is expressed by formula 3. T_{BP} represents a general form of the secondary form-response characteristic. T_3 represents the transfer function of the Deliyannis–Friend circuit, ω_3 represents the center frequency, Q_3 represents the sensitivity, and BW_3 represents the bandwidth. An example frequency characteristic is shown in Figure 12. The designed Deliyannis–Friend circuit is shown in Figure 13. Resistance $R2$ of Figure 11 is replaced with an analog photocoupler. From Figure 13, an analog photocoupler carries out parallel connection to resistance $R3$, which adds a limit to the center frequency of the lower bound of the designed bandpass filter. This particular filter obtains a constant pass band to the input signal. Using an input signal as a control signal, the control signal is input into an analog photocoupler and the center frequency of the designed bandpass filter is controlled. Moreover, an example frequency characteristic that carried out a cascade connection of the designed Bainter circuit and Deliyannis–Friend circuit is shown in Figure 14. From Figure 14, because it is found that a signal decreases by carrying out a cascade connection of the filter, it is necessary to amplify an output signal of the Deliyannis–Friend circuit. However, because the bypass signal of block A is used as input to the Deliyannis–Friend circuit, the frequency characteristic of this filter, shown by Figure 12, may sometimes change or overlap with the frequency characteristic of Figure 14. The frequency characteristic of each filter was obtained without the voltage-control circuit. Further, because the output signals of the multi-feedback low-pass filter and Deliyannis–Friend circuit are input into the voltage-control circuit of block B, the voltage-control circuit's output is the signal of each filter or a sum of the signals of the two filters.

$$\begin{aligned}
T_{BP} &= \frac{\frac{\omega_3}{Q_3}s}{s^2 + \frac{\omega_3}{Q_3}s + \omega_3^2} \\
T_3 &= \frac{-\frac{1}{C1R1}s}{s^2 + \frac{C1 + C2}{C1C2R2}s + \frac{1}{C1C2R1R2}} \\
\omega_3 &= \sqrt{\frac{1}{C1C2R1R2}} \\
Q_3 &= \frac{R2}{C1 + C2}\sqrt{\frac{C1C2}{R1R2}} \\
BW_3 &= \frac{\omega_3}{Q_3} \qquad (3)
\end{aligned}$$

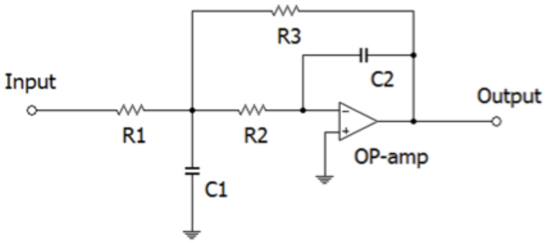


Figure 7. Conventional multiple-feedback low-pass filter

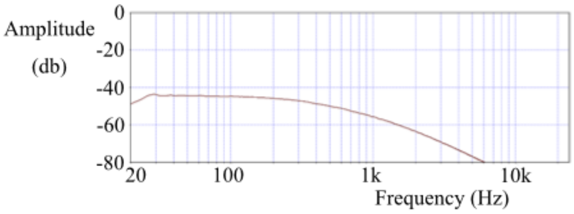


Figure 8. Frequency characteristic of multiple-feedback low-pass filter

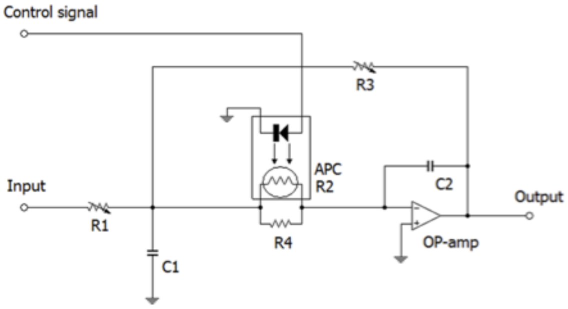


Figure 9. Designed multiple-feedback low-pass filter

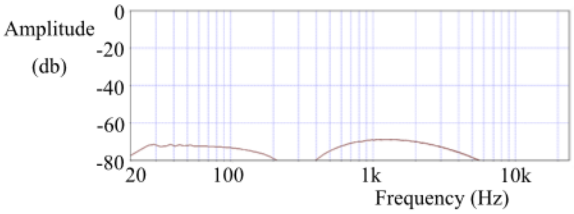


Figure 10. Cascade connection of designed Bainter circuit and multiple-feedback low-pass filter

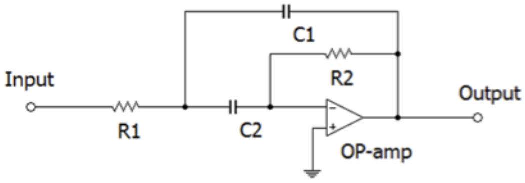


Figure 11. Conventional Deliyannis–Friend circuit

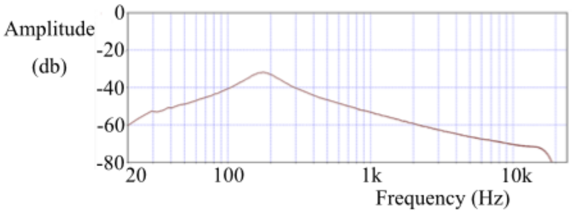


Figure 12. Frequency characteristic of Deliyannis–Friend circuit

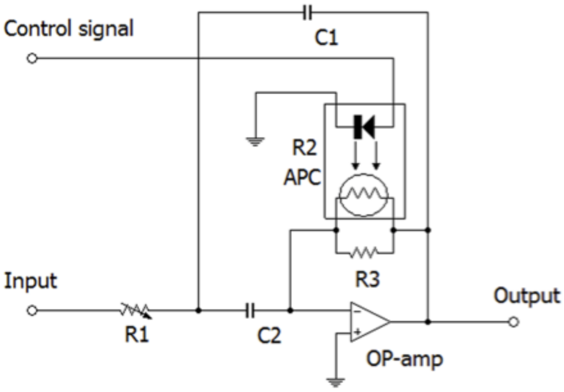


Figure 13. Designed Deliyannis–Friend circuit

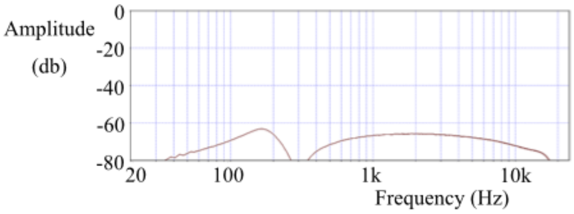
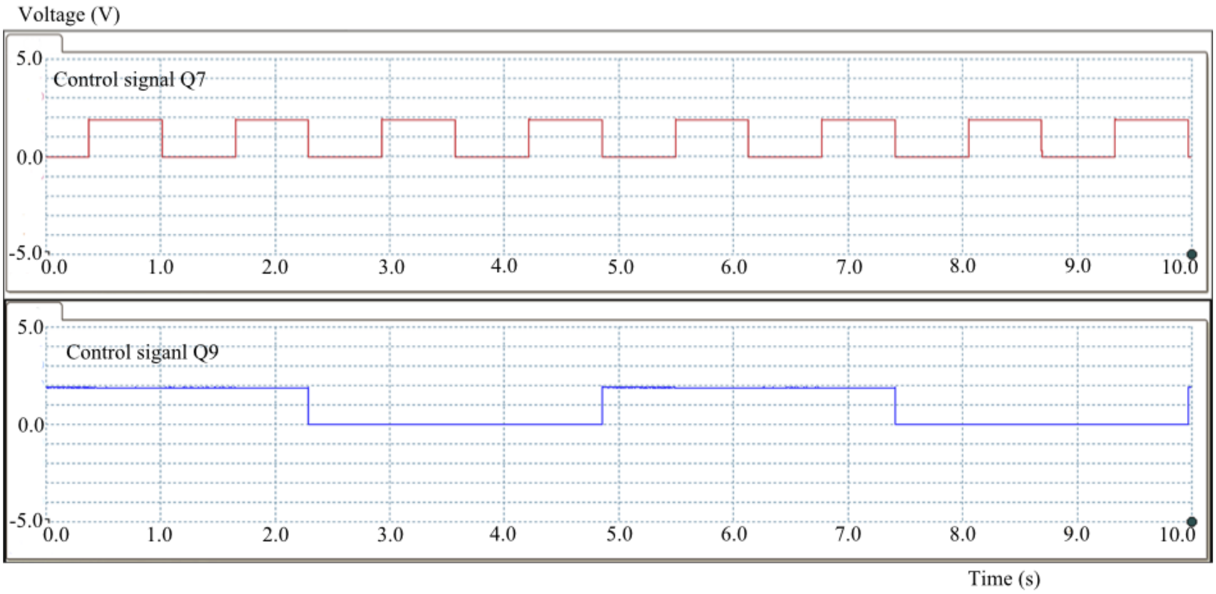
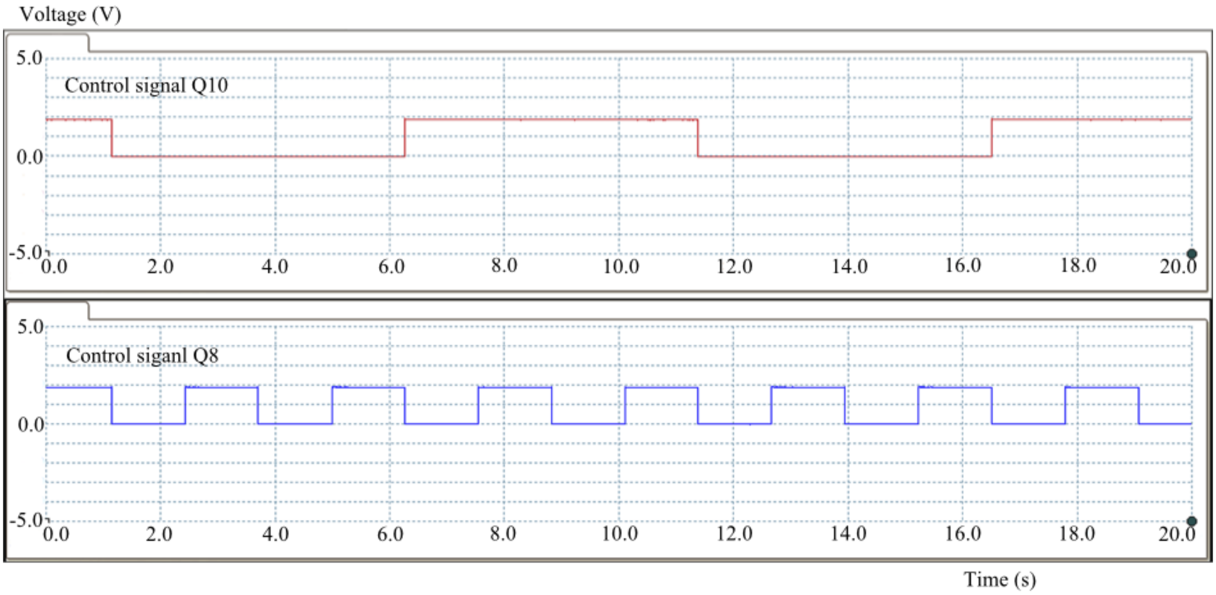


Figure 14. Cascade connection of designed Bainter circuit and Deliyannis–Friend circuit

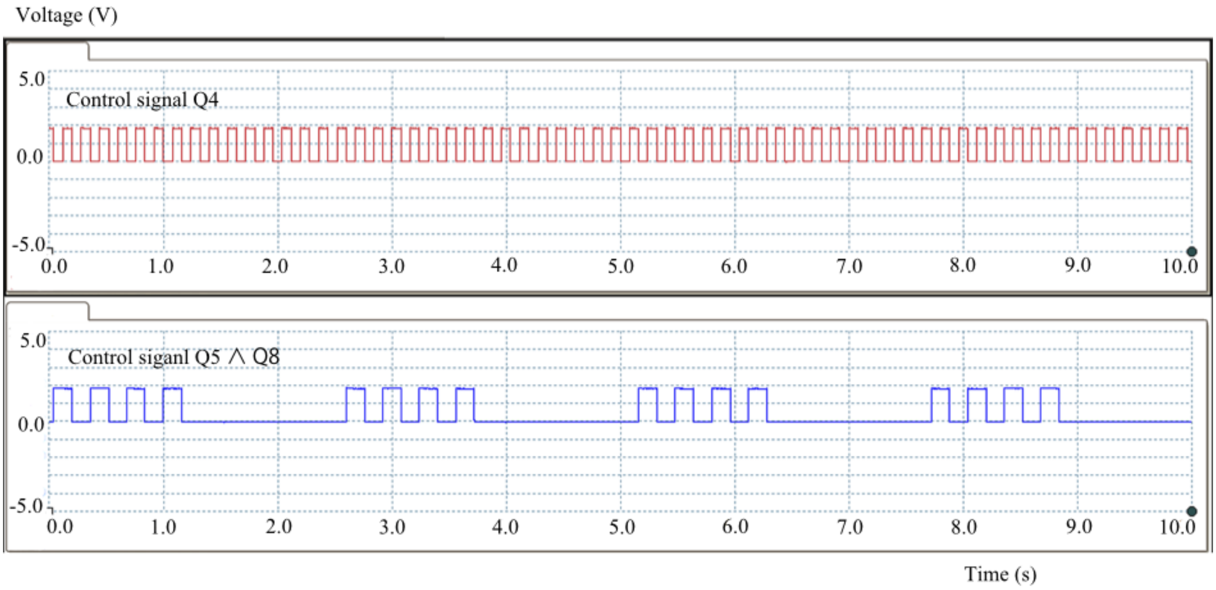


(a) Control signal of Q7 and Q9

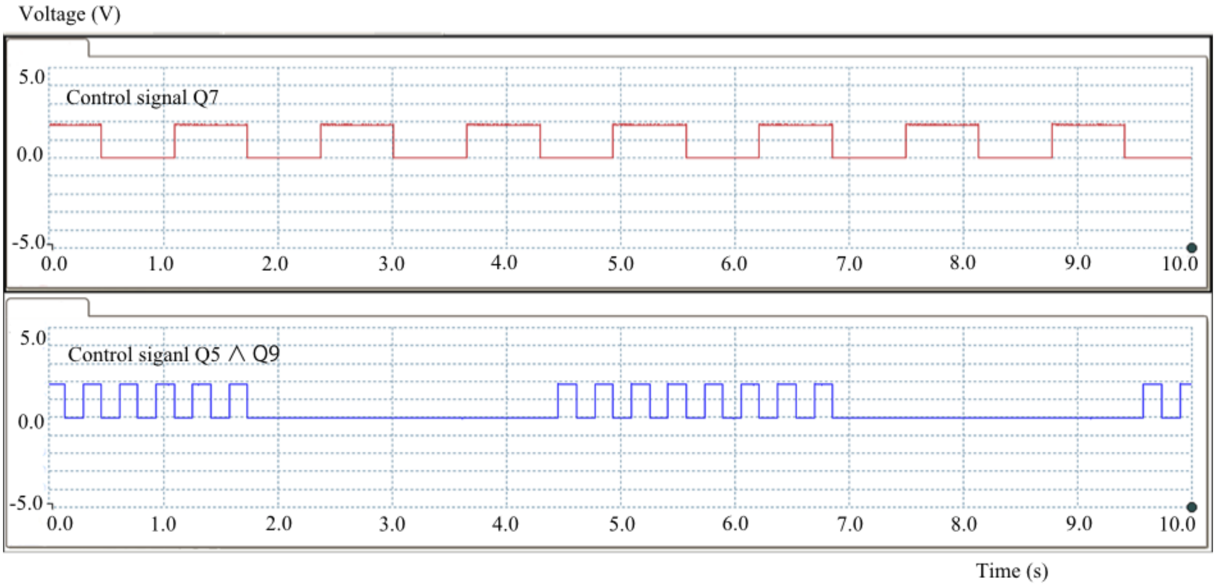


(b) Control signal of Q10 and Q8

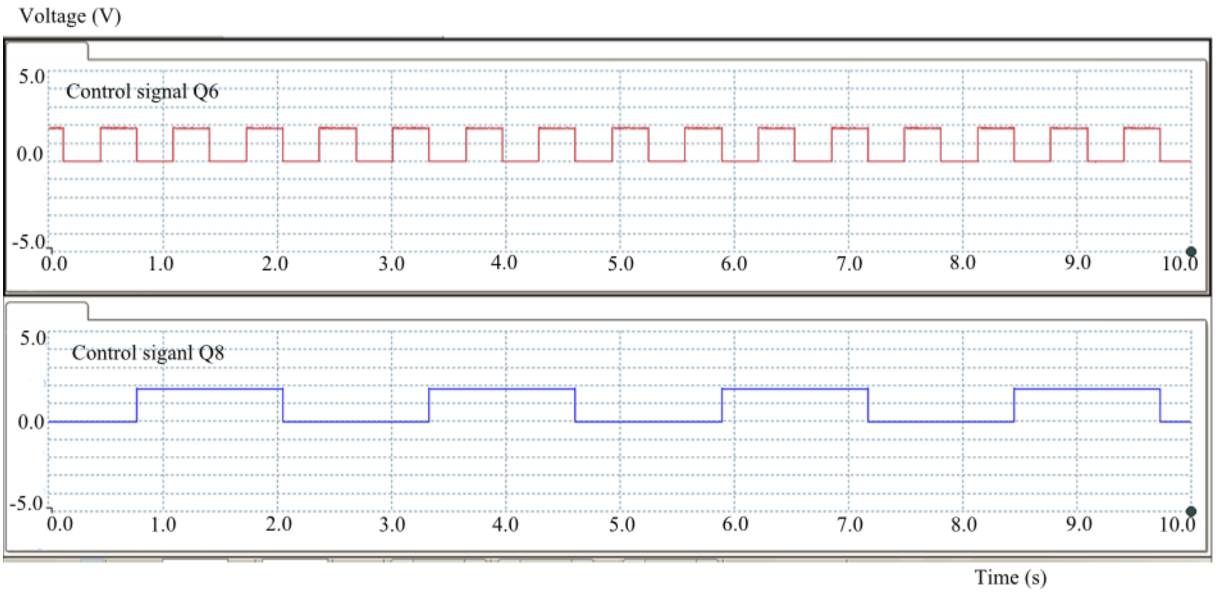
Figure 15. Control signal of block A



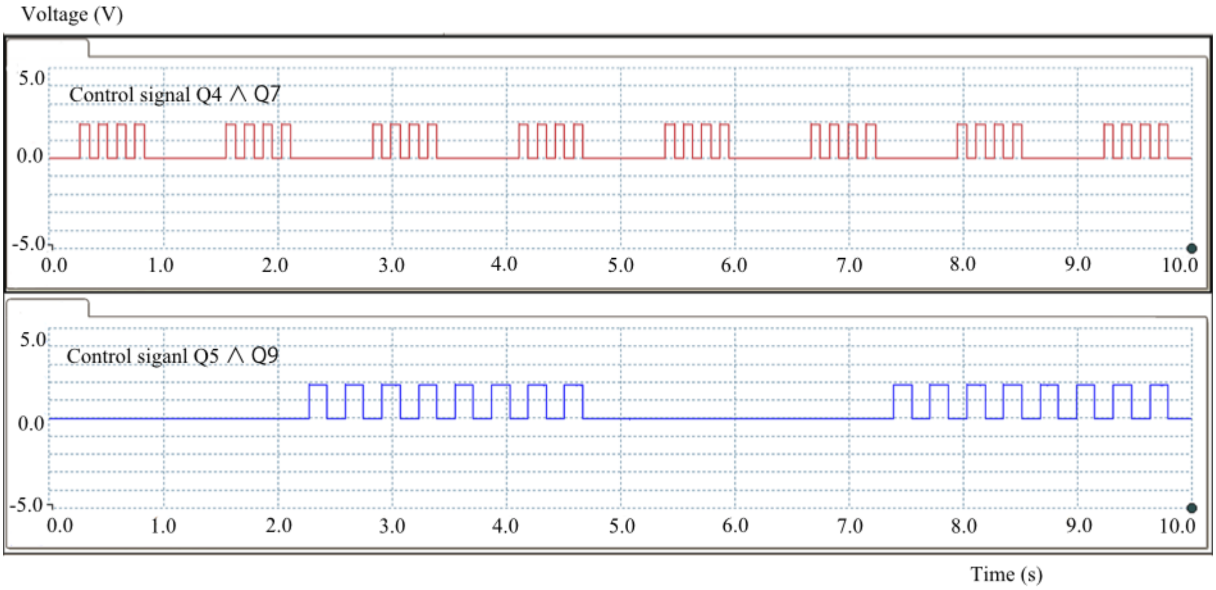
(a) Control signal of Q4 and Q5 ∧ Q8



(b) Control signal of Q7 and Q5 ∧ Q9



(c) Control signal of Q6 and Q8



(d) Control signal of Q4 ∧ Q7 and Q5 ∧ Q9

Figure 16. Control signal of block B

3. Digital circuit and control signal

From Figure 1, a binary counter that divides the frequency of an input signal was used for TC74HC4020AP (Toshiba Corp. 2014) of Toshiba Corp. The logical product of the output signals of a binary counter, TC74HC08AP (Toshiba Corp. 2014) of Toshiba Corp., was used. An analog switch, TC74HC4066AP (Toshiba Corp. 2008) of Toshiba Corp., that changes the control signals made by the binary counter and its logical product was used. From Table 1, the control signal of the voltage-control circuit of block A consists of signals $Q7$, $Q8$, $Q9$, and $Q10$, which divided the frequency by a binary counter. $Q7$, $Q8$, $Q9$, and $Q10$ are the output terminals of TC74HC4020AP. From Figure 1, the control signal $Q7$ or $Q10$ is input into a voltage-control circuit, and the voltage of an output signal from a band-elimination filter is controlled. The control signal $Q8$ or $Q9$ is input into a voltage-control circuit, and the voltage of a bypass signal is controlled. A player can change the control signals by a switch as needed. An example of these control signals is shown in Figure 15. When the measurement of the control signals is carried out, the input signal is a PWM signal with a frequency of ˜99.3 Hz and duty ratio of ˜50%. From Table 2, the control signal of the voltage-control circuit of block B consists of a signal that divided the frequency of an input signal by a binary counter and a signal that carried out the logical product of the output signals of a binary counter. Control signals are a combination of two signals and produce four patterns, A, B, C, and D. $Q4$, $Q5$, $Q6$, $Q7$, $Q8$, and $Q9$ are the output terminals of TC74HC4020AP. $Q5 \wedge Q8$, $Q5 \wedge Q9$, and $Q4 \wedge Q7$ are the signals generated by the logical product from TC74HC08AP. These control signals are shown in Figure 16. When the measurement of the control signals is carried out, the input signal is a PWM signal with a frequency of ˜99.3 Hz and duty ratio of ˜50%. From Figure 1 and Table 2, the four control signals output from a USB device are input into an analog switch, and patterns A, B, C, and D of the control signal, which carry out voltage control, are chosen by a computer. Through these control signals, the voltage control of an output signal of a low-pass filter, voltage control of an output signal of a bandpass filter, control of the cutoff frequency of a low-pass filter, and control of the center frequency of a bandpass filter are possible. USB-FSIO30 (Komatsu 2011) of Km2net was used as the USB device. This USB device was prepared using a dynamic link library (DLL), which can be coded in Microsoft Visual Basic 2010 Express. Therefore, a program can be created easily to output a control signal for input into an analog switch from the USB device.

4. Signal analysis

The frequency analysis was carried using the input signal and output signal of this filter. The PWM signal modulated by the low-frequency oscillator was input into this filter. The frequency analysis of an input and output signals is shown in Figure 17. The input and output signals were digitized with a sampling frequency of 44.1 kHz, and the linear quantization was 16 bits. The system requests a power spectrum by Burg's method of an auto-regression coefficient of the 48th order (Ishihara et al. 1988). One frame carries out frequency analysis of 100 ms of audio data (4410 samples). Next, the samples of one frame are shifted by 20 ms (882 samples), and the new audio data of 20 ms is input. This operation is repeated and a frequency analysis is performed for 20 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; $x(n)$ is expressed by formula 4. From formula 5, the frequency spectrum is normalized and allowed to compare an input signal and output signal (Tsuji 2018). $Y_e(f)$ expresses the frequency component and f expresses the frequency. $Z_e(f)$ expresses the normalized frequency component. From Figure 17, the frequency component of an output signal decreases by ˜12 kHz or less and increases by ˜12 kHz or more compared with the frequency component of the input signal.

$$x(n)\ (n = e \cdot s, e \cdot s + 1, e \cdot s + 2, ..., e \cdot s + (N-1), \\ e = 0, 1, 2, ..., 995, s = 882, N = 4410) \quad (4)$$

$$Z_e(f) = \frac{Y_e(f)}{\sum\limits_{f=0}^{20000} Y_e(f)} \\ (e = 0, 1, 2, ..., 995, f = 0, 1, 2, ..., 20000) \quad (5)$$

5. Application to synthesizer system

This study attempts to construct a synthesizer system using this filter. The basic structure of a synthesizer system is shown in Figure 18. From Figure 18, the line selector, which is an analog switch, was realized using TC74HC4066AP of Toshiba Corp. A synthesizer consists of a computer and a USB device. A computer program controls the PWM signal output from a USB device. The program has the function of a sequencer, which can carry out automatic composition (Tsuji 2015). The USB device USB-FSIO30 was used. Five PWM signals are output from the USB device. A computer chooses one of the four patterns of the line selector as the connection method. Four control signals are output from a USB device, and its control signals are input into a line selector. From the line selector, the four PWM signals are connected to Filter 1, Filter 2, Filter 3, and Filter 4. The connection method of the line selector is changed by a sequencer on a computer. The connection method of the PWM signal and filter is shown in Figure 19 and Table 3. PWM 1, PWM 2, PWM 3, and PWM 4 represent the PWM signals output from the USB device. Filter 1, Filter 2, Filter 3, and Filter 4 represent the analog filters that input a PWM signal. A PWM sig-

Table 1. Control signal of voltage-control circuit of block A

Signal to control	Output signal of BEF	Bypass signal
Control signal	Q7 or Q10	Q8 or Q9

BEF: Band-elimination filter

Table 2. Control signal of voltage-control circuit of block B

Pattern	A		B		C		D	
Signal and frequency to control	1	2	1	2	1	2	1	2
Control signal	Q4	Q5∧Q8	Q7	Q5∧Q9	Q6	Q8	Q4∧Q7	Q5∧Q9

1: Output signal and cutoff frequency of low-pass filter

2: Output signal and center frequency of bandpass filter

nal (PWM 5) is input to Filter 5 from the USB device directly. The cutoff frequency, center frequency, or phase of Filter 1, Filter 2, Filter 3, and Filter 5 are controlled by a sequencer on a computer using the control signals output from the USB device. Filter 1 and Filter 5 are a cascade connection of a biquad circuit and an all-pass filter, Filter 2 is the filter described in this study, Filter 3 is a cascade connection of a Sallen–Key circuit and biquad circuit (Tsuji 2018), and Filter 4 is a biquad circuit. The output signals of each filter are input to the six-channel amplifier. An input signal is distributed to a two-channel output using a voltage-control circuit, which is an analog photocoupler (Tsuji 2016). A control signal is input into a voltage-control circuit from the USB device, and a control signal is controlled by a sequencer on a computer. Therefore, it is a possible to control the localization of sound from the two-channel speaker connected to a six-channel amplifier. Five input signals are amplified with the six-channel amplifier, and the output signals of this amplifier are input into a six-channel speaker and played back (Tsuji 2016). All speakers are the author's original work (Tsuji 2015). The photograph of an actual synthesizer system is shown in Figure 20. The photograph of the complete system is shown in Figure 20 (a). The photograph of the sound-source part consisting of a synthesizer, a line selector, analog filters, and a six-channel amplifier is shown in Figure 20 (b). The arrangement of the speaker is shown in Figure 21. SP 1, SP 2, and SP 3 represent the arrangement of the two-channel speaker. Table 4 shows that because the line selector connection method considers a total of four possible patterns, the method for playback of the PWM signal with the two-channel speaker also involves four possible patterns. Furthermore, from Figure 21, because the localization of sound, like Pan 1, Pan 2, and Pan 3, is possible with a two-channel each speaker, this system can make a three-dimensional sound field using a line selector and six-channel amplifier.

6. Conclusion

This study attempted to carry out voltage control of an output signal from a low-pass filter, voltage control of an output signal from a bandpass filter, voltage control of an output signal from a band-elimination filter, voltage control of a bypass signal, control of the cutoff frequency of a low-pass filter, and control of the center frequency of a bandpass filter by using an input signal as a control signal. The input signal was a complicated control signal produced by a binary counter that divides the frequency of an input signal and carries out the logical product by an output signal from a binary counter. Thereby, the output signal of a low-pass filter, output signal of a bandpass filter, output signal of a band-elimination filter, and bypass signal were mixed intricately by a time series. It has been confirmed that this filter produces a rich sound signal. In the future, I would like to develop an analog filter and examine the analog filter and digital circuit again.

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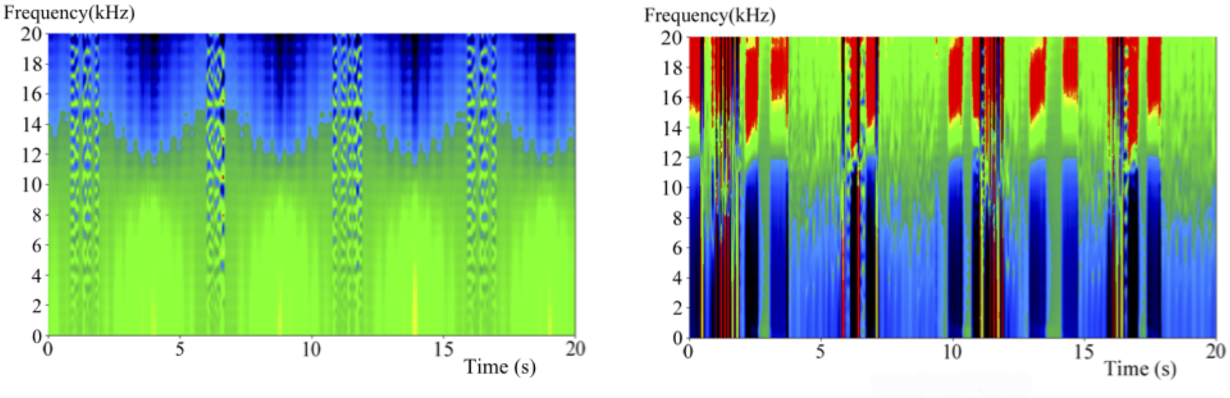


(a) Input signal

(b) Output signal

Figure 17. Frequency analysis of an input signal and an output signal

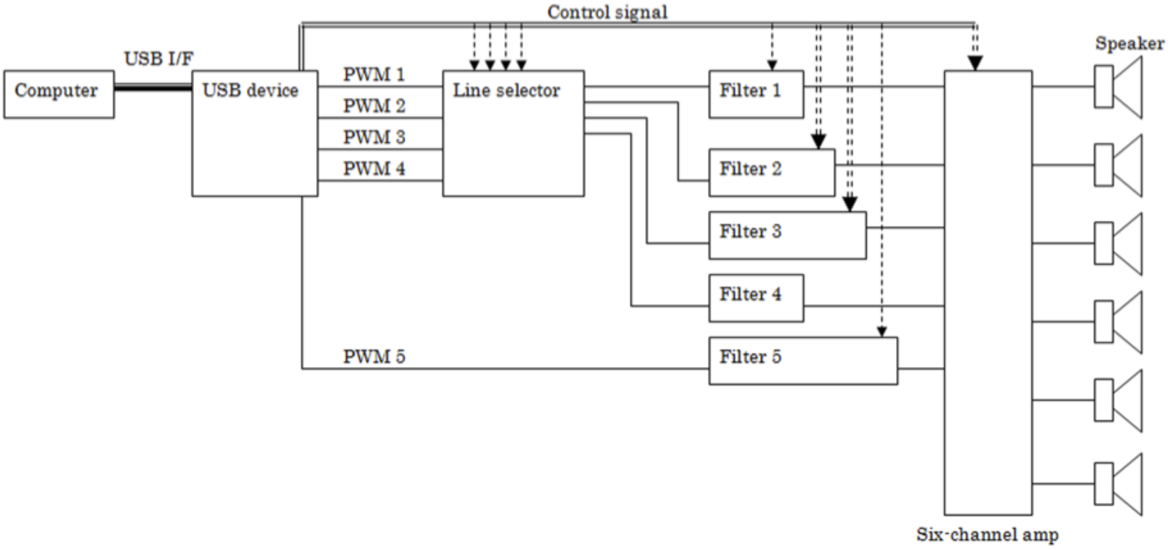


Figure 18. Basic structure of a synthesizer system

Table 3. Connection method of PWM signal and filter

PWM signal	PWM 1	PWM 2	PWM 3	PWM 4
Connection method 1	Filter 1	Filter 2	Filter 3	Filter 4
Connection method 2	Filter 3	Filter 4	Filter 1	Filter 2
Connection method 3	Filter 4	Filter 1	Filter 2	Filter 3
Connection method 4	Filter 2	Filter 3	Filter 4	Filter 1

Table 4. Methods for playing back PWM signal with two-channel speaker

PWM signal	PWM 1	PWM 2	PWM 3	PWM 4	PWM 5
Arrangement 1	SP 1	SP 2	SP 3	SP 2	SP 3
Arrangement 2	SP 3	SP 2	SP 1	SP 2	SP 3
Arrangement 3	SP 2	SP 1	SP 2	SP 3	SP 3
Arrangement 4	SP 2	SP 3	SP 2	SP 1	SP 3

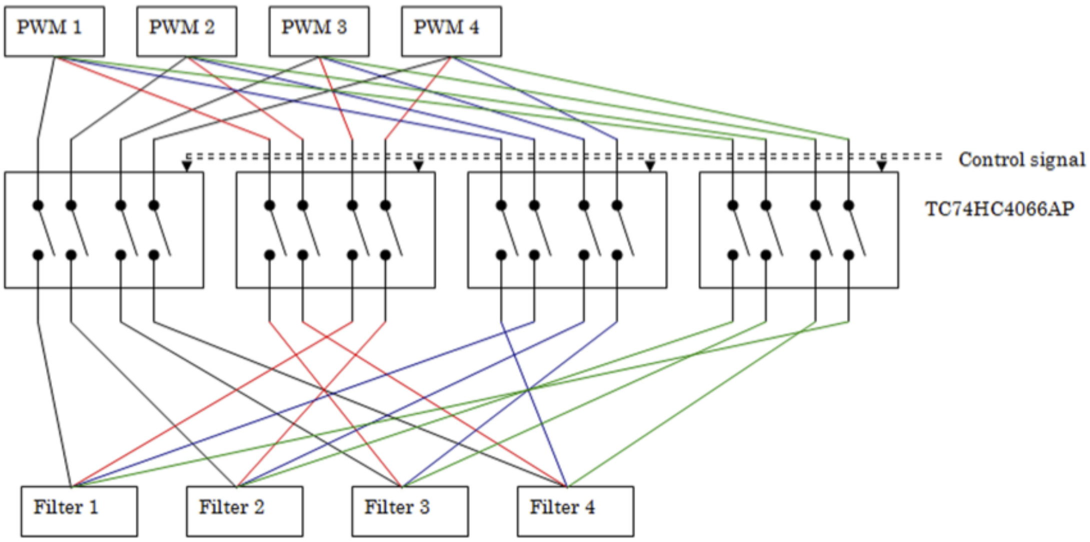
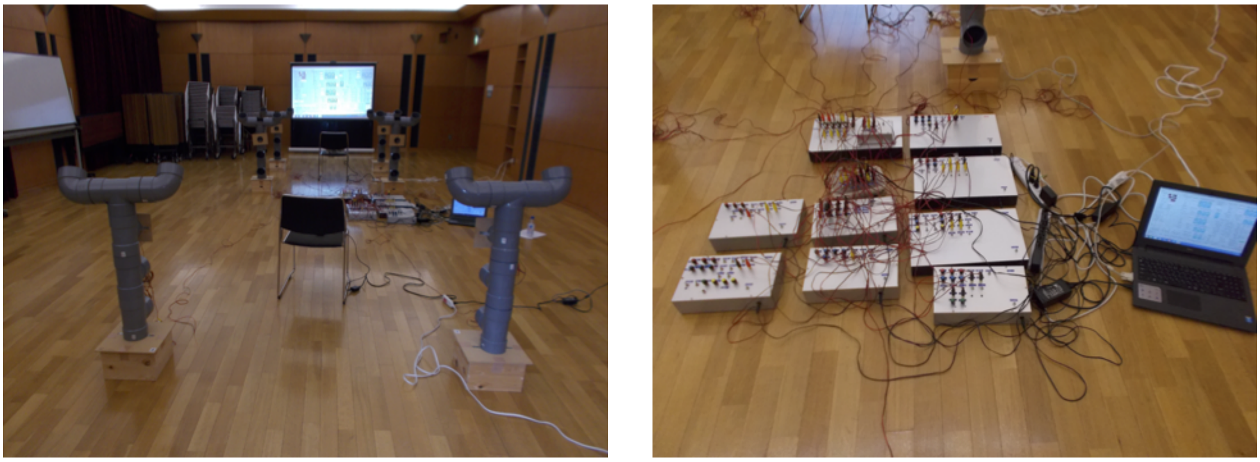


Figure 19. Connection method of PWM signal and filter



(a) Complete system

(b) Sound-source part

Figure 20. Actual synthesizer system

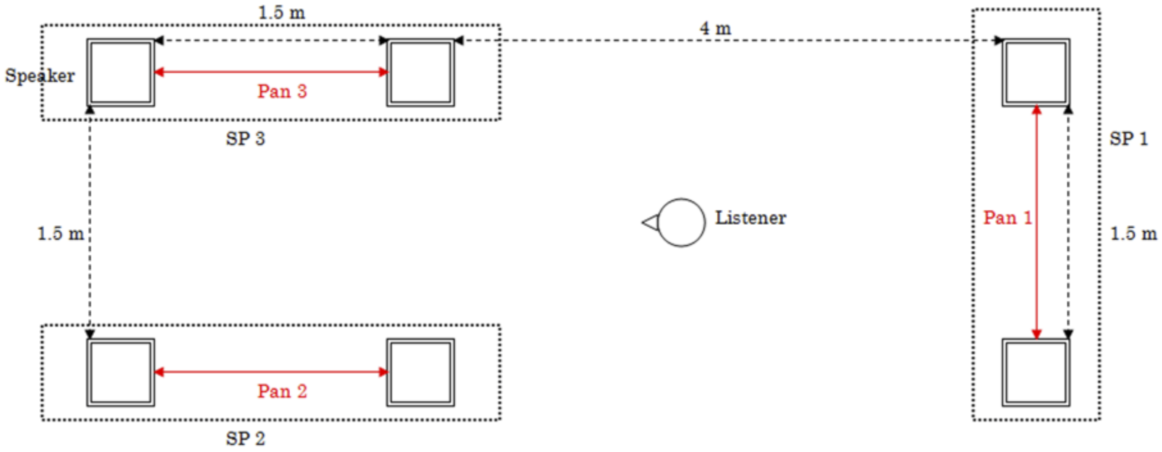


Figure 21. Top view of the speaker units

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7. 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.
